

This is to certify that the

thesis entitled

Niagaran Reefs
Northwestern Michigan

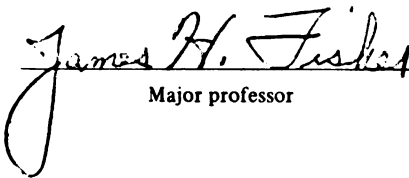
presented by

G. Daniel Orr

has been accepted towards fulfillment
of the requirements for

Master's degree in Geology

Date April 10, 1984


Major professor



RETURNING MATERIALS:

Place in book drop to
remove this checkout from
your record. FINES will
be charged if book is
returned after the date
stamped below.

~~MAR 19 87~~
~~JAN 7 88~~

NIAGARAN REEFS
NORTHWESTERN MICHIGAN

by

G. Daniel Orr

A THESIS

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

MASTER OF SCIENCE

Department of Geology

1984

ABSTRACT

PINNACLE REEFS:NORTHWESTERN MICHIGAN

BY

G. DANIEL ORR

Stratigraphic, structural, and lithological analyses of lower Salina - Niagaran units in off-reef wells were done to determine if changes evidenced in the analyses were related to production within the northwestern Michigan pinnacle reef belt.

Analyses support the model that A-1 Carbonate sedimentation represents a restricted marine tidal flat deposit and pinnacle reefs that underlie these tidal flats have been fully or partially dolomitized. Initial production in reefs below these areas gauged the highest flow rates. The tidal flat environments of the A-1 Carbonate are best depicted by lithologic changes occurring at the base of the A-2 Evaporite. Clean halite becomes a basal anhydrite indicating a shallowing in water depth over the tidal flats.

Lithological changes noted can be used as a tool for limiting exploration efforts to better productive areas.

ACKNOWLEDGEMENTS

Special thanks to my advisor, Dr. James H. Fisher, for direction and guidance on this project; to the geological staff at the DNR for their assistance in the data collection process; to Trendwell Oil, Hunt Energy Corporation, and Sullivan and Co. for financial assistance; to the geology department at Western Michigan University for their assistance in photo reduction of plates; to Chuck and Cari Ailes for the typing and editing of the manuscript; to my wife, Catherine, for her love and support; and most of all to the Lord God who, upon my request, gave me a generous dose of wisdom without finding fault (James 1:5).

TABLE OF CONTENTS

LIST OF FIGURES -----	iv
LIST OF PLATES-----	v
INTRODUCTION -----	1
Area and Purpose of Study -----	2
Method of Investigation -----	3
Previous Work -----	4
GENERAL STRATIGRAPHY AND SEDIMENTATION -----	8
STRUCTURAL HISTORY -----	15
FACTORS CONTROLLING PETROLEUM OCCURENCE -----	19
DESCRIPTION AND DISCUSSION OF MAPS	
Niagaran Structure Map -----	21
Brown Niagaran Isopach and Lithofacies Map ----	22
A-1 Evaporite Isopach and Lithofacies Map ----	23
A-1 Carbonate Isopach Map -----	24
A-2 Evaporite Isopach and Lithofacies Map ----	27
A-2 Carbonate Structure Map -----	29
A-2 Carbonate Isopach Map -----	30
B-Unit Isopach Map -----	31
PETROLEUM PRODUCTION -----	31
CONCLUSIONS -----	32
BIBLIOGRAPHY -----	37

LIST OF FIGURES

- Figure 1: Stratigraphic Succession in Michigan
- Figure 2: Niagaran Depositional Environments in the Michigan Basin
- Figure 3: Michigan Basin and Surrounding Structural Elements

LIST OF PLATES

Plate 1:	Brown Niagaran Structure Map
Plate 2:	Brown Niagaran Isopach Map
Plate 3:	Brown Niagaran Lithofacies Map
Plate 4:	A-1 Evaporite Isopach Map
Plate 5:	A-1 Evaporite Lithofacies Map
Plate 6:	A-1 Carbonate Isopach Map
Plate 7:	A-2 Evaporite Isopach Map
Plate 8:	A-2 Evaporite Lithofacies Map
Plate 9:	A-2 Carbonate Structure Map
Plate 10:	A-2 Carbonate Isopach Map
Plate 11:	B-Unit Isopach Map
Plate 12:	Oil and Gas Production Map
Plate 13:	Cross-Sections

INTRODUCTION

The search for Niagaran pinnacle reefs has been active in the Michigan Basin since the 1950's. Exploration was concentrated in southeastern Michigan on the St. Clair platform and remained active there into the 1960's. Gravimetry was highly successful in locating pinnacle structures and was the primary exploration tool. More notable discoveries on the platform were the Berlin, Peters, Boyd, Ray, and Belle River Mills fields. Two important discoveries made in the early 1950's were the Hamlin field in Mason County and the Chester field in Otsego County. The fact that these two discoveries were part of a reef trend in the Northern lower peninsula was not recognized then (Hartsell, 1982).

Interest shifted from southeastern Michigan to the north in 1968 when Pan American and Northern Michigan Exploration Company jointly drilled the Pan Am Drasey #1 in Presque Isle County. This well, though non-commercial, produced oil from the drill-stem test, and spurred a flurry of drilling activity for pinnacle reefs across northern Michigan (Fisher, 1973). Gravimetry was used in the early

stages of exploration, but gave way to reflection seismology, enabling explorationists to delineate reef positions more accurately at greater depths.

The Northern pinnacle trend stretches in a southwest-northeast direction from Mason County, on the shore of Lake Michigan, to Presque Isle County, on the shore of Lake Huron. Drilling for pinnacles along this trend has dominated Michigan exploration activity for the last 14 years.

AREA AND PURPOSE OF STUDY

The area of study includes Townships 21 North through 27 North and Ranges 9 West through 17 West encompassing all of Grand Traverse and Manistee Counties, and parts of Benzie and Wexford Counties of northwestern Michigan.

The major intent of this study was to make stratigraphic and structural analyses of Niagaran-Salina units in a localized area. Lithologic differences in the Brown Niagaran, A-1, and A-2 Evaporites were noted to determine if facies changes were related to production (i.e. salt-plugged, gas, oil, or water producing reefs). Looking at structural, lithologic, and isopachous trends, it was anticipated these could be related to petroleum occurrence, or to indications of pinnacle reef location. Information for analysis was limited to dry holes, as pinnacle related data

is anomalous to off-reef regional data. Directionally drilled, non-reef wells were used when drilling density for an area was low. Data was obtained from approximately 475 wells.

METHOD OF INVESTIGATION

Subsurface data were collected primarily from geophysical well logs on file at the Department of Natural Resources, Lansing, Michigan. The log most often used to determine formation tops was the Gamma Ray log in conjunction with the Borehole Compensated Sonic, and Compensated Neutron-Formation Density log. Lithologic determinations were made primarily from Compensated Neutron-Formation Density and Sidewall Neutron Porosity logs. When lithologic determination was not possible from geophysical logs, sample descriptions from drillers logs were used.

Subsurface information was used to construct isopachous maps of the Brown Niagaran, A-1 Evaporite, A-1 Carbonate, A-2 Evaporite, A-2 Carbonate, and B-Unit. Structural contour maps of the Brown Niagaran and A-2 Carbonate were constructed to observe rates of subsidence between periods of deposition in the Niagaran-Salina sequence. Lithofacies maps of the Brown Niagaran, A-1, and A-2 Evaporites were constructed to determine whether or not lithologic changes in these units could be related to petroleum occurrence, or

could be used as pinnacle indicators. Two cross-sections perpendicular to the reef trend (one through Grand Traverse County, the other through Manistee County) were drawn illustrating subsurface changes encountered in going from the Niagaran massive reef complex, basinward.

The Clinton carbonate was not included in the study due to the scarcity of wells penetrating the subsurface to that depth.

PREVIOUS WORK

Numerous outcrop and subsurface studies have been done on the Niagaran-Salina sequence of the Michigan basin. Faunal studies were done by Cummings and Shrock (1928) and Lowenstam (1950, 1957). Faunal assemblages of individual reefs were studied by Sharma (1966) and Gill (1977). Lithologic subdivision and classification of Niagaran units has been done by Landes (1945), Evans (1950), Ells (1967), Gill (1973), and Budros and Briggs (1977).

Regional studies, encompassing the lower peninsula of Michigan, which aid in the understanding of structure, stratigraphy, sedimentation, reef growth, and petroleum occurrence in the reef areas have been done by Alling and Briggs (1961), Autra (1977), Briggs and Briggs (1974, 1975), Cohee (1948), Ehlers and Kesling (1962), Ells (1963, 1967, 1969), Fisher (1969, 1973), Gill (1975), Lilienthal (1978), Mantek (1973), Melhorn (1958), Mesolella et al (1974, 1975),

Nurmi (1974), and Potter (1975).

Studies restricted to local areas in southeastern Michigan include: Bates (1970), Budros and Briggs (1977), Felber (1964), Gill (1973, 1977), Jodry (1969), Johnson (1971), and Sharma (1966); in southern and south central Michigan: Ells (1962), Fincham (1975), and Walles (1980); in western Michigan: Hartsell (1982); and in northern Michigan: Caughlin et al (1976), Fisher (1973), Gill (1979), Huh (1973), Huh, Gill, et al (1977), Meloy (1974), Mesolella et al (1974, 1975), and Sears and Lucia (1979, 1980).

One controversial topic is the growth history of Niagaran reefs. Three basic models have been proposed. Gill (1975), after studying the Belle River Mills field, proposed that reef growth was entirely of Niagaran age and terminated prior to the deposition of the A-1 Evaporite and Carbonate. This model was based on A-1 Carbonate being present above A-1 Evaporite in inter-reef areas, but not on top of the reef. Therefore, Gill placed the Niagaran-Salina contact at the base of the A-2 Evaporite which caps the pinnacles. Work done by Huh (1973, 1977), Mantek (1973), and Sears and Lucia (1979, 1980) supported Gill's proposal that reef growth entirely predated deposition of units surrounding and capping the reefs.

Jodry (1969), in the second model, proposed reef growth as being contemporaneous with inter-reef cyclic carbonates and evaporites. The reef material represented a facies change of the evaporites and carbonates being deposited. The

units are not laterally equivalent now, due to differential compaction of the sediments after deposition.

Mesolella et al (1974), offering paleontological evidence for an unconformity within the reef, proposed a third model for reef growth. He placed upper parts of the pinnacle reefs as being stratigraphically equivalent to the inter-reef A-1 Carbonate. Therefore, A-1 Carbonate deposition recorded a rejuvenation of growth on former Niagaran pinnacles following a hiatus in reef development associated with A-1 Evaporite deposition. This interpretation places the Niagaran-Salina contact within the pinnacle reef.

Sears and Lucia (1980) contested Mesolella's proposal, claiming in over 40 cored wells there was no supporting evidence for any unconformity within the pinnacles. They also questioned whether or not the paleontological evidence offered by Mesolella was sufficient to place the upper parts of the reef equivalent to the Salina units surrounding the reefs. They cited further evidence to support Gill in that clasts of calichified algal stromatolite, normally found on the reef crests, had been discovered beneath the A-1 Evaporite in flank wells. This implied reef growth entirely predated deposition of the Salina units.

Huh (1977) concluded that definite A-1 Carbonate equivalents overlaid the reefs, but that they represented tidal flat sediments, not reef regrowth. Sears and Lucia (1980) agreed and felt the carbonate deposited on the reef

tops represented a restricted marine sequence. This over-reef restricted marine unit interfingered on the reef flanks with an inter-reef "poker chip" facies, establishing contemporaneous deposition of the two units. These researchers concluded that A-1 Carbonate is present over the tops of reefs and represents a restricted marine deposit, not a rejuvenation of reef growth as Mesolella proposed.

Models one and three have the support of most researchers. Further study of reef models is needed to establish their validity.

A second area of debate centers on deep vs. shallow water origin of the Salina evaporites. Dellwig and Evans (1969), on evidence obtained in an underground salt mine in Detroit, concluded water depth needed to be "deep" to prevent disturbance of primary bedding structures by waves or currents. Other researchers favored shallow water origin for deposition of Salina evaporites. Nurmi (1974) felt evidence of ripple marks and observable unconformities in salts in an underground Ontario mine, suggested a sabkha-type depositional environment. Sears and Lucia (1980) cited evidence of sylvite, nodular anhydrite, halite hoppers, and brecciation of A-1 Evaporite as being indicative of shallow water deposition. A gradual change from laminated anhydritic dolomite in the A-1 Carbonate, to interbedded halite and anhydrite in the A-2 Evaporite also indicated shallow water deposition.

Evidence used to interpret water depths in the

formation of basin margin evaporites may help researchers conclude water depths for central basin evaporite deposits. Further thin section analysis of cores is needed before definite conclusions about water depth in the central basin can be drawn.

GENERAL STRATIGRAPHY AND SEDIMENTATION

The Michigan Basin is comprised of sediments ranging from Precambrian to Mesozoic in age. Except for the Permian, Paleozoic sediments of all ages are present. Of sediments Mesozoic in age, only Jurassic are present. Most of the basin is covered by Pleistocene glacial deposits (Fig. 1).

Silurian rocks account for close to 30 percent of the total sediment in the basin. Total Silurian thickness has been estimated at 4,000 feet in the central part of the basin. One-third to one-half of those sediments are pure salt deposits. Sediments of Middle and Upper Silurian age are highlighted in this study, and include units of the Niagara and Lower Salina Groups.

The Niagara has been divided into the following formations: "Clinton" (Burnt Bluff and Manistique equivalents), "White and Gray" Niagaran (Lockport equivalent), and "Brown" Niagaran (Guelph equivalent). Terms in parentheses represent formal formational usage, whereas "Clinton", "White", "Gray", and "Brown" Niagaran are correlative terms used by the oil industry, based on the

STRATIGRAPHIC SUCCESSION IN MICHIGAN

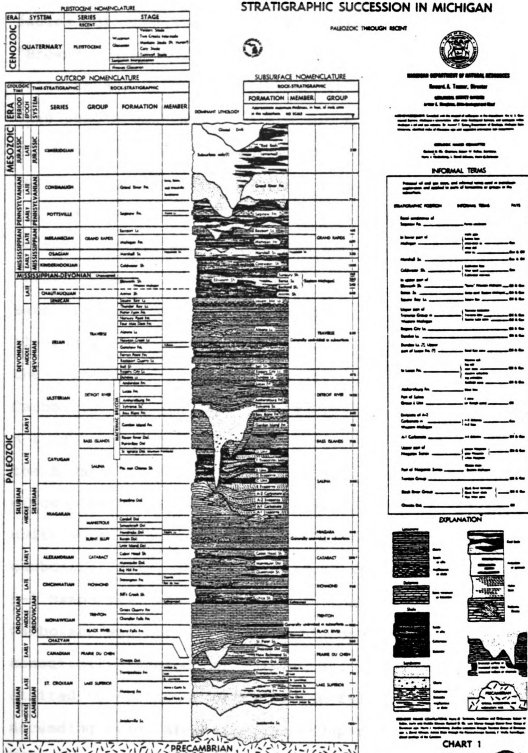


FIGURE 1

stratigraphic position and color of drill cuttings of these units (Ells, 1967). The "Brown", or Guelph, is the reef facies of the Niagara Group. Pinnacle reefs, within the "Brown", are the principal oil and gas reservoirs of Silurian age that interest the oil industry. Units older than the "Brown" Niagaran are not analyzed in this study due to the scarcity of wells that completely penetrate the entire thickness of the Niagara Group.

Salina Group rocks were divided by Landes (1945) into units A through H, with A being deposited directly above the "Brown" Niagaran. The H-Unit is presently referred to as the Bass Islands Group. Evans (1950) further divided the alternating evaporites and carbonates of Landes' A-Unit into the A-1 Evaporite, A-1 Carbonate, A-2 Evaporite, and A-2 Carbonate. Budros and Briggs (1977) formally named Evans' A-1 Carbonate Unit the "Ruff" Formation. Ells (1967) divided the B-Unit into the B-Carbonate and the B-Salt on the basis of geophysical log response, but for this study the two units were combined. Gill (1973) recognized an interreef carbonate unit, above the "Brown" Niagaran and beneath the A-1 Evaporite, and designated it the A-0 Carbonate. The A-0 Carbonate was not distinguishable on Gamma Ray logs and was essentially ignored for this study. This investigation was limited to the lower units of the Salina Group. The units in ascending order are: the A-1 Evaporite, A-1 Carbonate, A-2 Evaporite, A-2 Carbonate, and the B-Unit.

Mesolella et al (1974) offered the following

depositional history for the Niagaran-Lower Salina units. Carbonates were forming during Niagaran time and a system of organic, platform reefs developed around the margins of the basin. Basinward from this massive reef complex, pinnacles grew vertically as much as 100-200 meters. Niagaran carbonate was thickest adjacent to the reefs and thinner immediately basinward, where sedimentation rates were lower and the generation of carbonate was minimal (Fig. 2). Restriction, increasing salinity, and a lowering of sea level may have terminated Niagaran reef growth and initiated the deposition of the A-1 Evaporite.

The A-1 Evaporite is thickest in the center of the basin where it is predominantly halite. At the basin margins, the halite grades laterally into anhydrite. The anhydrite pinches out on the flanks of pinnacles and against the front of the Niagaran massive reef complex. This unit contains a sylvite lens (potassium chloride) which increases in thickness and purity basinward. The significance of sylvite as a possible near-reef indicator was summed up by Elowski (1980). He observed that sylvite occurred in the center of embayments between Niagaran reefs in the northern trend. These embayments surrounded reefs and groups of reefs along the basinward edge of the trend. The disappearance of sylvite in these areas may indicate proximity to pinnacle reefs. Because these embayments of sylvite are restricted in areal extent to the basinward half of the pinnacle trend, the usefulness of potash salts in the A-1 Evaporite as an

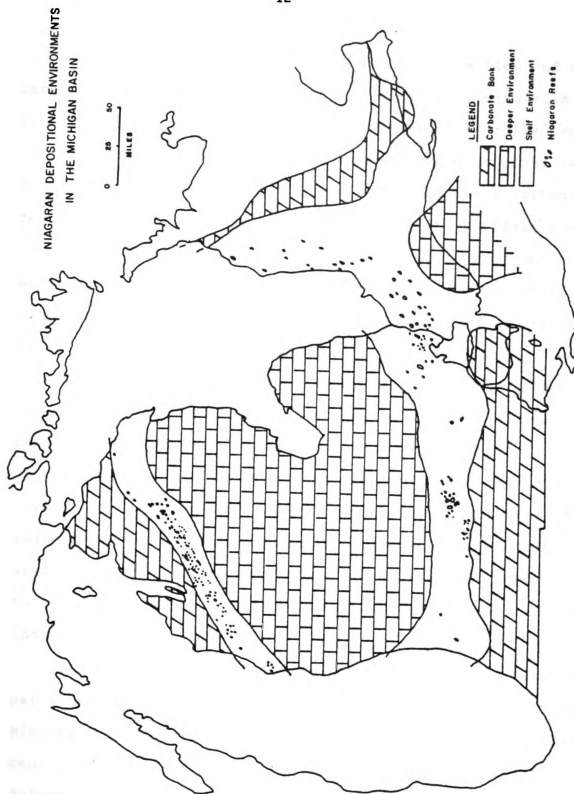


FIGURE 2. (MODIFIED AFTER MANTEK, 1973)

exploration tool is limited.

A rise in sea level initiated the deposition of A-1 Carbonate. This is where researchers disagreed. Mesolella et al (1974) felt that A-1 Carbonate deposition reflected a resurgence in reef growth on the tops of Niagaran pinnacles. Huh (1977) and Sears and Lucia (1980) felt A-1 Carbonate deposition represented an over-reef restricted, tidal flat, marine carbonate. The A-1 Carbonate, thickest near the massive reef complex and thinnest toward the basin interior, contains thin lenses of anhydrite proximal to pinnacles. These thin lenses of anhydrite ("rabbit ears") were deposited as halos on supratidal flats around the pinnacle reefs. The supratidal flats are limited in areal extent and resulted from regressions in sea level.

The two lenses of anhydrite are separated by a thin layer of carbonate. This separation indicates the regressions were cyclic in nature. Because of the limited areal extent of these anhydrite lenses and their proximity to pinnacle reefs, "rabbit ears" are used as near-reef indicators.

Sears and Lucia (1980), after studying dolomitization patterns in the A-1 Carbonate, concluded the depositional history of this unit involved periods of tidal flat conditions which were believed to be important to dolomitization of the underlying Niagaran reefs. Following deposition of the restricted marine carbonate, a tidal flat facies developed on top of the pinnacles. These tidal flat

sediments (later dolomitized) extended from the Niagaran shelf basinward, about half way through the reef belt. Reefs underlying this tidal flat environment had been entirely or partially dolomitized. Reflux of hypersaline brines through tidal flat sediments was given as the mechanism for dolomitization. Beyond this reef belt midpoint, basinward pinnacles were found to be less dolomitized and predominantly composed of limestone. If Sears and Lucia's theory is correct, then dolomitization of underlying reefs followed dolomitization patterns of the A-1 Carbonate.

Since dolomitized reefs are known to be more productive (due to better porosity) than limestone reefs, the conclusion drawn by Sears and Lucia is significant. Reefs which were beneath A-1 Carbonate tidal flat sediments should be more productive.

A lowering of sea level terminated A-1 Carbonate deposition and initiated the deposition of the A-2 Evaporite (Mesolella et al 1974). The A-2 Evaporite is thickest in the interior of the basin and thins toward the margins. It thins rapidly over the pinnacle and barrier reef complex and undergoes a facies change from halite to anhydrite, similar to the A-1 Evaporite. Anhydrite seals the tops of the pinnacles and the Niagaran massive reef complex.

A rise in sea level initiated deposition of the A-2 Carbonate. This unit was not characterized by reef building. There was also a reversal in carbonate thickening trends. The A-2 Carbonate thickened basinward and thinned toward the

basin margins. This suggested physical, not biological, processes were dominant during deposition. Lowering of sea level began another phase of evaporite deposition.

The B-Unit (B-Carbonate and B-Salt combined) is thickest in the basin interior and thins toward the margins. The B-Unit basin covers more area laterally than basins of earlier periods of deposition. Along the margins, the unit undergoes a facies change from halite to anhydritic dolomites and shales. Because this study area was located basinward of the margin, the facies change was not observed.

In the Northern trend the B-Unit is anomalously thick overlying the pinnacle reef belt. Mesolella et al (1974) believes this thickening coincides with A-2 Evaporite thinning caused by solution lower in the sequence. The B-Unit is the uppermost unit analyzed in this research.

STRUCTURAL HISTORY

The Michigan Basin has been classified as an intracratonic basin. Located on the southern edge of the highly fractured and faulted granites of the Canadian Shield, the basin is bordered on the west by the Wisconsin Arch and Wisconsin Dome. To the east and southeast lie the Algonquin and Findlay Arches, the two being separated by the Chatham Sag. To the south and southwest lie the Cincinnati Arch and the Kankakee Platform (Fig. 3).

These structural features on the southeast, south, and

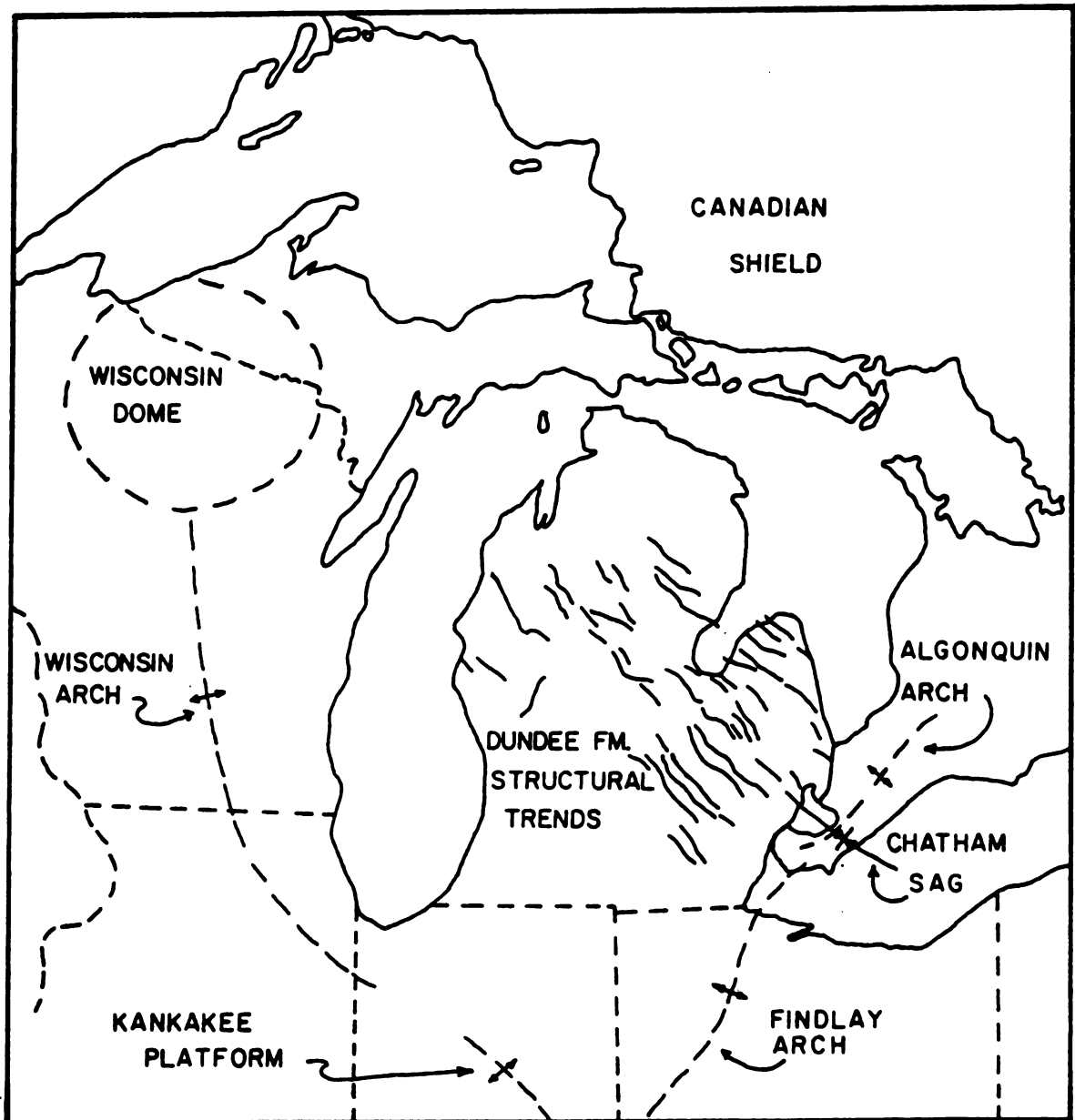


FIGURE 3. MICHIGAN BASIN AND SURROUNDING STRUCTURAL ELEMENTS (MODIFIED AFTER ELLS, 1969).

southwest separate the Michigan Basin from the Illinois and Appalachian Basins. During Niagaran and Lower Salina time, these features were believed to have had little structural influence on the basin due to their low relief. However, these features may have played an important role in the formation and growth of the Niagaran massive reef complex.

Structural trends within the Michigan Basin have a strong northwest - southeast alignment. The Albion - Scipio trend, Howell and Northville Anticlines, and many Devonian oil fields conform to this pattern. Pirtle (1932) believed this alignment reflected structural patterns of the Precambrian basement. Anticlinal structures and draping of Paleozoic sediments over these structures may have indicated reactivation of basement blocks along pre-existing fault and fracture systems (vertical tectonics). Although it seemed that basement tectonics controlled structural patterns in the Michigan Basin, it was not until Middle to Late Ordovician time that the present shape of the basin became apparent (Fisher, 1969 and Haxby et al, 1976).

Numerous theories have surfaced dealing with the creation and formation of the Michigan Basin. Newcombe (1933) proposed a downwarping of the basin resulting from forces imposed from the northeast. Hinze (1963), based on gravity work, proposed that the addition of dense, Keweenawan basalt flows to the Precambrian basement resulted in subsidence. Subsidence restored isostatic equilibrium between the Earth's crust and mantle. Haxby et al (1976)

proposed that mantle diapirs penetrating the lower crust resulted in density changes in the crustal rocks. Subsidence was needed to restore isostatic equilibrium. Whatever the cause of formation of the basin, Ellis (1969) believed the Appalachian Orogeny caused further structural deformation of basin sediments by imposing a force from the southeast. Cohee and Landes (1958) believed the basin underwent structural deformation throughout the Paleozoic. The most intense deformation occurred during the Mississippian period. Cohee and Landes also proposed that the basin underwent the greatest amount of subsidence during Late Silurian and Middle Devonian time. This conclusion was drawn from the vast thicknesses of salt present in units of these two periods. Assumptions about water depth at the time of salt formation become critical when thicknesses of salt deposits are used to determine rates of subsidence. Because researchers cannot unanimously conclude whether halite forms in deep or shallow water, the timing of subsidence in the Michigan basin by Cohee and Landes may be questionable.

Fisher (1973), after isopaching the entire Salina Group, concluded that the northern rim of the Michigan Basin subsided more rapidly than the southern during Salina time. Sediments over the crests of the massive reef complex were 1000 feet thicker in the north than in the south. This probably accounted for differences in depths to pinnacles, heights of pinnacles, and facies relationships of overlying A-1 and A-2 Evaporites to pinnacle positions between the

northern and southern rims.

Sears and Lucia (1979) believed the pinnacle reefs in the north grew on a ramp that was tectonically stable. The ramp subsided at a uniform rate, not at differential rates. This would imply the basinward pinnacle reefs grew at a faster rate in order to keep up with a rising sea level. Whatever the case, lithologic and stratigraphic relationships of Lower Salina units to Niagaran barrier and pinnacle reef complexes are not identical along the northern and southern rims of the Michigan Basin.

FACTORS CONTROLLING PETROLEUM OCCURRENCE

Niagaran pinnacle reefs are found along a "fairway" located basinward from the massive reef complex. This "fairway" is approximately 8 miles wide in the study area. Basinward pinnacles tend to be taller in height and smaller in areal extent. Shelfward pinnacles are generally shorter and broader.

A definite segregation of hydrocarbons is observable along the northern pinnacle trend (Gill, 1979) (Plate 12). Pinnacles lying farthest basinward are usually void of hydrocarbons and plugged with salt. Updip lie reefs that produce "sour" gas and, to a lesser degree, "sour" oil. "Sour" production denotes high concentrations of hydrogen sulfide present in the hydrocarbon. These "sour" reefs are generally composed of limestone and have limited pore space.

This makes production from these reefs difficult because the hydrocarbons cannot migrate easily through the reef to the well bore.

The pinnacle reefs in the center portion of the trend produce oil, gas, or a combination of both. The majority of the production is "sweet", although there are exceptions to this rule. Reefs in this portion of the trend are dolomitic, have better porosity, and tend to produce hydrocarbons more easily than the reefs down-dip. Pinnacles closest to the massive reef complex are often filled with anhydrite, or they produce water and limited amounts of low gravity oil.

This updip segregation of fluid types (from gas and light condensate, to high gravity oil, to low gravity oil and water, to water producing reefs) has been deemed a classic example of Gussow's theory on differential entrapment of oil and gas (Gill, 1979). According to this theory, if hydrocarbons are sourced from down-dip areas, a partitioning of fluids of different gravities would occur. Basinward pinnacles would fill up with higher gravity fluids (gas and high gravity oil) because less viscous hydrocarbons would migrate faster into reservoirs. Shelfward pinnacles would then fill with a mixture of low gravity oil and water, or just water.

Assuming constant slope along the length of the trend, these bands of production should be continuous across the study area and parallel to one another. As noted, this is not always the case. Pinnacles in Cleon Township of Manistee

County tend to produce "sour" gas. This "sour" production is embayed further up into the pinnacle trend than it should be. The width of the band of producing pinnacles narrows in Cleon Township. No production has been found to date in the northern-half of the township. This thinning is anomalous when looking at townships located to either side of Cleon. With that in mind, an attempt was made to discover why these production trends are not parallel to one another. By examining relationships of units surrounding and overlying the pinnacles in off-reef wells, determination was possible.

NIAGARAN STRUCTURE MAP

To determine whether production trends were structurally related, a contour map was drawn using the top of the Brown Niagaran as a datum (Plate 1). In looking at the Brown Niagaran structure map, the contours in the fairway trend essentially north-south through Township 21 north. From Township 22 north, the contours swing in a general direction of N 30° E until they reach a point in Cleon Township (T24N - R13W) where I have indicated a fault. Northeast of the fault, the contours follow a trend in the direction N 55° E. Assuming the fault is correctly placed, this abrupt change in direction could be related to vertical displacement of basement blocks along already existing northwest - southeast fault patterns. Another possible fault is located in Paradise Township (T25N - R10W) exhibiting the

same northwest - southeast trend. Since sufficient well control deeper than the Clinton is not available, structural contour trends attributed to fault mechanisms can only be hypothesized. Linear trends observed in pinnacle locations generally parallel Brown Niagaran structural trends.

BROWN NIAGARAN ISOPACH AND LITHOFACIES MAP

Niagaran reef growth is a reflection of biologic activity. It is assumed wherever concentrations of pinnacle reefs are fairly high, off-reef wells will reflect biologic activity by containing thicker sections of carbonate (Plate 2). Wells with 15 feet or less of Brown Niagaran were considered to be "regional" in nature. Wells with more than 15 feet were considered to represent areas of debris either adjacent to pinnacles (flank buildup) or debris fans off of the massive reef bank.

The interpretation of the Brown Niagaran isopach map may be questionable. Areas inside the 15 foot contours may not actually contain thicker sections of carbonate. Two or three flank wells contoured together would display the same result. Additional well control will confirm or deny the interpretation of this study.

The lithology of the Brown Niagaran in the study area is both limestone and dolomite (Plate 3). The break-point between the two lithologies parallels the massive reef bank and is located at about the mid-point of the trend. The

massive reef bank and the shelfward half of the pinnacle trend is composed of dolomite, while the basinward half of the pinnacle trend is composed of limestone. Two noticeable embayments of limestone into the dolomite region occur in Cleon Township (T24N - R13W) of Manistee County and East Bay Township (T26N - R10W) of Grand Traverse County. If limestone formation reflects a deeper water environment, then these embayments could be attributed to the faulting mentioned earlier. The limestone is present on the downthrown side of the fault in both areas. Water depth would be expected to be greater there. Around the margins, the Niagaran massive reef is 500 - 600 feet thick and pinnacles average 300 - 600 feet in thickness. In the center of the basin, the Niagaran averages 60 feet in thickness (Fisher, 1973).

A-1 EVAPORITE ISOPACH AND LITHOFACIES MAP

In examining A-1 Evaporite isopach trends (Plate 4), it is apparent that after evaporative drawdown of sea level, A-1 Evaporite deposition filled in existing Niagaran topography. In areas where Niagaran biologic activity was sparse, isopach lines reflect steep slopes and parallel Niagaran structure. In areas where Niagaran pinnacle growth was concentrated, the contour spacing widens.

In evaluating the lithology of the A-1 Evaporite (Plate 5), wells on the basinward side of the pinnacle trend

contain a clean salt section. Moving toward the bank, the evaporite section becomes a mixture of halite and anhydrite with the anhydrite being at the base. Off-reef wells throughout the entire pinnacle reef complex of the study area had an anhydrite cap over the top of the Brown Niagaran. Next to the massive reef complex, the evaporite becomes all anhydrite and pinches out against the face of the massive reef. As flanks of individual pinnacles are encountered, the anhydrite at the base of the A-1 Evaporite thickens. The evaporite pinches out against the sides of the pinnacles. The A-1 Evaporite thickness is generally less than 200 feet within the pinnacle trend. In the central basin, it thickens to about 400 feet (Mesolella et al, 1974).

A-1 CARBONATE ISOPACH MAP

Upon examining this map (Plate 6), a definite thickening trend is observed parallel to the massive reef complex. Areas inside the 100 foot contour interval are areas of isopachous thickening. Whether this thickening is attributable to a resurgence in reef growth, or whether it reflects areas of tidal flat sedimentation, the map shows that thick areas of A-1 Carbonate do exist. Using the 100 foot contour interval, support for either tidal flat sedimentation or a rejuvenation of biologic growth on existing Niagaran sites is plausible because thick sections

of A-1 Carbonate mask thick sections of Niagaran deposits.

If the 120 foot contour is used on the A-1 Carbonate map a different pattern develops. Areas inside the 120 foot interval tend to be located close to the massive reef complex and toward the back side of the pinnacle reef complex. When these areas are compared to areas of intense Niagaran biologic activity, the two do not generally coincide. The 120 foot contour isopach would support the theory that A-1 Carbonate deposition did not reflect a rejuvenation of reef growth. If it did, one would expect the areas of thicker sections on both maps to overlap. This researcher prefers the explanation that areas inside the 120 foot contour reflect areas of tidal flat sedimentation. They are located up against the massive reef complex where one would expect them to be.

At this point, Sears and Lucia's (1980) research is pertinent. Dolomitization of the A-1 Carbonate occurred in tidal flat areas. Refluxing of salt saturated brines down through the sediments is the mechanism they offer for accomplishing this lithologic change. They assume the process that dolomitized the A-1 Carbonate also dolomitized Niagaran reefs below the tidal flats. If so, there should be a general correlation observed between the tidal flat boundaries and the dolomite/limestone breakpoint on the Niagaran lithofacies map. If the 100 foot isopach contour is used on the basinward side of the pinnacle complex, the two boundaries are generally correlative. The exception to this

is in southern Whitewater (T27N-R9W) and northern Union (T26N-R9W) Townships of Grand Traverse County. Here the limestone boundary swings farther into the inter-reef area and cuts inside the 100 foot contour that approximates the basinward edge of the tidal flats.

On flanks of pinnacle reefs, the upper section of the A-1 Carbonate in the study area contains a "rabbit ears" anhydrite. This lithologic change has been noted by Gill (1973) and Huh (1973). The "rabbit ears" are described as being a nodular, supratidal anhydrite which suggests it formed under sabkha-type conditions. Since the A-1 Carbonate thins over the tops of pinnacles, the presence of "rabbit ears" anhydrite supports the existence of shallow water, tidal flat environments during the latter part of A-1 Carbonate deposition. Assuming the "rabbit ears" anhydrite is deposited around the entire periphery of the pinnacle reef, this lithologic change can be used to indicate proximity to pinnacles. Data from this study is supportive of Sears and Lucia's tidal flat model of A-1 Carbonate deposition. Along the margin of the study area, the A-1 Carbonate thickness averages between 80 - 120 feet. In the basin center the average thickness is 50 feet (Mesolella et al, 1974).

A-2 EVAPORITE ISOPACH AND LITHOFACIES MAPS

Following deposition of the A-1 Carbonate, evaporative drawdown of sea level and restriction of the basin allowed for deposition of the A-2 Evaporite. On this map (Plate 7), isopach lines parallel the front of the massive reef complex. A general thickening of the unit is noted basinward.

Lithofacies changes in the A-2 Evaporite lead to some exciting conclusions about depositional environments of that time period (Plate 8). Basinward of the pinnacle trend, the A-2 Evaporite is composed of a clean salt throughout the entire section. As the tidal flat environments of the A-1 Carbonate are approached, the base of the A-2 Evaporite becomes anhydritic. It is a "ratty" anhydrite intermixed with halite. This indicates a shallowing effect in water depth (i.e. slope environments off of the tidal flats). On top of the tidal flats, the base of the A-2 Evaporite becomes a clean anhydrite. It forms a cap over the underlying A-1 Carbonate. Passes through the pinnacle trend become very apparent, as the water is deeper there and the A-2 Evaporite remains a clean salt (halite).

One such pass is located in Cleon Township (T24N-R13W), southwest of the fault noted on the Niagaran structure map. Another is located in Paradise Township (T25N-R10W) near the fault indicated there. A third possible pass is located between Mayfield (T25N-R11W) and Grant (T25N-R12W) Townships

but this one may or may not be fault related. The pass in Cleon Township and the pass in Paradise coincide with limestone embayments in the Niagaran. This supports deeper water conditions in a localized area, as well as the presence of a clean halite section in the A-2 Evaporite. The above conditions line up near the downthrown side of the fault where the water depth would be greater.

It is interesting that behind these passes lie possible lagoon or back-reef areas in front of the massive reef complex that contain a clean halite section. Currents through the passes may have scoured out tidal flat sediments enough to create a regime where water depth inhibited anhydrite deposition. It is interesting that where the possibility of lagoon environments exist, the width of the pinnacle trend narrows. It seems odd that few or no producing pinnacles have been found in northern Cleon and northwestern Grant Townships. The environment of deposition determined from using the lithologic changes at the base of the A-2 Evaporite could possibly explain the lack of producing pinnacles in those areas.

As the massive reef complex is approached from behind the pinnacle reef complex, the A-2 Evaporite becomes pure anhydrite. This is true except in areas that are behind or near passes in the pinnacle complex. In many of those areas, a clean halite section is present right up against the front of the massive reef complex. The evaporite section thins abruptly at the front of the massive reef, and continues up

over the top and caps it.

In studying initial production of producing pinnacles of the study area, it is interesting that the most productive pinnacles underlie areas that are capped by anhydrite at the base of the A-2 Evaporite or areas where the base of the A-2 Evaporite is becoming anhydritic (the "ratty" zone where the halite and anhydrite are interbedded). If these two areas best represent proximity to tidal flat environments of the underlying A-1 Carbonate, then this would support conclusions drawn from Sears and Lucia's work. Niagaran pinnacles beneath A-1 Carbonate tidal flats were dolomitized by the same processes that dolomitized the A-1 Carbonate. In areas where Niagaran reefs were dolomitized, greater initial production would be expected. In conclusion, the lithology of the salt at the base of the A-2 Evaporite may be used as a mapping tool for delineating areas of more productive Niagaran reefs.

On top of the Niagaran massive reef complex, the A-2 Evaporite thickness averages less than 40 feet. In the pinnacle belt, it is generally less than 250 feet thick. In the central basin, the A-2 Evaporite averages thicknesses between 450 - 500 feet (Mesolella et al, 1974).

A-2 CARBONATE STRUCTURE MAP

Structural contours indicate the slope into the basin is gentler than it was during Niagaran time. The contours

are wider apart and evenly spaced. The shape is no longer controlled by the Niagaran massive reef complex. Contours trend N 20° E until they reach Cleon Township. There they take a turn and trend in a direction of N 45° E. The turn here may be related to the fault indicated on the Niagaran structure map. Two structural noses into the basin are apparent. They are located approximately where faults are indicated on the Niagaran map.

A-2 CARBONATE ISOPACH MAP

The A-2 Carbonate is thinnest on top of the Niagaran massive reef complex and thickens basinward (Plate 10). Thick areas of sedimentation occur along the front edge of the massive reef complex where draping of carbonate might be expected. Thick sections of carbonate are also present within the boundaries of the pinnacle reef complex. These areas may represent topographic lows where A-2 Evaporite was scoured away by currents or wave action. Most of the thicker sections of A-2 Carbonate occupy slope positions off of the A-1 Carbonate tidal flats either on the front or back sides of the pinnacle reef complex. In the study area, the A-2 Carbonate is generally less than 120 feet thick. In the central basin, this carbonate unit averages 50 feet in thickness (Mesolella et al, 1974).

B-UNIT ISOPACH MAP

In general, the B-Unit thickens basinward, but thickens locally in the study area (Plate 11). Localized thickening is found inside the 400 foot contour interval. Mesolella et al, (1974) attributes the thickening to A-2 salt solution lower in the stratigraphic section. Upon examination of the A-2 Evaporite Isopach map no thinning of this unit is observed over the top of the pinnacle reef fairway. It may be possible the Michigan Basin was actively undergoing subsidence along old Niagaran structural boundaries, but at this point, an explanation for localized thickening of the B-Unit seems elusive. In the study area, the B-Unit is 300 - 350 feet thick except over the top of the pinnacle fairway. There it thickens to between 350 and 450 feet. In the central basin, the B-Unit averages 400 feet in thickness (Mesolella et al, 1974).

PETROLEUM PRODUCTION

In the northern pinnacle belt, a definite updip partitioning of petroleum products exists. Basinward pinnacles produce gas (unless salt plugging has occurred) while pinnacles updip produce oil and water (close to the massive reef complex). Oil downdip is less viscous and of higher degree than oil updip. Production along the basinward edge contains appreciable amounts of hydrogen sulfide

contaminants. These observations concur with those of Gill (1979) and present further questions that need to be answered.

If the oil migrated into place before the pinnacle reefs were sealed with A-2 Evaporite, what part did refluxation of brines during A-1 Carbonate time play in contaminating production ? If the oil was generated in place after the reefs were capped, did contamination result from organisms within the reefs, or does the presence of hydrogen sulfide depend on hydrocarbon maturation and depth of burial? If carbonates from a central basin reducing environment sourced the oil for the pinnacle reefs updip, what limited the hydrogen sulfide components from contaminating all of the pinnacles in the northern pinnacle belt ? These unanswered questions need to be investigated for a better understanding of production trends observed within the northern pinnacle belt.

CONCLUSIONS

A stratigraphic, structural, and lithological analysis was done on Niagaran-Lower Salina units in northwestern Michigan. From the analysis, it was determined that lithologic changes in the Brown Niagaran and the A-1 and A-2 Evaporite units could be used as pinnacle reef indicators, and could be related to petroleum type and occurrence.

Brown Niagaran reef growth was determined by Gill

(1975) and Sears and Lucia (1980) to be entirely of Niagaran age. Brown Niagaran buildup is thickest in the massive reef complex and in individual pinnacles. It thins basinward where carbonate generation was minimal and sedimentation rates were lower. The pinnacles are found in a "fairway" located basinward of the massive reef complex. The linear trends observed for pinnacle locations generally parallel regional structure that existed at the time. Lithology of the Brown Niagaran in the study area is both limestone and dolomite. The dividing line between the two lithologies parallels the massive reef complex and is located at the approximate mid-point of the pinnacle reef trend. The Brown Niagaran is dolomite north of this line and limestone south of it. Embayments of limestone into the dolomite region have been attributed to faulting and reflect a deeper water environment.

A definite segregation of hydrocarbons within the pinnacle reefs has been observed in the study area. Most pinnacles lying farthest basinward are plugged with salt and are void of hydrocarbons. Updip, the pinnacles are generally composed of limestone and have pore space. The limestone composition and taller heights of these pinnacles reflect a deeper water environment than the pinnacles located farther updip. Production rates are lower for these basinward pinnacles and production has been contaminated with hydrogen sulfide. Pinnacles located in the center and upper portion of the pinnacle trend have been dolomitized and have

appreciable pore space. Rates of production are higher than pinnacles located downdip and "sweet" oil is produced. Near the massive reef complex, many pinnacles are filled with anhydrite, or they produce limited amounts of low gravity oil and water, or just water.

A-1 Evaporite deposition filled in existing Niagaran topography. This evaporite is composed of halite in the center of the basin where it is the thickest. From the basinward edge of the pinnacle trend, to the front edge of the Niagaran massive reef complex, the A-1 Evaporite becomes a mixture of halite and anhydrite with the anhydrite at the base. When approaching the flanks of pinnacle reefs, the anhydrite at the base increases in thickness. The A-1 Evaporite pinches out on the flanks of pinnacles and against the front of the Niagaran massive reef complex.

Data from this study support the restricted marine tidal flat model for A-1 Carbonate deposition proposed by Huh (1977) and Sears and Lucia (1980). Tidal flat sediments extend from the massive reef complex approximately half way through the pinnacle reef belt. Within the pinnacle belt, and proximal to pinnacle reefs, the "rabbit ears" anhydrite appears in the upper portion of the A-1 Carbonate section. The tidal flat sediments were dolomitized by refluxing of salt saturated brines during A-2 Evaporite time. The process that dolomitized the A-1 Carbonate was believed to have dolomitized the Niagaran pinnacle reefs located beneath these tidal flat environments. In conclusion, pinnacles

beneath tidal flat environments that had been fully or partially dolomitized would be expected to be more productive. Upon studying initial production rates of producing pinnacles in the study area, it was found that the most productive reefs were located beneath A-1 Carbonate tidal flat environments, which can be detected by lithologic changes at the base of the A-2 Evaporite.

The A-2 Evaporite is thickest in the interior of the basin and thins towards the margins. Over the tops of pinnacles this evaporite thins and becomes anhydritic at the base. Lithologic changes in this unit are similar to those of the A-1 Evaporite. Basinward of the pinnacle trend the A-2 Evaporite is composed of halite. As tidal flat environments of the underlying A-1 Carbonate are approached, the base of the evaporite becomes a ratty mixture of halite and anhydrite. On top of the underlying tidal flats, a clean anhydrite lens is present at the base of the section. These lithologic changes at the base of the A-2 Evaporite simply reflect a change in water depth. Passes through the pinnacle trend become apparent, as the deeper water depth is reflected by the presence of a clean halite section. As the massive reef complex is approached, the A-2 Evaporite becomes anhydrite, thins abruptly, and continues up over the top of the massive reef complex and caps it. Exceptions are noted in areas directly behind, or near passes in the pinnacle reef complex. In those two areas, a clean halite section is present in contact with the front of the massive

reef complex.

Combining results of the initial production rates study with lithologic changes observed at the base of the A-2 Evaporite has produced a mapping tool for delineating general areas where Niagaran reefs should be more productive. Areas where the base of the A-2 Evaporite is a ratty mixture of halite and anhydrite, or where a clean anhydrite lens is present, best represent tidal flat environments of the underlying A-1 Carbonate. Dolomitized pinnacles located beneath these areas have the highest rates of initial production.

The A-1 Carbonate is thinnest on top of the massive reef complex and thickens basinward. This suggests physical, not biological, processes were dominant during deposition of this unit.

Localized thickening of the B-Unit was observed in the study area, but an explanation for this phenomenon seems elusive.

No conclusions were drawn as to how and when the hydrocarbons along the basinward edge of the pinnacle reef trend were contaminated with hydrogen sulfide, or as to what limited the areal extent of the contamination. Further examination of questions such as these is needed to gain a better understanding of production trends in the northern Michigan pinnacle reef belt.

BIBLIOGRAPHY

BIBLIOGRAPHY

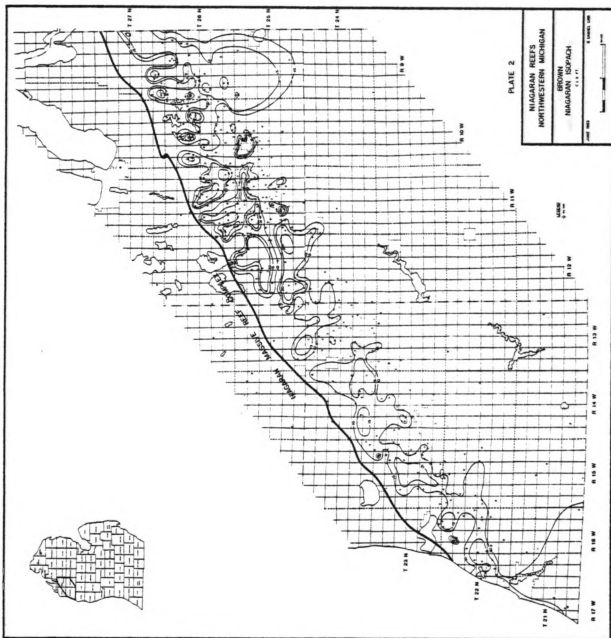
- Alling, H.L. and Briggs, L.I., 1961, Stratigraphy of Upper Silurian Cayugan evaporites: AAPG Bulletin, v.45, p. 515-547.
- Autra, M.D., 1977, A regional study of the Niagaran and Lower Salina of the Michigan Basin: Unpub. Master's Thesis, Michigan State University.
- Bates, E.R., 1970, The Niagaran reefs and overlying carbonate evaporite sequence in southeastern Michigan: Unpub. Master's Thesis, Michigan State University.
- Briggs, L.I., and Briggs, D.Z., 1974, Niagara-Salina relationships in the Michigan Basin: Silurian reef-evaporite facies, Michigan Basin (abs); Michigan Basic Geol. Soc. Ann. Field Conf., p. 1-23.
- Briggs, L.I., and Briggs, D.Z., 1975, Petroleum potential as a function of tectonic intensity of reef-evaporite facies, Michigan Basin (abs), AAPG Annual Mtg. Abstr, v.2, p.7.
- Budros, R. and Briggs, L.I., 1977, Depositional environment of Ruff Formation (Upper Silurian) in southeastern Michigan, in Reefs and evaporites, concepts and depositional models: AAPG Studies in Geology, no. 5, p. 53-71.
- Caughlin, W.G., Lucia, F.J., McIver, N.L., 1976, The detection and development of Silurian reefs in northern Michigan: Geophysics, v. 41, p. 646-658.
- Cohee, G.V., 1948, Thickness and lithology of Upper Ordovician and Lower and Middle Silurian rocks in the Michigan Basin: U.S. Geol. Surv. Prelim. Chart 33, Oil and Gas Inv. Serv.
- Cohee, G.V., and Landes, K.K., 1958, Oil in the Michigan Basin: in Weeks, L.G. (ed.), Habitat of Oil, AAPG, p. 473-493.

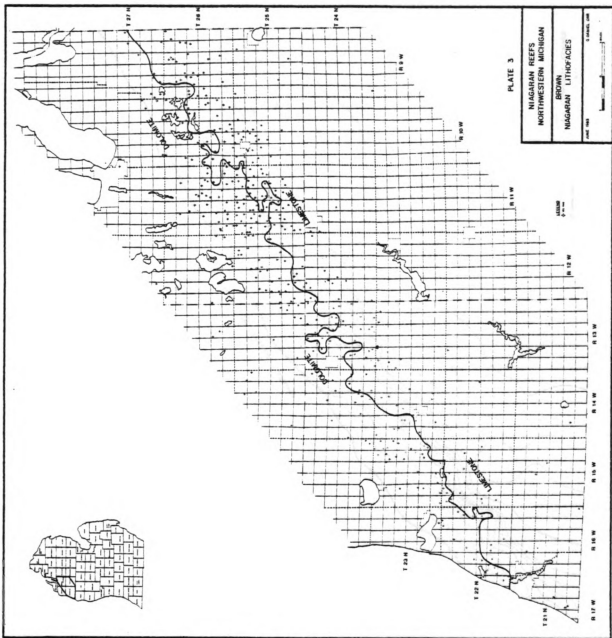
- Cummings, E.R., and Schrock, R.R., 1928, Niagaran coral reefs of Indiana and adjacent states and their stratigraphic relations: GSA Bulletin, v. 39, p. 579-620.
- Dellwig, L.I. and Evans, R., 1969, Depositional processes in Salina salt of Michigan, Ohio, and New York: AAPG Bulletin, v. 53, p. 949-956.
- Ehlers, G.M., and Kesling, R.V., 1962, Silurian rocks of Michigan and their correlations: Mich. Geol. Soc. Ann. Field Excursion, p. 1-20.
- Ells, G.D., 1962, Silurian rocks in the subsurface of southern Michigan, Silurian rocks of the southern Lake Michigan area: Mich. Basin Geol. Soc. Ann. Field Excursion, p. 39-49.
- Ells, G.D., 1963, Information on Michigan's Silurian oil and gas pools, Michigan Dept. of Conserv., Geol. Surv. Div., 49p.
- Ells, G.D., 1967, Michigan's Silurian oil and gas pools: Report of Investigation no. 2, Geol. Surv. Div., Mich. Dept. Conserv. 49p.
- Ells, G.D., 1969, Architecture of the Michigan Basin: Mich. Basin Geol. Soc. Ann. Field Excursion, p. 60-88.
- Elowski, Ronald C., 1980, Potassium Salts - Potash - of the Salina Al Evaporite in the Michigan Basin: Report of Investigation 25, Michigan Department of Natural Resource, Geological Survey Division, 15p.
- Evans, C.S., 1950, Underground hunting in the Silurian of southwest Ontario: Geol. Assoc. Can. Proc., v. 3, p. 55-85.
- Felber, B.E., 1964, Silurian reefs of Southeastern Michigan: Unpublished Ph.D. dissertation, Northwestern Univ., 104p.
- Fincham, W.J., 1975, The Salina Group of the southern part of the Michigan Basin: Unpub. Master's Thesis, Michigan State University.
- Fisher, J.H., 1969, Early Paleozoic history of the Michigan Basin: Mich. Basin Geol. Soc. Ann. Field Excursion Guidebook, p. 89-93.
- Fisher, J.H., 1973, Petroleum occurrence in the Silurian reefs of Michigan: Ontario Petroleum Inst. Tech. Paper 9, 10p.

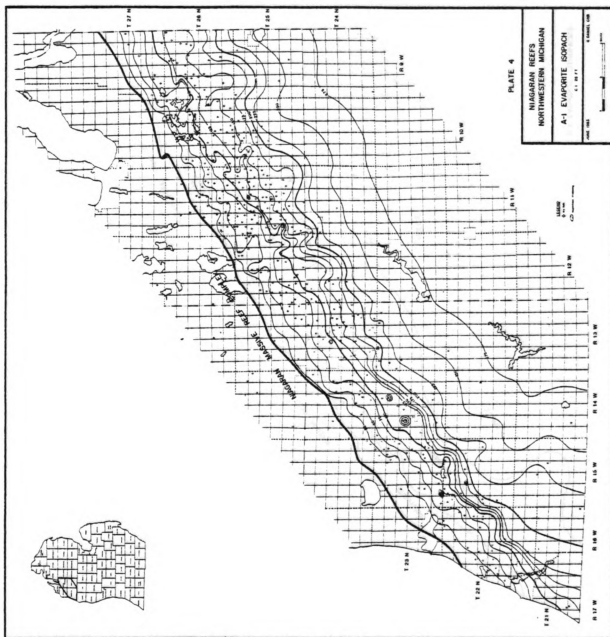
- Gill, D., 1973, Stratigraphy, facies, evolution, and diagenesis of productive Niagaran Guelph reefs and Cayugan sabkha deposits, Bell River Mills gas field, Michigan Basin: Ph.D. dissert., Univ. Mich., 276p.
- Gill, D., 1975, Cyclic deposition of Silurian carbonate and evaporite in the Michigan Basin, Discussion: AAPG Bulletin, v. 59, p. 535-538.
- Gill, D., 1977, Salina A-1 sabkha cycles and the Late Silurian paleogeography of the Michigan Basin: Jour. Sed. Petrol., v. 47, p. 979-1017.
- Gill, D., 1979, Differential entrapment of oil and gas in Niagaran pinnacle reef belt of northern Michigan: AAPG Bulletin, v. 63, p. 608-620.
- Hartsell, M.Y., 1982, Niagaran pinnacle reefs of western Michigan, unpublished M.S. Thesis, Michigan State University, 109p.
- Haxby, W.F., Turcotte, D.L., and Bird, J.M., 1976, Thermal and mechanical evolution of the Michigan Basin: Tectonophysics, v. 36, p. 57-75.
- Hines, W.J., 1963, Regional gravity and magnetic anomaly maps of the southern peninsula of Michigan: Mich. Geol. Surv. Report of Investigation, no. 1, 26p.
- Huh, J.M.S., 1973, Stratigraphy and diagenesis of the Niagaran pinnacle reefs (Silurian) in northern Michigan Basin (abs), AAPG Bulletin v.57, p. 785.
- Huh, J.M.S., Briggs, L.I., and Gill, D., 1977, Depositional environments of pinnacle reefs, Niagara and Salina Groups, northern shelf, Michigan Basin: in Reefs and evaporites, concepts and depositional models: AAPG Studies in Geology, no. 5, p. 1-21.
- Jodry, R.L., 1969, Growth and dolomitization of Silurian reefs, St. Clair County, Michigan: AAPG Bulletin, v. 53, p. 957-981.
- Johnson, K., 1971, The interrelationship of the Lower Salina Group and Niagaran reefs in St. Clair and Macomb Counties, Michigan: Unpub. Master's Thesis, Michigan State University.
- Landes, K.K., 1945, The Salina and Bass Islands rocks in the Michigan Basin: U.S. Geol. Surv. Prelim. Map, no. 40, Oil and Gas Inv. Serv.

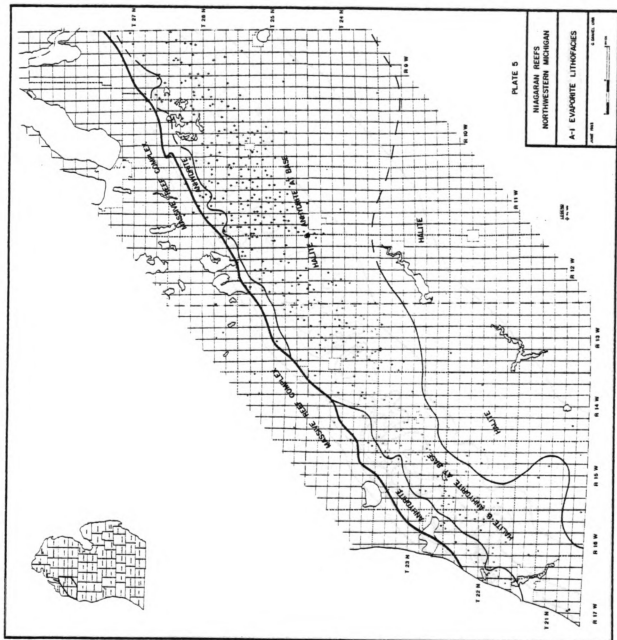
- Lilienthal, R.T., 1978, Stratigraphic cross sections of the Michigan Basin: Geol. Surv. Div. Report of Investigation, no. 19.
- Lowenstam, H.A., 1950, Niagaran reefs of the Great Lakes area: Jour. of Geology, v. 58, p. 430-487.
- Lowenstam, H.A., 1957, Niagaran reefs of the Great Lakes area: GSA Memoir, 67, p. 215-248.
- Mantek, W., 1973, Niagaran pinnacle reefs in Michigan: Mich. Basin Geol. Soc. Ann. Field Excursion Guidebook, p. 35-46.
- Melhorn, W.M., 1958, Stratigraphic analysis of Silurian rocks in the Michigan Basin: AAPG Bulletin, v. 42, p. 816-838.
- Meloy, D. U., 1974, Depositional history of the Silurian northern carbonate bank of the Michigan Basin: Master's thesis, Univ. Mich., 78p.
- Mesolella, K.J., Robinson, J.D., McCormick, L.M., and Ormiston, A.R., 1974, Cyclic deposition of Silurian carbonates and evaporites in the Michigan Basin: AAPG Bulletin, v. 58, p. 34-62.
- Mesolella, K.J., 1975, Cyclic deposition of Silurian carbonates and evaporites in the Michigan Basin: Reply: AAPG Bulletin, v. 59, p. 538-542.
- Newcombe, R. J., 1933, Oil and Gas fields of Michigan, a discussion of depositional and structural features of the Michigan Basin: Michigan Geol. Survey Div. Pub. 38 Geol. ser. 32, 293p.
- Nurmi, R.D., 1974, The Lower Salina (Upper Silurian) stratigraphy in a dessicated, deep Michigan Basin: Tech. Paper no. 14, Ontario Petrol. Inst. Ann. Conf., 25p.
- Pirtle, G.W., 1932, Michigan structural basin and its relationship to surrounding areas: AAPG Bulletin, v. 16, p. 145-152.
- Potter, D.L., 1975, The Lower and Middle Silurian of the Michigan Basin: Unpub. Master's Thesis, Michigan State University.
- Sears, S.O., and Lucia, F.J., 1979, Reef growth model for Silurian pinnacle reefs, northern Michigan reef trend: Geology, v. 7, p. 299-302.

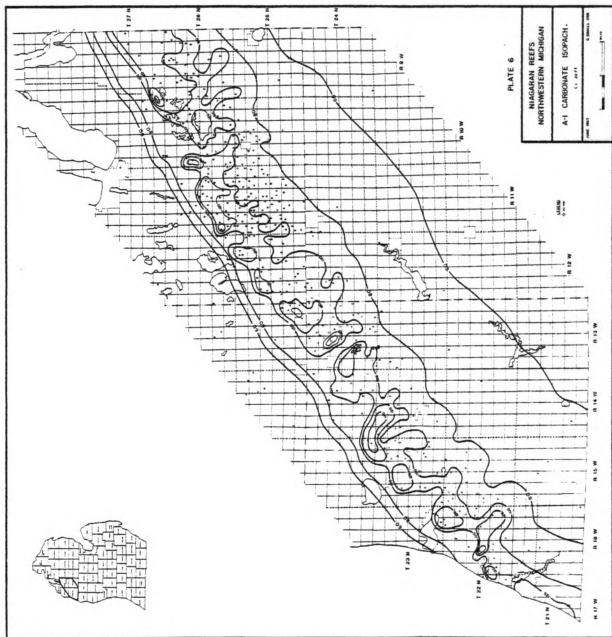
- Sears, S.O. and Lucia, F.J., 1980, Dolomitization of northern Michigan Niagara reefs by brine refluxation and freshwater/seawater mixing: in Concepts and models of dolomitization (Zenger, Donald H., editor; et al.), Special Publication-Society of Economic Paleontologists and Mineralogists, No. 28, p.215-235.
- Sharma, G.D., 1966, Geology of Peters Reef, St. Clair County, Michigan: AAPG Bulletin, v. 50, p. 327-350.
- Walles, F.E., 1980, Niagara pinnacle reefs of south central Michigan: Unpub. Master's Thesis, Michigan State University.

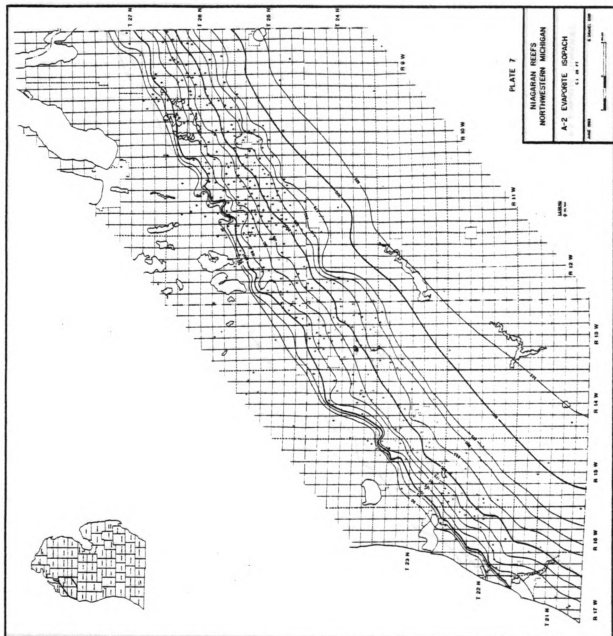


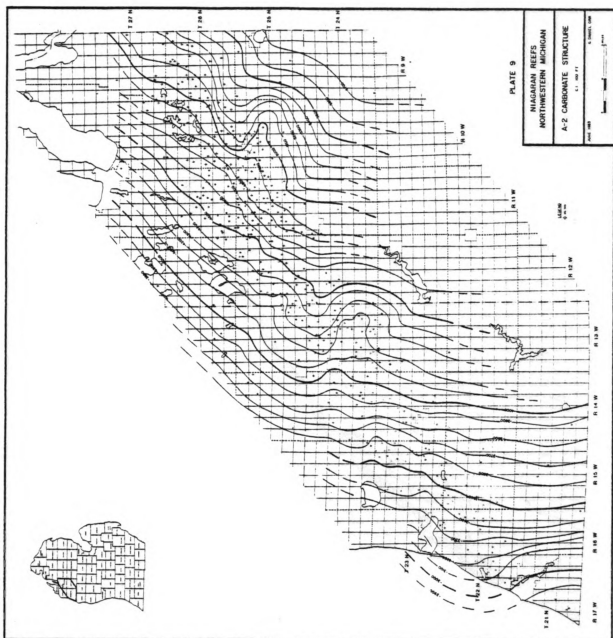


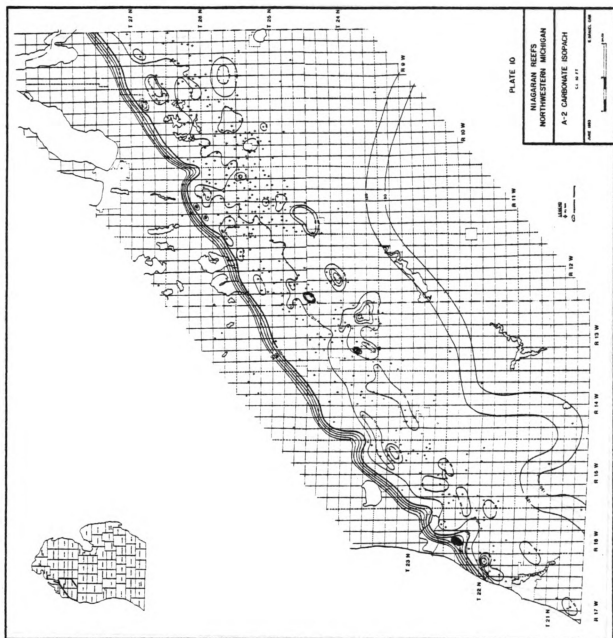


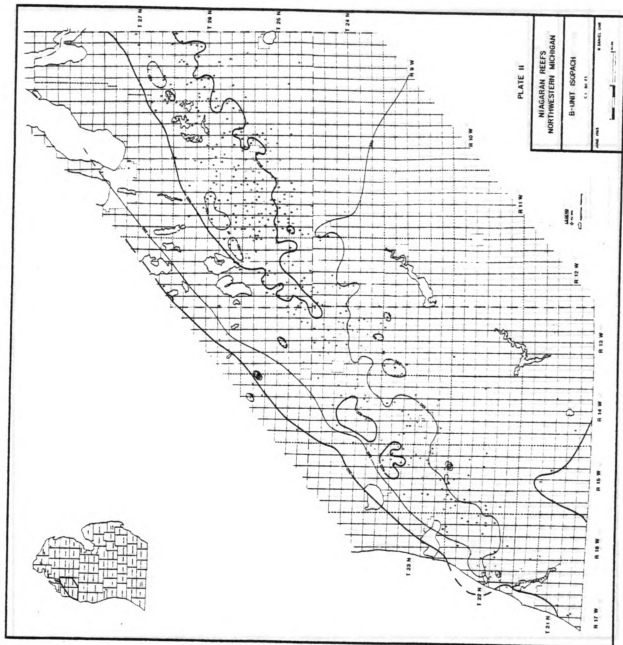


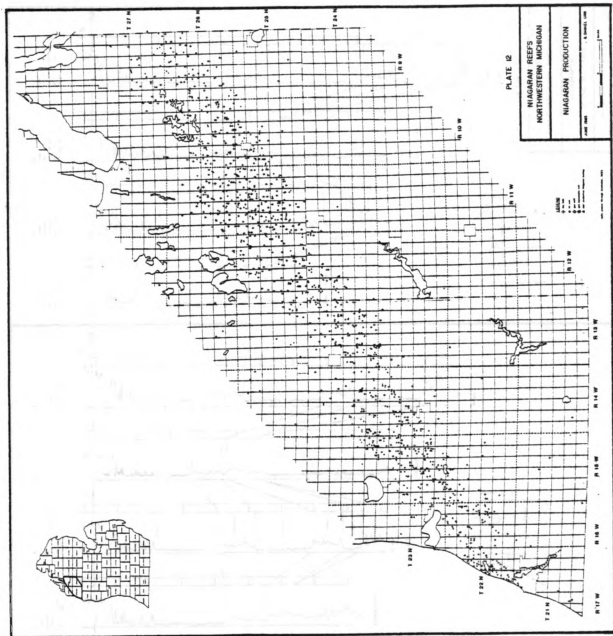


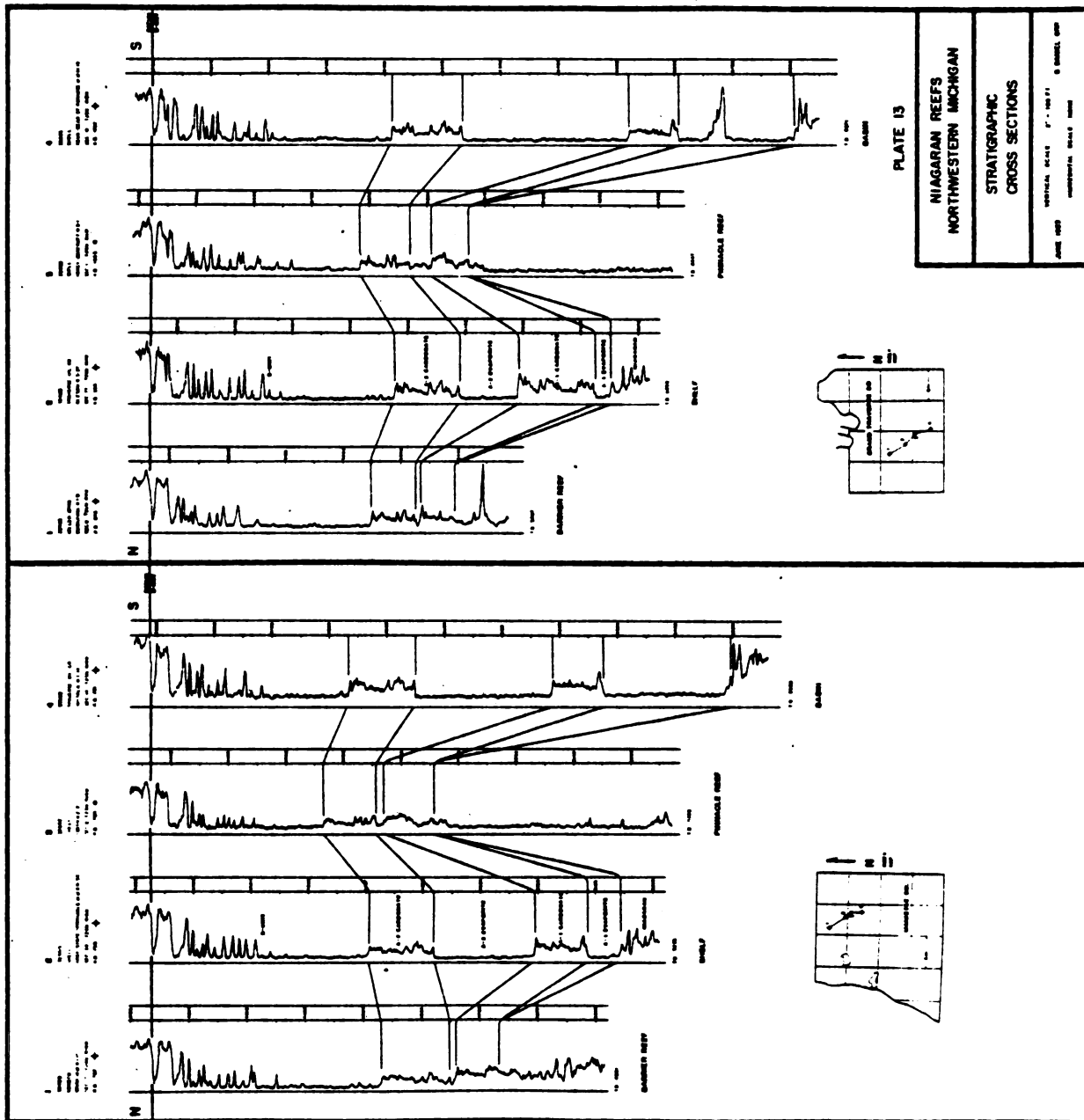












MICHIGAN STATE UNIV. LIBRARIES



31293106298007