UPPER ORDOVICIAN STRATIGRAPHY OF THE SOUTHERN PENINSULA OF MICHIGAN

Thesis for the Degree of M. S.
MICHIGAN STATE UNIVERSITY
ROY DAVID NURMI
1972

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ABSTRACT

UPPER ORDOVICIAN STRATIGRAPHY OF THE SOUTHERN PENINSULA OF MICHIGAN

By

Roy David Nurmi

The Southern Peninsula of Michigan during the Late Ordovician was the location of a shallow, slowly subsiding basin centered in the Ogemaw County area. The deposition of an eastwardly thickening wedge of dark gray to black shale, the Utica Shale, was followed by interbedded limestones and shales. Lenses of red silty shales, Queenston Formation tongues, interfingered with carbonates and gray shales of the Michigan Basin. Maximum Upper Ordovician depths were reached during the deposition of a dark, organic basinal limestone (Unit Four) which was deposited slightly below wave base. Subsequent to the deposition of this basinal limestone was a regressive cycle which culminated in erosion along the southern margins of the basin and in supratidal evaporite deposition in the Upper Peninsula of Michigan. The close of the Late Ordovician in Michigan was marked by a very shallow restricted basin.

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UPPER ORDOVICIAN STRATIGRAPHY OF THE SOUTHERN PENINSULA OF MICHIGAN

By

Roy David Nurmi

A THESIS

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

MASTER OF SCIENCE

Department of Geology

1972

I dedicate this work to Carol Ann Nurmi, my life, my wife.

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ACKNOWLEDGMENTS

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INTRODUCTION

The Upper Ordovician shales and carbonates of the Michigan Basin are in close stratigraphic proximity to the prolific oil producing Trenton Formation and the gas producing Niagaran carbonates, but have received little attention from the geologic community. The isopach of the Upper Ordovician rocks (Plate 7) indicates that the Michigan Basin, as we know it today, existed during the Upper Ordovician. The basin seems to have been a rather shallow, stable basin centered slightly northwest of Saginaw Bay. Following the deposition of the eastwardly thickening wedge of dark gray to black shale, the Utica Shale (Unit One, Plate 1), was a transgressive-regressive cycle which ended with erosion on many of the arches which bounded the basin and with supratidal evaporite deposition in the Upper Peninsula of Michigan. The Upper Ordovician of the Michigan Basin has been subdivided into six regionally persistent rock-stratigraphic units (Figure 1).

PURPOSE AND SCOPE

Abundant subsurface data in the form of geophysical well logs, sample logs, and a small number of well cores are available for the lower half of the Southern Peninsula of Michigan. The northern edge of the dense control roughly corresponds to township fourteen north, or the southern shore of Saginaw Bay. North of this line only a small number of wells have been drilled to Ordovician age rocks.

PURE #1 EMERY
MIDLAND COUNTY
SEC. 21, T 13N, R 1W

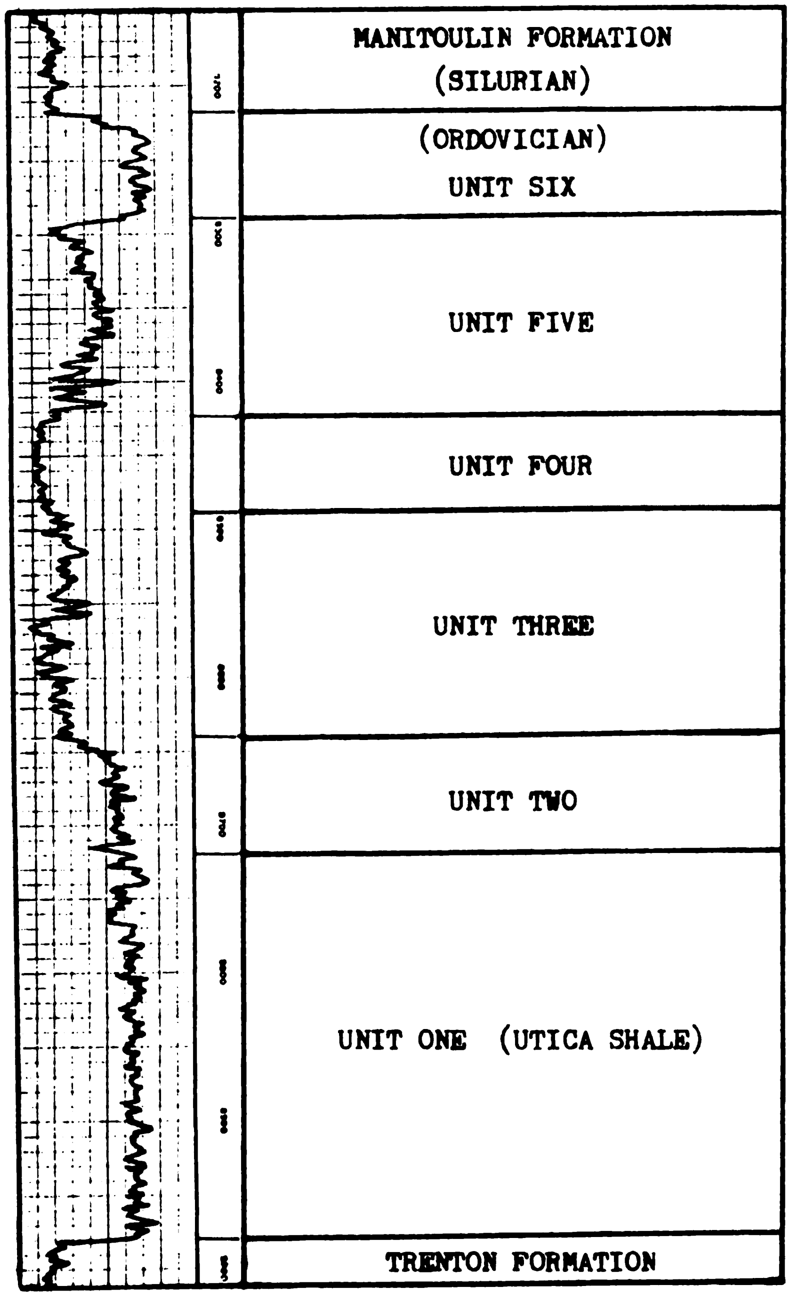

Fig. 1.- A representative Upper Ordovician subsurface section.

The primary purpose of this study is to determine persistent, regional rock-stratigraphic boundaries which may be used to subdivide the Upper Ordovician and to evaluate the vertical and lateral relationships of these units. The ultimate goals of this thesis are: 1), to relate the rock-stratigraphic units of the Michigan Basin to adjacent areas; 2), to determine the nature of the contacts of this group in the Michigan Basin; 3), to discern environments of deposition and areas of erosion during the Late Ordovician; and 4), to provide data with which we might better interpret the structural history of the Michigan Basin from Middle Ordovician to Early Silurian time.

ENVIRONMENTAL CONSIDERATIONS

Since the outlining of an environmental pattern should be the ultimate objective of a stratigraphic analysis, a very cursory discussion of the possible depositional environments of the Upper Ordovician is contained in this study. Only a gross macro-environmental sequence is considered. It is hoped that the general descriptions will encourage the study of this much ignored group of rocks in the Michigan Basin.

The stratigraphic environmental interpretations of this study are based on two important assumptions. The first is that there are no major erosional breaks within the Upper Ordovician section between the uppermost Utica shales and a pre-Manitoulin Formation unconformity. The second, according to Walter's Law, is that "the pattern of juxtaposed depositional environments of a geologic 'instant' is reflected in the stratigraphic column as a vertical sequence of rocks representing these various environments" (Johnson and Friedman, page 462, 1969). It is recognized that this is only an idealized model and that there will be minor variations, of a local nature, to the broad pattern exhibited.

The placement of the published Upper Ordovician fossils and depositional features into a sedimentary environment was accomplished using those models described by Laporte (1969), Walker and Laporte (1970), and Bretsky (1970). The publication by Walker and Laporte (1970) was employed to a greater degree than any other because the formations they studied were predominantly carbonates as are the Upper Ordovician strata examined in this study.

METHODS

The greatest source of information for the study of the Upper Ordovician rocks is the thousands of geophysical logs available for the Southern Peninsula of Michigan. Virtually all of the geophysical logs of wells which penetrated the Ordovician were studied and correlated during the course of this investigation. Well sample descriptions were examined, and samples were also checked for critical wells. Through the use of samples and geophysical logs, the Upper Ordovician Group was subdivided into six rock-stratigraphic units whose boundaries are identifiable using both logs and samples. Further subdivision was accomplished for local areas, but these units did not have the regional persistence of the aforementioned six.

Initial studies were carried out in the Albion-Scipio Trend Area to determine the existence of any persistent lithostratigraphic units. The hundreds of wells drilled along "the Trend" made possible the correlation of five persistent lithostratigraphic units for a distance of approximately forty miles in a northwest-southeast direction. The distance between each well never exceeded one mile, and it was possible, when necessary, to utilize wells spaced at distances of one thousand feet or less.

LOCATION

The area of study is the Southern Peninsula of Michigan (Figure 2), approximately 60,000 square miles. This area represents the central portion of the present-day Michigan Basin, a major structural feature of the North American Craton. The Michigan Basin, which has an area of 122,000 square miles (Ells, 1969), is bounded on the southern circumference by a series of arches and on the northern circumference by features of the Canadian Shield.

PREVIOUS INVESTIGATIONS WITHIN THE MICHIGAN BASIN

The only published investigations of the Michigan Basin Upper Ordovician Group are those of Cohee (1947, 1948, 1948). These studies were conducted as part of the United States Geological Survey's program of oil and gas investigations. Cohee recognized three lithostratigraphic units in southeastern Michigan, all three of which he characterized as shales. Cohee (1948) states that he was unable to carry the boundaries of these shales out of the southeast corner of the Michigan Basin, and hence, subdivision of the Upper Ordovician was not completed for the major portion of the basin.

Regional studies of the Upper Ordovician Group have been completed in many areas adjacent to the Michigan Basin: the Eastern Interior region (Gutstadt, 1958), southwestern Ontario (Sanford, 1961), northeastern Illinois (Buschbach, 1964), and Iowa (Parker, 1971). Recent conodont collections from the Upper Peninsula of Michigan should aid in

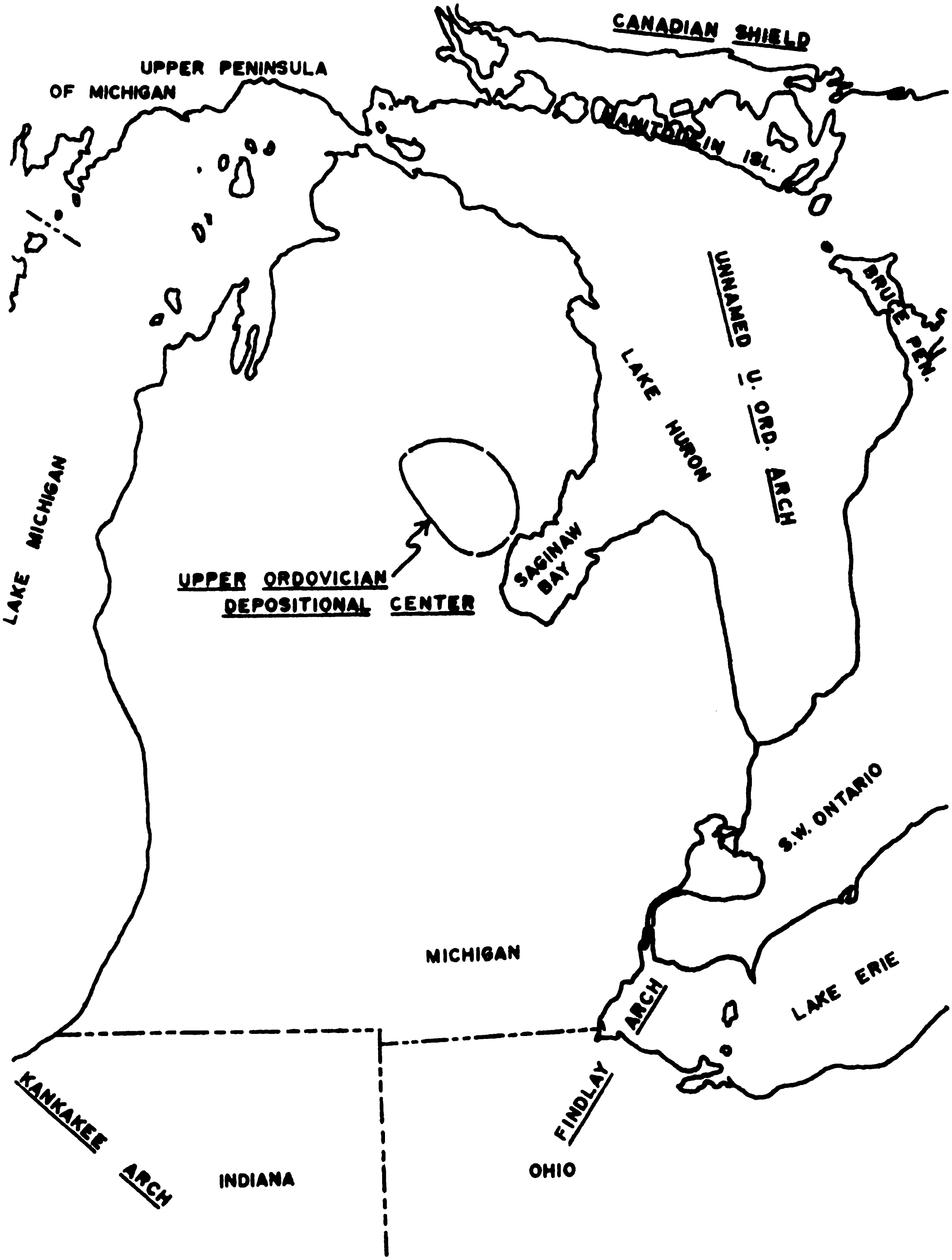

Fig. 2.- Location map.

the proper location of the Ordovician-Silurian boundary. The identification of Eden age graptolites (Berry, 1970) from the Utica-Trenton transitional beds indicates a more complete Upper Ordovician Series than postulated by Hussey (1950, 1952) in his study of outcrops in the Upper Peninsula. A core in Schoolcraft County (Ehlers et al., 1967) records the only complete rock section of the Upper Ordovician available in the Upper Peninsula, since only a small portion of the Upper Ordovician is exposed at outcrops. Three well cores which cut small portions of the Upper Ordovician Group in the Southern Peninsula of Michigan have also been described (Fauser, 1951; Coupal, 1954; and Wilson, 1955). In 1969 the Stratigraphic Committee of the Michigan Basin Geological Society published a set of cross sections for the Southern Peninsula accompanied by a publication describing many of the subsurface formations. The Stratigraphic Committee (1969) listed a two-fold division of the Upper Ordovician. The lower portion being the Utica Shale, a lithostratigraphic unit, and an upper portion of undifferentiated shales and limestones between the Utica Shale and the Manitoulin Formation. The outcrops of the Upper Ordovician rocks on Manitoulin Island, Ontario, and the Bruce Peninsula area of Ontario have been described by Liberty (1968, 1971 respectively). The Upper Ordovician section in the Cincinnati area has been divided into rock-stratigraphic units by Brown and Lineback (1966). Unfortunately, there are no published subsurface studies which help bridge the area between the outcrops and the Michigan Basin.

Formational units in the Southern Peninsula of Michigan were originally recognized by a mixture of biostratigraphic and lithostratigraphic criteria. The term "Utica" was introduced in the Great Lakes area by Ulrich (1888) who considered the Eden Shale, or Kope Formation,

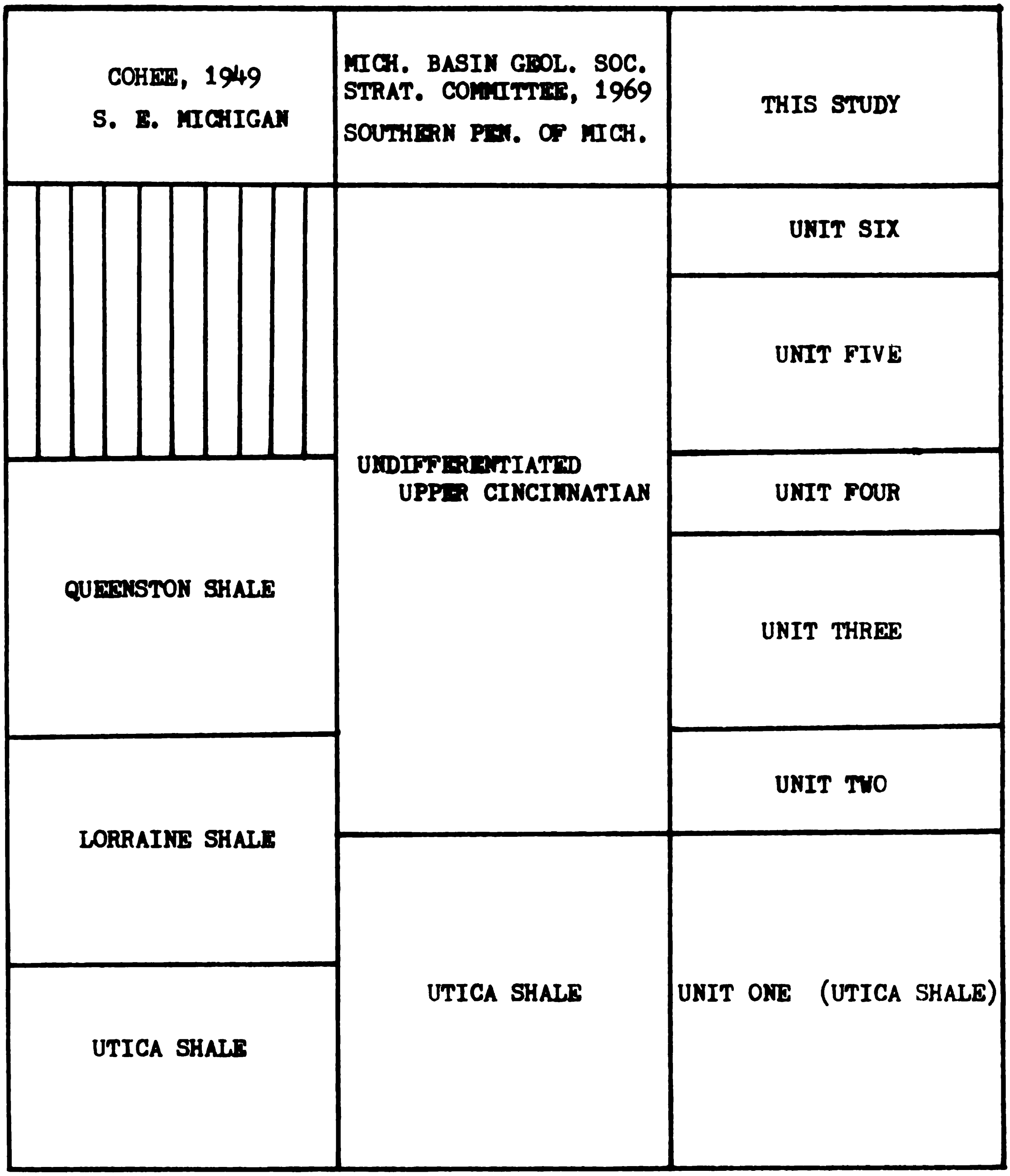

Fig. 3.- Southern Peninsula of Michigan Upper Ordovician subdivisions.

to be identical to the New York Utica Shale. Outside of New York, "Utica" as a formation name is no longer used, with the exception of the Southern Peninsula of Michigan. Although Cohee (1948) maintained that the Utica Shale was mainly "Utica" in age, he defined the unit, as well as the other two shales comprising the Upper Ordovician, on the basis of their lithologic characteristics. The Utica Shale was defined as a dark gray to black shale which could not be separated from the overlying Lorraine Shale west of Washtenaw and Lenawee Counties. Cohee believed that the unit continues across the basin to the Upper Peninsula where it is ten to twenty feet thick in the subsurface. Since Cohee's work, the upper boundary of the Utica Shale has been placed somewhat higher in the shale section (M.B.G.S. Stratigraphic Committee, 1969) and includes portions of Cohee's (1948) Lorraine Shale. It is the Utica Formation top defined by the M.B.G.S. Stratigraphic Committee (1969) which is used as the upper contact of Unit One. The contact of Unit One with the underlying Trenton is "one of the most clear-cut and reliable markers in the basin on both logs and samples" (M.B.G.S. Stratigraphic Committee, 1969) with the exception of the northern portion of the Southern Peninsula, where the Utica Shale interfingers with the Trenton Formation.

CORRELATION OF THE UPPER ORDOVICIAN WITH SOUTHERN ONTARIO

Excellent subsurface correlations into southern Ontario, Canada, are possible using Beards' (1967) and Sanford's (1961) subsurface stratigraphic studies. Beards (1967) tied his regional cross sections into the Consumer's Power Company, Brine Disposal Well # 1 in St. Clair County, Michigan. The subsurface Meaford-Dundas Formation plus the Collingwood Formation are rock-stratigraphic equivalents of Unit One,

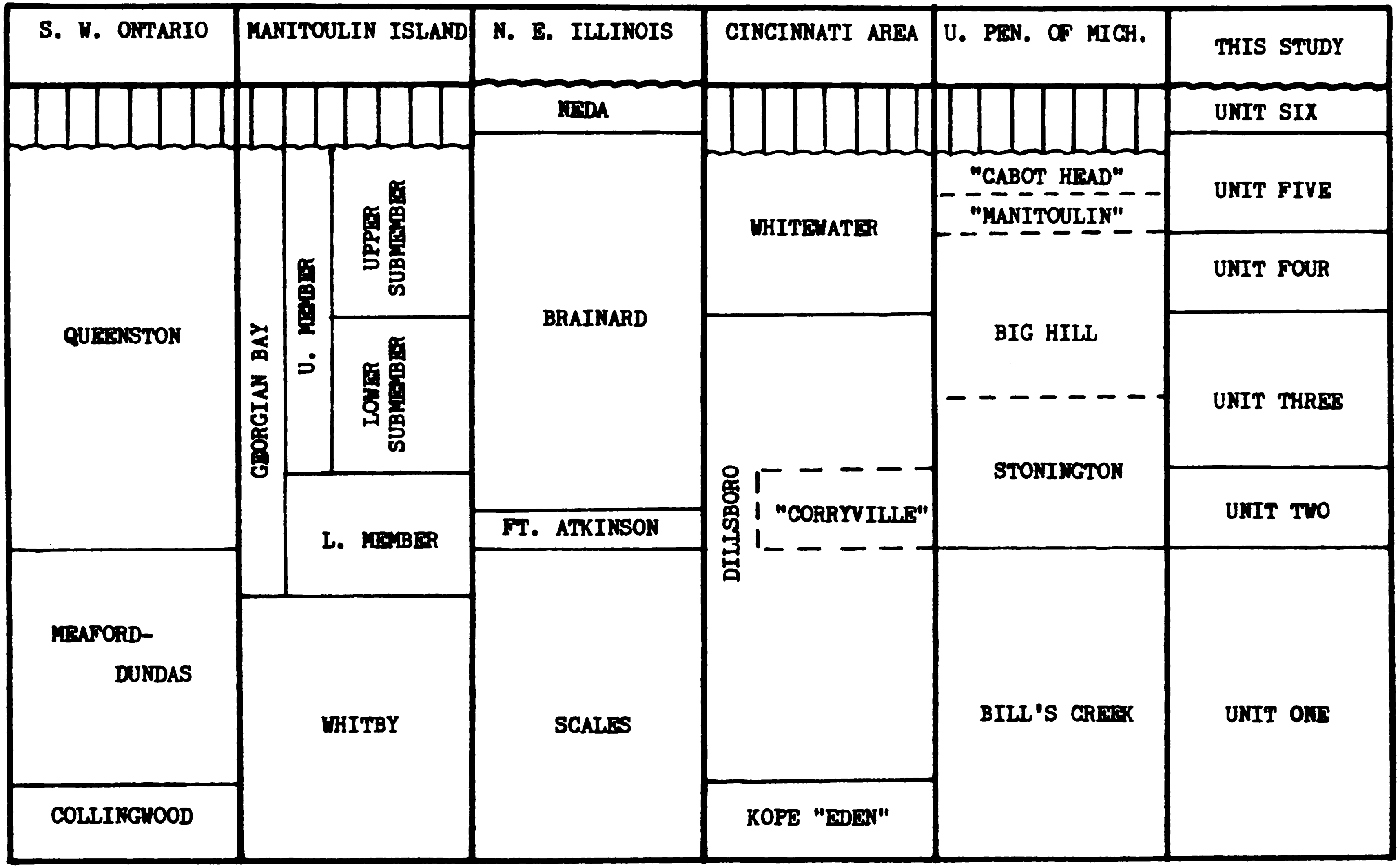

Fig. 4.- Regional Upper Ordovician correlations.

or the Utica Shale. The upper contact of Unit One in this well is at 3,270 feet, and the lower contact at 3,547 feet; thus the unit has a thickness of 277 feet. The section from 3,270 feet to the base of the Manitoulin at 2,987 feet is considered to be the Queenston Formation by Beards (1967). This section would include Units Two, Three, and a very thin Unit Four. Units Five and Six thin to zero in a southwesterly direction in southern St. Clair County. Unit Four, one of the best developed carbonate units of the Upper Ordovician, thins to less than ten feet in southern St. Clair County and grades into shale. The thinning is due to a facies relationship with the Queenston shales rather than an erosional thinning which is postulated for the absence of Units Five and Six. The carbonates of Units Two, and especially Three, also demonstrate a facies relationship, becoming more argillaceous and slightly silty approaching Ontario. The thinning of Unit Four coincides with an increase in red shale and a thickening of Unit Three towards Ontario.

Liberty (1971) describes the interfingering of the Queenston Formation with marine carbonates in the northern area of the Bruce Peninsula of Ontario. The Queenston Formation is absent on Manitoulin Island. On Manitoulin Island the Silurian Manitoulin Formation overlies the Upper Ordovician biostromal and dolomite Kongawong Formation.

NORTHEAST ILLINOIS CORRELATIVES

The Maquoketa Group of Illinois, Wisconsin, and Iowa has been divided into four formations (Bushbach, 1964) which can be correlated with the Upper Ordovician of the southwest corner of Michigan. The Scales Shale is the lithostratigraphic equivalent of Unit One, the Utica Shale. The Fort Atkinson Dolomite is correlative with the carbonate

member of Unit Two. The Brainard Shale overlies the Fort Atkinson Dolomite in northeast Illinois and is correlative with at least a portion of the interbedded dolomites and green-gray shales of Unit Three and the shale member of Unit Two. The Neda Formation consists of a few feet of red, hematitic oolite-bearing shale. The lithology of the Neda Formation is identical to that of Unit Six. This unit may have been continuous with the Neda Formation across the southwest corner of Michigan and later removed by Pre-Silurian erosion. The absence of Unit Four in a southwesterly direction, if due to a facies relationship, would make the division of Units Three and Five impossible to the west. The Brainard Shale appears to be equivalent to Unit Three, Unit Five, and the shale member of Unit Two. Both Units Three and Five consist of interbedded, argillaceous dolomites and silty, greenish-gray shales.

UPPER PENINSULA CORRELATIVES

The Upper Ordovician section of the Upper Peninsula of Michigan is only partially exposed, and the age relationships of some formations have recently been redefined. Eden age graptolites have been found in the lowest shales of the Upper Ordovician (Berry, 1970). Ordovician conodonts (Pollock *et al.*, 1970) were found in a shale identified by Ehlers (1957) as the "Cabot Head Formation." If one accepts the above-mentioned age determinations of Berry and Pollock *et al.*, the Upper Ordovician of Michigan would include a more complete Ordovician succession than Hussey (1952) recognized. Strata of Eden or Maysville age were not noted by Hussey. He suggested that rocks of these ages might never have been deposited in the Upper Peninsula or that they could have been stripped away by erosion. Eden age biostratigraphic determinations of the lowermost shales in the Upper Peninsula indicate that at least part of the interval between the Trenton age and the Richmond is present. Hussey's search for a major Upper Ordovician unconformity may be unnecessary.

The middle portion of the Bill's Creek Formation exposed at Delta County outcrops is described as unfossiliferous (Hussey, 1950, 1952). There are no descriptions of sedimentary features which might be of help in the interpretation of its depositional environment. The linguloid brachiopod, Leptobolus, has been recovered from the base of this unit and also in the upper portion. An increasing water depth is indicated by both fossil communities and sedimentological criteria for the transition from Unit One shales, the Bill's Creek Formation, into Unit Three carbonates, the Stonington Formation. A high intertidal environment is postulated for the upper portion of the Bill's Creek Formation.

The fossil communities of the Stonington Formation are analogous to the Zygospira-Hebertella Community of the Upper Ordovician of the Appalachians (Bretsky, 1970). As concluded by Bretsky, this community represented inner and outer sublittoral environments on a broad, gently sloping shelf. A low intertidal environment is recognized by Walker and Laporte (1970) for some of these genera. An even deeper water environment is intimated by the communities of the carbonates of the Big Hill Formation above the Stonington Formation. The fossil assemblage is comparable to the subtidal communities described by Walker and Laporte (1970) for the Middle Ordovician, Black River Group in New York. The shales, lying stratigraphically higher than the Big Hill Formation, were called the "Cabot Head Formation" by Ehlers and Kesling (1957). They represent a return to very shallow water depths and, eventually, supratidal and erosional conditions. The author is placing Ehlers' "Cabot Head Formation" in the Upper Ordovician as a result of the stratigraphic relations reported in this investigation and the Ordovician conodonts found in this unit by Pollock et al. (1970).

Ehlers and Kesling (1957) identified Leperditia in these shales as well as described pebbles of gypsum and bedded gypsum. Berdan (1968) maintained that Leperditia morphology suggests ostracod adaptations to temporary subaerial exposure. The over-all evidence indicates shallower water conditions continuing to supratidal evaporites. The evaporites are overlain by the dolomitic Moss Lake Formation (Ehlers and Kesling, 1957) which is the stratigraphic position of the Manitoulin Formation.

The Schoolcraft County core contains a similar sequence of deepening water depths upward from Unit One to a section containing lobate and digitate bryozoan growth forms, indicating a neritic below wave base environment. A return to shallower water conditions is postulated for a section with corals, becoming shallower upward. The uppermost Ordovician was deposited in a sabkha environment, which is typified by supratidal evaporites containing Leperditia. Ehlers et al. (1967) described a marine carbonate section above the supratidal unit which contains chert nodules and reworked gypsum from the unit below. The Silurian-Ordovician conodont boundary was placed within a few feet of this erosional interface through conodont dating (Pollock et al., 1969).

The Bill's Creek Formation is considered correlative with Unit One of this investigation. Unit Two is not clearly recognizable from Hussey's (1950, 1952) outcrop descriptions. It is possible that the persistent carbonate stringer at the top of the Bill's Creek Formation is the carbonate member of Unit Two. The erosional surface on the upper

surface of the persistent limestone unit may explain the absence of the shale member of Unit Two, which denotes a deeper water environment. The incompletely exposed Stonington Formation above the Bill's Creek is correlative with Unit Three. The lobate to digitate bryozoan section described by Ehlers et al. (1967) in the Schoolcraft County core, but not described in Hussey's outcrop studies, is roughly correlative with Unit Four. The section above this bryozoan unit is considered correlative with Unit Five and would include the coralline section just above the bryozoan unit and the remainder of the core including the supratidal evaporites. The Big Hill Formation (Hussey, 1950) and the "Cabot Head Formation" of Ehlers and Kesling (1957) are also correlative with Unit Five. Unit Six is absent due to erosion or nondeposition.

MICHIGAN-CINCINNATI AREA CORRELATIONS

A regional cross section from Lenawee County, Michigan, to the Cincinnati area was constructed to relate the outcrop studies of that area to this investigation. The use of the Cincinnati area formations in Michigan is impractical for the same reasons which caused Michigan geologists to drop the formation criteria utilized by Cohee (1948). The carbonate stringers dividing the Kope and Dillsboro Formations thin to zero in a northward direction. Unit One is correlative to the Kope Formation ("Eden") and the lower third of the Dillsboro Formation. The base of the "Corryville" limestone is correlative with the limestone member of Unit Two. A Dillsboro-Kope ("Maysville-Eden") contact can be carried from the Cincinnati area to southern Monroe County. North of Monroe County the shales equivalent to the Dillsboro and Kope ("Eden") are no longer divided by a recognizable limestone. The carbonates of the

Whitewater Formation correlate approximately with the interbedded carbonates and shales of Unit Four in southcentral Michigan.

NORTHWEST ONTARIO CORRELATIVES

Upper Ordovician outcrops on Manitoulin Island, Ontario, are more complete than those of the Upper Peninsula of Michigan. These outcrops have been studied by geologists since the end of the nineteenth century. Recently, Liberty (1968) divided the Upper Ordovician of Manitoulin Island into lithostratigraphic units which can in part be related to the units of this investigation.

The basal shales of the Whitby Formation overlap the Trenton Formation correlatives and lie disconformably on the Precambrian (Caley, 1936; Sproule, 1936). Erosion is indicated by the presence of breccias and conglomerates of Precambrian quartzite and Trenton-equivalent limestone in the black shales at the base of the Whitby Formation. The Whitby Formation and the lower member of the Georgian Bay Formation are correlative with Unit One and probably Unit Two also. The lowest 22 feet of the Whitby contains a fossil assemblage similar to that found in the basal and upper portions of the Bill's Creek Formation, the Unit One correlative on the Upper Peninsula. The fossil assemblage includes: species of Lingula, Leptobolus, Primitia, and two species of Serpulites. The shales above this lower fossiliferous portion are described as "sparsely fossiliferous, great thicknesses appearing to be barren" (Liberty, 1954, p. 11). The more important species reported by Liberty includes brachiopods found in the subtidal to intertidal range in Walker and Laporte's (1970) studies in New York. Bretsky (1970) placed these brachiopods and the gastropod Lophospira abbreviata in the sublittoral environment. These unfossiliferous shales are in turn overlain by a shale section in which limestone stringers are present in its middle portion. This interbedded shale and limestone sequence is the lower member of the Georgian Bay Formation and correlates with the upper part of Unit One in Presque Isle County, Michigan. The reported fossils of the lower member of the Georgian Bay Formation include genera which have been placed in the intertidal environment by Walker and Laporte (1970) and Bretsky (1970) and also include genera placed in the subtidal environment by these geologists. From the published reports, even a very sketchy environmental sequence cannot be presented for the transition from Unit One shales to Unit Three carbonate correlatives in the Manitoulin Island area. The upper member of the Georgian Bay Formation is in part correlative with Unit Three. The fossils described from this formation are those of a subtidal environment. Correlation of biostromes with units in the Southern Peninsula will have to await a detailed subsurface analysis of the Manitoulin Island formations in a direction towards northeastern Michigan. These biostromes may relate to Unit Four, but a possible correlation with the transgressive carbonates of Unit Three should be considered. To the south in St. Clair County, both of these carbonate sections persist as tongues into the Queenston Formation.

UPPER ORDOVICIAN ROCK-STRATIGRAPHIC UNITS

UNIT ONE

In the area of study the lithology of Unit One is almost entirely that of shale. The unit is thinnest along the western margin of the Southern Peninsula, thickening in an eastward direction above St. Clair County and in a southeastward direction below St. Clair County, forming a clastic wedge (Plate 8). Unit One continues to thicken eastwardly across Ontario (Sanford, 1961; Beards, 1967). The region of maximum thickness in the Southern Peninsula is in Lenawee County (Plate 10) where this unit is slightly thicker than four hundred feet. This thickening persists into central Ohio. As this unit approaches a thickness of four hundred feet in southeast Michigan, limestone stringers become prominent in the middle of the unit.

Typically, the unit darkens in color from a gray or dark gray, with occasional greenish tints in the upper portion, to a dark gray to black in its lowest portion. This generalization holds true whether the unit is two hundred or four hundred feet thick. In the area of Lenawee and Counties, the entire unit becomes browner in color, but the generalization of darkening still persists.

Anomalous areas of thinning and thickening of this unit (Plate 1) appear to be closely related to structures which have been mapped using the Trenton top as the structural datum. The thinning in the Howell Region of northern Livingston County coincides with a structural feature identified by Ells (1969). The Northville Anticline, a Trenton oil field with structural closure (Checkley, 1968), also coincides with an anomalously thin Unit One section. It is located in southwestern Oakland County and in the adjacent areas of Washtenaw and Wayne Counties. Areas of anomalously thick and thin Unit One sections in Washtenaw, Monroe, and Lenawee Counties could also be explained by tectonic influences in these areas (oral communication Fisher, 1972). "The Trend" area, evaluated by Ells (1962), is an area of anomalous thickening of the Unit One section which, due to the scale of the Unit One isopach map (Plate 1), is not demonstrated. Ells (oral communication, 1972) believes that the thickening was due to tectonic activity along "the Trend" rather than the solution erosional feature described by Rooney (1966). The apparent similarity of Ells (1962) Utica isopach map and the Trenton structure contour map to an erosional valley could be reconsidered in light of a Mariner 9 photo taken on January 12, 1972. This photo can be found on the cover of the February issue of "Geotimes." The feature photographed is described as "a vast chasm with branching canyons eroded in the adjacent plateau lands appears in this view ...." "The resemblance to dendritic stream patterns of Earth is probably superficial, for many of the 'tributary' canyons are closed depressions. Subsidence along lines of weakness in the crust, and possibly deflation by wind, may have produced the pattern." This writer refers to this martian feature not for an analogy to "the Trend", but to point out that features of totally different origins may look very similar, especially those studied only in the subsurface.

The thickening of the Unit One shale in Schoolcraft County (Plate 8) is probably best accounted for by a facies relationship with either the

Trenton below or the carbonates above.

UNIT TWO

Unit Two is a thin lithostratigraphic unit directly above Unit One, and has an argillaceous limestone at the base and a gray to dark gray shale above. The limestone unit thins towards the center of the basin, and for this reason, it would be possible to miscorrelate the top of the Unit One shale with the upper shale of Unit Two.

In the Northville Anticline area there is a distinct thinning of Unit Two towards the structure. The thinning is restricted to the shale portion of this unit and appears to be due to a facies change of shale to limestone.

The embayment of Unit Two in the Saginaw Bay area may be an indication of deeper water and the beginning of basinal development for the Upper Ordovician. The fact that this unit is not thicker in the center of the structural basin does not rule out the existence of deeper water conditions in that area. The model of a sediment starved basin described by Adams _et al_. (1951) should be considered for any environmental interpretation of the Upper Ordovician shales. Starvation within the basin is caused by deposition of the sediments shoreward in such a manner that little deposition takes place in the basin center.

UNIT THREE

The lithostratigraphy of Unit Three represents a complex pattern of lithologies which in future studies of a more local nature should be subdivided. An acceptable regional subdivision was not feasible during this investigation, but with a detailed environmental analysis, it is probable that the subdivision of this unit is possible. A very general discussion of the lithologies and possible environments of deposition is presented in this study.

Unit Three in the Monroe and Lenawee Counties area is predominantly a gray to greenish-gray shale section with interbedded, gray argillaceous limestones. The limestone stringers thicken northwardly into the Michigan Basin (Plate 10).

In a southeastward direction away from the center of the basin and towards St. Clair County, the limestones interfinger with red and greenish-gray shales of the Queenston Formation of Ontario (Plate 8). The reddish shales become siltier and thicken in a southeastward direction.

In a southwestward direction the carbonates of Unit Three become dolomitic, and there is also an increase in shale content (Plate 9). The shale changes from gray shales at the basin center and Lenawee County area to greenish-gray shales which become dolomitic in a westward direction. The dolomitization in the southwestern area of Michigan may represent either an early dolomitization, indicating shallower conditions, and/or a later stage of dolomitization. It was not possible to determine which is the case at this time.

UNIT FOUR

Unit Four is a massive, slightly argillaceous, dark brown limestone in the basin center. By Folk's (1959) limestone classification, Unit Four is a biomicrite, with bryozoans being the predominant fossil allochem. In the center of the basin the unit is bounded by the fossiliferous units Three and Five. In the Brazos-Sun-Superior, State-Foster # 1 well in Ogemaw County, the fossiliferous section below Unit Four includes coral material. Associated with Unit Four are thin, black, very carbonaceous fissile shales. Unit Four thins uniformly in all directions (Plate 4) except south and southwest from the area of maximum thickness at the center of the structural basin. A broad area of constant thickness exists in the Allegan-Barry County area. This area is also anomalous on isopachous maps of Units Five and Six (Plate 5, Plate 6 respectively). The greatest anomaly to the uniform thinning of Unit Four is a region centered in western Lenawee County. In this region Unit Four thickens to over ninety feet. The limestones are less massive, gray, and much lighter than the dark brown limestones of Unit Four in the basin center. This unit with a few carbonate stringers above persists well into the red Queenston shales of Saniliac County and northern St. Clair County (Plate 8).

UNIT FIVE

Unit Five is a sequence of interbedded carbonates and shales. The carbonates are argillaceous limestones in the center of the basin and grade into dolomites both vertically and laterally. The shales tend to be a gray to gray-green color in the center of the basin and grade laterally and vertically into green and red shales containing gypsum. This unit thickens to a maximum of 248 feet in Ogemaw County and thins to zero in southern St. Clair County and southwest Berrien County (Plate 5). Approaching southern Ontario from northern St. Clair County (Plate 8), there is a facies change from thin, gray carbonates and shales to a lighter gray, slightly siltier, occasionally red shale sequence. The thinning may be a consequence of nondeposition to the east, but the rapid thinning may be due in part to Late Ordovician or Early Silurian erosion.

In three Southern Peninsula counties this unit has been cored; two of these cores have been described (Coupal, 1954; Wilson, 1955). The fossils identified by Coupal (1954) from the Sun Oil Company, Horning # 1 well drilled in Washtenaw County appear to be of little help in establishing a Silurian-Ordovician boundary. Unit Six is absent in this area so we can expect the transition to be from the Manitoulin Formation into Unit Five. By the log and sample criteria, the contact should be placed at 3,193 feet. From the core description at this depth, there is a change from light gray dolomite to dark greenish-gray shale with one inch of black shale near the top. Brachiopods and bryozoans are locally abundant in the 25 feet of greenish-gray shale below the Manitoulin dolomite. The genera identified are common to both the Ordovician and Lower Silurian. The dolomite stringers below this fossiliferous shale become argillaceous and darker, ranging from dark brown to dark gray. Within this section there is an increase in gypsum along with nodular dolomite, an intraformational conglomerate, and occasional pebbles of shale. Fossils are rare to poorly preserved in this lower shale sequence from 3,218 to 3,240.5 feet.

Although a Silurian-Ordovician boundary would be picked at 3,193 feet by log and sample analysis, the regional consideration of Unit Five might best be explained by an Ordovician or Unit Five top placed below the fossiliferous shale and just above the more supratidal, and perhaps erosional, section at 3,218 feet. A systemic boundary could be verified by microfossil analysis as done in Indiana (Shaver, 1964) and various Upper Peninsula areas (Pollock et al., 1970).

A core from Oakland County was of greater assistance in placing a Silurian-Ordovician boundary by macrofossils. Wilson (1955) described this core and the fossils present in it. Wilson located the boundary at a sharp lithologic change from clean limestones and dolomites of the Manitoulin Formation to the argillaceous limestones and dolomites of the Upper Ordovician. Marking this boundary are green shale partings which contain a specimen of Hebertella sinuata (Hall), an index fossil of the Upper Ordovician. The 51.5 foot thickness of the Manitoulin Formation fits in well with the thickness of the formation in this area. Unfortunately, a geophysical log was not run on this well. All of the brachiopods collected below the Manitoulin Formation and identified by Wilson have also been observed in the Richmond age rocks of Ontario.

The lack of any shallow water criteria, especially gypsym, is understandable in that the isopach line convergence may indicate erosion in the area of the well core (Plate 5). The truncation of the upper portion of Unit Five represents rapid thinning; hence, a well which is within this zone could be expected to have an incomplete sedimentary cycle.

Other evidence of erosion of this unit, and Unit Six above, can be found in the southwestern area of the Lower Peninsula. A pattern of thin and thick areas mapped for this unit strongly suggests erosion (Plate 6). The anomalous thicknesses of Unit Six correspond with thick zones of Unit Five (Plate 5). Similarly, the thinning of the two units is related. There is no evidence that the thickness variability is caused by structural features below. Unit Four maintains a fairly uniform thickness throughout the area in question, supporting the idea that the thinning is related to a post-Unit Four event. Thinning by erosion subsequent to the deposition of Unit Six explains the isopach patterns under consideration. This conclusion is reinforced by studies of the Upper Ordovician of northeast Illinois (Workman, 1950; Willman, 1971) which indicate uplift and erosion following Upper Ordovician deposition.

Unit Six is highly radioactive on gamma-ray curves. The upper contact is sharp and easily placed in areas where Unit Six is present. As one nears the margins of the basin, where Unit Six is commonly absent, Unit Five is overlain by the dolomites of the Manitoulin Formation. The carbonate stringers of Unit Five in these marginal areas are usually dolomite, which causes a problem in placing the Ordovician-Silurian boundary. It was noted during the course of this study that the basal portion of the Manitoulin Formation often contains chert, which, if regionally persistent, could be a valuable stratigraphic marker.

Tiny black gastropods (steinkerns) are frequently found in well cuttings from Unit Five. Min Din (1950), in an examination of Ordovician microfossils from four wells located in the Southern Peninsula, described the steinkern genera Cyclora in two of these. He also identified the gastropods Hormotoma gracilis and Maclurites magnus in the lower portion of Unit Five. Ells (oral communication, 1972) of the Michigan Geological Survey has found steinkerns in three additional wells, and this writer has noted steinkerns in samples from thirteen more wells in the Southern Peninsula. They are invariably found in Unit Five, although in a few cases, they have also been reported from lower units. In the Upper Peninsula outcrops, Hussey (1950) recovered Cyclora from all of the Upper Ordovician formations with the exception of the coral biostrome, the Bill's Hill Formation.

In the Treatise on Invertebrate Paleontology (Knight, 1960), the geologic range for Cyclora is cited as the Upper Ordovician. Cyclora is described as a "naticiform, very minute, probably based on steinkerns of protoconchs of some other genus, possibly Cyclonema, locally very abundant" (p. I309). The range of Cyclonema is from the Middle Ordovician to the Upper Silurian. The abundance of the steinkerns in Unit Five makes them a potentially valuable stratigraphic marker for the Upper Ordovician, especially in areas where Unit Six is absent.

UNIT SIX

Unit Six has the smallest areal distribution of the Upper Ordovician units. This unit may have been physically continuous with the Neda Formation of northeast Illinois and eastern Wisconsin but later removed from marginal areas of the Michigan Basin. It attains its maximum thickness in excess of 150 feet in Ogemaw County. This unit is dominantly one of red shale in the southern portion of the basin with dolomite stringers increasing in a northward direction. In Newaygo, Allegan, and Mason Counties, oolitic hematite has been recovered from Unit Six. The Turner Petroleum Corporation, Bradley # 4 well in Newaygo County, cored approximately two feet of Unit Six just below the Manitoulin Formation limestones and dolomites. The Unit Six section in this core is a shale: dark red, hematitic and very hard. It contained many small, flattened, spheroidal shaped bodies, producing a texture referred to as flax seed iron ore. Fauser (1951) identified three genera of Conularida in the core and states that "Dr. G. W. Sinclair (personal communication) informed the writer that he has never found the genera of Conularida present in the core in any epoch above the Upper Ordovician" (p. 25). Oolitic hematite was also reported in the samples of Unit Six from the

Superior Oil Company, Sippy # 17 well in Mason County and in a well from Allegan County.

UPPER ORDOVICIAN TECTONICS

The total Upper Ordovician isopach map (Map 7) demonstrates a Michigan Basin centered in Ogemaw County and displays a remarkable similarity to the Trenton structure map. The Canadian Shield to the north was probably stable throughout the Upper Ordovician and provided little terrigenous clastic sediment to the Michigan Basin. This stability is particularly indicated by the uppermost portion of the Ordovician which has a nondetrital facies for both Units Five and Six in the northern half of the Southern Peninsula.

The basin is separated from Ontario by an area of thinning which roughly parallels the center of Lake Huron (Plate 7) and which crosses the western portion of Manitoulin Island in a northward direction. South of Lake Huron this thin area is coincident with the St. Clair River and Lake St. Clair, and it continues southwardly through the western tip of Ontario. This arch is not coincident with the Algonquin Arch which has been defined as a structural feature from Trenton structural studies in Ontario. Although Cohee (1948) also mapped the thinning along the Lake Huron median, he applied no name to it. This arch did not develop until the period of deposition of Units Four, Five and Six. Erosion, or non-deposition, is suggested by the rapid thinning of Units Five and Six in the direction of Ontario. It should be noted that the Precambrian high on Manitoulin Island is along this general isopach thin trend. The incomplete Upper Ordovician sedimentary depositional sequence is present on Manitoulin Island. The thinning may be related to a lack of deposition, a pre-Manitoulin Formation period of erosion, or a combination of these two alternatives. Whichever the case, a feature affecting the sedimentation is evidenced.

There is another area of Upper Ordovician thinning between the Michigan Basin and a northwestern extension of the Appalachian Basin in Lenawee and Hillsdale Counties. This feature indicates nondeposition and/or erosion during the time of deposition of Unit Five through the deposition of the Manitoulin Formation. This region of thinning between the two basins has been described by Ells (1969) as the Washtenaw anticlinorium. He asserts that no significant amount of thinning occurred in the Trenton-Black River rocks over the higher parts of the structures located in this anticlinorium.

Thinning of Units Three, Four and Five towards Lake Erie from the southeast corner of Michigan could be a facies relationship to shallower water sediments towards the east. Without any subsurface information for the Upper Ordovician in northern Ohio, the thinning cannot alone be used to identify the structural Findlay Arch. The thinning, however, is towards the area where the Findlay Arch has been described. To the south in the Cincinnati Arch area, erosion of the Upper Ordovician has been shown by many studies, including a recent Silurian investigation by O'Donnell (1972).

Erosion is suggested for the southwestern corner of the Southern Peninsula approaching the Kankakee Arch. Studies by geologists in northeastern Illinois, which have been cited earlier, give additional proof of erosion along the Kankakee Arch following the deposition of the Upper Ordovician. Thinning of the units below the erosional surface has also been demonstrated, indicating that this feature affected sedimentation during the Upper Ordovician.

Over each of the above arches adjacent to the Michigan Basin, erosion, or at least nondeposition, is shown to have taken place during the time of Units Five and Six. Unit Four thins towards each of these arches from the center of the basin, suggesting that the arches were affecting sedimentation at the time of Unit Four deposition. The marked thickening of Unit Four and the units above in the center of the basin intimates that subsidence may have been more pronounced towards the end of the Upper Ordovician. The water depth at the center of the basin was probably never below wave base with the possible exception of Unit Four which may represent low energy carbonate deposition just below wave base.

DEPOSITIONAL ENVIRONMENTS

ORDOVICIAN ENVIRONMENTAL SETTING

If paleomagnetic data are correct, the area which is now the north-central United States was close to the equator during the Upper Ordovician (Dott and Batten, 1970). The Southern Peninsula of Michigan has been placed on the western margin of the Upper Ordovician Appalachian Mobile Belt which was filled by clastic sediment derived from an eastern source area. The Upper Ordovician clastic sediment becomes finer in grain size in a westerly and northerly direction from central Pennsylvania. During Richmondian time, a delta or a clastic wedge prograded in a westward direction. These clastic sediments interfinger with marine carbonates in the central Appalachian area (Thompson, 1969) and in Ontario (Liberty, 1971). It is recognized that the Queenston Formation clastics continue into Michigan in St. Clair, Macomb, Wayne, Sanilac, Lapeer, and parts of Tuscola Counties. Although silt is common, very little sand size detritus is present in the Queenston Formation of Ontario or in the clastic tongues in eastern Michigan. Since the strata evaluated in this study includes the section between the Trenton Limestone and the Manitoulin Formation, a stratigraphic problem is encountered in central Ohio and central Ontario. In these areas the Whirlpool Sandstone lies below the Manitoulin-Brassfield Formation and above the Queenston Formation. Although the Whirlpool Sandstone is considered Silurian in age, this writer finds it plausible that this sandstone represents a final clastic stage of deposition of the Queenston delta-clastic wedge. Knight (1969) considered this sand unit to be a strand plain deposit in central Ohio, and Martini (1971) also considered these sands to be littoral in northwestern New York and in the Niagara Peninsula.

The lower portion of the Upper Ordovician, Unit One (Utica Shale), needs more study if the environmental history of the Ordovician in Michigan is to be understood. The interbedded limestone stringers, which are common in the southeastern counties of Michigan, in northern Ohio, and in the Cincinnati area, pinchout northwardly and westwardly leaving a thick, undifferentiated shale section. It is possible that this shale section ranges from supratidal to subtidal below wave base as does the predominantly carbonate section above, but due to reducing geochemical conditions, suitable fossil criteria may be very sparse. If the Unit One age sea was poorly oxygenated, perhaps as a result of decomposition of vegetation, the sedimentary depositional and erosional criteria associated with varying kinetic energy zones may also be very different from those applied in most geological studies today.

The contact of the Unit One shale with the carbonate section below may be conformable in some areas, such as in the Cincinnati area (Anstey and Fowler, 1969). The erosional surface recognized by Rooney (1966) at the top of the Trenton Formation in Indiana may represent intertidal erosion (Weiss, 1958) rather than a prolonged period of erosion. For a long time it has been generally accepted that there are no Eden age equivalents present to the north in the Upper Peninsula or to the west in Iowa, but recent paleontological work has shown this assumption to be false (Berry, 1970; Herr, 1972). Graptolite finds, together with conodont studies in the Upper Peninsula, will have to be evaluated very carefully as they indicate the need for reconsideration of the present Upper Ordovician geological history of the central United States.

DEPOSITIONAL ENVIRONMENT OF UNIT ONE

Unit One can be correlated with the Bill's Creek Shale of the Upper Peninsula described by Hussey (1950, 1952). The lower portion of the Bill's Creek Shale is unfossiliferous, with fossil content increasing upward in the section. Unfortunately, nowhere on the Upper Peninsula is there a complete section of the Bill's Creek Shale exposed. From the faunal assemblage described, the exposed upper portion contains an intertidal community ranging from high intertidal to low intertidal. The most abundant fossils of this section are: Lingula and Leptobolus brachiopods; ostracode genera, including Tetradella and Primitia; the pelecypod genus Cleidophorus; the annelid genus Cornulites; and a bryozoan, Arthropora shafferi. The occasional occurrence of small dessication features, "numerous water-worn specimens of Cleidophorus" (Hussey, p. 45, 1952), and numerous mud lumps add to the interpretation of an intertidal to near-shore environment for the upper portion of the shale section. The top of the Bill's Creek Shale is marked by a persistent, fine-grained argillaceous limestone member having a distinct erosional upper surface. Immediately above this unconformity, there is a coarsely crystalline argillaceous limestone with a basal conglomeratic unit. Hussey (1950) states that innumerable water-worn fragments of Isotelus are found at the base of the limestone above the unconformity. Although the section above the Bill's Creek Shale is not completely exposed, the fossils described by Hussey are of deeper water communities ranging perhaps from the low intertidal community to high subtidal. The biota contains some anthozoans and numerous genera of bryozoan and brachiopods. The irregular surface and conglomeratic zone can be formed in littoral to sublittoral environments, so the "disconformity" need not be due to subaerial erosion.

Ehlers et al. (1967) described a core from a well drilled approximately twenty miles from the type locality of the Bill's Creek Shale in Schoolcraft County which is the only continuous rock record of the Trenton-Utica transition in northern Michigan. Immediately above a 72 foot section of Trenton limestone, there is a conglomerate one and one half inches thick overlain by a dolomite. On top of the dolomite is a calcareous shale which in turn is overlain by a nine foot limestone. Above this nine foot, fossiliferous limestone lies Unit One. The linguloid brachiopod, Leptobolus, was recovered from the lower four feet of this shale.

In placing this shale unit into a very shallow environment, the stratigraphy of Manitoulin Island bears mentioning at this point. Unit One lithostratigraphical equivalent shales rest locally on the Precambrian quartzites (Liberty, 1954). The absence of Trenton-like carbonates is most simply explained by regarding the shale to be of a shallower depositional environment than the carbonates below. The fauna described for the lowermost sequence of shale is similar to that of the upper portion of the Bill's Creek Shale. The fossils described include species of Lingula, Leptobolus, the ostracode genus Primitia, and two species of the annelid genus Serpulites.

DEPOSITIONAL ENVIRONMENT OF UNIT TWO

Throughout the Southern Peninsula of Michigan Unit Two is a limestone-shale couplet, with the limestone being the lower member. In the Northville Anticline areas the limestone percentage in this unit increases while the shale content correspondingly decreases. The thickness of Unit One below undergoes a marked decrease in the Northville Anticline (Plate 1). Towards the center of the Michigan Basin the shale content of the Unit Two couplet increases to the point that the correlation of this unit becomes difficult. The shale content increases towards the basin center, and its decrease over structures seems to indicate that the shale represents deposition in a slightly deeper environment than the limestone associated with it. A deeper environment for the shale is supported by the fact that the shale of this couplet is also lost in marginal directions.

DEPOSITIONAL ENVIRONMENT OF UNIT THREE

Unit Three represents a complex of depositional environments which might be better understood if the unit was subdivided. In the center of the basin the unit is predominantly one of fossiliferous limestones with minor shale breaks. The shale content increases in most marginal areas of the basin. In an eastward direction in St. Clair County, there is a facies relationship between the more basinal limestones and gray shales and the red and greenish-gray silty shales. The reddish terrigenous section is part of the Queenston Formation of southwestern Ontario. These reddish shales become siltier and more highly oxidized in a southeastern direction. Unit Three also thickens southeastwardly in this area (Plate 3). These shales may represent prodelta terrigenous clastics of the delta complex which prograded westward towards the Michigan Basin. The limestone beds at the center of Unit Three extend well into the eastern shales. They may be related to a rise in sea level rather than subsidence of the Michigan Basin at this time. These transgressive carbonates hold a cyclic position similar to the "Arnheim-Waynesville" of the Cincinnati area (Anstey and Fowler, 1969). In a southward direction towards the Cincinnati area, Unit Three becomes progressively shalier. In the Lenawee and Monroe Counties area, the unit is substantially one of gray shales with only thin stringers of argillaceous limestone.

Unit Three correlates with the Stonington Formation of the Upper Peninsula. The fossil assemblage of this formation includes many of the genera of Bretsky's (1970) Zygospira-Hebertella Community and Walker and Laporte's (1970) low intertidal communities from the Black River Group of New York. Bretsky concluded that this community represented inner and outer sublittoral environments on a broad, gently sloping shelf. The relative fossil abundance of Unit Three in the basin, as noted during this investigation, would be consistent with a low intertidal through high subtidal environment in consideration of the criteria of taxonomic diversity utilized by Walker and Laporte (1970). Corals, brachiopods, bryozoans, gastropods and ostracodes have all been identified in sample descriptions of this unit. In the well samples examined for microfossils by Din (1950), this unit has the greatest number of genera as well as the greatest number of individuals. Most of the microfossils were ostracodes, which have received little environmental attention in studies of the Ordovician. Laporte (1969) found ostracodes to be abundant in the subtidal carbonate beds of the Devonian rocks of New York.

In Presque Isle County there is little increase in shale in Unit Three as compared to most marginal areas. This fact could be an indication that Presque Isle County does not represent a depositionally marginal area, or that this area was receiving less terrigenous clastic material than most marginal areas. The latter would be consistent with environmental interpretations of younger Upper Ordovician units.

DEPOSITIONAL ENVIRONMENT OF UNIT FOUR

A rise in sea level, possibly due to subsidence of the structural Michigan Basin, is considered for the depositional period of Unit Four. There is much substantiating evidence for this conclusion. Perhaps the most important evidence is the fact that the lateral carbonate equivalents of this basinal limestone carry into the Queenston red shales. Also, the dark coloring of the Unit Four limestones and the presence of carbonaceous units may point to chemical conditions of a more reducing nature during Unit Four deposition than for the deposition of the associated carbonates. Good basinal geometry is displayed by the isopachous map of this unit (Plate 4). The environment of deposition could be viewed as shallow neritic below mean wave base. The correlation of Unit Four from the wells drilled on Beaver Island, Charlevoix County, to the core from Schoolcraft County of the Upper Peninsula also supports the postulated sublittoral environment (Plate 8). Lobate and digitate bryozoan growth forms in the correlative section are described by Ehlers et al. (1967). Although Schopf (1969) states that the evidence is not conclusive, he does indicate a neritic below wave base environment for these growth forms. Lagaaij and Gautier (1965), however, found that the zoarial form of ectoprocts in the Rhône delta area depends more on the sedimentation rate and water turbulence than simply on water depth.

DEPOSITIONAL ENVIRONMENT OF UNIT FIVE

Unit Five in the center of the basin appears to be the reverse sequence of Unit Three. This unit tends to be more fossiliferous than Unit Four below. Like Unit Three it contains a variety of lithologies deposited in environments ranging from subtidal to intertidal. Oolites have been described for this unit from a well drilled in Ostego County. The Unit Five correlative section in the Schoolcraft County core ranges from a shallow subtidal coral section upward into supratidal evaporites. A similar regressive sequence is considered for Unit Five through Unit Six towards the center of the basin. Minor variations are probably present throughout this sequence. In the northern half of the basin there is less shale in the upper portion of Unit Five, which perhaps is related to the distance from the source areas. Further discussion of the depositional environment of Unit Five is included in the following section.

DEPOSITIONAL ENVIRONMENT OF UNIT SIX

Hematitic oolites have been reported in the uppermost Ordovician rocks in Wisconsin and northeast Illinois (Cohee, 1948; Workman, 1950) and in Iowa (Parker, 1971). In these areas the oolitic hematite is in the Neda Formation of the Maquoketa Group. Parker (1971) states that the Neda Formation appears to be highly weathered. Workman (1950) noted that the Neda Formation occurs only in localities in northeast Illinois where the Maquoketa Group is at, or near its maximum thickness. Willman (1971) explains that the irregular thinning of the Maquoketa Group and the areas of Neda Formation absence is the result of post-Neda valleys which were cut as much as 150 feet deep into the Maquoketa Group. These valleys were filled with early Silurian sediments. He asserts that "between the valleys there is only slight evidence of unconformity" (p. 15). The northernmost reports of oolitic hematite in Wisconsin are in the position where a facies boundary between the highly clastic red clays of the lower half of the Southern Peninsula and the interbedded carbonates to the north may be drawn. The similarity between the Neda Formation and Unit Six of this study suggests that the depositional environments are analogous. However, this similarity need not imply any time equivalence, but merely a repetition of the depositional conditions necessary for the formation of oolitic hematitic material associated with the red and greenish-gray shales. There is general agreement in the literature that these hematitic oolites represent a primary chemical precipitation followed by mechanical transport and sorting of the ooliths. The water depth is described as shallow to intertidal for most oolitic hematite deposits in the geologic record (James, 1966). Plaksenko (1959) comments that hematite-rich sediments near shore with shales more seaward are to be expected during a regressive cycle; it is expected because of the clastic material contributed from the land, especially if the clastic material is clayey.

Since the Neda Formation is identified in parts of Wisconsin, South Dakota, Iowa, Illinois, Kansas, and Missouri, a western source for the clays does not seem as probable as the well established eastern Queenston Delta complex. A northern source of terrigenous clays seems improbable considering that the northern portion of the Southern Peninsula is an area containing little terrigenous sediment.

The irregular thickness of Units Five and Six mentioned in the discussion of Unit Five may be significant not only in considering the Unit Six post-depositional history in the southwest corner of the state, but also with regard to the depositional history in the center of the basin. The irregular thick and thin areas of Unit Six in Allegan and Barry Counties correspond closely to those of Unit Five below. The oolitic hematite which is found in Allegan County is in that area where Unit Six reaches its maximum thickness. The Manitoulin Formation thickens in the regions where the Upper Ordovician Units Five and Six thin as if it were filling topographically low areas. It would seem that Unit Six was deposited and followed by erosion. These conclusions are the same as those of Workman (1950) and Willman (1971) in their studies of the Upper Ordovician of northeast Illinois. If the thinning which has been mapped in this study is due to stream erosion, as suggested by Willman (1971) for northeast Illinois, the direction of flow and the ultimate area of deposition should be taken into account. The most logical area for the deposition of this youngest of Ordovician clastic material would be the Southern Peninsula depositional center of Unit Six. If this hypothesis is correct, the Michigan Basin depositional center contains some of the youngest Ordovician and/or oldest Silurian rocks in the Michigan area. Units Five and Six appear to be of shallower water depths than the carbonate Unit Four below. This upper sequence thus represents a regressive and a shallower, more restricted environment upwards. Din (1950) recorded a decrease in the abundance and number of ostracod genera upward from the lower portion of Unit Five into the upper portion of Five, with ostracodes being rare to absent in Unit Six.

If the reason for their abundance could be established, the steinkerns in Unit Five could be a valuable environmental indicator as well as a stratigraphic marker. Possible explanations for this type of occurrence are summarized by Tasch (1953). Two of the possibilities are: juveniles that met catastrophic death due to toxicity, either salinity or iron content; or a pebble (gastropod-protoconch) necrocoenosis, indicating sedimentary processes (sorting). The environment of deposition postulated for Units Five and Six would make possible the acceptance of either of the above reasons for the steinkern abundance. The biological causes would point to the beginning of a hostile environment which may have continued throughout Unit Six's deposition. Din (1950) indicated that ostracodes were rare in Unit Six. Bretsky and Bermingham (1970) stated that "under the most restrictive environmental conditions only bivalves and gastropods would survive, but in a stunted condition." In his studies of the Upper Ordovician of Iowa, Agnew (1955) noted a depauperative horizon at the top of the Maquoketa Group "where the Neda zone (Unit Six equivalent) is lacking, or just below that zone where it is present" (p. 1718). The highly oxidizing environment, which is indicated by the oolitic hematite, might mean that conditions for the preservation of organisms may not have been very good, a factor that could handicap an environmental approach.

A difference in the sediment types from the northern mapped area compared to the southern area has been described earlier for Unit Six and was also recognized for Unit Five. Carbonate units of Unit Five, as well as those below, are calcareous near the center of the basin and grade into dolomites towards the margins of the basin. This lateral limestone to dolomite facies has been obscured by a later dolomitization that is indicated by the dolomitization of most of the Upper Ordovician rocks in the Schoolcraft County core, including the fossils.

It is possible that Unit Six represents either deposition in an isolated basin during the Late Ordovician, or is a western extension of very shallow marine Queenston shales. The thickening of Unit Six towards the Ogemaw County region may be more an indication of structural subsidence than an indication of equivalent water depth prior to Unit Six deposition. In considering the age of Unit Six, it is possible to infer that the center of the basin contains the youngest Ordovician and/or oldest Silurian rocks of the Great Lakes region.

CONCLUSIONS

The isopach map (Plate 7) of the Upper Ordovician of the Southern Peninsula of Michigan indicates that the Michigan Basin, as we know it today, existed during at least part of the Upper Ordovician. The Michigan Basin during Late Ordovician time seems to have been a rather shallow, stable basin centered around Ogemaw County. It was bounded by the Kankakee Arch to the southwest, possibly a Findlay Arch to the southeast, and an unnamed arch between Ontario and Michigan trending north-south along the international border through Lake Huron. The northern and northwestern margins appear to be broad, stable areas with no indication of erosion or significant periods of nondeposition. The thick Upper Ordovician rock section in the area of western Lenawee County, which continues to thicken southeastwardly, suggests that the area may best be considered a northwestern extension of the Appalachian Basin.

The basinal geometry and lithofacies of Units Four, Five and Six indicate slow subsidence for the Michigan Basin during the Late Ordovician. The sequence is a regressive pattern beginning with the subtidal below wave base carbonates of Unit Four and terminating with erosion in the southern arch areas and with supratidal evaporites in the more stable Upper Peninsula area. Unit Six, where present in the southern half of the basin, is highly radioactive on gamma-ray logs and is typically a nonfossiliferous red shale, occasionally containing oolitic hematite. The units below the regressive sequence described above do not demonstrate either a good basinal geometry or clearly defineable basinal patterns of the recognizable lithofacies. Unit One, the Utica Shale, is a wedge of argillaceous material which thickens eastwardly into Ontario and southeastwardly into Ohio. The isopach map (Plate 1) of Unit One does not of itself indicate a basin at that time. There is some suggestion that Unit One is in some places isochronous with the stratigraphically lower Trenton Formation. To determine whether a depositional basin existed during the Utica deposition, further studies must include the Trenton Formation carbonates.

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MATERIAL

PLATE 8.- CROSS SECTION NW TO SE MICHIGAN

ROY D. NURMI

PLATE 9. - CROSS SECTION SW TO BASIN CENTER

ROY D. NURMI

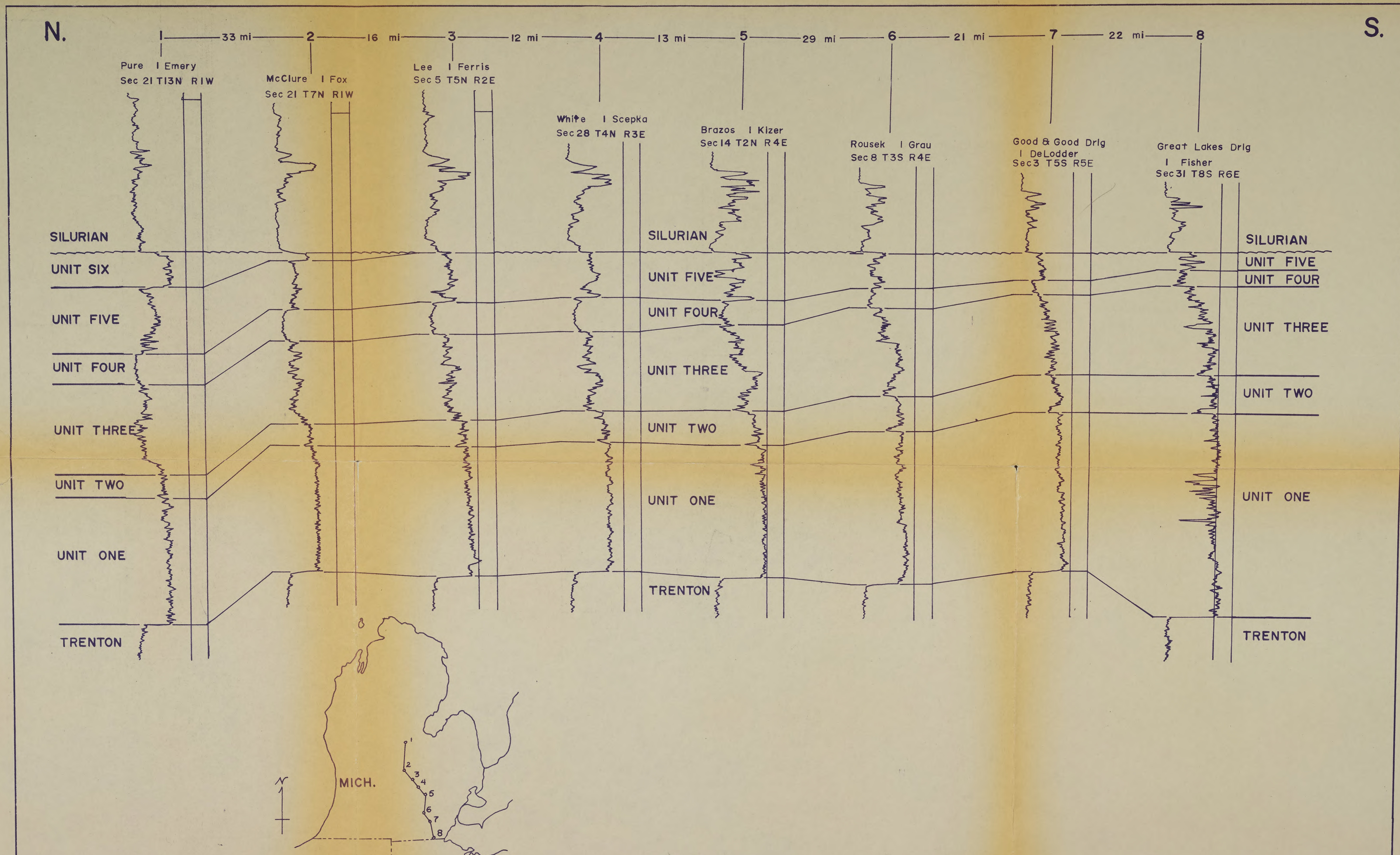

PLATE 10.- CROSS SECTION BASIN CENTER TO SE

ROY D. NURMI