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MODELS OF DOLOMITIZATION FROM PETROGRAPHIC AND SELECTED TRACE ELEMENT DATA WITHIN THE MIDDLE DEVONIAN CARBONATES OF THE REED CITY STORAGE FIELD, LAKE AND OSCEOLA COUNTIES, MICHIGAN

presented by

RONALD RAY CARLTON

has been accepted towards fulfillment
of the requirements for

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C. E. Prouty
Major professor

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# MODELS OF DOLOMITIZATION FROM PETROGRAPHIC AND SELECTED TRACE ELEMENT DATA WITHIN THE MIDDLE DEVONIAN CARBONATES OF THE REED CITY STORAGE FIELD, LAKE AND OSCEOLA COUNTIES, MICHIGAN

By

Ronald Ray Carlton

A THESIS

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AN ABSTRACT

MODELS OF DOLOMITIZATION FROM PETROGRAPHIC AND SELECTED TRACE ELEMENT DATA WITHIN THE MIDDLE DEVONIAN CARBONATES OF THE REED CITY STORAGE FIELD, LAKE AND OSCEOLA COUNTIES, MICHIGAN

By

Ronald Ray Carlton

The Reed City Field's main structural axis has been cut by several cross faults (right lateral wrench faults). Isopach studies indicate that a structure was present during Dundee deposition, but has been shoved up to 1600 meters west by the time of Traverse deposition.

Isodol studies indicate that dolomite content of all three Middle Devonian horizons studied (Traverse, Dundee, Detroit River) appear to be structurally controlled. Dolomite content at most levels of the Traverse, Dundee, and Detroit River increases up the flanks of the structure and as it nears the apex begins to decrease. This suggests that the epigenetic dolomite associated with the structure has been removed by dedolomitization. Nevertheless, it is clear that there is two kinds of dolomite in this field; regional early diagenetic dolomite and a late diagenetic (epigenetic) dolomite associated with the structure.

Ronald Ray Carlton

A lateral study of the Sr, Mn, and Na content in the Reed City Field suggests that the carbonates near the apex of the structure has undergone a change in geochemistry when compared to those on the flanks of the structure.

ACKNOWLEDGMENTS

I do not believe words can adequately express my appreciation and thanks to C. E. Prouty (chairman of the committee) for his help on this study. Without his help, this study could not have been completed. He helped overcome each obstacle encountered and encouraged me to try new ideas.

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# INTRODUCTION

## General Statement of the Problem

The purpose of this study is: (1) to determine the distribution of dolomite, epigenetic and/or diagenetic, observed in the Reed City Storage Field; (2) use certain trace element patterns to help differentiate between epigenetic and diagenetic dolomite.

Weber (1964), Kinsman (1969), Friedman (1969), Badiozamani (1973), Land and Hoops (1973), Land and others (1975), Veizer (1977), Veizer and others (1977, 1978), and others have noted that trace element assemblages in carbonates may reflect the chemistry of the water in which these rocks formed, and some of the diagenetic alterations these rocks have undergone. In short, they could be used as rough paleoenvironmental indicators when used in conjunction with a facies study. Brand and Veizer (1980) took this one step further and suggested that: "Theoretical considerations (i.e., partition coefficients, water/rock ratio, chemistry of interstitial water) of elemental behavior during diagenetic stabilization with metoric waters suggest that it leads to a decrease in strontium, sodium, and possibly magnesium and an increase in manganese, iron and zinc in progressively altered carbonates." The diagenetic (formed penecontemporaneous with deposition) dolomite would therefore exhibit a different trace element chemistry than the epigenetic (late diagenetic) dolomite.

Recently there have been several rather detailed studies of dolomite/calcite ratios in the Middle Devonian linear anticlinal oil structures within the Michigan Basin (Dastanpour, 1977; Hamrick, 1978; Ten Have, 1979; Hyde, 1979; Richey, 1980). The x-ray diffraction data in each of these studies indicates a close relationship between dolomite occurrence and fracture pathways, both vertically and horizontally within the closure of the anticlinal flexure. One type of dolomite, restricted to the structure proper, and typically with increased dolomite percentages toward the fold axis, is considered to be epigenetic in origin, with surrounding, regional dolomite of a diagenetic origin. The percent of dolomite at the outer closure of the structure represents regional diagenetic dolomite.

From this previous work on the Middle Devonian oil fields in the Michigan Basin and the known presence of a structure in the Reed City area, it is suggested that the Reed City Storage Field should contain two kinds of dolomite; epigenetic and diagenetic. This should afford an excellent opportunity to use trace element patterns in addition to dolomite/calcite ratios to help differentiate between the epigenetic and diagenetic dolomite found in the Reed City Field.

## Previous Work

The use of calcium carbonate/magnesium ratios, magnesium/calcium ratios, dolomite/calcite ratios in relation to the producing zone and the structure of an oil field began in 1950. It was expected that the higher the ratio the more porosity would be present (Landes, 1946). Powell (1950) used calcium carbonate/magnesium ratios in the Rogers City and Dundee Formations in the Pinconning Oil Field to test this. He was not able to show how the ratios were related to the structure of the oil field. Jodry (1954) developed a fast titration technique for the determination of magnesium/calcium ratios. Young (1955) applied this method to the Stoney Creek Field and found little or no correlation to the structure of this field. Tinklepaugh (1957) using Jodry's (1954) titration method and statistical tests was able to show a positive correlation between structure and the magnesium/calcium ratios in fields found in the central part of the Michigan Basin. Goodrich (1957) and Egleston (1958) looked at the magnesium/calcium ratios in the Reynolds and Winfield Oil Fields. They found little correlation between the magnesium/calcium ratios and structure of the fields.

Dastanpour (1977) modified this approach by using x-ray diffractometry. This method, measures the relative heights of the calcite and dolomite peaks, and is not affected by the presence of other calcium and magnesium bearing minerals (which could have had an adverse affect on the earlier

studies). He studied the Reynolds Oil Field and found evidence that dolomitization shows a close positive correlation to the structure map drawn on the top of the Traverse Group. He concluded that the dolomite that was clearly related to the structure of the field was epigenetic in origin while the surrounding dolomite was diagenetic. Hamrick (1978) studied the dolomitization pattern in the Walker Oil Field using x-ray diffractometry. He was able to show that the geometry of the folds found in the field and the distribution of dolomite percentages suggest a relationship to faulting. He also noted epigenetic and diagenetic dolomite in the field. Hyde (1979), Ten Have (1979), and Richey (1980) using x-ray diffractometry studied the dolomite/calcite ratios in the Kawkawlin, West Branch and North Adams Fields respectively. When comparing the lateral dolomite/calcite pattern to the structural configurations of each field they were all in agreement that the dolomitization pattern in each field was related to its structure. They also concluded that the dolomite related to the structure was epigenetic in origin and the dolomite not related to the structure was of a diagenetic origin.

Regional studies of Middle Devonian carbonates using a semi-quantitative technique (Colorado School of Mines, 1951) for the determination of dolomite have been done by Bloomer (1969) and Runyon (1976). They have shown regional changes in dolomite content as one moves westward across Southern Michigan. The lines of equal dolomite content

("isodols") trend in an approximate north-south direction and achieve 100% dolomite in southwest and northwest Michigan before reaching Lake Michigan.

This particular dolomite trend perhaps takes on more meaning when considering the West Michigan lagoon of Jodry (1957). He concluded that the western part of Southern Michigan was, in Middle Devonian time, a semi-restricted area ("lagoon") separated from Central Michigan (open sea) by a roughly north-south "barrier." Jodry attributed this barrier to the presence of a linear Precambrian high. Evidence for the structure is a positive gravity anomaly mapped by Logue (1954) in his gravity map of Michigan. Jodry saw facies differences in the Middle Devonian-Traverse on either side of the barrier; dark, cherty dolomite and limestone, with some evaporites to the west; gray shales, lighter colored carbonates, increased limestone/dolomite ratios, clastics and fossiliferous limestone, and almost no evaporites to the east. Both Gardner (1974) and Runyon (1976) were impressed with the facies differences of the Middle Devonian in western and central Michigan. Runyon, especially recognized the presence of the "barrier" observed by Jodry, based on his work on the limestone, dolomite and evaporite trends during the Traverse.

Prouty (1976b, 1980) has studied the geometry of dolomite-fracture porosity producing oil fields and believes that the strike-slip mechanism of a simple shear model exists; further the anticlinal folds represent shear folds

generated by the shear (strike-slip) faults. The vertical shear faults apparently served as channelways for the dolomitizing fluids as well as later hydrocarbons.

This past work suggests that the Reed City Storage Field is located in an area that contains diagenetic (western Michigan) as well as epigenetic dolomite.

The work on trace elements in carbonates is now volumninous and impossible to review. Only the most pertinent papers to this study will be reviewed here.

In 1964, Weber analyzed 450 carbonate samples for trace and minor elements. He noted statistically significant variations in trace element content in primary and secondary dolostones. According to Weber this represents the differences in the original mineralogy of the rock; secondary dolomite replaces aragonitic limestone and primary dolomite replaces calcitic limestone.

Kinsman (1969) showed that the $Sr^{2+}$ concentration of diagenetically altered limestone has a potential value in indicating the mechanism of diagenesis. Ancient carbonates have a rather low $Sr^{2+}$ concentration when compared to modern carbonates. Kinsman concluded that an open system prevailed through which large volumes of pore fluid migrated during diagenesis. This he noted, tended to "purify" the rock of $Sr^{2+}$.

Friedman (1969) believes that the geochemical composition of carbonate sediments reflects some of the variables in the chemistry of the waters in which they were deposited.

The aim of his study was to determine if a relationship exists between the trace element configuration of carbonate sediments and major carbonate depositional environments: marine, lagoonal, and fresh water. He found that a correlation exists between trace element concentrations and depositional environment for carbonate sediments.

Land and Hoops (1973) concluded that sodium should be a good indicator of salinity during marine carbonate precipitation. They proposed that the low sodium content of most ancient carbonates indicate that these rocks have re-equalibrated with solutions low in sodium.

Badiozamani (1973) used both $Sr^{2+}$ and $Na^{+}$ concentrations in limestones and dolostones to demonstrate how the Mifflin Carbonates (Middle Ordovician along the Wisconsin arch) became equilibrated with meteoric waters. He was able to demonstrate the loss of $Na^{+}$ through diagenetic processes.

Land and others (1975), Veizer and others (1977, 1978) concluded that sodium was a good indicator of salinity during the deposition of marine carbonates, as well as reflecting the chemistry of diagenetic solutions. Veizer and others (1977) were able to show that sodium was more concentrated in restricted marine carbonates. The sodium concentration was clearly facies controlled.

Brand and Veizer (1980) demonstrated that diagenetic stabilization of the carbonate constituents of the Burlington Limestone (Mississippian, Iowa, and Missouri) and the Read Bay Formation (Silurian, Arctic Canada) was accompanied

textural and chemical changes. They were able to show that an increase in the degree of post-depositional alteration results in a decrease of $Sr^{2+}$ and $Na^{+}$ as well as an increase in $Mn^{2+}$. Such a relationship should hold for the differences between diagenetic and epigenetic dolomite.

Land (1980) considered quantitative interpretations of absolute trace element values of dolomite to be tenuous at best. He believes that because of our "present state of ignorance" qualitative interpretations of regional or stratigraphic variations in chemical parameters to be a valid approach, and should prove to be quite useful in future studies.

Based on the structure present and past work in this area the Reed City Storage Field should contain both epigenetic and diagenetic dolomite. From the above discussion it is apparent that each type would have its own unique trace element "fingerprint." Using trace elements in a field like the Reed City Field should help to illustrate this "fingerprint."

# STRATIGRAPHIC SETTING

The stratigraphic terms employed in this study are shown in Figure 1. This study involves a section from the top of the Traverse Limestone to the top 6-15 meters (20-50 feet) of the Detroit River Group.

## Traverse Group

In 1893 A.C. Lane grouped all strata between the Dundee and the black shales (Antrim) under the term Traverse. Grabau (1902) studied the Traverse using both well samples and outcrops. He was the first to assign the Bell Shale as the basal formation of the Traverse Group. Pohl (1930) studied the Traverse Group in the northwest corner of Michigan and did much to break the Traverse into formations based on faunas.

As described by Cohee and Underwood (1945) the Traverse Group with the Bell Shale formation at the base lies conformably on top of the Rogers City formation.

For purposes of this study, the Traverse Group will be divided into three major units: the upper Traverse Formation, the middle Traverse Limestone, and the lower Bell Shale.

Figure 1

The Traverse Formation as described by Fisher (1969) is a medium gray shale and shaley limestone which is interpreted to be a transition zone between the black Antrim Shale and the Traverse Limestone. In western Michigan, there is some interbedding between the Antrim and Traverse Formation.

The Traverse Limestone is composed of a white, brown to tan, micritic to sparry, fossiliferous limestone, with occasional alternating shale layers. The upper 6 meters (20 feet) contain coarse grained ferroan dolomite to dolomitic limestone. The average thickness in the area of study is 170 meters (560 feet).

Jodry (1957) attempted to carry surface subdivisions of the Traverse Group across the Michigan Basin. He noted a coincidence of facies changes and a structural barrier defined by a gravity anomaly (Logue, 1954), and believed this "West Michigan barrier" would be responsible for these environmental changes. He mapped his "West Michigan Lagoon" over a large area of Allegan, Ottawa, Muskegon, Newaygo, Oceana, Mason, and Lake Counties.

The Bell Shale lies on top of the Dundee. It is a dark gray to black, calcareous fossiliferous shale. Near the bottom there are abundant crinoid stems, brachiopods and an occasional ostracod. The formation is about 18 meters (60 feet) thick.

## Dundee Formation

The Rogers City and Dundee formations are difficult to distinguish in the subsurface, especially in the western part of the Basin. For purposes of this study it will be referred to as Dundee. In the Reed City Storage Field it is a buff to gray, dense to subcrystalline, fossiliferous limestone. The fossils consist primarily of crinoid columnals.

## Detroit River Group

Cohee and Underwood (1945) mapped and described the Dundee stratigraphy in west Michigan according to the common concept that the first anhydrite encountered downhole is the top of the Detroit River Group. It is instructive to note that Baltrusaitis (1974) disagrees with this practice. In well permit no. 8944 (number 99, as used in this study) occurs a bentonite bed which he named the Kawkawlin Bentonite. Cohee and Underwood (1945) would place the top of the Detroit River at 1073 meters (3,520 feet). Baltrusaitis (1974) placed the contact at 1126 meters (3,695 feet) in this well, basing his call on the position of this bentonite bed in this well. The bentonite is correlated with the bentonite occurring in the Middle Devonian in Osceola and Clare Counties and elsewhere in the Basin. Cohee and Underwood (1945) placed the top of the Detroit River at 1073 meters (3,520 feet). Of the samples from the Reed City field available at the MSU Subsurface Lab, only well permit no. 7628 (sample number 106 in this study) contains any evidence of volcanics; but these are much higher in the column than those of Baltrusaitis. To remain consistent with the drillers logs only Cohee and Underwood's interpretation will be used. To look for the Kawkawlin Bentonite in nearby wells in an attempt to resolve this problem would be beyond the scope of this study.

The Detroit River Group consists of a buff to gray, finely crystalline dolomite. With associated anhydrite and salt. Gardner (1974) has broken the Detroit River Group into members. He considers the Detroit River on the western flank of the Basin to represent a sabkha type environment.

## STRUCTURAL SETTING--MICHIGAN BASIN

The Southern Peninsula of Michigan has been described as a basin after the work of Douglass Houghton, Michigan's first state geologist. The Michigan Basin is a roughly circular, symmetrical basin. Which includes the Southern and Northern Peninsula of Michigan, Southwestern Ontario, Northwestern Ohio, Northern Indiana, Northeastern Illinois, and Eastern Wisconsin. The Basin is bordered on the west by the Wisconsin Highland, Wisconsin Arch and on the southwest by the Kankakee Arch; on the southeast by the Findlay Arch and the Algonquin Axis; and on the north by the Canadian Shield.

The Michigan Basin has subsided at various rates since probably the Cambrian with an accumulation of about 4.5 kilometers (15,000 feet) of Phanerozoic sediments (Hinze & Merritt, 1969). Drawn to scale the Basin would be comparable to an inverted post-1968 major league pitchers mound on a baseball diamond.

Over the years many theories for the formation of the Michigan Basin have been advanced. Pirtle (1932) and Newcombe (1933) both believed that the subsidence of the Basin was due to an inherent weakness in the Precambrian

basement rock. Newcombe believed that the subsidence of the Basin was somehow related to the Appalachian Orogeny. Both investigators were in agreement on the origin of the minor folds and faults in the Basin. They concluded that the folds and faults were controlled by trends of folding and lines of structural weakness in the basement rocks.

Kirkham (1937) concluded that there was a series of northwest-southeast faults in the basement. His conclusions were based on his work in the trends found in the crystalline rocks exposed in the Upper Peninsula of Michigan. The mechanism for subsidence was that of movement of magma from under this region allowing it to sink along these faults.

Lockett (1947) agreed with Kirkham's fault system. However, he attributed in part the subsidence to the major positive structural features surrounding the Michigan Basin. He believed that these structures were supported by the crystalline cores of Precambrian mountain systems, and that the dominent crustal movement during the Paleozoic was the subsidence of intervening areas. The subsidence in Michigan was enhanced by the basement fault system. Local structure in the Basin, such as closed synclines and anticlines, were formed because of the migration of salt to the zones of differential subsidence above the basal faults.

Ells (1969) reviewed the theories of the formation of the Michigan Basin. He concluded that most workers agreed that the basement rocks, and the faults and fractures in them, are central in the formation of the Basin.

Hinze and Merritt (1969), Chase and Gilmer (1973), Hinze and others (1975) and Fowler and Kuenzi (1978), based on subsurface and geophysical studies suggest that the Mid-Michigan gravity high may be a failed arm of a rift system. This anomally is apparently created by Keewenawan basalts filling in the rift structure. The greater load created by these dense mafic rocks would depress the predominantly granitic crust causing the subsidence of the Bain.

Prouty (1976b) from lineament analysis using LANDSAT imagery has indicated the presence of vertical, strike-slip faults which involves the Precambrian and Paleozoic section. He believes that lateral stresses from the East-Southeast, perhaps from the Appalachian Orogeny, show a simple shear mechanism which brought about shear faults and related shear folds.

Because lines of weakness and lithology within the basement rocks are thought to be critical factors in the development of the Michigan Basin, it would be reasonable to expect to find facies changes across the Basin in response to the movements occurring throughout the development of the Basin (Gardner, 1974).

Grabau (1902) may have been the first to note the differences in fauna in the Traverse Group across an east-west line in northern Southern Peninsula. Pohl (1930) also noted this difference in the Traverse faunas and proposed the existence of an intermittent land barrier separating the two regions.

Newcome (1933, p. 48) published an isopach map showing the Ellsworth of western Michigan as being comparable to the Bedford section of eastern Michigan. Bishop (1940) noted that a barrier is shown on this map trending in a north-northeasterly direction through central Michigan. She felt that this suggested the presence of a low barrier that originated at the end of the Traverse Limestone deposition; which becomes more pronounced throughout Antrim-Ellsworth time.

Hale (1941) showed a barrier running from central Osceola County down to western Calhoun County. This barrier was present during the Antrim deposition to the close of Ellsworth time.

Jodry (1957) using lithologic, facies, and sedimentation studies combined with regional gravity studies was able to show the presence of a structural barrier in the western part of Michigan. This barrier was apparently higher at the beginning of Traverse time with its effect eventually diminishing by the end of Traverse deposition. This barrier separated the "West-Michigan Lagoonal facies" on the west from open sea facies to the east.

Asseez (1967) using more well data than previous authors noted a facies barrier between the Ellsworth Shale on the west and the Bedford Shale-Berea Sandstone on the east. From his isopach map of the Ellsworth Shale and Bedford-Berea sequence it is apparent that the barrier was strongest from southwestern Clare County to northeastern Barry County.

It is interesting to note that the limit of the dolomite-limestone facies of the Ellsworth Shale approximates the location of Jodry's (1957) barrier in Osceola and Mecosta Counties. Keep in mind that Jodry's barrier represents the Traverse (Middle Devonian) while Asseez's structure represents the Ellsworth Shale (Devono-Mississippian).

Runyon (1976) in a stratigraphic analysis of the Traverse Group also noted a general north-south trending barrier. He based the location of the barrier on an evaporite percent map. From his map it appears he used only five control points to set his boundry. Nevertheless it falls generally between Jodry's (1957) and Newcomb's (1933) barriers.

## THE REED CITY STORAGE FIELD

### Location

The Reed City Storage Field is located principally in the southwest quarter of Lincoln Township, and the northwest quarter of Richmond Township, Osceola County, T18N, T17N, R10W, R11W (Figure 2).

### History of Development

The presence of an anticlinical nose had long been suspected near Reed City as a result of nearby wildcatting. Further evidence of structure was revealed in 1939 when the Weber Oil Company in a joint test with Pure Oil Company and Gulf Refining Company drilled a well in section 8, Richmond Township (permit #6238) which was structurally high and had a show of oil in the Dundee and Monroe Formations. The field was discovered in October, 1940 by a cooperative test between these three companies, in section 31, Lincoln Township (permit #7628).

Development of the field began in earnest in 1941 when 111 producing and four dry holes were completed. The Gulf Refining Company had imported its own portable rotary rigs. Gulf was the first in Michigan to "drill in" with rotary

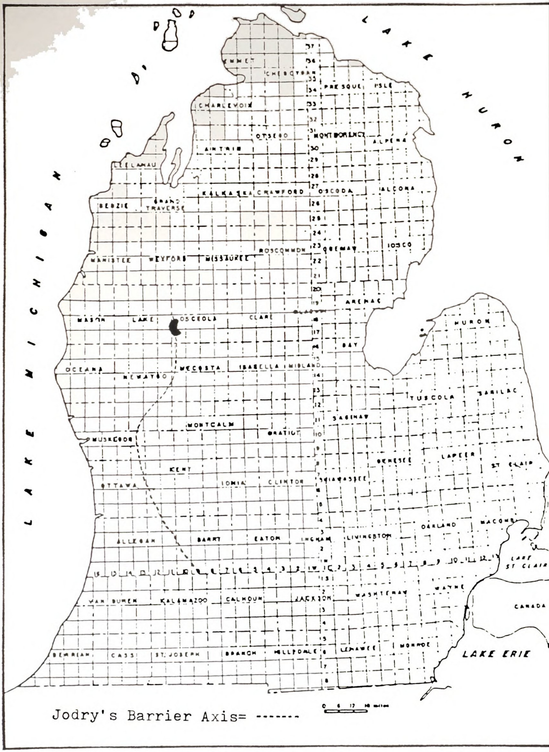



Figure 2. Location of the Reed City Storage Field.

tools. Many of the wells were finished using cable tool rigs. (The above is a summary of the report on the Reed City Field published in the National Oil Scouts & Landmen's Association Yearbooks for 1942 and 1943.)

## Production

The producing formations in the Reed City Field are (1976 summary):

| Producing Formation | Pay Zone | | | |
|---|---|---|---|---|
| | depth | thickness lithology | oil gravity A.P.I. | active wells (1976) |
| Traverse | 892m (2925') | 1.5 meters limestone | 43.7 | 4 |
| Dundee | 1064m (3490') | 0.9 meters limestone | 46.3 | 0 |
| Reed City | 1093m (3585') | 2.1 meters dolomite | 42.8 | 167 |
| Detroit River Sour zone | 1275m (4184') | 22.3 meters dolomitic lime | 48.2 | 20 |
| Richfield | 1412m (4633') | 3.7 meters sandy lime | 45.8 | 2 |

The Reed City Field is now part of the Michigan Consolidated Gas Company's unit gas storage project in an oil reservoir. The Loreed Unit in the Reed City Field is part of a gas storage-secondary oil recovery operation. This unit includes the Dundee Oil Zone and the Reed City Pay Zone.

The Traverse through 1975, has produced 3,676,022 BBLS. of oil and 388,638 Mcf. of gas. The Dundee has produced

16,257,876 Mcf. of gas through 1975. The Reed City (part of the Detroit River Group) has produced 41,927,228 BBLS. of oil. The position of the pay zones within these formations may be observed in Figures 3 and 4.

## Structure and Stratigraphy

The Pleistocene drift in the Reed City area has an average thickness of 183 meters (600 feet). The Pennsylvanian rocks average 97 meters (317 feet) thick and consist of primarily shales and sand. The Mississippian rocks average 529 meters (1735 feet) and consists of sands, shales, anhydrites and limestone. The Devonian Antrim averages 87 meters (284 feet) and consists of a black, organic rich shale.

The Traverse Lime averages 1706 meters (560 feet) thick. Figure 5 shows the locations of all the wells used in this study in constructing the structure and isopach maps.

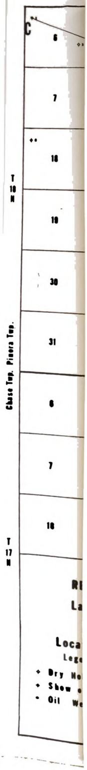
To aid in the interpretation of the structure and timing of structural events, three structural maps were constructed. These show the structure drawn on the top of the Traverse, Dundee, and Detroit River. Along with the structure maps, two isopach maps were constructed, the Traverse and the Dundee formations. (See Appendix B-Structural and thickness data.)

The Traverse structural map, as well as the other maps, was constructed by using data from drillers' logs and sample chips. The producing field lies directly on the structural


Well
5
A


W
5
B

Figure 5. Location of wells.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19
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31
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T 18 N
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Chase Twp. Pinora Twp.
Loca
Lege
Dry Ho
Show
Oil We

anticline found in the field. Wells that have a show of oil and gas in the Traverse (this show is found in the top 6 meters (20 feet) of the formation), tend to cluster around the perimeter of the structure.

Drawn on a 5 foot (1.5 meter) contour interval structural map the field consists of an anticlinal flexure with about 26 meters (85 feet) of closure. The main structural trend of the field appears to be north-south. The center of the field also appears to be cut by a right-lateral strike slip fault that trends N57W, the offset being about 1 kilometers (0.62 miles). In addition there appears to be five other subparallel faults each showing right-lateral offset and showing an en echelon relationship. The total offset to the northeast along the six faults seems to be on the order of over 6.4 kilometers (4 miles) (the faults are marked in black).

These faults trend about N55-62E. This general direction fits satisfactorily into that half of a first order shear couple that would occur in the northeast quadrant, assuming a stress from a general eastward direction (Appalachian) as proposed by Prouty (1976a). The Reed City field is atypical for a "linear" producing oil field in Michigan. This is probably true because of the unusual amount of right-lateral displacement along the en echelon cross faults. The original orientation of this field very likely was northwesterly. This is best shown by the relic northwest trends indicated on the isodol maps for the

(Figures 15 to 25) to be discussed later. The dolomitizing fluids left traces along the main fault channelways which are in a northwest or northeast general direction. The northwest fault trace represents the other component of the first order shear couple and, under a shear model, would have formed the northwest principle anticlinal fold, a shear fold. Dolomitization along the faults accompanied by porosity development and consequent development of reservoir rock, has been reported by several workers including Dastanpour, 1977; Hamrick, 1978; Hyde, 1979; Ten Have, 1979; and Richey, 1980. (For a basic shear model applicable to the Michigan see Ten Have, op. cit., p. 24; for a list of azimuths of observed faults (limements) in the Michigan Basin, see Campbell, 1981, Appendix A.)

Structurally, the Dundee and Detroit River are very similar to the Traverse, although they have more subtle representations of the right-lateral shear cross faults (Figures 7 and 8). The faults with most displacement in the Traverse (Figure 6), especially near the center of the structure, are also identifiable in the Dundee and Detroit River.

Comparison of the three maps indicates an increase in the general size of the structure upward from the Detroit River to the Traverse, which may have implications as to additional offset along the faults through time (episodic). However, the axes of the Detroit River, Dunee, and Traverse are in essentially the same position.

Figure 6. Structure map of the Traverse. Sea level datum.

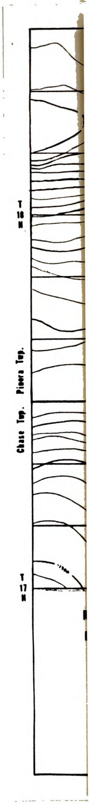

T
18
N
Chase Twp.
Pinora Twp.
T
17
N

Figure 7. Structure map of the Dundee. Sea level datum.

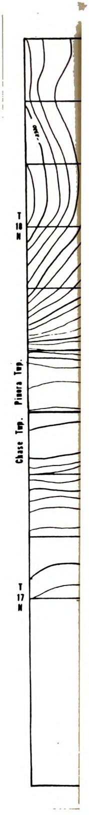
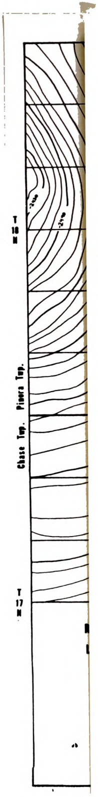

T
18
N
Pinora Twp.
Chase Twp.
T
17
N

Figure 8. Structure map of the Detroit River. Sea level datum.


T 18 N
Pinora Twp.
Chase Twp.
T 17 N

## Isopachous Study

Figure 9 represents an isopach map of the Traverse, using wells with samples that include the Traverse Formation-Traverse Lime (top of Thunder Bay in Figure 1) and the Bell Shale-Dundee break. Many of these well samples were used in the x-ray diffractometry study, while several were not for various reasons (rotary samples, large gaps in samples, etc.).

The map shows a general thinning of the Traverse on structure, with most of the thinning, about 18.3 meters (60 feet) near the axis of the fold. This thinning could be a result of karsting and solution coincident with the fault channelways along the fold, or because of thinning along a pre-existing regional structure (perhaps the "barrier" of Jodry, as referred to before).

The isopach map of the Dundee (Figure 10) does not mirror that of the Traverse. There is about 12.2 meters (40 feet) of thinning across the map. The axis of the thinning is about 800 meters (0.5 miles) west of the structural axis and swings around in a rather sinuous pattern. The axis of thinning also occurs west of the Traverse axis of thinning.

The crenulated, highly deformed isopachs of both the Dundee and Traverse suggests considerable distortion in an unusually plastic manner (compared to other structures farther east in the Basin). One possibility might be the response of movement in an area of increased amount of

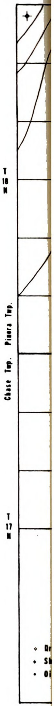
Figure 9. Isopach map of the Traverse Group.

T 18 N

Chase Twp. Pinora Twp.

T 17 N

Figure 10. Isopach map of the Dundee Formation.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Chase Twp.
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plastically-yielding sediments. This eastward shift of the isopachs could reflect the additional right lateral faulting with displacement to the northeast between Dundee and Traverse time.

## PETROGRAPHIC ANALYSES

One hundred forty-three thin sections were prepared from cable tool sample chips. Only a limited amount of information can be had from grain mounts. Among these are: mineralogy, fossils, and to a limited degree the rock classification. All slides were stained for calcite using an Alizarin Red-S solution in a 0.1% v/v HCl cold solution and a potassium ferricyanide stain in a weak HCl solution. These stains help differentiate calcite from dolomite and gives a rough idea the amount of ferroan calcite and dolomite present in the sample.

To supplement the thin section information the sample chips were also examined under the binocular microscope. A sample description of a well using this method is given in Appendix A.

Samples from the Traverse were grouped together for descriptive purposes to represent the top 20 feet (6.1 meters) and every 100 feet (30.5 meters) thereafter, because lithologic boundrys are difficult to determine owing to the nature of the samples. The Dundee samples include the entire formation while the Detroit River samples include the top 50 feet (15 meters).

## Traverse Limestone

### Traverse 0-20'

The samples found in this interval consist mainly of crystalline carbonates to mudstones (Dunham's classification, 1962). Dolomite rhombs are abundant, with some rhombs replacing fossils, suggesting a late diagenetic or epigenetic origin of the rhombs. The majority of this dolomite is strongly ferroan (Plate 2B). Much of the calcite is also ferroan (Plate 2B and 3). From a core chip near the top of this interval, the rock was found to consist of 100% ferroan dolomite along with an opaque mineral. Reflected light shows a brassy color suggesting the presence of pyrite. Within this sample a shadow of a crinoid columnal was found, with crystals showing no preferred orientation.

Fossils found within this interval include brachiopods, crinoids, estracods, and bryozoans. Chert is abundant.

### Traverse 20-120'

This section is composed primarily of a mudstone-wackestone with minor amounts of crystalline carbonate fragments. The majority of the slides contain ferroan dolomite along with a lesser amount of ferroan calcite. Enfacial junctions of crystal faces are common in samples that consist primarily of dolomite, also in such samples relics of brachiopods and bryozoan fragments. Many samples contain brown shale along with small amounts of pyrite and

chert. The common fossils in this section are brachiopods, crinoids, trilobites, and bryozoans.

Traverse 120-220'

The rocks in this interval consist almost entirely of mudstones with a lesser amount of shale as seen in the other intervals. Dolomite ranges from 0-26% in this section. The dolomite that can be seen is generally non-ferroan. In a couple of slides swarms of small dolomite rhombs were associated with what appears to be a microstylolite (Plate 2A), a situation observed by Hyde (1979) who pointed to the bedding places as avenues for the fluid movement in the epigenetic dolomitization process. A small amount of pyrite and ferroan calcite were also scattered in loose grains. Fossils consist of brachiopods, crinoids, bryozoans, corals, and one ostracod. This interval also contained abundant chert.

Traverse 220-320'

This sequence of slides shows an even mix of mudstones and wackestones. Within this interval there is once again abundant amounts of shale. Dolomite contents of these rocks range from 2 to 18%. Anhydrite and gypsum are present. The fauna in this interval consists of many brachiopods, bryozoans, crinoids, corals, and trilobites. There is a lesser amount of ferroan calcite and dolomite.

Traverse 320-420'

This interval contains both mudstones and wackestones. Dolomite content of these rocks ranges from 4-19% and generally consits of randomly scattered dolomite rhombs. There is relatively little shale in this interval and almost no pyrite. The calcite appears to be slightly ferroan while the dolomite is almost all non-ferroan. Fossils consist of brachiopods, bryozoans, corals, ostracods, crinoids, and trilobites. No anhydrite was observed.

Traverse 420-520'

The rocks in this interval range from packestones to mudstones with some crystalline grains. Many of the fossils have been replaced with ferroan calcite. The zooecia of a bryozoan is filled with calcite spar. Dolomite ranges from 4-35% and is confined mostly to mudstones in which there are randomly located rhombs. This interval contains abundant shale and chert, but has relatively little pyrite. Fossils consist of brachiopods, bryozoans, corals, and crinoids. A small amount of anhydrite was seen.

Lowest Beds of Traverse

Just above the Bell Shale the Traverse consists of packestones to mudstones with abundant shale associated with them. The dolomite comprises 5-23% of these rocks and is found as euhedral crystals. The dolomite is primarily ferroan as is the calcite. Many of the fossils appear to be recrystalized, being in some cases only shadows. Fossils

consist of brachiopods, bryozoans, and ostracods. Oolites were found in some of the slides; anhydrite is present.

## Dundee Formation

The rocks of the Dundee formation range from mudstones to packestones. Almost no fossils were observed although there was a questionable brachiopod spine in one slide. Near the bottom of the Dundee, directly above the Detroit River, the rock is composed mostly of well rounded to angular quartz grains (some showing undulatory extinction); also some microcline about the same size as the quartz grains. The carbonate portion of these rocks is a wackestone. The slides that were prepared for thin sectioning contained relatively small amounts of dolomite. The calcite is still slightly ferroan, similar to that seen in the Traverse.

## Detroit River Group

Anhydrite is common in samples near the Dundee-Detroit River boundry. The carbonate portion of the rock is made up of tightly packed euhedral dolomite. Sample #106 (permit #7628) 26 feet beneath the top, consists of tightly packed dolomite rhombs, with quartz sand and evaporites present. This sample is unusual in that it contains abundant plagioclase, pyroxene, albite, and microcline. It is believed that this material is from a bentonite bed. It is questioned that it would represent the Kawkawlin Bentonite of Baltrusaitis (1974) which should be much lower in the

section in the Reed City Field or it could be another bentonite whose stratigraphic position has not been established. Alternatively, the zone could represent sediments derived from the Wisconsin Arch area or perhaps crystalline exposures in the Canadian Shield to the northwest. Below this is a thick sequence of salt.

## Environmental Interpretation of Petrographic Data

The Detroit River Group as represented by the samples found in the Reed City Field consist in the lowest samples of a massive salt bed. This salt bed is thought to be part of the Horner member (Gardner, 1974) and represents the regressive phase of the Horner, followed by dolomite and anhydrite of the transgressive phase of the Horner. This interpretation is consistent with the succession in the Reed City Field.

There is considerable controversy about where to place the top of the Detroit River in western Michigan. The following designations have been offered: the top is placed at the first downward stratigraphic occurrence of an anhydrite as the bottom of the Dundee (Cohee & Underwood, 1945); or the anhydrite bed the Reed City anhydrite (Gardner, 1974); or at the top of the Dundee Formation (Baltrusaitis, 1974). This divergence of opinion can lead to differing environmental interpretations for the Dundee. The writer prefers to use the interpretation of Cohee and Underwood (1945) and to note both Gardner's (1974) and Baltrusaitis (1974) objections.

At the close of Detroit River time the Reed City area was part of a lagoon in which anhydrite was being precipitated. East of this lagoon a barrier consisting of shell banks separated it from an open marine environment (Gardner, 1974). Dolomite formed in this environment closely parallels the observation of Freidman (1980) that the formation of dolomite is closely related to a hypersaline environment, which in this case was most probably the "West Michigan Lagoon" of Jodry (1957).

The Dundee formation as seen in the Reed City Field is interpreted as being part of a biostromal shelf carbonate deposited in a sea transgressing from east to west (Gardner, 1974). In the Reed City area the Dundee is primarily a limestone with small amounts of dolomite.

Although the sharp contrast between the Dundee and Bell Shale observed from mechanical logs might suggest an unconformable (actually disconformable) relationship (as proposed by Cohee and Landes, 1958), no such break was inferred by the writer as gleaned from the structural contour map (Figure 5).

The Traverse Group in the Reed City area is representative of a transgressive-regressive sequence with alternating beds of limestone and shale. Jodry (1957) has postulated the presence of a barrier trending through the Reed City Field. The presence of a reef community in Lincoln Township found by the writer tends to support this hypothesis. At the beginning of Traverse time the rocks

deposited were mainly packestones-wackestone. Rocks of this nature may indicate a slightly agitated to calm water (Dunham, 1962). This is supported by the presence of oolites in a few samples. As Traverse deposition continued, the rocks in the Reed City area became more of a mudstone which would indicate calm water. At this time a coral community developed, perhaps acting to restrain mixing of the two environments (back reef and fore reef). The reef community probably migrated with the transgression and regression of the sea in a manner suggested elsewhere by Laporte (1969). This is apparently the case in the Reed City Field with the coralline reef community migrating between about 12.9 kilometers (8 miles) of distance east-west. Presumably it could have migrated farther but well control does not allow a closer testing of this, and the lack of core makes it difficult to test the vertical stacking of reef communities expected in a transgressive sea. From thin sections, sample chips and x-ray analysis of the minerals in the rock, anhydrite and gypsum are found in samples west of section 20, 29, 32, Lincoln Township and sections 5, 8, 17, and 20, Richmond Townships (Figures 3 and 7). From the x-rayed samples minute quantities of anhydrite are seen (Figure 4) as far east as well #156 (permit #9931), perhaps reflecting a regression of the sea. On the scale at which this study was carried out, no significant difference in dolomite content can be seen on either side of the barrier. It is believed that the dolomite content may be effected by the

presence of the barrier as noted by Runyon (1976) in his regional study of the Traverse.

Runyon (1976) believed that the restricted nature of the water west of the barrier would develop a highly saline environment. Both Gardner (1974) and Runyon (1976) believe that the diagenetic dolomite which formed in the area did so under a model close to Deffeyes' (1965) model of evaporative-refluxing. This environment would also seem to fit Friedman's (1980) contention that dolomite is an evaporite. For a more detailed account of current theory dealing with dolomitization in the Traverse, and west Michigan in general, see Hamrick (1978).

## CARBONATE ANALYSIS

All samples used in this study are from the MSU Subsurface Lab. The samples consist entirely of cable tool samples with the single exception of some core chips from a rotary rig well.

Cable tool wells require casing to seal off artesion aquifers and to bring about cementing of formations that tend to cave in. Consequently, an open hole situation is carried as long as there is no excess flooding and caving. Because of this, cable tool samples are relatively pure and include only a minor amount of cavings from open hole formations (Krumbein & Sloss, 1963).

A cable tool rig "makes hole" by raising and dropping a chisel-like bit and heavy drill stem at the end of a cable. This repeated pounding breaks up the rock, and at intervals it is removed and replaced by a bailer which removes the cuttings from the hole (Krumbein & Sloss, 1963). This makes for a relatively accurate accounting of the depth at which the samples were taken.

Thirty-one cable tool wells were available that contained all of the Traverse, Dundee and upper part of the Detroit River samples. These samples were examined under

a 10 power binocular microscope along with 12.5% v/v HCl, using the Colorado School of mines technique of sample description. See Appendix A for a detailed description of a well using this technique, and also see Figure 11 for a stratigraphic cross section. This cross section and sample study was used to familiarize the writer with the lithologies of these formations and to check the accuracy of the drillers' logs. It was found that the drillers' logs were not entirely consistent in picking the top of the Traverse Lime. This inconsistency was taken into account when constructing the Traverse structure and isopach maps.

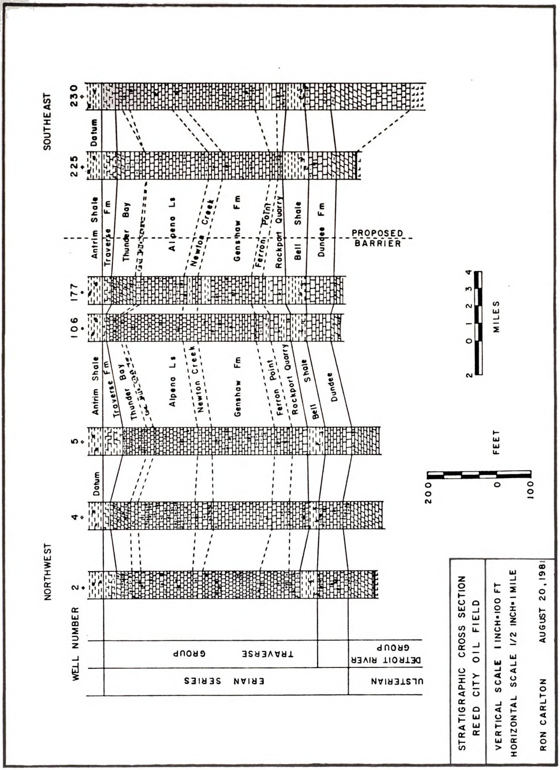
## Preparation of Samples for X-ray Study

The cable tool sample chips came in glass vials that contained samples from intervals ranging from 6 inches (15 cm.) to 20 feet (6 meters). These samples were weighed out proportionately using a triple beam balance so that, for example, a 60 foot interval sample would contain proportionate parts from each sample vial.

The weighed samples were then washed with distilled water in an Ultra-sonic cleaner, until the rinse water was clear (usually about three times). The samples were then dried at 60°C in an oven. After drying, a magnet was run across each sample several times to remove the iron from the sample.

The samples were then crushed in a Spex Mixing/Grinding Mill for 12 minutes (Ginsmer & Weiss, 1980). This is to

Figure 11. Stratigraphic cross section, Reed City Field.


NORTHWEST
SOUTHEAST
WELL NUMBER
2
4
5
106
177
225
230
Datum
Datum
Antrim Shale
Traverse Fm
Thunder Bay
Alpena Ls
Newton Creek
Genshaw Fm
Ferron Point
Rockport Quarry
Bell Shale
Dundee Fm
PROPOSED BARRIER
TRAVERSE GROUP
DETROIT RIVER GROUP
ERIAN SERIES
ULSTERIAN
FEET
200
0
100
MILES
2
0
1
2
3
4
STRATIGRAPHIC CROSS SECTION
REED CITY OIL FIELD
VERTICAL SCALE 1 INCH=100 FT
HORIZONTAL SCALE 1/2 INCH=1 MILE
RON CARLTON AUGUST 20, 1981

insure that the dolomite grains are approximately the same size as the calcite grains. After each grinding the mill was completely disassembled and washed using the ultrasonic cleaner, this was to insure that there was no contamination of samples from the mill. Several samples were then run through a 320 mesh seive to insure uniform grain size. This method is tedious and extremely messy, and it was found that passing the samples through an 80 mesh seive gave the same results in removing the material that tended to clump together. Samples prepared both ways were x-rayed with no significant differences.

Four hundred and eleven samples were prepared in this way.

## Diffractometry Method

The method used in this study is similar to that used by Hyde (1979), Ten Have (1979), and Richey (1980). The following procedures were used to analyze the samples:

1. About 2 grams of powdered sample were tightly packed into a sample holder. It is important to uniformly pack all samples whether it be tight or loose, to give consistent results. In this study, all samples were packed tightly.
2. General Electric X-ray Diffractometer; CuK$\alpha$ ($\lambda$ = 1.5418 A) radiation, 50 Kv and 10 mA; count rate of 200 counts per second, receiving-slit opening of 1°; time-constant 2; amplitude pulse height

selector 8.6, coarse 16; $\Delta E$ 6.0 volts; EL 2.0 volts.

3. The goniometer was set on the major calcite and dolomite peaks. The ideal calcite peak is at 29.38° 2θ, but because of stoichiometric effects it was usually found to give a maximum reading at 29.5° 2θ. The ideal dolomite peak is at 30.94° 2θ and was found to give a maximum reading at 30.95-31.05° 2θ.
4. Each sample was scanned twice for 100 seconds.
5. The average background just before and after the peaks was taken at the baseline. The background under each peak was assumed to be a linear function, thus a background value at any angle (°2θ) can be estimated from the slope of two background points. The intensity at peak maxima were counted for this background value.
6. External standards prepared by Dastanpour (1977) of known calcite and dolomite weight ratios were analyzed in the same manner. These data give a linear plot of intensity versus weight ratio (Figure 39, Appendix C).

Sample calculations and standard curve are presented in Appendix C.

## Interpretation of Data

### Traverse Isodols

Figure 12 is a histogram representing the vertical dolomite distribution. Below the top 6.1 meters (20 feet) the amount of dolomite decreases, until about 146 meters (480 feet) below the top of the Traverse where it begins to increase. This vertical distribution may be compared to the stratigraphic position of the hydrocarbon producing zones (pay) in Figures 3 and 4, which also shows Dundee and Detroit River pay zones.

Figure 13 represents an isodol (contours of equal dolomite content) map at the top (0-20') of the Traverse Lime. The isodol trend is northwest with increasing dolomite to the northeast. The trend of the highest dolomite on structure is N40W with at least two directions 70 to 90° from this trend. The well in the northeast part of the map is very close to the Ashton oil and gas field. This northeastward dolomite trend may be readily explained by the right lateral fault (Figure 6) which served as a channel-way for the dolomitizing fluids. Figure 23 also shows this dolomite trend. Most of the isodol maps, but especially, 13, 18, and 23 show what would appear to be an offset to the northeast, as does the structure contours in Figures 6, 7, and 8. This northeastward offset could mean that the cross-faulting was at least partly post dolomitization in age. In the south central portion of the

Figure 12. Histograms representing the vertical distribution of dolomite. Traverse Group.

FEET BELOW TOP OF TRAVERSE LIME

Figure 13. Dolomite percent map 0-20 feet below the top of the Traverse.


T 18 N
Chase Twp.
Pinora Twp.
T 17 N

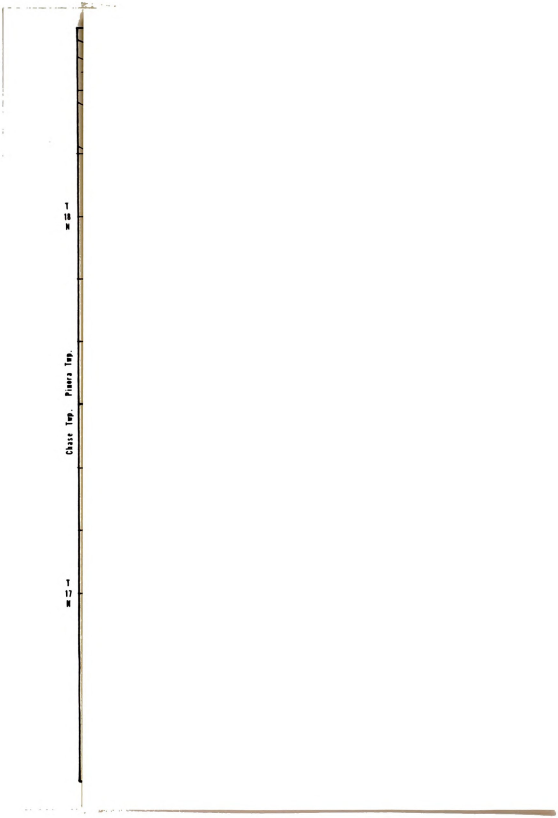
map there is an anomolous well with 87% dolomite. This dolomite high is located on and probably accountable to the presence of the fault shown on the structural map (Figure 6).

The 20-60' interval (Figure 14) again retains the general regional pattern as that above it. At least three faults cut this map at N53-60E. In the center of the map the wrench fault seen on the structure map shows up as an area of increased dolomite content. The original northwest axial (fault) trend is inferred by the isodols to the northwest and also southeast part of the map. The right lateral offset of the field is nicely shown.

The interval from 60-120' (Figure 15) again shows the same regional trend as the interval above. An eastward offshoot roughly along the T17N-T18N township line may be fault related (Figure 6). Considerable uncertainty exists around the well in the south because of lack of control.

The 120-180' interval (Figure 16) shows a marked change in the regional pattern of dolomite with the 5% isodol off structure and 25% isodol on structure. This is the usual pattern to be expected and has proved to be the case in other studies of dolomite distributions on faulted anticlines in the Basin. It is also true in the upper 20' of the Traverse (Figure 13) and for part of Figure 14. However, Figure 15 shows lower dolomite near the axis rather than along the flanks of the structure. This anomolous occurrence is difficult to explain but might be attributed to the number of wells producing the data.

Figure 14. Dolomite percent map 20-60 feet below the top of the Traverse.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N

Figure 15. Dolomite percent map 60-120 feet below the top of the Traverse.


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Pinora Twp.
Chase Twp.
T
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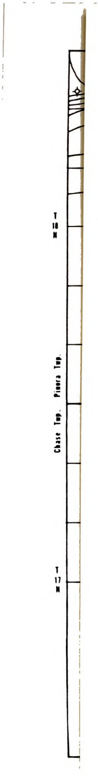
N

Figure 16. Dolomite percent map 120-180 feet below the top of the Traverse.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Pinora Twp.
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In interval 180-240' (Figure 17) the greatest amount of dolomite appears to be in the northwest corner. The regional trend increases in dolomite content to the northeast. On the structure proper there is a general depletion of dolomite on structure as opposed to the flanks of the structure.

The interval from 240-300' (Figure 18) shows the regional pattern continuing in a northeasterly direction. Once again there is a depletion of dolomite on structure. The main trend on structure is N37W with a strong trend along the familiar northeastward extension.

From 300-360' (Figure 19) the regional dolomite pattern has changes again. The amount of dolomite increases to the west and once again increases as one goes on structure until just before the highest point of the structure. The northwest-southeast axial trend is strong.

The 360-420' interval (Figure 20) again has reverted to the old regional pattern of dolomite increasing to the northeast along the right-lateral offset so persistent in most of the sample levels. Dolomite is also high in the northwest, probably because of the structural high and faulting in that area. Dolomite content on structure is high once again but shows anomalous decrease towards the axis along the lower flanks. The general trend is N43W and N45E. These trends are at right angles and represent the anxial and right lateral offsets (two) respectively.

Figure 17. Dolomite percent map 180-240 feet below the top of the Traverse.

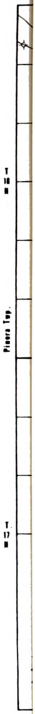
T 18 N
Pinora Twp.
T. 17 N

Figure 18. Dolomite percent map 240-300 feet below the top of the Traverse.


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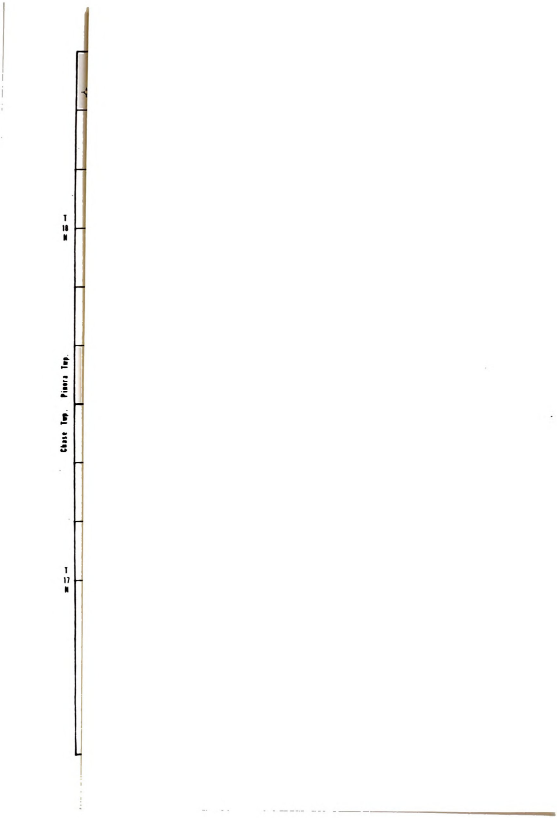
Chase Twp.
T 17 N

Figure 19. Dolomite percent map 300-360 feet below the top of the Traverse.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Pinora Twp.
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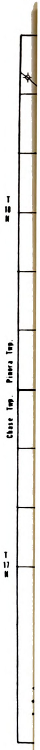
N

Figure 20. Dolomite percent map 360-420 feet below the top of the Traverse.

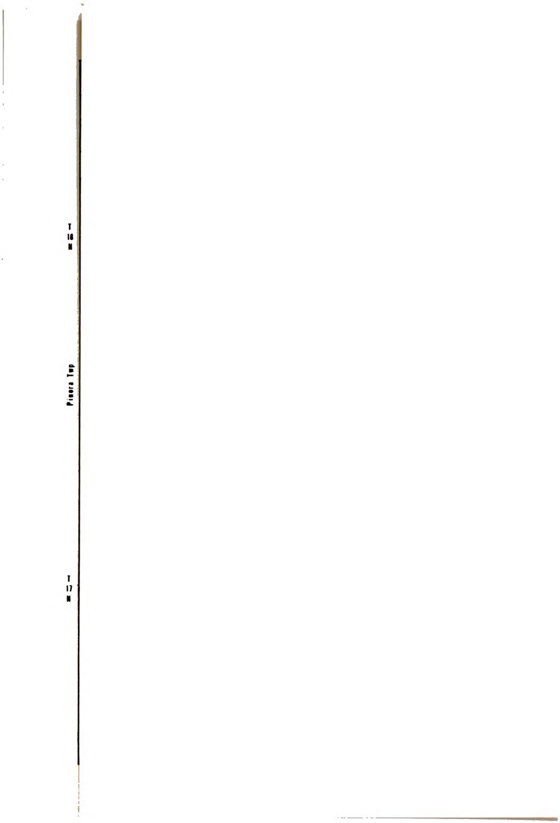

T 18 N
Chase Twp.
Pinora Twp.
T 17 N

Interval 420-480' (Figure 21) shows structural control of dolomite with the percentages increasing towards the axis until reaching the promixity of the axis at which point it decreases. The dolomite spread farther from the northwestward-trending axis at this sample interval than any of the other levels.

The final Traverse interval, 480-540' (Figure 22) is difficult to interpret. In general dolomite content on-structure is less than that found off-structure.

The Traverse dolomite as weighted mean (Figure 23) has a regional trend increasing to the northwest, a fairly strong northwest axial alignment, and the right-lateral offset to the northeast. Because of the strong relationship of dolomite percentages to the structure, the dolomite is probably epigenetic. The dolomite concentration decreases significantly at the axis. As stated earlier other studies show higher dolomite/calcite ratios up to the axis of the folds. The situation in the Traverse of this field is anomolous and difficult to account for. It is almost as if dedolomitization has occurred near the axis of the fold (where occurs the shear fault that brought about the shear fold). In Figure 23 the dolomite/calcite ratio increases along the flank of the structure towards the top reaching a maximum, and then decreasing to the axis at the top of the fold. More will be discussed later in regard to the possibility of dedolomitization in this structure.

Figure 21. Dolomite percent map 420-480 feet below the top of the Traverse.


T
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Pinora Twp
T
17
N

Figure 22. Dolomite percent map 480-540 feet below the top of the Traverse.


T 18 N
Pinora Twp.
Chase Twp.
T 17 N

Figure 23. Dolomite map 0-540 feet below the top of the Traverse.


T
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Chase Twp.
Pinora Twp.
T
17
N

Dundee Isodols

The general vertical dolomite pattern as shown in Figure 24 shows that the greatest amount of dolomite is found in the upper 20' and lower 20' (6 meters).

Figures 25 through 27 represent lateral variations of dolomite percent in the Dundee. Figure 25 represents the lateral dolomite variations from an interval from 0-20'. The most striking feature of this map is the apparent break between the north and south half of the on-structure wells. This break apparently represents the right lateral cross fault offset observed on the Dundee and Traverse structure maps (Figures 6 and 7). The two high dolomite centers probably occur along a fault. Examination of the structure map, Figure 7, indicates the possibility of a wrenching fault in a general northwest direction.

As in the Traverse, the general dolomitization pattern is to the northwest.

The 20-40' isodol interval (Figure 26) retains the break between the north and south halves. The Y shaped pattern is still evident suggesting folding/faulting in a similar configuration. There is an anomalous well in this interval that contains 100% dolomite. Clearly this well is drilled on or near a fault that has allowed for the dolomitization. The general dolomite trend is still to the northwest.

The final interval, 40-60' (Figure 27) retains the general features as the two preceding maps. The axis of

Figure 24. Vertical dolomitization patterns in the Dundee Formation.

Vertical Distribution of Dolomite Dundee

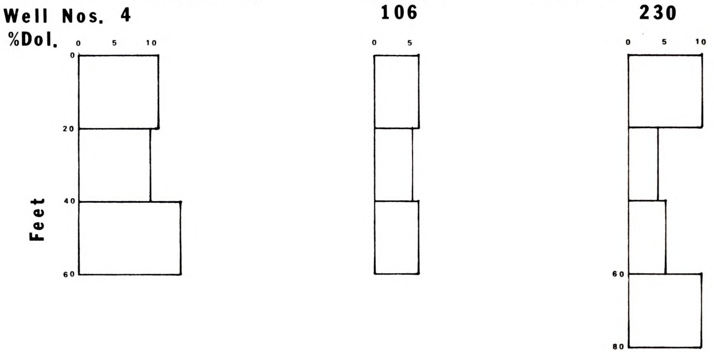


Figure 25. Dolomite percent map 0-20 feet below the top of the Dundee.

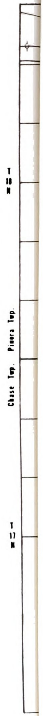
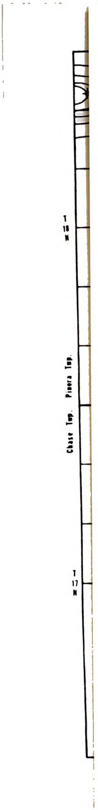

T 18 N
Chase Twp.
Pinora Twp.
T 17 N

Figure 26. Dolomite percent map 20-40 feet below the top of the Dundee.


T
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Chase Twp.
Pinora Twp.
T
17
N

Figure 27. Dolomite percent map 40-60 feet below the top of the Dundee.


T
18
N
Chase Twp.
Pinora Twp.
T
17
N

the area of greatest dolomitization is N35W. The general pattern of dolomitization has swung to the east. In the lower right hand corner of Figure 27 there is an anomalous well with high dolomite content (Appendix A has a complete description of this well), once again suggesting a small localized fault.

The Dundee compares to the Traverse in general regarding the lower dolomite/calcite near the top of the structure. Dedolomitization may also be the answer in the Dundee to account for this and will be discussed beyond.

Detroit River Isodols

The isodol maps, Figures 28 and 29, were constructed from wells from the upper 50 feet of the Detroit River. Many of the wells are from the production zone. The dolomite content is the highest observed in this study. Figure 28, from 0-20 feet shows a reduction in the dolomite/calcite ratio towards the axis, as observed in the Dundee and Traverse. However, in this instance the decrease is continuous towards the axis. This occurrence is particularly difficult to account for in view of the opposite results found in Figure 27, from 20-50 feet, where the isodols increase from 75% to 100% towards the axis. The latter, considered normal for other structures studied quantitatively for dolomite content, probably was normal for the Reed City structure but was later altered. The fact that the dolomite decreases in the upper 20 feet near the axial shear fault

Figure 28. Dolomite percent map 0-20 feet below the top of the Detroit River.


T 18 N
Pinora Twp.
Chase Twp.
T 17 N

Figure 29. Dolomite percent map 20-50 feet below the top of the Detroit River pay zone.


T 18 N
Chase Twp.
Pinora Twp.
T 17 N

(Prouty, 1976b) that formed the shear fold strongly infers that a loss of dolomite content has occurred sometime after the original distribution of dolomite on the Reed City structure.

## Dolomitization Models for the Reed City Oil Field

The isodolic patterns found in the Reed City Oil Field differ significantly from past work on Middle Devonian oil fields in Michigan. Dastanpour (1977), Hyde (1979), Ten Have (1970), and Richey (1980) all showed the dolomite percent increasing on structure, with the greatest amount of dolomite concentrated on the apex of the structure. Hyde's (1979) work showed isolated dolomite lows on the structure of the Kawkawlin Oil Field, but for the most part dolomite content increased on structure. They all agreed that the dolomitizing fluids ascended through pre-existing fractures, faults and bedding planes, resulting in a "Christmas Tree" pattern of dolomitization, the major fractures and faults being the main conduit for these fluids. It should be noted that these studies dealt with Middle Devonian oil fields located in central and eastern Michigan.

Hamrick's (1978) study of the Walker Oil Field and this study show a different pattern; the dolomite content is clearly controlled by structure, it increases along the flanks of the structure and decreases as it approaches the apex. Hamrick, however, did not stress this trend, probably

because of a lack of control did not believe this pattern to be significant. Jodry (1957) makes reference to the Reed City Field being "squarely on the barrier" (referring to the "West Michigan Barrier") and also to the probability of the Walker Field being directly associated with this barrier. Both the Reed City Field and the Walker contain abundant evaporites and pyrites in the Traverse. The Reed City Field also contains a bed of anhydrite at the top of the Detroit River (Hamrick's study was restricted to the Traverse Group), and using petrographic staining techniques ferroan dolomite and ferroan calcite were found to be abundant in the Traverse Group.

Any hypothesis or models put forth to explain these observed patterns should take into account the possible effect of a structural axis in the proximity of the Walker and Reed City Fields, and the similar lithologies found in each area. Following are two models offered to account for the observed data:

(1) The crest of the structure was never dolomitized as extensively as the flanks.

The composite isodol map (0-540') of the Traverse (Figure 24) shows that the dolomite percent on the structural crest (6%) is about the same as the regional or off-structure dolomite percentages, and thus may represent regional "background" dolomite.

A possible mechanism for this to occur involves the master faults and fracture to be blocked by any number of

ways such as slickensides, mineralization, and fault gouges. This in turn caused the ascending dolomitization fluids to seek alternative avenues, possibly lesser faults and fractures that are in concern with the master faults and fractures.

This model fits the general pattern in the Reed City Field as illustrated by the isodol maps. It would also account for the pattern observed in the Dundee. The Isopach Map of the Dundee indicates the presence of a pre-existing structure in Dundee time approximately 800 meters west of the existing structure. This model would be independent of this Dundee structure, with the fluid flow and blockage of the channelways occurring in post-Traverse time.

This model does not adequately explain why the main channelways were selectively blocked leaving the peripheral channels open. A detailed petrographic study of the well samples from these dolomite lows shows euhedral dolomite crystals that have replaced fossils and dolomite rhombs associated with microstylolites. The evidence indicates secondary dolomitization or rather, epigenetic dolomite. This would not be the expected case if the apex of the fold was not dolomitized by the ascending fluids, rather one would expect a fine grained crystalline dolomite indicative of diagenetic dolomite, similar to the regional dolomite.

(2) The dolomite along the crest of the fold was removed--a dedolomitization model.

Von Morlot (1847) coined the term dedolomitization to describe the process by which dolomite is replaced by calcite. This would occur as a result of leaching by groundwater in the presence of $CaSO_4$, which could be offered by gypsum and/or anhydrite, both of which are present in the Reed City and Walker Fields (Hamrick, 1978).

Studies by DeGroot (1967) and Evamy (1967) accepted the supposition that dedolomitization is a near-surface, late diagenetic process. Work by Chafetz (1972) and Al-Hashimi and Hemingway (1973) and others support this view.

DeGroot (1967) and Evamy (1967) believe the following criteria are necessary for the occurrence of dedolomitization:

1. high Ca/Mg ratio.
2. high rate of water flow.
3. $P_{CO_2}$ less than 0.5 atm.
4. temperature should not be greater than 50°C.

The accepted reaction for the occurrence of dedolomite (calcite pseudomorphous after dolomite) as proposed by von Morlot (1847) is illustrated by the following reaction:

$$CaSO_4 + CaMg(CO_3)_2 = 2CaCO_3 + MgSO_4$$

Evamy (1963, 1967), Chafetz (1972) and others have set forth petrographic criteria for the recognition of dedolomite. Foremost among these criteria is the tacit assumption that rhombohedral calcite is pseudomorphic after dolomite.

Petrographic studies of sample chips from the Reed City Field show ample evidence for dedolomitization:

1. Discrete rhombohedral crystals of dolomite and calcite. These are often times associated with iron hydroxide and pyrite.
2. Dolomite rhombs partially replaced by calcite.
3. Calcite rims surrounding an unaltered dolomite core.
4. Clear dolomite rhombs (dolomitizing stage) and calcite rhombs (dedolomitizing stage) occurring in microstylolites.
5. Zones ferroan dolomite rhombs with a clear calcite outer rim.
6. Zoned ferroan dolomite, ferroan calcite, non-ferroan calcite.

Figure 30 is an excellent representation of various stages of dedolomitization. Plates 1 to 13 show the above textures.

Al-Hashimi and Hemingway (1973) noted that ferroan dolomite tended to be dedolomitized much more readily than non-ferroan dolomite. It should be noted that dedolomitization is not restricted to ferroan dolomite. In the Reed City Field both non-ferroan and ferroan dolomite show evidence for dedolomitization.

A factor to be considered in this model is the timing of the dolomitizing and dedolomitizing events. The calcite rhombs and the altered dolomite rhombs all appear to be

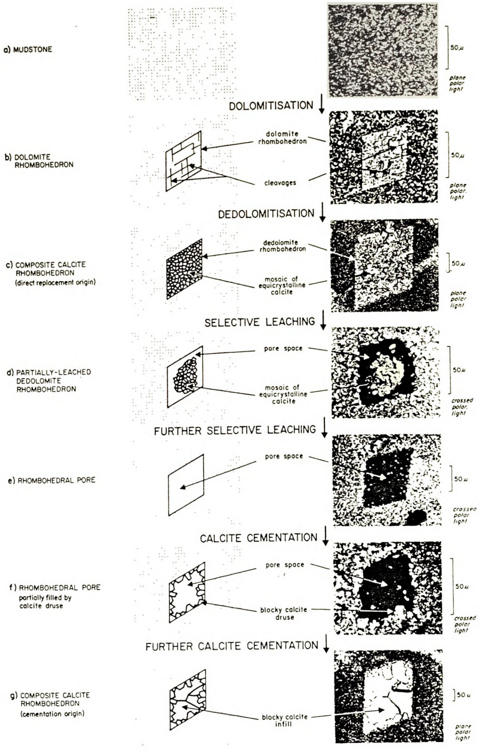


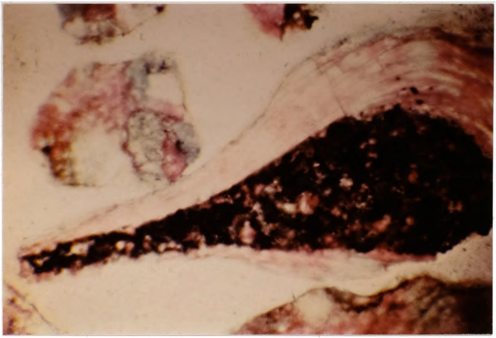

Figure 30. Diagenetic history of certain dedolomitized limestones (schematic) from Evamy, 1967.

Plates 1-4

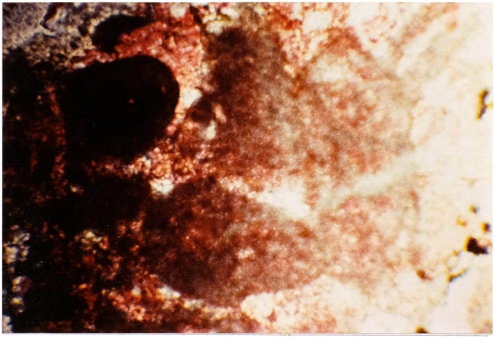
Legend:

| | | |
|---|---|---|
| Pink | = | calcite |
| Mauve (Purple) | = | ferroan calcite |
| Blue | = | ferroan dolomite |
| Scale | = | 100X |

Plane polarized light

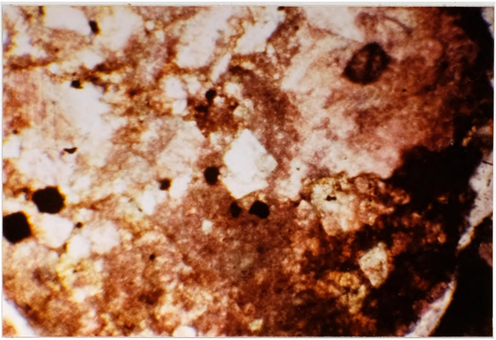


A. Original carbonate mud within brachiopad shell.

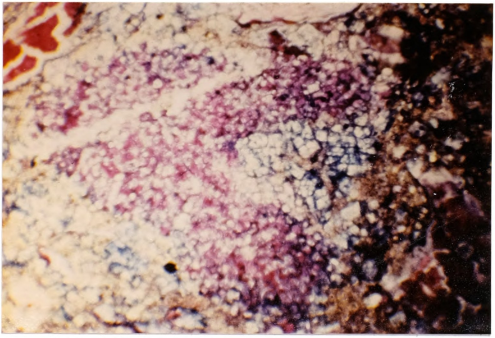


B. Pellets in original carbonate mud.

Plate 1

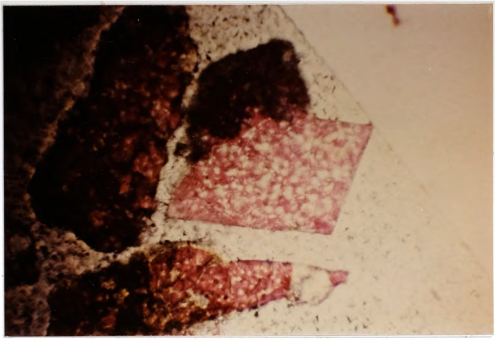


A. Dolomite rhombs associated with a microstylolite. Bedding planes apparently served as channelways for dolomitizing fluids after entering the folded structures along the shear faults. This dolomite is believed to be epigenetic in origin. Pyrite (opaque mineral) is an important constituent in the original carbonate mud.

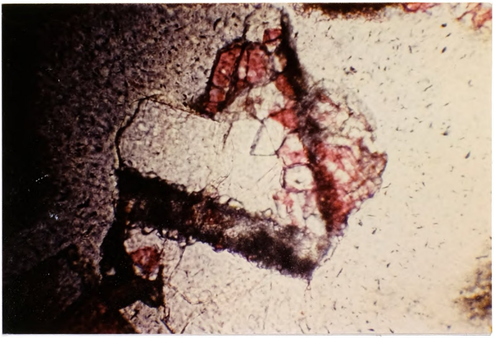


B. Ferroan dolomite and ferroan calcite exhibiting a rhombohedral crystal shape growing from original carbonate mud. Ferroan calcite is replacing ferroan dolomite in the rhomb.

Plate 2

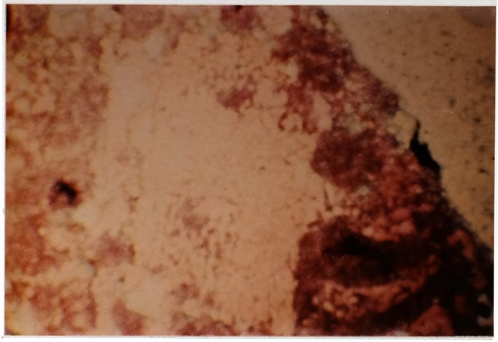


A. Calcite rhomb, note small amount of dolomite inclusions in rhomb. Probably represents intermediate dedolomitization between stages B and C of Figure 30.



B. Drusy calcite along rim of dolomite rhomb. Rhombohedron pore with calcite druse representing early stage of infilling (stage F of Figure 30, Evamy, 1967); with quartz representing a later stage of infilling.

Plate 3



A. Calcite rhomb. Composite calcite rhobohedron. Note blocky calcite druse along the outer edges and blacky calcite infill. Dedolomitization stage (g) of Evamy (1967) in Figure 30.

B. Quartz filling fossil void space. Note blocky calcite druse on fossil wall. Compare to plate 3B where infilling of calcite druse followed by quartz occurs in a rhomb pore.

Plate 4

late diagenetic (epigenetic) in origin. This would indicate that the dedolomitization occurred after the formation of the epigenetic dolomite and is bourne out by zoning stages mentioned above. It has been indicated that most faulted/ folded structures in the Basin were formed in post-Traverse time and in fact about Middle Mississippian time (Prouty, 1976a, 1976b). However, the isopach maps of both the Dundee and Traverse (Figures 9 and 10) indicate the presence of the Reed City field before at least Dundee time, and as such represents one of a few structures formed this early. The cross-faulting obscrued on the structure maps (Figures 6, 7, and 8) show offset of the isodols on at least some of the maps (Figures 13 and 29). The epigenetic, and later dedolomitization, must have occurred sometime between the shear faulting that developed the Reed City structure (drag fold) and the time of cross faulting (northeast-trending faults). Thus the dedolomitization could have occurred before Middle Mississippian time on this structure. Therefore the Traverse could have been the near surface rock at that time. Most work has shown that dedolomitization is a near surface weathering process, not something that should be considered a deep burial process.

The Reed City and Walker Fields were on an emergent structural high. This would put the rocks near the surface and in a favorable environment for dedolomitization to occur. In this case the crest of the structure which presumably carried higher dolomite content (like that shown in

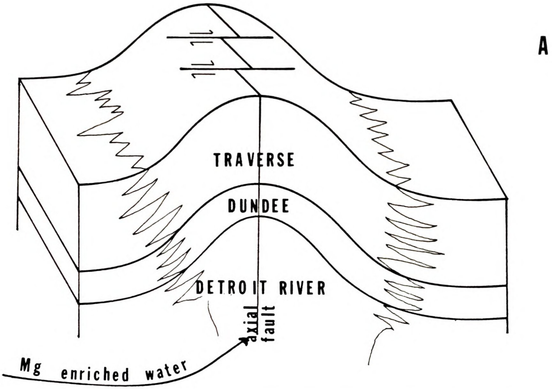
Figure 29) would be reduced in dolomite with respect to the regional dolomite pattern. The presence of both the Reed City and Walker Fields astride the "West Michigan Barrier" adds credence to this model. The petrographic evidence bears this out as dolomite has been shown to have been altered to calcite.

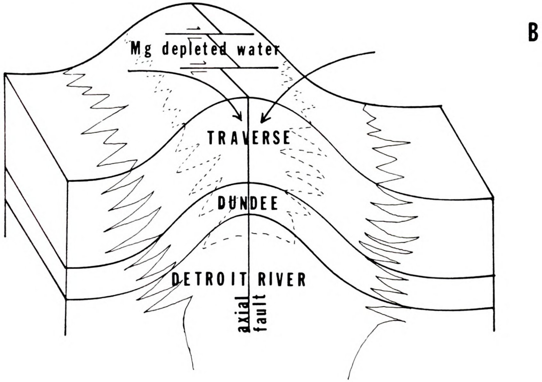
More work needs to be done in order to arrive at a firm conclusion as to the actual mechanism of dedolomitization in the Middle Devonian Oil Fields of western Michigan. One question to be answered is whether this phenomena is restricted to the western part of the Basin; to structures astride the "West Michigan Barrier"; or are random.

Figure 31 illustrates the paths the dolomitizing and dedolomitizing fluids may have followed in the Reed City field.

Figure 31. A. An idealized cartoon of an east-west cross section of the Reed City field showing the path that the dolomitizing fluids followed.

B. Same as above, but shows the path the dedolomitizing fluids followed. (Not to scale.)


A
TRAVERSE
DUNDEE
DETROIT RIVER
axial fault
Mg enriched water


B
Mg depleted water
TRAVERSE
DUNDEE
DETROIT RIVER
axial fault

# TRACE ELEMENT ANALYSIS

## Geochemical Rationale

Brand and Veizer (1980) concluded that the trace element composition of ancient carbonates may serve as a potential tool for evaluating the relative degree of diagenesis of these carbonates. Previous work by Kinsman (1969), Land and Hoops (1973), Badiozamani (1973), Veizer (1977), and others have demonstrated that the $Sr^{2+}$ and $Na^{+}$ concentrations in carbonates tend to decrease with greater diagenetic alteration, while at the same time $Mn^{2+}$ concentrations would increase. It follows then that $Sr^{2+}$ and $Na^{+}$ concentrations in samples from the Reed City Field would show a marked decrease in $Sr^{2+}$ and $Na^{+}$ concentration as it nears the crest of the structure while $Mn^{2+}$ concentrations would increase.

In order to test this isopleth maps (lines of equal trace element concentrations) were constructed for $Sr^{2+}$, $Na^{+}$, and $Mn^{2+}$ for the upper ten feet of the Dundee Formation and Detroit River Group. These maps were then compared to the structure maps.

## Theoretical Concepts

Trace elements such as $Sr^{2+}$, $Mn^{2+}$, $Mg^{2+}$, $Fe^{2+}$, $Pb^{2+}$, $Zn^{2+}$, and $Na^{+}$ tend to substitute for $Ca^{2+}$ in the $CaCO_3$ lattice. This substitution can take on many forms, among them are: (1) interstitial, (2) diadochic, (3) adsorption for unsatisfied charges, and (4) filling of unoccupied lattice positions in lattice defects of the structure (Krauskopf, 1979; Brand & Veizer, 1980).

The distribution coefficient (sometimes referred to as partition coefficient) for trace elements in any substance is given by:

$$\underline{K} = \frac{(m_t/m_c)\,S}{(m_t/m_c)\,L}$$

where $\underline{K}$ = distribution coefficient

$m_t$ = trace element concentration

$m_c$ = carrier element concentration

S = solid

L = liquid (McIntire, 1963)

This equation represents the ratio in which an element will distribution itself between the solid and liquid phase.

In general during diagenesis a $\underline{K}$ <1 ($Sr^{2+}$, $Na^{+}$, $Mg^{2+}$) will result in a decrease in these elements in the solid phase while $\underline{K}$ >1 ($Mn^{2+}$) will result in an increase. The greater the deviation from unity the stronger the depletion or enhancement of the element (Brand & Veizer, 1980).

## Geochemical Sample Preparation

Fifty-two samples were selected that represent the Traverse, Dundee, and Detroit River formations (see Figure 32 for location of sample sites). These samples were taken near the top of each formation to give some time stratigraphic control. Below is a breakdown of sample characteristics: (Dolomite is defined as a sample that contains more than 50% dolomite mineral.)

Table 1.--Sample distribution for trace element analysis.

| | | Producing Wells | Non-producing Wells |
|---|---|---|---|
| Traverse | limestone | 5 | 4 |
| | dolomite | 2 | 4 |
| Dundee | limestone | 14 | 4 |
| Detroit River | limestone | 3 | 0 |
| | dolomite | | |
| TOTAL | | 36 | 16 |

Because the Traverse samples consisted of both limestones and dolomites it was found to be unsuitable to use in this study. It would result in a lateral comparison of two different rock types with variations due to either the mineralogy or diagenetic alternation. Using only the Dundee limestones and Detroit River dolomites eliminates the added variable of mineralogy in lateral comparisons of trace element geochemistry.

Figure 32. Location of sample sites used in the trace element study.

P

Ch

All shale was removed from each sample using a binocular microscope and tweasers; thus each sample chosen had to have chips that were large enough to make it feasable to do this. Many samples from the Dundee and Detroit River were very fine and contained almost no shale particles, consequently only a cursory examination for shale was necessary. Approximately one gram of sample was prepared for analyses. These sample chips were washed at least four times in distilled/deionized water in an ultrasonic cleaner and allowed to dry at 80°C in an oven. Each sample had a magnet passed over it several times to remove minute iron fillings. The samples were then crushed in an agate mortar for about five minutes to approximately 80 mesh. A 0.5g sample from each was dissolved in 25 ml of 25%v/v acetic acid. Acetic acid was used because it is a much more gentle acid than hydrochloric acid and is less likely to attack any stray shale particles that might have been missed (Barber, 1974). The samples that contained mostly calcite were allowed to sit overnight at room temperature while the samples that contained mostly dolomite were placed in an oven at 60°C and allowed to sit overnight. Each sample was centifuged and the liquid portion decanted off. Each sample was diluted to 100 ml (it is preferable to take an aliquot of each sample and dilute it). The insoluble residue was rinsed several times and allowed to thoroughly dry (the samples were placed in a desicator). The insoluble residue was weighed and subtracted from the initial weight of each powered sample to

give the weight of the dissolved material. All discussion herein is based on concentrations recalculated for total dissolved carbonate.

A standard solution was prepared to mimic the background for the samples. This solution consisted of 1300 ppm Ca, 250 ppm Mg, and 6.25%v/v acetic acid. These values represent the approximate major element concentrations in the diluted 100 ml samples to be analyzed. All elements were determined by atomic absorption spectroscopy or flame emission spectroscopy using a spectrophotometer Perkins-Elmer 560. For Mn a standard containing 3 ug/ml was used, 87% of all samples fell within the linear working range. The reproducibility for Mn is ±5-9%. For Sr a standard containing 4 ug/ml was used, 100% of all samples fell within the linear working range for Sr. An excess of lanthinum was added to the Sr standard and samples to control the chemical interferences from Si, Al, and P. The average reproducibility for Sr was ±7-23%. Na was analyzed using flame emission at a wavelength of 589Å with an air-acetylene flame. An excess of K was added to each sample and standard to overcome ionization effects. The standards used had concentrations of 2 ug/ml and 5 ug/ml with 100% of all samples falling within this range. The average reproducibility for Na was ±10%. For Ca determinations an aliquot of each sample was diluted 454 times (.11 ml of sample to 50 ml of deionized distilled water). A standard solution of 4 ug/ml was prepared. Each sample and standard was poisoned with an

excess of lanthinum to control interferences from Si, Al, P, and sulfates. For Ca the average reproducibility was ±3-17%.

## Interpretation of Data

### Trace Elements

SODIUM--Sodium concentrations in the Dundee limestone ranges from 356 to 490 ppm with a mean concentration of 384±17 ppm (Appendix D and Table 2). The Detroit River dolomite (a carbonate that contains more than 50% of the mineral dolomite) has a sodium concentration that ranges from 343 to 949 ppm, with an average concentration of 438±53ppm (Appendix D and Table 2).

Figures 33 and 34 (see back pocket) illustrate the lateral variation of $Na^+$ concentrations across the Reed City Field for the Dundee limestone and Detroit River dolomite.

The Dundee limestone shows a general decrease in Na concentration going on-structure. At the approximate center of the structure the $Na^+$ values increase to 490 ppm; not a value that would be expected. Nevertheless, $Na^+$ concentrations seem to be controlled in the Dundee limestone by the structure, otherwise the pattern would be relatively constant throughout the field.

Figure 34 represents a plot of the $Na^+$ values for the Detroit River dolomite. It is difficult to contour this map because of the greater variation in $Na^+$ content. Of the 15 sample sites within the dotted line (the dotted line

Table 2.--Trace element concentrations of the Dundee and Detroit River and other data for comparison.

| Sample | ppm Na | ppm Sr | ppm Mn |
|---|---|---|---|
| Dundee limestone | 393±33 | 141±43 | 220±165 |
| Detroit River dolomite | 438±53 | 110±212 | 186±132 |
| Bonaire dolomites (Sibley, 1980) | 280 | -- | -- |
| Miette dolomite (Mattes & Mountjoy, 1980) | 368 | 65 | 63 |
| Ste Genevieve limestone (Choquette & Steinan, 1980) | 810 | 166 | -- |
| El Naqb Formation (Land & others, 1975) | 300 | 96 | -- |
| Primary dolostones (Weber, 1964) | 391 | 84.5 | 402 |
| Secondary dolostones (Weber, 1964) | 251 | 175 | 632 |
| Sommerset Island Formation | 310±81 | 161±18 | 160±8 |
| Cape Storm | 383±150 | 216±206 | 194±70 |
| Allen Bay | 200±65 | 66±45 | 105=161 |
| Long River (Veizer & others, 1978) | 182±67 | 72±26 | 161=129 |

represents the outer limits of the producing zones) ten of them have values less than those from the surrounding sites. Because of this it is difficult to make any conclusions as to the relationship of $Na^+$ to the structure of the Detroit River Group.

The $Na^+$ concentration found in the Reed City Field are difficult to interpret. In the Dundee limestone the values seem to be related to the structure while any such conclusion about the Detroit River dolomite would be impossible to make. The distribution coefficient of $Na^+$ for calcite and dolomite is not exactly known (Mattes & Mountjoy, 1980). What is known is that the distribution coefficient is less than one. If the value is close to one any change in concentration would be minute, making it unsuitable as a diagenetic indicator.

STRONTIUM--Strontium values were normalized using $Ca^{2+}$ and presented as a ratio of molar weights: 1000(mSr/mCa). These values were plotted to show the lateral variations in the Dundee limestone and Detroit River dolomite (Figures 35 and 36).

The Dundee limestone (Figure 35, see back pocket) shows a strong relationship to the structure. In general the 1000(mSr/mCa) ratio decreases as one moves toward the axis of the structure, and clearly mimics the pattern of at least one wrench fault. This pattern fits very closely with that which was predicted. It suggests that the crest of the structure, and at least one wrench fault were the

sites of the greatest diagenetic alteration, as expected with epigenetic alteration.

The pattern developed in Figure 36 (see back pocket) for the Detroit River dolomite also mimics the structure. It decreases to 0.0 at the crest of the structure and parallels at least two wrench faults. This is again suggestive of the greatest diagenetic alteration occurring in an area were the presence of epigenetic dolomite is postulated (also dedolomite, but more on this later).

Strontium has proven to be an excellent tool for evaluating the pattern of diagenetic alteration. With more well control a study of this nature could probably pick out as much detail as to location of faults and epigenetic dolomite as does dolomite/calcite ratios in the first part of this study.

MANGANESE--Manganese values should be found to be higher in samples near the crest of the structure when compared to those not associated with the structure. The $Mn^{2+}$ concentration for the Dundee limestone ranges from 105 to 795 ppm with a mean concentration of 223±169 ppm (Appendix D and Table 2). For the Detroit River dolomite it ranges from 57 to 669 ppm with an average concentration of 192±133 ppm (Appendix D and Table 2).

Figure 37 (see back pocket) shows the lateral variations of $Mn^{2+}$ concentrations in the Dundee limestone. The pattern that emerges shows the greatest concentrations of $Mn^{2+}$ in the southeastern part of the field. The highest

$Mn^{2+}$ values do not seem to follow the crest of the structure, but to parallel it. When superimposed on a structure map of the Dundee at least three of the higher $Mn^{2+}$ concentration sites fall on wrench faults. This would seem to fit the predicted pattern of greatest diagenetic alteration occurring in conjunction with these faults. It is interesting to note that a $Mn^{2+}$ low occurs along the northern most wrench fault. This anomaly is difficult to explain, but may be the result of lack of control, or a lack of $Mn^{+}$ in the fluids in this part of the field.

Figure 38 (see back pocket) represents a plot of $Mn^{2+}$ concentrations in the Detroit River dolomite. The dashed line represents the extent of the producing zones. On this map the highest and lowest values are found within the dashed line. Because of the tremendous differences in values for some of the sample sites contouring it is impossible. Any conclusions as to the relationship of $Mn^{2+}$ to the structure is impossible to make.

$Mn^{2+}$ shows some promise as a tool in locating areas of diagenetic alteration. This is especially apparent in the Dundee limestone where wrench faults patterns are mimiced by $Mn^{2+}$ concentrations. Perhaps with more control the Detroit River dolomite might exhibit a pattern. It is not clear how the dolomite effects the $Mn^{2+}$ concentration in the Detroit River, and this may be a factor in the $Mn^{2+}$ distribution.

## Summary

The trace element study illustrates how $Sr^{2+}$ and $Mn^{2+}$ tend to be controlled by structure, both faults and related folds, with the idea that the rocks associated with the structure have undergone late diagenetic (epigenetic) alteration. What has not been touched upon is the effect of dedolomitization on the trace element geochemistry. Dedolomitization is best described as a late diagenetic process. In the Reed City Field the dedolomitizing fluids probably used the same channelways as did the dolomitizing fluids, although in a different direction. The dedolomitizing fluids would probably effect the trace element concentrations in the rocks in a similar manner as the dolomitizing fluids did, to what degree they added or subtracted from the system is difficult to determine. Nevertheless, trace elements, especially $Sr^{2+}$, have proven to be an excellent tool to supplement the dolomite/calcite data in locating epigenetic dolomite and diagenetically altered carbonates.

# CONCLUSIONS

From the analytical data obtained from the Middle Devonian carbonates of the Reed City Field, certain conclusions can be made.

1. The highest concentrations of dolomite are found at the top of the Traverse Group, the bottom of the Dundee Formation and in the producing zone (20-50 feet) of the Detroit River.
2. There is a general correlation between the dolomite content and the structural configuration of the Reed City Field. This suggests a late diagenetic, clearly epigenetic origin for this dolomite.
3. A few wells with high dolomite content, off-structure, are most likely situated on faults or fractures resulting in local epigenetic dolomitization.
4. The regional dolomitization pattern is likely related to the presence of a barrier, causing a hypersaline environment west of it conducive to widespread dolomitization, in a manner not unlike that suggested by Friedman (1980) elsewhere.

5. Wrenching deformation, en echelon folding and faulting resulted in permeable channelways along which sedondary dolomitization occurred and the development of reservoir rock.
6. Faults and fractures not readily recognized on a structure map are often readily seen on an isodol map.
7. Anaomalous decrease in dolomite content towards the axial fault and fold infer that dedolomitization has occurred.
8. Petrographic criteria including replacement transitions from ferroan dolomite to ferroan calcite to equigranular rhombahedral calcite support dedolomitization.
9. The lateral pattern of 100(mSr/mCa) and $Mn^{2+}$ values suggest that the carbonates found near the crust of the structure and those associated with wrench faults have undergone a late diagenetic (epigenetic) alteration.
10. Isopach studies indicate that a structure was present during Dundee deposition, but was shoved west by some 1600 meters by the time of Traverse deposition.

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APPENDICES

# APPENDIX A

## DESCRIPTION OF A TYPICAL WELL SAMPLE

## LAND C. M. GABEL #1

APPENDIX A

DESCRIPTION OF A TYPICAL WELL SAMPLE

LAND C. M. GABEL #1

Permit No. 7628 Sample Well No. 106

Location: NE¼ NE¼ SW¼ section 31, T18N, R10W

Elevation: 1162.4 feet above sea level.

DEVONIAN:

Traverse Lime:

| | |
|---|---|
| 2950-64 | Dolomite, buff, crystalline; limestone, gray, dense to fine grained; gray shale, trace pyrite. |
| 2964-65½ | Limestone, buff to white, fine grained to subcrystalline; gray shale. |
| 2965½-87 | Limestone, buff to white, crystalline; gray shale; trace to pyrite. |
| 2987-3010 | Limestone, buff, dense to crystalline; drills up fine. |
| 3010-66 | Limestone, buff, dense to crystalline; some gray micaceous shale. |
| 3066-3155 | Limestone, buff and brown, crystalline; some gray and brown limy shale. |
| 3155-3200 | Limestone, brown, crystalline, drills up fine; some gray and buff crystalline limestone; a little gray micaceous shale. |
| 3200-3367 | Limestone, brown, crystalline; a little buff limestone and a few fossils; trace chert. |
| 3367-85 | Limestone, buff and light brown, crystalline; some gray, flaky, micaceous shale. |

| | |
|---|---|
| 3385-3405 | Shale, gray, micaceous, splintery; some gray and light brown dense to finely crystalline limestone. |
| 3405-15 | Limestone, gray and brown, dense to crystalline; drills up fine; some gray micaceous shale. |
| 3415-21 | Shale, gray, micaceous, flaky and splintery. |
| 3421-80 | Limestone, gray and buff, dense to crystalline; shale, gray, flaky and splintery. |

Bell Shale

| | |
|---|---|
| 3480-3515 | Shale, gray, flaky and splintery, micaceous; trace of gray limestone. |
| 3515-21 | Shale, dark gray, somewhat sandy, limy; a little buff crystalline limestone. |
| 3521-24 | Limestone, gray and buff, dense to crystalline drills up fine (lime); gray limy shale; fossils. |

Dundee Formation:

| | |
|---|---|
| 3524-30 | Limestone, buff and gray, crystalline, drills up coarse, many fossils. |
| 3530-33 | Limestone, buff and brown, crystalline, fossiliferous, drills up fine. |
| 3533-3601 | Limestone, buff and light brown, crystalline, drills up very fine. |

Detroit River:

| | |
|---|---|
| 3601-09 | Dolomite, gray, sandy, crystalline; some buff crystalline limestone. |
| 3609-19 | Dolomite, gray, somewhat sandy, crystalline; some buff crystalline limestone and a little gypsum. |
| 3619-25 | Dolomite, buff, crystalline, cemented with lime. |
| 3625-29 | Dolomite, brown, crystalline, sandy. |
| 3629-39 | Dolomite, containing some volcanic material (bentonite). |

TOTAL DEPTH 3639

Main Pay 3625-39.

# APPENDIX B

# STRUCTURAL AND THICKNESS DATA

APPENDIX B

STRUCTURAL AND THICKNESS DATA

| well # | permit # | location | top of Traverse sea level datum | thickness | top of Dundee | thickness | top of Detroit River |
|---|---|---|---|---|---|---|---|
| | | | T18N, R11W | | | | |
| 1 | 12885 | NW SE SE-2 | -1827 | 603 | -2430 | 117 | -2547 |
| 2 | 8912 | S/2 NW NW-6 | -1772 | 574 | -2346 | 117 | -2463 |
| 3 | 18382 | C NE SE-6 | -1770 | 589 | -2359 | - | - |
| 4 | 9467 | N/2 NE NE-9 | -1771 | 599 | -2370 | - | - |
| 5 | 8894 | S/2 SE SE-15 | -1849 | 567 | -2416 | 74 | -2490 |
| 6 | 10214 | S/2 NW NW-18 | -1726 | 607 | -2333 | 80 | -2413 |
| 7 | 8943 | S/2 SE SE-24 | -1797 | 573 | -2370 | 78 | -2448 |
| 8 | 8986 | S/2 NE NE-24 | -1783 | 606 | -2389 | - | - |
| 9 | 9110 | N/2 SE SE-24 | -1787 | - | - | - | - |
| 10 | 8914 | N/2 NE SE-25 | -1782 | 592 | -2374 | 69 | -2453 |
| 11 | 8936 | S/2 SE NE-25 | -1779 | 602 | -2381 | 76 | -2457 |
| 12 | 9018 | S/2 NE SE-25 | -1809 | 579 | -2388 | 65 | -2453 |
| 13 | 9370 | N/2 SE SE-25 | -1755 | 618 | -2373 | 80 | -2453 |
| 14 | 9409 | N/2 SW NE-25 | -1802 | - | - | - | - |
| 15 | 18932 | NE NE SE-25 | -1815 | 557 | -2372 | - | - |
| 16 | 8843 | S/2 NE NE-36 | -1770 | 612 | -2382 | - | - |
| 17 | 18881 | NE NE NE-36 | -1764 | 633 | -2397 | - | - |

STRUCTURE DATA

| well # | permit # | location | top of Traverse sea level datum | thickness | top of Dundee | thickness | top of Detroit River |
|---|---|---|---|---|---|---|---|
| | | | T18N, R10W | | | | |
| 18 | 19075 | S/2 SW SE-8 | -1817 | 593 | -2410 | - | - |
| 19 | 24152 | SW NW SE-14 | -1909 | 592 | -2502 | - | - |
| 20 | 9527 | S/2 SW SW-17 | -1825 | 558 | -2456 | 73 | -2456 |
| 21 | 9868 | S/2 SE SW-17 | -1795 | 592 | -2387 | 72 | -2459 |
| 22 | 9553 | S/2 SE SE-18 | -1796 | - | - | - | - |
| 23 | 8814 | S/2 SW SW-19 | -1744 | 620 | -2364 | 50 | -2414 |
| 24 | 8902 | S/2 SW SE-19 | -1759 | 565 | -2324 | 75 | -2399 |
| 25 | 8916 | S/2 SE SE-19 | -1760 | - | - | - | - |
| 26 | 8932 | N/2 SW SW-19 | -1781 | 583 | -2364 | 75 | -2459 |
| 27 | 8933 | S/2 SE SW-19 | - | - | -2341 | 78 | -2419 |
| 28 | 8956 | S/2 NE NE-19 | -1788 | 593 | -2381 | 67 | -2448 |
| 29 | 8957 | N/2 SE SE-19 | -1764 | 556 | -2320 | 75 | -2395 |
| 30 | 9001 | S/2 NW SW-19 | -1783 | 588 | -2371 | 78 | -2449 |
| 31 | 9002 | N/2 SE SW-19 | -1770 | 573 | -2343 | 79 | -2422 |
| 32 | 9111 | S/2 NW SE-19 | -1758 | 577 | -2335 | 72 | -2407 |
| 33 | 9447 | S/2 NE NW-19 | -1798 | 588 | -2386 | 75 | -2461 |
| 34 | 9554 | S/2 NE NW-19 | -1794 | 583 | -2377 | 77 | -2457 |
| 35 | 11140 | N/2 NE SW-19 | -1778 | 575 | -2354 | 76 | -2430 |
| 36 | 26426 | NW NE SE-19 | -1819 | 517 | -2336 | - | - |
| 37 | 8908 | S/2 SE SE-20 | -1789 | 569 | -2358 | 39 | -2397 |
| 38 | 8961 | S/2 SW SE-20 | -1921 | 501 | -2422 | 71 | -2422 |
| 39 | 8962 | S/2 SE SW-20 | -1773 | 562 | -2335 | 79 | -2414 |
| 40 | 8963 | S/2 SW SW-20 | -1777 | 549 | -2326 | 77 | -2403 |
| 41 | 8973 | N/2 SE SE-20 | -1805 | 561 | -2366 | 63 | -2429 |
| 42 | 9003 | S/2 NE SE-20 | -1775 | 585 | -2360 | 80 | -2440 |
| 43 | 9113 | S/2 NW SW-20 | -1762 | 573 | -2335 | 76 | -2411 |
| 44 | 9233 | S/2 SW NW-20 | -1759 | 587 | -2346 | 77 | -2423 |
| 45 | 9722 | S/2 NW NE-20 | -1816 | 531 | -2347 | 91 | -2438 |
| 46 | 10304 | N/2 SE NW-20 | -1759 | 606 | -2361 | 78 | -2439 |

STRUCTURE DATA

| well # | permit # | location | top of Traverse sea level datum | thickness | top of Dundee | thickness | top of Detroit River |
|---|---|---|---|---|---|---|---|
| | | | T18N, R10W (cont.) | | | | |
| 47 | 10978 | N/2 SW/NW-20 | -1775 | 579 | -2354 | - | - |
| 48 | 11360 | N/2 NW NW-20 | -1770 | 608 | -2378 | 80 | -2458 |
| 49 | 11398 | N/2 NE SW-20 | -1783 | 559 | -2342 | 75 | -2417 |
| 50 | 26427 | S/2 NW SW-20 | -1769 | 581 | -2350 | - | - |
| 51 | 26428 | W/2 NE SW-20 | -1771 | 566 | -2337 | - | - |
| 52 | 8717 | S/2 SW NW-21 | -1806 | 587 | -2393 | 72 | -2465 |
| 53 | 8852 | S/2 NW NW-28 | -1819 | 572 | -2391 | 71 | -2462 |
| 54 | 8881 | N/2 NW NW-28 | -1875 | 531 | -2406 | 42 | -2448 |
| 55 | 8767 | S/2 NW NW-29 | -1775 | 559 | -2334 | 76 | -2410 |
| 56 | 8791 | S/2 SW NW-29 | -1793 | 547 | -2340 | 75 | -2415 |
| 57 | 8716 | S/2 NE NE-29 | -1808 | 552 | -2360 | 71 | -2431 |
| 58 | 8800 | N/2 SW NW-29 | -1782 | 550 | -2332 | 72 | -2404 |
| 59 | 8867 | N/2 NW SW-29 | -1796 | 554 | -2350 | 71 | -2421 |
| 60 | 8868 | NW NE NE-29 | -1801 | 556 | -2357 | 47 | -2404 |
| 61 | 8874 | S/2 NW NE-29 | -1786 | 559 | -2345 | 80 | -2425 |
| 62 | 8875 | N/2 SW SE-29 | -1795 | 564 | -2359 | 63 | -2420 |
| 63 | 8876 | N/2 NW NE-29 | -1803 | 547 | -2350 | 66 | -2416 |
| 64 | 8877 | S/2 SW NE-29 | -1792 | 568 | -2360 | 77 | -2416 |
| 65 | 8882 | N/2 NW NW-29 | -1763 | 570 | -2333 | 69 | -2402 |
| 66 | 8904 | N/2 NE NW-29 | -1777 | 570 | -2347 | 66 | -2413 |
| 67 | 8905 | S/2 NE NW-29 | -1782 | 567 | -2349 | 70 | -2419 |
| 68 | 8915 | N/2 SE NE-29 | -1817 | 552 | -2369 | 73 | -2442 |
| 69 | 8945 | S/2 NW SW-29 | -1778 | 567 | -2345 | 74 | -2419 |
| 70 | 9072 | N/2 NE SW-29 | -1771 | 600 | -2371 | 71 | -2442 |
| 71 | 9073 | S/2 SW SW-29 | -1802 | 548 | -2350 | 73 | -2423 |
| 72 | 9074 | N/2 SW SW-29 | -1777 | 572 | -2349 | 72 | -2421 |
| 73 | 9431 | N/2 SW SE-29 | -1805 | 572 | -2377 | 84 | -2461 |
| 74 | 9510 | N/2 NE SE-29 | -1828 | 554 | -2382 | 73 | -2455 |
| 75 | 8245 | SW SW SE-30 | -1747 | 603 | -2351 | 80 | -2431 |

STRUCTURE DATA

| well # | permit # | location | top of Traverse sea level datum | thickness | top of Dundee | thickness | top of Detroit River |
|---|---|---|---|---|---|---|---|
| | | | T18N, R10W (cont.) | | | | |
| 47 | 10978 | N/2 SW/NW-20 | -1775 | 579 | -2354 | - | - |
| 48 | 11360 | N/2 NW NW-20 | -1770 | 608 | -2378 | 80 | -2458 |
| 49 | 11398 | N/2 NE SW-20 | -1783 | 559 | -2342 | 75 | -2417 |
| 50 | 26427 | S/2 NW SW-20 | -1769 | 581 | -2350 | - | - |
| 51 | 26428 | W/2 NE SW-20 | -1771 | 566 | -2337 | - | - |
| 52 | 8717 | S/2 SW NW-21 | -1806 | 587 | -2393 | 72 | -2465 |
| 53 | 8852 | S/2 NW NW-28 | -1819 | 572 | -2391 | 71 | -2462 |
| 54 | 8881 | N/2 NW NW-28 | -1875 | 531 | -2406 | 42 | -2448 |
| 55 | 8767 | S/2 NW NW-29 | -1775 | 559 | -2334 | 76 | -2410 |
| 56 | 8791 | S/2 SW NW-29 | -1793 | 547 | -2340 | 75 | -2415 |
| 57 | 8716 | S/2 NE NE-29 | -1808 | 552 | -2360 | 71 | -2431 |
| 58 | 8800 | N/2 SW NW-29 | -1782 | 550 | -2332 | 72 | -2404 |
| 59 | 8867 | N/2 NW SW-29 | -1796 | 554 | -2350 | 71 | -2421 |
| 60 | 8868 | NW NE NE-29 | -1801 | 556 | -2357 | 47 | -2404 |
| 61 | 8874 | S/2 NW NE-29 | -1786 | 559 | -2345 | 80 | -2425 |
| 62 | 8875 | N/2 SW SE-29 | -1795 | 564 | -2359 | 63 | -2420 |
| 63 | 8876 | N/2 NW NE-29 | -1803 | 547 | -2350 | 66 | -2416 |
| 64 | 8877 | S/2 SW NE-29 | -1792 | 568 | -2360 | 77 | -2416 |
| 65 | 8882 | N/2 NW NW-29 | -1763 | 570 | -2333 | 69 | -2402 |
| 66 | 8904 | N/2 NE NW-29 | -1777 | 570 | -2347 | 66 | -2413 |
| 67 | 8905 | S/2 NE NW-29 | -1782 | 567 | -2349 | 70 | -2419 |
| 68 | 8915 | N/2 SE NE-29 | -1817 | 552 | -2369 | 73 | -2442 |
| 69 | 8945 | S/2 NW SW-29 | -1778 | 567 | -2345 | 74 | -2419 |
| 70 | 9072 | N/2 NE SW-29 | -1771 | 600 | -2371 | 71 | -2442 |
| 71 | 9073 | S/2 SW SW-29 | -1802 | 548 | -2350 | 73 | -2423 |
| 72 | 9074 | N/2 SW SW-29 | -1777 | 572 | -2349 | 72 | -2421 |
| 73 | 9431 | N/2 SW SE-29 | -1805 | 572 | -2377 | 84 | -2461 |
| 74 | 9510 | N/2 NE SE-29 | -1828 | 554 | -2382 | 73 | -2455 |
| 75 | 8245 | SW SW SE-30 | -1747 | 603 | -2351 | 80 | -2431 |

STRUCTURE DATA

| well # | permit # | location | top of Traverse sea level datum | thickness | top of Dundee | thickness | top of Detroit River |
|---|---|---|---|---|---|---|---|
| | | | T18N, R10W (cont.) | | | | |
| 76 | 8514 | SE SE SW-30 | -1776 | 580 | -2356 | 73 | -2429 |
| 77 | 8615 | SW SE NE-30 | -1828 | 504 | -2332 | 74 | -2406 |
| 78 | 8701 | S/2 SW NW-30 | -1772 | 591 | -2368 | 73 | -2436 |
| 79 | 8732 | N/w SW SE-30 | -1779 | 588 | -2359 | 61 | -2420 |
| 80 | 8733 | N/2 NE SW-30 | -1777 | 562 | -2339 | 70 | -2409 |
| 81 | 8734 | N/2 NW SW-30 | -1784 | 566 | -2350 | 70 | -2420 |
| 82 | 8739 | S/2 NW SE-30 | -1730 | 620 | -2350 | - | - |
| 83 | 8759 | S/w NE SE-30 | -1754 | 589 | -2343 | 73 | -2416 |
| 84 | 8760 | S/2 NE SW-30 | -1770 | 580 | -2350 | 71 | -2421 |
| 85 | 8762 | SE SW NE-30 | -1768 | 581 | -2349 | 59 | -2408 |
| 86 | 8763 | NW NE SE-30 | -1755 | 587 | -2342 | 70 | -2412 |
| 87 | 8777 | N/2 SE SW-30 | -1764 | 588 | -2352 | 73 | -2425 |
| 88 | 8789 | S/2 SE SE NW-30 | -1767 | 573 | -2340 | 72 | -2417 |
| 89 | 8790 | NE NW SE-30 | -1789 | 543 | -2332 | 90 | -2422 |
| 90 | 8815 | S/2 SW SW-30 | -1796 | 573 | -2369 | 65 | -2432 |
| 91 | 8817 | N/2 SW SW-30 | -1764 | - | - | - | - |
| 92 | 8831 | S/2 NE NE-30 | -1781 | 551 | -2332 | 79 | -2411 |
| 93 | 8832 | N/2 SE NE-30 | -1760 | 581 | -2341 | 70 | -2411 |
| 94 | 8841 | S/2 NW SW-30 | -1785 | 573 | -2358 | 70 | -2428 |
| 95 | 8865 | N/2 SW NE-30 | -1827 | 524 | -2351 | 72 | -2423 |
| 96 | 8866 | S/2 NW NE-30 | -1769 | 576 | -2345 | 104 | -2449 |
| 97 | 8903 | N/2 NE NE-30 | -1754 | 572 | -2326 | 94 | -2420 |
| 98 | 8935 | N/2 NW NW-30 | -1776 | 584 | -2360 | 78 | -2438 |
| 99 | 8944 | N/2 SE SE-30 | -1766 | 592 | -2358 | 72 | -2430 |
| 100 | 8964 | N/2 NE NW-30 | -1767 | 578 | -2345 | 76 | -2421 |
| 101 | 8965 | S/2 NW NW-30 | -1769 | 590 | -2359 | 70 | -2429 |
| 102 | 8966 | N/2 SE NW-30 | -1763 | 585 | -2348 | 76 | -2424 |
| 103 | 8967 | N/2 SW NW-30 | -1780 | 568 | -2348 | 73 | -2421 |
| 104 | 9088 | N/2 SW NW-30 | -1785 | 579 | -2364 | 71 | -2435 |

STRUCTURE DATA

| well # | permit # | location | top of Traverse sea level datum | thickness | top of Dundee | thickness | top of Detroit River |
|---|---|---|---|---|---|---|---|
| | | | T18N, R10W (cont.) | | | | |
| 105 | 9108 | N/2 NW NE-30 | -1765 | 573 | -2338 | 75 | -2413 |
| 106 | 7628 | NE NE SW-31 | -1788 | 580 | -2368 | 71 | -2430 |
| 107 | 8662 | NW NW NE-31 | -1774 | 577 | -2351 | 73 | -2424 |
| 108 | 8664 | NE NE NW-31 | -1771 | 595 | -2366 | 66 | -2432 |
| 109 | 8702 | SE SE NW-31 | -1761 | 602 | -2363 | 70 | -2433 |
| 110 | 8709 | NW NW SE-31 | -1784 | 579 | -2363 | 79 | -2442 |
| 111 | 8710 | SW SW NE-31 | -1800 | 568 | -2368 | 76 | -2444 |
| 112 | 8728 | S/2 NE NW-31 | -1830 | 539 | -2369 | - | - |
| 113 | 8729 | N/2 SE NW-31 | -1815 | 543 | -2358 | - | - |
| 114 | 8731 | S/2 NW NW-31 | -1754 | 614 | -2368 | 80 | -2448 |
| 115 | 8735 | N/2 NE SE-31 | -1797 | 561 | -2358 | 75 | -2433 |
| 116 | 8757 | N/2 SW NE-31 | -1777 | 577 | -2354 | 100 | -2454 |
| 117 | 8758 | S/2 NW NE-31 | -1796 | 555 | -2351 | 78 | -2429 |
| 118 | 8768 | N/2 SW SW-31 | -1792 | 594 | -2397 | - | - |
| 119 | 8778 | S/2 NW SE-31 | -1790 | 571 | -2361 | 74 | -2435 |
| 120 | 8798 | N/2 SE NE-31 | -1803 | 565 | -2359 | 85 | -2444 |
| 121 | 8799 | S/2 SE NE-31 | -1789 | 560 | -2349 | 97 | -2446 |
| 122 | 8816 | S/2 NE NE-31 | -1787 | 560 | -2337 | 80 | -2427 |
| 123 | 8850 | N/2 SW SE-31 | -1796 | 561 | -2357 | 75 | -2432 |
| 124 | 8864 | N/2 NW NW-31 | -1806 | 584 | -2390 | 48 | -2438 |
| 125 | 8934 | N/2 NW NE-31 | -1786 | 561 | -2347 | 76 | -2423 |
| 126 | 8974 | N/2 NW SE-31 | -1758 | 635 | -2393 | 58 | -2451 |
| 127 | 8987 | S/2 SE SE-31 | -1809 | 555 | -2362 | 42 | -2404 |
| 128 | 9011 | N/2 SE SE-31 | -1797 | 566 | -2363 | 77 | -2440 |
| 129 | 9119 | S/2 NE SE-31 | -1771 | 592 | -2363 | 75 | -2438 |
| 130 | 8871 | S/w NW NW-32 | -1805 | 570 | -2373 | 79 | -2452 |
| 131 | 8872 | N/2 NW NW-32 | -1773 | 586 | -2359 | - | - |
| 132 | 8942 | N/2 NW SW-32 | -1795 | 570 | -2365 | 70 | -2434 |
| 133 | 8999 | S/2 NE NW-32 | -1808 | 558 | -2366 | 77 | -2443 |

STRUCTURE DATA

| well # | permit # | location | top of Traverse sea level datum | thickness | top of Dundee | thickness | top of Detroit River |
|---|---|---|---|---|---|---|---|
| | | | T18N, R10W (cont.) | | | | |
| 134 | 9000 | N/2 NE NW-32 | -1797 | 569 | -2366 | 80 | -2446 |
| 135 | 9005 | N/2 SW NW-32 | -1798 | 566 | -2364 | 72 | -2436 |
| 136 | 9006 | S/2 SW NW-32 | -1782 | 574 | -2356 | 74 | -2430 |
| 137 | 9109 | S/2 NW SW-32 | -1782 | 576 | -2358 | 74 | -2432 |
| 138 | 9407 | N/2 NW SE-32 | -1799 | 572 | -2371 | 84 | -2455 |
| 139 | 9495 | N/2 SW SE-32 | -1810 | 630 | -2440 | - | - |
| 140 | 9653 | C SE SE-32 | -1805 | 583 | -2388 | 60 | -2448 |
| 141 | 10279 | C SW NE-32 | -1820 | 559 | -2379 | 65 | -2444 |
| 142 | 11416 | S/2 SW SW-32 | -1796 | 554 | -2350 | 76 | -2426 |
| 143 | 11417 | S/2 SE SW-32 | -1796 | 555 | -2351 | 74 | -2425 |
| 144 | 11418 | S/2 NE SW-32 | -1796 | 564 | -2360 | 75 | -2435 |
| 145 | 11589 | S/2 NW SE-32 | -1805 | 567 | -2372 | 75 | -2447 |
| 146 | 2586 | SW SE NW-34 | -1901 | 561 | -2462 | 51 | -2513 |
| 231 | 8939 | S/2 SE SE-8 | -1831 | 577 | -2408 | 79 | -2487 |
| | | | T17N, R11W | | | | |
| 147 | 19764 | NE NE NE-4 | -1844 | 577 | -2421 | 100 | -2521 |
| 148 | 9470 | N/2 SW SW-5 | -1876 | 557 | -2433 | 89 | -2522 |
| 149 | 26137 | C SW SE-11 | -1867 | 578 | -2445 | 88 | -2533 |
| 150 | 16610 | NE NW NW-15 | -1908 | 554 | -2462 | 85 | -2547 |
| 151 | 15016 | NW NE NW-23 | -1888 | 568 | -2456 | - | - |
| 152 | 11369 | NE SW NE-24 | -1873 | 560 | -2433 | 80 | -2513 |
| 153 | 9415 | NW NW NW-29 | -1906 | 555 | -2461 | 98 | -2559 |
| 154 | 9713 | SW NW NE-35 | -1875 | 593 | -2468 | 105 | -2573 |

STRUCTURE DATA

| well # | permit # | location | top of Traverse sea level datum | thickness | top of Dundee | thickness | top of Detroit River |
|---|---|---|---|---|---|---|---|
| | | | T17N, R10W | | | | |
| 155 | 2144 | SW SE NE-1 | -1998 | 594 | -2592 | - | - |
| 156 | 9931 | N/w NE NW-2 | -1957 | 569 | -2528 | 77 | -2602 |
| 157 | 9675 | N/2 SW SW-4 | -1827 | 549 | -2376 | 71 | -2447 |
| 158 | 9687 | SW SW NW-4 | -1807 | 566 | -2374 | 73 | -2447 |
| 159 | 9687 | N/2 NW SW-4 | -1804 | 565 | -2369 | 70 | -2439 |
| 160 | 9815 | N/2 NE SW-4 | -1825 | 552 | -2377 | 87 | -2464 |
| 161 | 10012 | W/2 NW NW-4 | -1807 | 570 | -2378 | 74 | -2452 |
| 162 | 20663 | N/2 SE SW-4 | -1831 | 560 | -2391 | - | - |
| 163 | 20754 | W/2 NE SW-4 | -1836 | 552 | -2376 | - | - |
| 164 | 20800 | N/2 SW SE-4 | -1851 | 552 | -2403 | - | - |
| 165 | 20839 | N/2 SW SW-4 | -1860 | 520 | -2386 | - | -- |
| 166 | 8761 | N/2 SE SW-5 | -1800 | 565 | -2365 | 68 | -2433 |
| 167 | 9120 | N/2 NE SW-5 | -1808 | 549 | -2357 | 84 | -2441 |
| 168 | 9195 | N/2 NE NE-5 | -1798 | 572 | -2370 | 73 | -2443 |
| 169 | 9219 | N/2 NW SE-5 | -1801 | 560 | -2361 | 68 | -2429 |
| 170 | 9221 | N/2 NE SE-5 | -1799 | 563 | -2362 | 74 | -2436 |
| 171 | 9223 | N/2 SE SE-5 | -1809 | 565 | -2374 | 71 | -2445 |
| 172 | 9255 | N/2 NW NW-5 | -1787 | 558 | -2346 | 82 | -2428 |
| 173 | 9410 | N/2 SW NW-5 | -1800 | 551 | -2351 | 78 | -2429 |
| 174 | 9417 | N/2 NE NW-5 | -1803 | 553 | -2356 | 75 | -2431 |
| 175 | 9465 | N/2 NW NE-5 | -1828 | 532 | -2360 | 73 | -2433 |
| 176 | 9466 | N/2 SE NW-5 | -1805 | 552 | -2367 | 73 | -2436 |
| 177 | 9481 | N/2 NW SW-5 | -1808 | 560 | -2368 | 77 | -2445 |
| 178 | 9528 | N/2 SW NE-5 | -1821 | 530 | -2351 | 74 | -2425 |
| 179 | 9538 | C N/2 SW-5 | -1813 | 558 | -2371 | 72 | -2443 |
| 180 | 9580 | N/2 NE SE-5 | -1823 | 550 | -2373 | 85 | -2458 |
| 181 | 9596 | N/2 SE NE-5 | -1801 | 565 | -2367 | 70 | -2437 |
| 182 | 9754 | N/2 SW SW-5 | -1842 | 545 | -2381 | 78 | -2459 |
| 183 | 11141 | S/2 SE NW-5 | -1795 | 570 | -2365 | 65 | -2430 |

STRUCTURE DATA

| well # | permit # | location | top of Traverse sea level datum | thickness | top of Dundee | thickness | top of Detroit River |
|---|---|---|---|---|---|---|---|
| | | | T17N, R10W (cont.) | | | | |
| 184 | 11275 | S/2 SW NW-5 | -1805 | 553 | -2358 | 76 | -2434 |
| 185 | 11349 | S/2 NE NW-5 | -1785 | 559 | -2344 | 75 | -2419 |
| 186 | 11546 | S/2 NE NE-5 | -1801 | 571 | -2363 | 79 | -2442 |
| 187 | 11598 | S/2 NW NE-5 | -1792 | 563 | -2355 | 74 | -2429 |
| 188 | 11645 | S/2 NE SE-5 | -1806 | 561 | -2367 | 73 | -2440 |
| 189 | 11702 | S/2 NW NW-5 | -1799 | 552 | -2351 | - | - |
| 190 | 19049 | N/2 NW SW-5 | -1814 | 554 | -2369 | - | - |
| 191 | 19806 | NE SW NW-5 | -1816 | 533 | -2349 | - | - |
| 192 | 20358 | N/2 SW SW-5 | -1827 | 555 | -2345 | - | - |
| 193 | 20370 | N/2 SE SW-5 | -1828 | 552 | -2366 | - | - |
| 194 | 20743 | C SE SW-5 | -1877 | 504 | -2381 | - | - |
| 195 | 20771 | C NW SE-5 | -1801 | 571 | -2372 | - | -- |
| 196 | 20829 | C SE SE-5 | -1815 | 568 | -2383 | - | -- |
| 197 | 20898 | C NE SE-5 | -1796 | 564 | -2395 | 75 | -2470 |
| 198 | 9280 | N/2 NE NE-6 | -1801 | 559 | -2360 | 75 | -2435 |
| 199 | 9281 | N/2 NW NE-6 | -1802 | 568 | -2370 | 73 | -2443 |
| 200 | 9439 | N/2 SE NE-6 | -1806 | 563 | -2369 | 81 | -2450 |
| 201 | 9580 | N/2 NE SE-6 | -1823 | 550 | -2373 | 85 | -2458 |
| 202 | 9802 | N/2 NE NW-6 | -1810 | 565 | -2375 | - | -- |
| 203 | 19885 | N/2 SE SE-6 | -1824 | 594 | - | - | - |
| 204 | 20593 | N/2 SW NE-6 | -1838 | 549 | -2387 | - | - |
| 205 | 20718 | N/2 SW SE-6 | -1855 | 560 | - | - | - |
| 206 | 20719 | N/2 NE SW-6 | -1840 | 574 | -2414 | 83 | -2502 |
| 207 | 20589 | N/2 NE NE-7 | -1829 | 559 | -2388 | - | - |
| 208 | 6238 | NE SE NE-8 | -1840 | 558 | -2395 | 69 | -2464 |
| 209 | 9252 | N/2 NW NE-8 | -1819 | 557 | -2376 | 73 | -2449 |
| 210 | 9411 | N/2 NW NW-8 | -1831 | 551 | -2382 | 74 | -2456 |
| 211 | 9412 | N/2 NE NW-8 | -1824 | 556 | -2380 | 73 | -2453 |
| 212 | 20266 | N/2 NW NE-8 | -1823 | 573 | -2396 | - | - |

STRUCTURE DATA

| well # | permit # | location | top of Traverse sea level datum | thickness | top of Dundee | thickness | top of Detroit River |
|---|---|---|---|---|---|---|---|
| | | | T17N, R10W (cont.) | | | | |
| 213 | 20371 | N/2 NE NW-8 | -1841 | 539 | -2380 | - | - |
| 214 | 20498 | N/2 NW SE-8 | -1819 | 573 | -2392 | - | - |
| 215 | 20597 | N/2 NW NW-8 | -1830 | 557 | -2386 | 87 | -2502 |
| 216 | 20779 | N/2 NE NE-8 | -1821 | 581 | -2403 | - | - |
| 217 | 21019 | N/2 SE NW-8 | -1825 | 557 | -2382 | - | - |
| 218 | 21136 | N/2 NE SW-8 | -1883 | 506 | -2389 | - | - |
| 219 | 20777 | NE NE NW-9 | -1844 | 549 | -2393 | - | - |
| 220 | 21110 | N/2 NW NW-9 | -1828 | 564 | -2392 | - | - |
| 221 | 17761 | NW SE SW-18 | -1864 | 557 | -2421 | - | - |
| 222 | 16237 | NW SW SE-19 | -1856 | 549 | -2405 | 81 | -2486 |
| 223 | 25685 | C NE NE-19 | -1867 | 541 | -2408 | - | - |
| 224 | 2419 | C NE SE-20 | -1927 | 531 | -2458 | - | - |
| 225 | 10132 | NE SE SW-22 | -1943 | 584 | -2527 | 80 | -2607 |
| 226 | 10584 | SW SW NW-30 | -1886 | - | - | - | - |
| 227 | 14958 | NE NE SE-30 | -1872 | 544 | -2416 | 70 | -2486 |
| 228 | 19216 | N/2 SE NW-30 | -1778 | 573 | -2351 | - | - |
| 229 | 14270 | NW SW SE-32 | -1893 | 547 | -2440 | 89 | -2529 |
| 230 | 4934 | SE SW SW-35 | -1973 | 547 | -2520 | 75 | -2592 |

# APPENDIX C

## SAMPLE CALCULATIONS AND STANDARD CURVE

## FOR X-RAY DIFFRACTION

## APPENDIX C

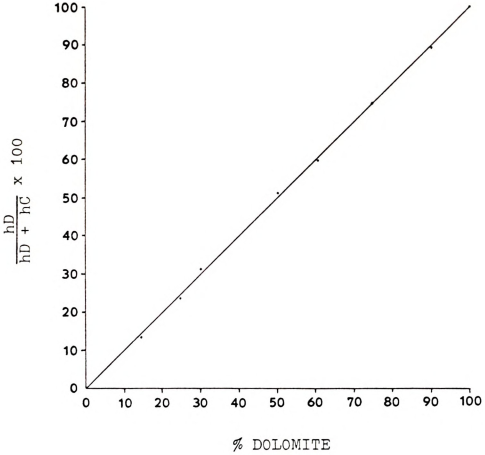
## SAMPLE CALCULATIONS AND STANDARD CURVE FOR X-RAY DIFFRACTION

Dastanpour (1977) prepared the dolomite calibration standards that were used in this study. The meaning of percent dolomite, as used in this study, is the amount of dolomite found in the carbonate fraction of the sample.

The calibration curve consists of plotting dolomite/(dolomite + calcite) X 100 intensity ratios versus weight percent of dolomite in the standard samples. Each point on the curve represents the average results of six measurements. Figure 39 is the calibration curve obtained. The correlation coefficient for the curve is 0.996. This curve can be used to show that the calculated intensity, $\frac{hD}{hD + hC}$ X 100, is analogous to the dolomite percent. Table 3 contains the data Dastanpour (1977) obtained in constructing the curve.

The dolomite percentage for each sample well was calculated in the following manner:

1. Background counts were subtracted from the peak counts. Background was determined by taking counts just before and after the calcite and dolomite peaks, and by using a linear relationship, calculate the background at each peak position.




hD = Height of Dolomite Peak at 2.88 Å
hC = Height of Dolomite Peak at 3.03 Å

Figure 39. Calibration curve of dolomite percent.

Table 3.--Different components used for standardization.

| Weight percent dolomite | Grams / Mass dolomite | Grams / Mass calcite |
|---|---|---|
| 15 | 0.3000 | 1.7000 |
| 25 | 0.5000 | 1.5000 |
| 30 | 0.6000 | 1.4000 |
| 50 | 1.0000 | 1.0000 |
| 60 | 1.2000 | 0.8000 |
| 75 | 1.5000 | 0.5000 |
| 90 | 1.8000 | 0.2000 |
| 100 | 2.0000 | 0.0000 |

2. Calculations were made using the following relationship:

$$\text{dolomite percent} = \frac{\text{dolomite average count X 100}}{\text{(dolomite + calcite) ave. counts}}$$

3. Samples ran at the beginning of the x-ray analyses and at the end of the analyses had a reproducability of 1.2%. In other words, results varied by as much as 1.2% from the beginning of the analysis to the end.

DOLOMITE DATA

Traverse Limestone

| well no. %Dol. | 0-20 | 20-60 | 60-120 | 120-180 | 180-240 | 240-300 | 300-360 | 360-420 | 420-480 | 480-460 |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 38 | 13 | 10 | 38 | 4 | 9 | 17 | 10 | 6 | 26 |
| 4 | 68 | 22 | 17 | 18 | 14 | 9 | 12 | 18 | 10 | 23 |
| 5 | 76 | 25 | 9 | 6 | 3 | 5 | 6 | 2 | 3 | - |
| 7 | 53 | 8 | 5 | 7 | 3 | 5 | 8 | 10 | 9 | 12 |
| 8 | 75 | 57 | 5 | 7 | 4 | 15 | 7 | 6 | 12 | 16 |
| 23 | - | - | - | 9 | 4 | 4 | 5 | 7 | 5 | 4 |
| 25 | 44 | 36 | 11 | 4 | 6 | 3 | 8 | 6 | 7 | 9 |
| 26 | 61 | 25 | 7 | 7 | 5 | 16 | 6 | 9 | 7 | 4 |
| 29 | 38 | 8 | 8 | 6 | 4 | 3 | 5 | 10 | 12 | 5 |
| 45 | 48 | 8 | 11 | 6 | 7 | 6 | 8 | 7 | 19 | 10 |
| 55 | 40 | 17 | 22 | 4 | - | - | 9 | 6 | 9 | 23 |
| 75 | 55 | - | - | - | 9 | 4 | 5 | 5 | 3 | 6 |
| 76 | 23 | 22 | 3 | 10 | 3 | 3 | 4 | 7 | 7 | 5 |
| 89 | 23 | 13 | 6 | 6 | 5 | 3 | 4 | 8 | 19 | 35 |
| 106 | 55 | 30 | 5 | 5 | 4 | 5 | 10 | 8 | 4 | 15 |
| 120 | 41 | 5 | 3 | 15 | 2 | 3 | 11 | 5 | 7 | 38 |
| 123 | 57 | 9 | 4 | 8 | 5 | 5 | 11 | 6 | 5 | 15 |
| 126 | - | - | - | - | - | - | 11 | 14 | 9 | 12 |
| 130 | - | - | 4 | 27 | 5 | 7 | 5 | 8 | 14 | 27 |
| 139 | 28 | 26 | 3 | 7 | - | - | - | - | - | - |
| 150 | 22 | 7 | 1 | 4 | 3 | 8 | 12 | 5 | 6 | - |
| 156 | - | - | 4 | 7 | 7 | 7 | 7 | 5 | 6 | 42 |
| 177 | 74 | 29 | 2 | 5 | 6 | 5 | 13 | 8 | 8 | 11 |
| 182 | - | 3 | 13 | - | - | - | - | - | - | - |
| 183 | 64 | 21 | 8 | 8 | 4 | 7 | 7 | - | - | - |
| 208 | 51 | 19 | 5 | 3 | 3 | 5 | 11 | 6 | 8 | 44 |
| 221 | 88 | 56 | 26 | 22 | 4 | 8 | 7 | 5 | 19 | 11 |
| 224 | 17 | 10 | 10 | 3 | 6 | 6 | - | - | - | - |
| 225 | 26 | 2 | 3 | 18 | 4 | 13 | 10 | 8 | 17 | 32 |
| 230 | 27 | 10 | 7 | 6 | 2 | 3 | 6 | 8 | 12 | 43 |
| 231 | 96 | 40 | 10 | 18 | 7 | 8 | 6 | 15 | 7 | 18 |

DOLOMITE DATA

| %Dol. | Dundee | | | | Detroit River | | |
|---|---|---|---|---|---|---|---|
| well no. | 0-20 | 20-40 | 40-60 | 60-80 | 0-20 | 20-50 | 50-TD |
| 2 | 12 | 18 | 12 | 49 | 97 | 99 | 99 |
| 4 | 11 | 10 | 14 | - | - | - | - |
| 5 | - | - | - | - | - | - | - |
| 7 | 6 | 5 | 6 | - | 28 | 99 | - |
| 8 | 13 | 5 | 7 | - | 43 | 96 | - |
| 23 | 11 | 2 | 11 | - | 31 | 100 | - |
| 25 | 39 | 4 | 10 | - | 90 | 99 | - |
| 26 | 11 | 9 | 6 | - | 66 | 89 | - |
| 29 | 32 | 5 | 5 | 14 | 86 | 93 | - |
| 45 | 10 | 12 | 26 | - | 95 | 100 | - |
| 55 | 11 | 11 | 10 | - | 99 | - | - |
| 75 | 7 | 5 | 8 | - | 97 | - | - |
| 76 | 7 | 9 | 7 | - | 99 | 100 | - |
| 89 | 5 | 7 | 15 | 79 | 100 | - | - |
| 106 | 6 | 5 | 6 | - | 92 | 84 | - |
| 120 | 5 | 4 | 6 | 8 | 99 | 100 | - |
| 123 | 8 | 6 | - | - | 61 | - | - |
| 126 | 5 | 7 | 7 | - | 100 | - | - |
| 130 | 5 | 6 | 7 | 37 | 100 | - | - |
| 139 | 22 | 100 | - | - | - | - | - |
| 150 | 7 | 5 | 8 | 17 | 96 | 78 | 67 |
| 156 | 14 | 13 | 28 | - | 98 | - | - |
| 177 | 6 | 4 | 5 | - | 82 | 100 | - |
| 182 | 5 | 3 | 6 | - | 49 | 99 | - |
| 183 | - | - | - | - | 98 | 97 | - |
| 208 | 5 | 7 | 8 | - | 89 | 98 | - |
| 221 | 5 | 4 | 5 | - | 77 | - | - |
| 224 | 7 | 6 | 6 | - | 99 | - | - |
| 225 | 9 | 13 | 99 | - | 95 | 99 | - |
| 230 | 10 | 4 | 5 | 10 | 95 | 93 | - |
| 231 | 9 | 10 | 19 | 81 | 100 | - | - |

# APPENDIX D

# GEOCHEMICAL CALCULATIONS AND TRACE ELEMENT DATA

## APPENDIX D

## GEOCHEMICAL CALCULATIONS AND TRACE ELEMENT DATA

The Perkin-Elmer Atomic Absorption Spectrophotometer gives results, when in the continuous mode, in ug/ml for solutions. These results are easily converted to ppm in the rock using the following equations:

$$\text{For liquid samples: Element (ug/ml)} = (C)(d.f.) \quad (1)$$

$$\text{For solid samples: Element (ppm)} = \frac{(C)(V)(d.f.)}{(W)} \quad (2)$$

Where C is the concentration of the element in the sample solution in ug/ml; V is the volume of the undiluted sample solution in ml; W is the sample weight in grams; and d.f. is the dilution factor as described below:

$$d.f. = \frac{\text{(volume of diluted sample solution in ml)}}{\text{(volume of aliquot taken for dilution in ml)}}$$

Sample Calculations

A typical result when measuring $Ca^{2+}$ in solution is 3.87 ug/ml for this study, after taking into account the background noise. Because the concentration of Ca is high in the original sample solution, these solutions were diluted in the following manner:

0.10 ml of sample solution diluted to 50 ml

Therefore, the concentration of Ca in the original sample solution is given as:

$$\text{Element (ug/ml)} = 3.87\text{ug/ml}\cdot\frac{50\text{ml}}{0.10\text{ ml}}$$

$$= 1935 \text{ ug/ml}$$

To convert this to ppm for the dissolved rock, the weight of the dissolved portion is needed. In this case it is 0.4790 grams.

Substituting this value into equation 2 gives the following results:

$$\text{Element (ppm)} = \frac{1935\text{ug/ml(V)(d.f.)}}{0.4790\text{grams}}$$

The dilution factor is $= \frac{100\text{ml}}{25\text{ml}\pm 0.1\text{ml}}$*, and V is 25ml.

This gives a value of 403967 ppm Ca for the total dissolved portion of the rock. Similar calculations were performed for the other elements.

---

*Because the decanted solution was diluted, rather than an aliquot, an experiment was performed to see what the actual undiluted sample volume was. It was found to vary by no more than 0.1 ml. This amounts to, at the most, a 3% error in sample concentrations.

TRACE ELEMENT DATA

| Traverse Group | | | | | | |
|---|---|---|---|---|---|---|
| sample/well no. | Dol. % | Sr ppm | Na ppm | Mn ppm | Ca ppm | 1000(mSr/mCa) |
| 5 | 77 | nd. | 493 | 902 | 96,964* | 0 |
| 7 | - | - | - | - | - | - |
| 23 | - | - | - | - | - | - |
| 25 | - | - | - | - | - | - |
| 26 | - | - | - | - | - | - |
| 29 | - | - | - | - | - | - |
| 45 | - | - | - | - | - | - |
| 55 | 40 | nd. | 484 | 170* | 276,817 | 0 |
| 75 | 55 | 33 | 378 | 741 | 160,373 | 0.46* |
| 76 | 23 | nd. | 213* | 303* | 117,632 | 0 |
| 89 | - | - | - | - | - | - |
| 106 | 55 | nd. | 478 | 1375*# | 136,053 | 0 |
| 120 | 41 | nd. | 305 | 543 | 168,653 | 0 |
| 123 | - | - | - | - | - | - |
| 130 | - | - | - | - | - | - |
| 150 | 22 | 34 | 322 | 341 | 206,353 | 0.35 |
| 156 | - | - | - | - | - | - |
| 177 | 74 | nd. | 493 | 1222# | 184,865 | 0 |
| 182 | 32 | nd. | 921* | 1210 | 139,735 | 0 |
| 183 | - | - | - | - | - | - |
| 208 | 51 | 50* | 435 | 947 | 301,427 | 0.31 |
| 221 | 88 | nd. | 694* | 2039*# | 314,921* | 0 |
| 224 | 17 | 33 | 414 | 428 | 379,934* | 0.19 |
| 225 | 26 | nd. | 362 | 482 | 332,058* | 0 |
| 230 | 27 | 87* | 511 | 1008 | 319,364 | 0.60 |
| 231 | 96 | nd. | 543 | 912 | 190,377 | 0 |
| n=15 | $\bar{X}$=48 | $\bar{X}$=15 ± 26 | $\bar{X}$=470 ± 169 | $\bar{X}$=842 ± 496 | $\bar{X}$=221,702 ± 90,408 | $\bar{X}$=0.13 ± 0.20 |

nd. = not detected.
* = value differs by one standard deviation of the mean.
# = sample exceeded linear working range of standards.

TRACE ELEMENT DATA

Dundee

| sample/well no. | Dol. % | Sr ppm | Na ppm | Mn ppm | Ca ppm | 1000(mSr/mCa) |
|---|---|---|---|---|---|---|
| 5 | - | - | - | - | - | - |
| 7 | 6 | 107 | 363 | 148 | 397,283 | 0.59 |
| 23 | - | - | - | - | - | - |
| 25 | 39 | 208* | 390 | 105 | 386,543 | 1.18 |
| 26 | 11 | 64 | 410 | 192 | 328,690 | 0.42 |
| 29 | 32 | 107 | 394 | 140 | 347,775 | 0.68 |
| 45 | - | - | - | - | - | - |
| 55 | 11 | 165 | 368 | 476* | 388,958 | 0.92 |
| 75 | 7 | 112 | 390 | 148 | 392,241 | 0.63 |
| 76 | 7 | 123 | 384 | 140 | 391,548 | 0.68 |
| 89 | 5 | 168 | 377 | 114 | 399,027 | 0.92 |
| 106 | - | - | - | - | - | - |
| 120 | 5 | 117 | 417 | 193 | 393,247 | 0.66 |
| 123 | 8 | 133 | 492* | 183 | 438,942 | 0.66 |
| 130 | 5 | 212* | 395 | 257 | 296,658 | 1.55* |
| 150 | - | - | - | - | - | - |
| 156 | 14 | 122 | 365 | 184 | 484,518* | 0.55 |
| 177 | 6 | 161 | 356 | 201 | 395,934 | 0.90 |
| 182 | 5 | 69 | 393 | 795* | 285,275 | 0.52 |
| 183 | - | - | - | - | - | - |
| 208 | 5 | 189* | 370 | 159 | 336,095 | 1.22 |
| 221 | - | - | - | - | - | - |
| 224 | - | - | - | - | - | - |
| 225 | 9 | 137 | 381 | 149 | 121,852* | 2.45* |
| 230 | 10 | 190* | 441 | 199 | 389,814 | 1.18 |
| 231 | - | - | - | - | - | - |
| n=17 | $\bar{X}$=11±10 | $\bar{X}$=140±44 | $\bar{X}$=393±33 | $\bar{X}$=223±169 | $\bar{X}$=360,847±78,552 | $\bar{X}$=0.92±0.50 |

*Value differs by at least one standard deviation of the mean.

TRACE ELEMENT DATA

Detroit River

| sample/well no. | Dol. % | Sr ppm | Na ppm | Mn ppm | Ca ppm | 1000(mSr/mCa) |
|---|---|---|---|---|---|---|
| 5 | - | - | - | - | - | - |
| 7 | 28 | 136* | 437 | 136 | 320,317 | 0.92 |
| 23 | - | - | - | - | - | - |
| 25 | - | - | - | - | - | - |
| 26 | 66 | 185* | 406 | 232 | 306,652 | 1.31 |
| 29 | 86 | 34 | 396 | 218 | 276,600 | 0.26 |
| 45 | 95 | nd. | 498 | 252 | 179,207 | 0 |
| 55 | 99 | nd. | 488 | 131 | 162,336 | 0 |
| 75 | 97 | 105 | 483 | 116 | 120,787 | 1.90* |
| 76 | 99 | 58 | 322* | 272 | 207,594 | 0.61 |
| 89 | 100 | nd. | 433 | 194 | 90,720 | 0 |
| 106 | 92 | 168* | 394 | 181 | 258,710 | 1.42* |
| 120 | 99 | nd. | 949* | 195 | 194,492 | 0 |
| 123 | 61 | 104 | 411 | 140 | 240,761 | 0.94 |
| 130 | 100 | 40 | 549 | 669* | 64,091 | 1.36 |
| 150 | - | - | - | - | - | - |
| 156 | 98 | 102 | 450 | 148 | 158,151 | 1.40* |
| 177 | 82 | nd. | 383 | 57* | 86,566 | 0 |
| 182 | 49 | 97 | 393 | 91 | 402,156 | 0.52 |
| 183 | 98 | nd. | 343 | 77 | 75,641 | 0 |
| 208 | - | - | - | - | - | - |
| 221 | 77 | 63 | 470 | 183 | 200,407 | 0.68 |
| 224 | - | - | - | - | - | - |
| 225 | - | - | - | - | - | - |
| 230 | - | - | - | - | - | - |
| 231 | 100 | 40 | 480 | 162 | 168,373 | 0.52 |
| n=18 | $\bar{X}$=85 | $\bar{X}$=63±61 | $\bar{X}$=460±135 | $\bar{X}$=192±133 | $\bar{X}$=261,908±247,338 | $\bar{X}$=0.66±0.62 |

*Values differs by at least one standard deviation of the mean.

# APPENDIX E

## CORRELATION MATRICES--TRAVERSE, DUNDEE AND DETROIT RIVER CARBONATES

## APPENDIX E

## CORRELATION MATRICES--TRAVERSE, DUNDEE AND DETROIT RIVER CARBONATES

Correlation matrix for all samples studied.

| | Log Sr | Log Na | Log Mn | Log Ca |
|---|---|---|---|---|
| Log Ca | 0.426 | -0.132 | -0.096 | - |
| Log Mn | -0.466 | 0.298 | - | - |
| Log Na | -0.131 | - | - | - |
| Log Sr | - | - | - | - |

Correlation matrix for Traverse limestone.

| | Log Sr | Log Na | Log Mn | Log Ca |
|---|---|---|---|---|
| Log Ca | 0.215 | 0.161 | -0.166 | - |
| Log Mn | 0.991 | 0.514 | - | - |
| Log Na | 0.824 | - | - | - |
| Log Sr | - | - | - | - |

Correlation matrix for Traverse dolomite.

| | Log Sr | Log Na | Log Mn | Log Ca |
|---|---|---|---|---|
| Log Ca | - | 0.361 | 0.428 | - |
| Log Mn | - | 0.804 | - | - |
| Log Na | - | - | - | - |
| Log Sr | - | - | - | - |

Correlation matrix for Dundee limestone.

| | Log Sr | Log Na | Log Mn | Log Ca |
|---|---|---|---|---|
| Log Ca | 0.049 | 0.011 | -0.087 | - |
| Log Mn | -0.305 | 0.013 | - | - |
| Log Na | -0.084 | - | - | - |
| Log Sr | - | - | - | - |

Correlation matrix for the Detroit River.

| | Log Sr | Log Na | Log Mn | Log Ca |
|---|---|---|---|---|
| Log Ca | 0.445 | -0.081 | -0.031 | - |
| Log Mn | -0.449 | 0.296 | - | - |
| Log Na | -0.224 | - | - | - |
| Log Sr | - | - | - | - |

Pocket has: Fig. 33 & Overlay – Fig. 38 & overlay = 12 pieces