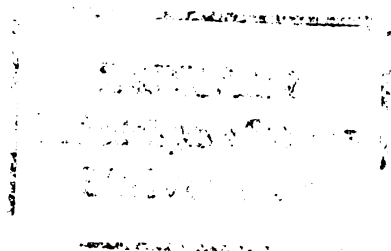


DUNDEE FIELDS IN THE CENTRAL MICHIGAN BASIN

Thesis for the Degree of M. S.
MICHIGAN STATE UNIVERSITY
CHARLES VINCENT BUSH
1983



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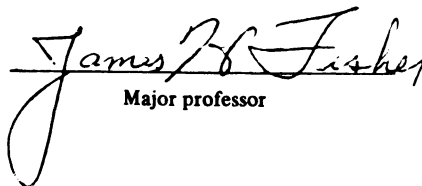
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ABSTRACT
DUNDEE FIELDS IN THE CENTRAL MICHIGAN BASIN

By
Charles Vincent Bush

The Dundee Formation of the Michigan Basin has been studied since the late 1800's. The purpose of this study includes the determination of relationships between structural, lithologic and production trends.

Within the basin, the Dundee exhibits dominant northwest-southeast lineaments which create positive trends and control the distribution of structures. The shape of these structures are determined by this trend and subordinate east-west cross-folding.

The Dundee varies in thickness from 200 feet to 440 feet in the study area. Reefing, increased carbonate buildup on positive areas, yields thick intervals on positive structures.

The Dundee is a brown, locally dolomitized, wackestone or packstone. Fossils include brachiopods, corals, and stromatoporoids. A strong relationship exists between structure and dolomitization. Systems of fractures developed during folding provided pathways for dolomitizing fluids. Much of the production comes from epigenetic dolomites along these fractures. Primary porosity on the flanks of these structures may also create traps.

DUNDEE FIELDS IN THE CENTRAL MICHIGAN BASIN

by

Charles Vincent Bush

A THESIS

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

MASTER OF SCIENCE

Department of Geology

1983

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INTRODUCTION

General

The Dundee Formation in Michigan has been the subject of study since the late 1800's. Since the discovery of oil in the Dundee in 1928, the studies have taken an economic turn. To date, the Dundee is the most prolific oil producer in the state. Studies have been conducted on a variety of aspects of the formation in different areas of the state. Most of the investigations have concentrated on the conditions present in known producing structures (Tinklepaugh, 1957; Jackson, 1958; Paris, 1977; Ten Have, 1979; Richey, 1980; and others). A few studies have addressed the problems involving the Dundee from a regional view (Bloomer, 1969; Landes, 1946).

The purpose of this study includes the determination of the factors and mechanisms that control petroleum accumulation in the Dundee. The formations in the central Michigan Basin show distinct structural, lithologic, and production trends. The relationship of these trends to controls on the Dundee will be examined.

Utilizing well logs, drillers' records, and literature, the Dundee Formation is delineated. This is accomplished by the construction of maps depicting porosity, thickness, structure, and lithology in the area of study.

The mechanisms controlling the formation of primary and secondary porosity are considered. This allows the prediction of favorable conditions for the occurrence of porosity in the Dundee. The relationship between secondary porosity and dolomitization in the basin has been the subject of various studies involving several formations including the Dundee. The conditions and

restrictions concerning secondary porosity are outlined and related to the Dundee in the area of study.

This study represents the first regional investigation of the Dundee Formation in the central Michigan Basin in some time. Radical changes have taken place recently in the understanding of dolomitization, diagenesis, porosity formation and preservation, and well treatment. Analysis of the completed data and maps indicates the relationships between lithology, porosity, structure, and production. It is the hope and purpose of this writer that the results of this study will provide comprehensive and current information regarding the geological characteristics of the Dundee and the related production trends. It is also hoped that this study will serve as a useful basic framework for study and exploration in the central Michigan Basin, as well as outlining areas in need of further study.

Area of Study

The area of study is a four county region in central Michigan consisting of Clare, Midland, Isabella, and Gladwin Counties (Figure 1). This region of the Michigan Basin encompasses a large percentage of the current Dundee oil and gas production. Although many of the fields date back to the 1930's, recent activity has yielded substantial new data and spurred interest in the area.

Method of Study

Data for the subsurface maps prepared for this project were obtained by the correlation of approximately 400 well logs from the Michigan State Geological Survey files and the Michigan State University collection. Well locations were chosen to yield the best control pattern. Preference was given to recent, more sophisticated well logs over those with older surveys.

Where well logs were not available, drillers' logs on file at the Michigan Geological Survey were used to obtain formation tops and lithologic descriptions.

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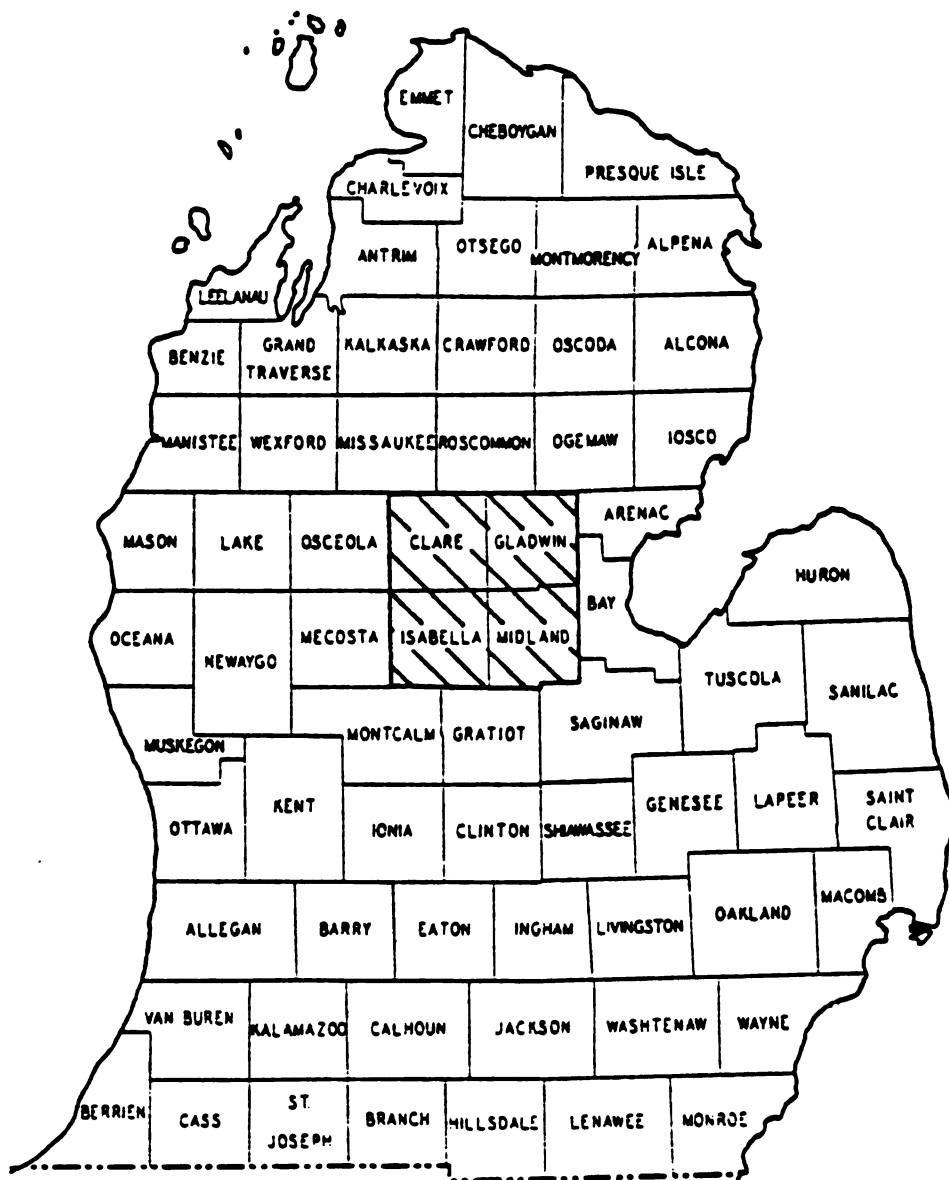


Figure 1. Area of study.

The quality of the drillers' logs varied. Those logs which appeared accurate and well recorded generally agreed with nearby well control and were included in the data base. Others which seemed poorly documented or which were significantly different from surrounding information were omitted.

Formation tops were recorded for the Bell Shale, the Dundee Formation, and the Detroit River Group. The top of the Bell Shale and the Dundee Formation top are distinctive markers on logs in the area of study (Figure 2). The log signature of the Bell and Dundee carried extremely well from log to log. The tops of these two formations can be picked consistently and accurately.

The top of the Detroit River Group has been the subject of debate for many years in the Michigan Basin. Landes (1951) studied the information available and summarized the controversy surrounding the top of the Detroit River Group as follows:

"Because the basal part of the Dundee Formation is a limestone or a dolomite and the upper part of the Lucas Formation is also a limestone or a dolomite in most places, it is not always possible to ascertain the exact position of the contact of the two formations. Furthermore, the task is complicated by an erosional unconformity at the top of the Detroit River Group that cuts out certain beds within a relatively short distance due to different levels of erosion. As fossils are not available in most cuttings, the determination of the contact in wells must be based on lithologic differences.

The following criteria are useful in various parts of the basin: sand in the basal part of the Dundee, chert in the lower part of the Dundee, limestone in the Dundee, darker color of carbonate rocks in the basal part of the Dundee, dolomite in the Lucas, and anhydrite in the Lucas. Calcium sulfate, present mainly as anhydrite, occurs in the top few feet of the Lucas over much of the Basin.

Lilienthal (1978) denotes a radioactive marker called "DR-1" and a porosity zone used in various combinations to represent the top of the Detroit River Group: 1) at the marker "DR-1" only, 2) below the marker "DR-1" and

Figure 2. Typical well log.

above the porosity zone, 3) below the marker "DR-1" and in the porosity zone. The character and extent of the marker and the porosity zone are not consistent enough in the area of study to allow regional correlation.

For the purpose of this study, the top of the Detroit River Group will be placed at the first anhydrite observed on well logs, commonly called the "Detroit River Anhydrite".

STRUCTURE

General

The Michigan Basin is a roughly circular, asymmetrical, autogeosyncline or intracratonic basin, located in the Central Interior Platform (Figure 3). It covers the entire southern peninsula and part of the northern peninsula of Michigan, eastern Wisconsin, portions of Ontario, northern Indiana, northeastern Illinois, and northwestern Ohio. The basin is surrounded by major tectonic features: the Wisconsin Arch to the west, the Canadian Shield to the north, the Algonquin Arch to the east, the Findlay Arch to the southeast, and by the Kankakee Platform on the southwest.

Many theories on the mechanisms responsible for the formation and the structure of the Michigan Basin region have been proposed. Pirtle (1932) described the structure in the basin in relation to the surrounding positive features. He believed the structures within the basin were controlled by trends of folding or lines of structural weakness which originated in the basement rock and that the basin originated in Precambrian time. Deposition was controlled by the Wisconsin Arch, the Cincinnati Arch, and the Kankakee Platform. He suggested the Wisconsin Arch of today represents the remnant of a Precambrian mountain range that once bordered an ancestral geosyncline in the Michigan area. The subsequent erosion of the mountain range supplied sediment to the embryonic basin. Many of Pirtle's interpretations were based on his recognition of dominant northwest-southeast trends in the basin, as well as subordinate trends running northeast-southwest.

Newcombe (1933) also cited the structural trends in the basin. Newcombe's report on the geology of the Michigan Basin is an excellent reference and an aid

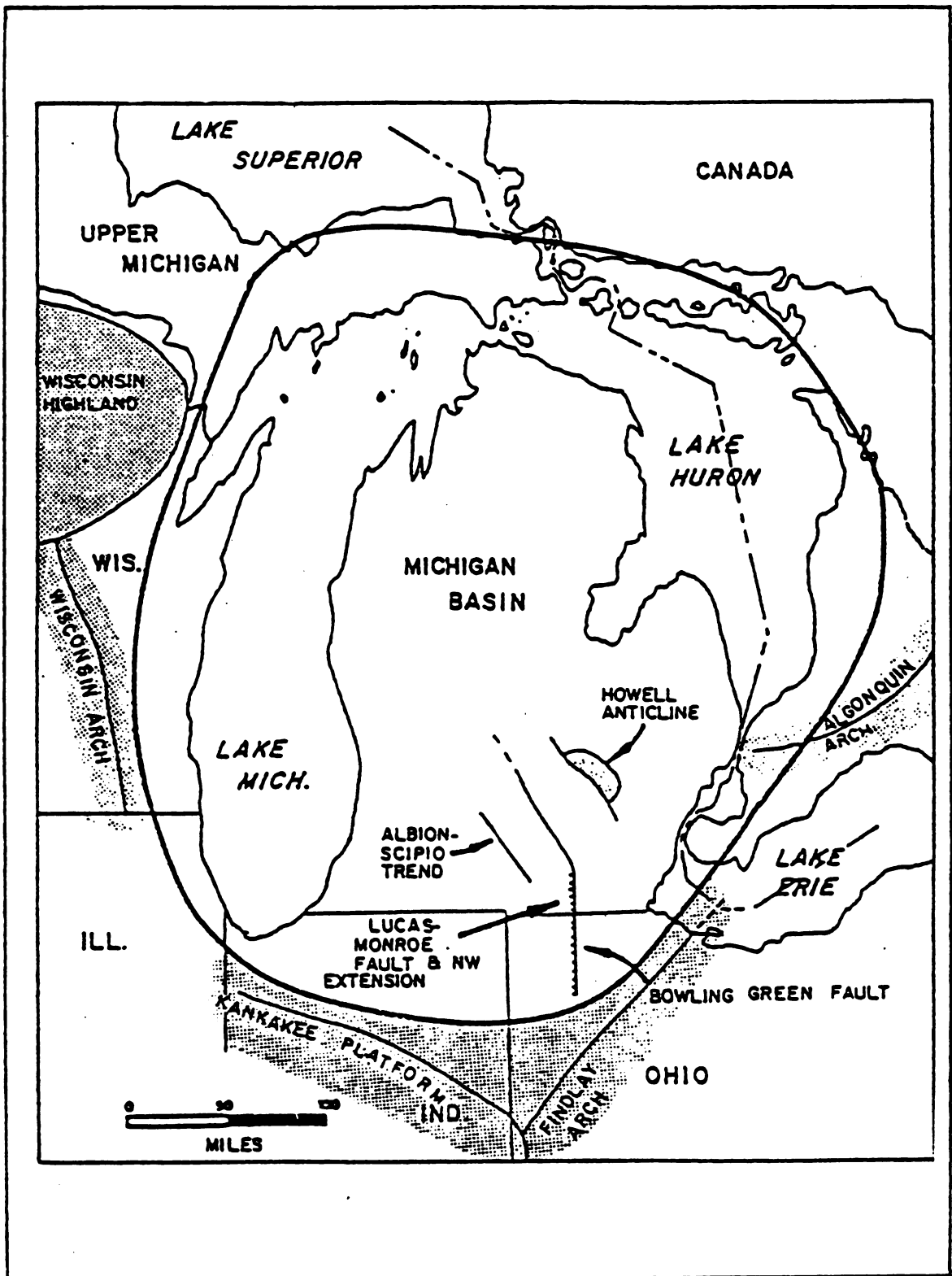


Figure 3. Major structural features of the Michigan Basin and surrounding areas.

in the studying of the basin. Several theories on the structural and geological aspects of the basin proposed by Newcombe have since been supported by evidence gathered since 1933. Newcombe believed zones of weakness in the basement rock controlled the formation of the Michigan Basin in Precambrian time. These zones of weakness were thought to be related to the Keweenaw disturbance. The principle folding of the anticlinal trends in the basin occurred in the Late Devonian. Subsequent movements during the Late Mississippian accentuated the structures already present and created new structures as well.

Kirkham (1937) proposed that the shifting of large bodies of magma from one area of the crust to another created a downwarping and not a true basin. He did not believe that horizontal and tangential forces played a role in the origin of the basin. He did believe, however, that during the movement of the magma, the Precambrian surface became marked by faults, rifts, and joints. These features caused zones of weakness along which forces could later act.

Lockett (1947) took the same approach as Pirtle. Lockett related the surrounding positive features to the origin of the basin. These dominant features are the remnants of Precambrian mountain ranges. Erosion of these mountains supplied sediment, and the weight of the sediment initiated subsidence. He states that the zones of weakness were present in the Precambrian surface, but that the differential subsidence along the zones was in response to sediment loading, not orogenic forces. The layering of sediments over the Precambrian surface created the basis for the anticlinal and the synclinal features observed in the basin.

Cohee (1944-1949) prepared numerous maps and texts on the Michigan Basin, in particular, the Traverse, Dundee, and Rogers City Formations. This series of isopachs, structure contour, and lithology maps aided the exploration effort in the basin. Cohee depicts the dominant trends in the basin. Cohee and

Landes (1958) consider the basin to first show closure in Late Silurian time. Intermittant folding and subsidence occurred throughout the Paleozoic, with the major folding event in the Late Mississippian.

Gravity and magnetic studies have also been used as a basis for theories of the basin origin. Hinze and Merritt (1963, 1969) conducted regional gravity and magnetic surveys in the Michigan Basin. A gravity and magnetic anomaly was observed which runs northwest-southeast through the basin (Figure 4). They suggested the anomaly represents an ancestral rift zone, and that the rift zone had a dominating effect on the development of the basin. High density mafic rocks of Keweenawan age were being emplaced along the rift. These dense rocks may have initiated subsidence in the basin.

Ells (1969) published a summary of much of the previous work done in the Michigan Basin. He presented the important theories concerning the origin of the basin and discussed the major structures. Ells cited the dominant northwest-southeast anticlinal trend. These trends, he suggests, record the periods of intermittant activity throughout the Paleozoic.

J. H. Fisher (1969) constructed isopach maps on a number of Paleozoic intervals. He suggested that an embryonic Michigan Basin was present during Cambrian time. In Trenton time, the Michigan Basin evolved into a true basin in the shape and size as we know it today. During the Mohawkian and Cincinnati, periods of significant subsidence took place. Thin layers of shales and carbonates accumulated in Early Silurian time, and during the Middle Silurian time a massive reef developed around the margin of the basin. These encircling reefs starved the interior of the basin during the Niagaran, as observed by the thinning of the sediments toward the center of the basin. The major sinking in the basin in Salina time is recorded by a thick accumulation of carbonates, shales, and evaporites in a depocenter near the southwest end of Saginaw Bay. In

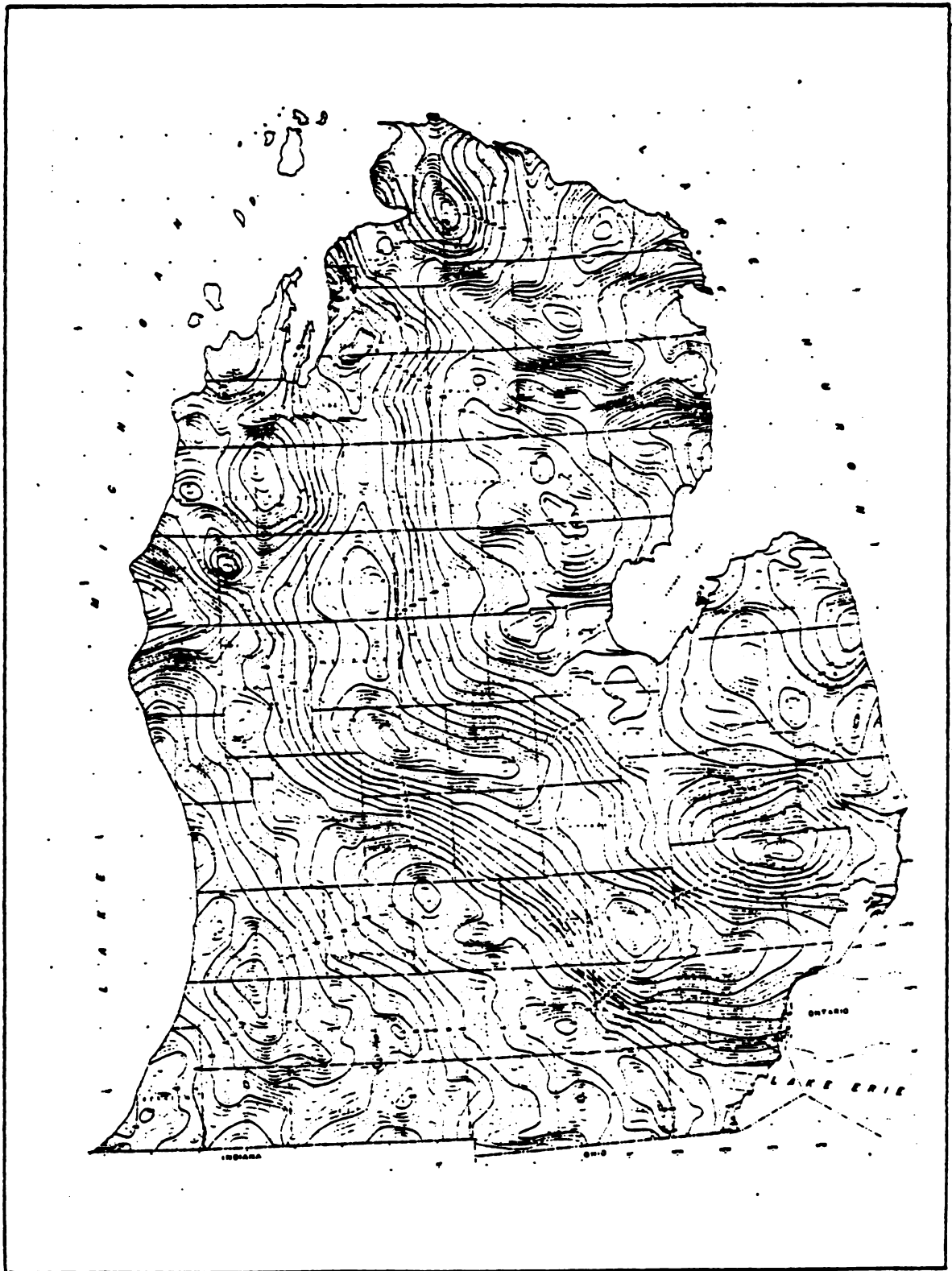


Figure 4. Bouguer gravity anomaly map of the southern peninsula of Michigan. Contour interval = one milligal (Hinze and Merritt, 1969).

the Devonian, the depocenter was slightly northwest of Saginaw Bay (Figure 5). Several major unconformities were created by uplifts during the Early Devonian. A thicker Middle and Upper Devonian sequence of carbonates and black shales developed during a period of increased subsidence. Fisher believes the trends in the Michigan Basin may be in part controlled by a rectilinear pattern of faulting in the basement rocks. This pattern of faulting is reflected in the rectilinear faulting pattern observed in the Canadian Shield (Figure 6). The trends of the fault patterns may control the observed orientation of the Dundee oil fields present in the central Michigan Basin.

Prouty (1976) suggested that lineaments observed in the LANDSAT imagery of the Michigan Basin are traces of faults. These lineaments reflect both the interior structures of the basin and the radial features around the perimeter of the basin (Figure 7). The orientation of the fault traces can be used to construct a model for the tectonic history of the basin (Ten Have, 1979). Prouty attributes the faults to a wrenching deformation model and related the folds present in the basin to the resultant movement on these faults. The stresses applied to the region are due in part to the structural activity in the Appalachians throughout the Paleozoic. Evidence indicates many episodes of deformation and shearing. Although many orientations occur for fault lineaments, major trends can still be distinguished. Prouty believes the most intense period of folding occurred in Pre-Marshall Mississippian time.

Lilienthal (1978) constructed a series of cross-sections of the basin. These cross-sections radiate from the Sparks deep test well in Gratiot County and are based on the correlation of gamma-ray and neutron logs. The cross-sections cover most of the lower peninsula of Michigan. These sections are useful in determining general geologic trends, position of depocenters through time, and the presence or absence of particular horizons in a region of the basin.

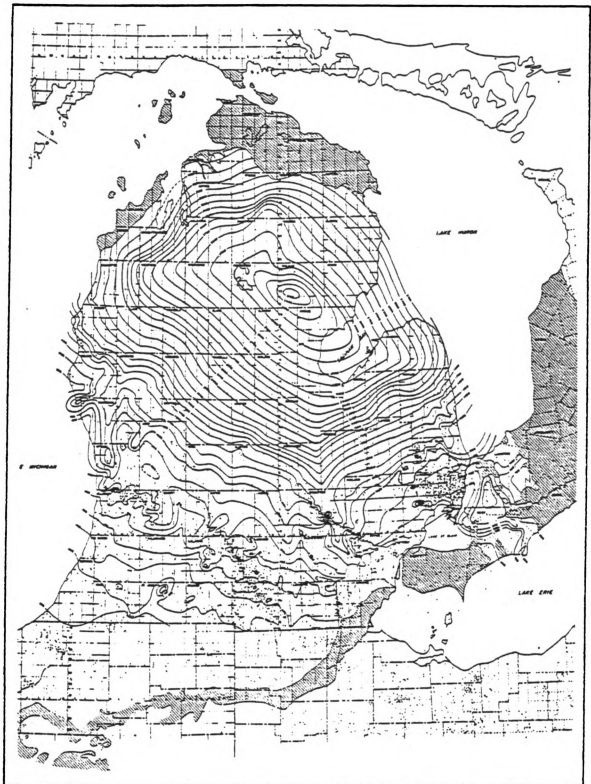


Figure 5. Devonian isopach depicting location of depocenter (Fisher, J. H., 1969).

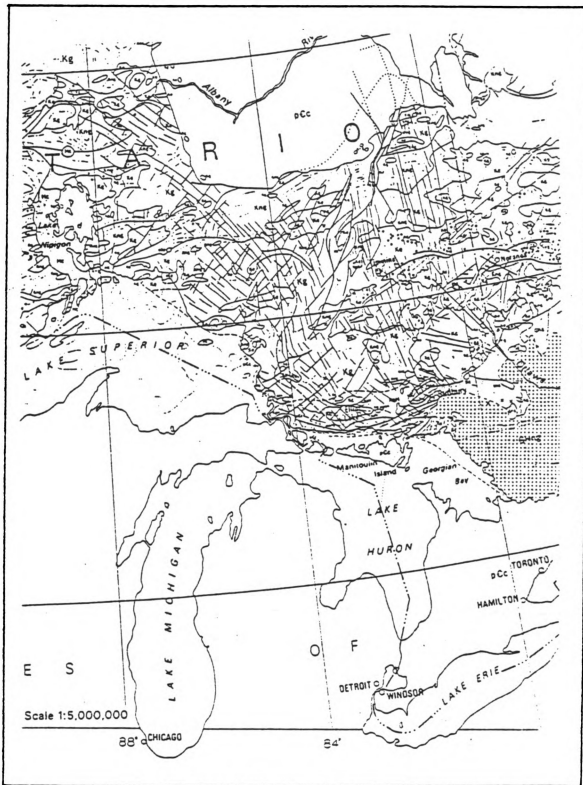


Figure 6. Rectilinear pattern of faulting in the Canadian Shield (tectonic map of Canada, 1969; Fisher, J. A., 1981).

Figure 7. Structural trends in the Michigan Basin (compiled by Prouty, 1976).

Central Michigan Basin Structure

A structure contour map was constructed on the top of the Dundee Formation (Plate 1). Formation tops were picked from well logs and drillers' records. Locations of the key well logs used in the study are given in Appendix I. Tops obtained from drillers' logs were only recorded for map use and do not appear in the Appendix. While control was good in most areas, some areas lacked adequate coverage for detailed mapping. The contour patterns in these areas are inherently more interpretive, but were constructed in such a way as to honor all the data available. Township names and locations are given on Figure 22 in Appendix I.

The central Michigan Basin area occupies the deepest part of the basin. Newcombe (1933) described the area as a single structural province. The region is characterized by broad anticlinal and synclinal folds in subparallel trends. These trends of folding roughly parallel the axis of the slightly ovate Michigan Basin. Relief on structures ranges from tens of feet to hundreds of feet. The age of the folding is not fully known, but the structures record multiple periods of tectonic activity. The configurations of the structures are thought to be controlled by vertical tectonics in the basement rocks of the basin.

The regional dip of the area of study is difficult to establish because of the complexity of structure and the variability of dip values near local structures. The regional dip trends to the north and northeast toward the Devonian depocenter. In areas less affected by structures, dip values range from 25'/mile to 80'/mile along a line trending N45°E.

Distinct structural trends can be outlined in the area of study. A strong northwest-southeast lineament is observed in structures in this area, with a weaker northeast-southwest lineament. These lineaments may be reflections of fault patterns in the basement rocks.

Structural highs occur en echelon in the dominant northwest to southeast trend. On the map (Plate 1) three major structurally high trends are observed. The Broomfield trend runs from Sherman Township to Deerfield Township in Isabella County. The Freeman-Porter trend runs from Redding Township, Clare County, southeast to Porter Township, Midland County. The third major trend, the Headquarters-Bentley trend, runs from Franklin Township, Clare County, southeast through Bentley Township, Gladwin County. Several minor highs occur subparallel to these major trends.

Two types of oil field structures occur along these high trends. Several of the larger fields in the area are of one type - arcuate structures with pistol-like outlines. Examples of this type are the Mount Pleasant, Porter, and Bentley fields. These structures are generally asymmetrical. The major structural axis is interrupted by subordinate cross folding and faulting. These fields can be several miles long, as shown by the Mount Pleasant field. Along these structures, cross-folding and saddles change the size, shape, and direction of the fields. The fields have numerous structural irregularities caused by these features which create traps for hydrocarbons.

Circular oil fields are the other type of structures. Newcombe (1933) and Ells (1969) suggested these fields were caused by cross buckling in the Dundee. The displacement in the folding is about the same in all directions, as opposed to the other type of fields which have major and minor directions of folding. These circular fields tend to be somewhat smaller than the Mount Pleasant type fields. Examples of the circular fields are the Grout, Edenville, Billings, and Leaton fields.

Both types of oil field structures may be controlled by vertical tectonics. These relative movements originate in the Precambrian and effect the overlying

strata as well. Structural trends of faulting and zones of weakness in the Precambrian control the orientation of Devonian Dundee oil fields.

An example of Dundee oil field orientations is shown in Figure 8. Two directions of structure are indicated by the field shapes. A dominant northwest-southeast trend controls the shape of the oil fields as well as the distribution. Oil fields in this area occur in sub-linear groups along this direction. The east-west trends create cross folding in the fields which changes the direction of the axes. The arcuate shapes of the fields and the irregularities in the outline of production result from cross folding.

Many of the structures exhibit steep dips on one flank and gentler or shallower dips on the other flank. Most tend to have a steep dip on the southwest side of the structure and the lesser dip on the northeast side. The Mount Pleasant field and the Porter field show this well. The steep dips are generally 150'/mile to 200'/mile, and the gentler dips being approximately 35'/mile to 70'/mile. This configuration may be in part due to the regional dip in the area of study. Folding of the dipping beds occurs almost parallel to the strike of the beds. This could result in two different dip values on the flanks. Normal faulting movement at depth is another possibility for some structures. The upthrown side of the structure creates the steep dip, and the downthrown side creates the shallow dip. A more complete structural study of each field would be necessary to determine the dominant structural controls.

The complex structural configuration in the central Michigan Basin lends itself to many different interpretations. Each of these interpretations may outline areas of economic interest. Many of the areas of the region have yet to be explored in detail. Along with the refinement of geophysical data in the area, determination of the structure in the central Michigan Basin may become increasingly more detailed.

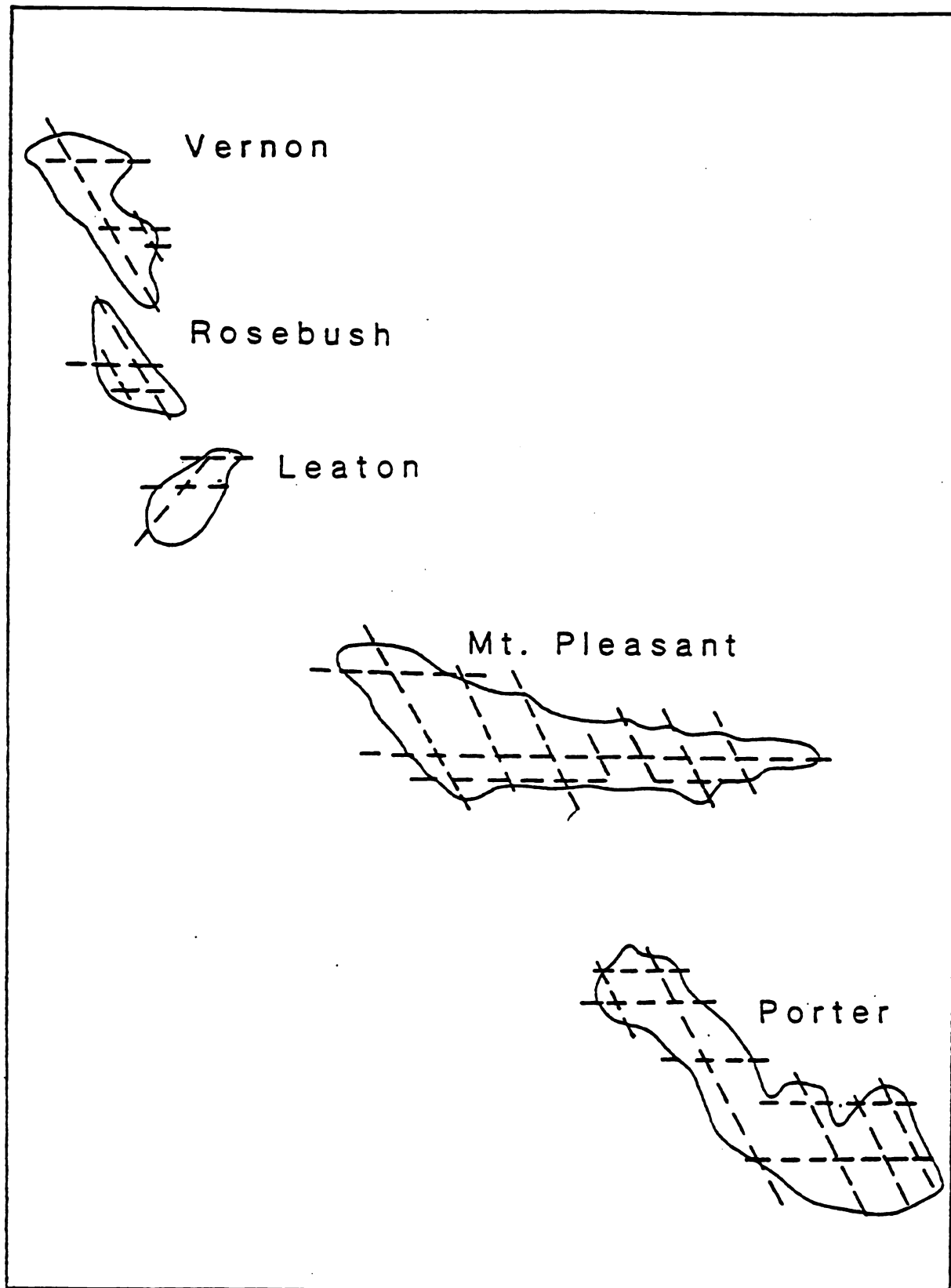


Figure 8. Structural trends in oil fields.

STRATIGRAPHY

General

The Middle Devonian strata in the area of study is comprised of the Traverse Group, the Dundee Formation, and the Detroit River Group. Of particular interest in the study are the Bell Shale at the base of the Traverse Group, and the Dundee Formation (Figure 9).

The tops of these formations were obtained from well logs and drillers' records on file at the Michigan Geological Survey. Where recent geophysical well logs were available, accurate formation tops could be determined. Some of the older electric and gamma-ray surveys did not distinguish the formations as clearly, and estimations of the contacts were required. Even in these cases, the tops can be assumed to be accurate to within a few feet. The characteristic well log tracks and my interpretations of the formation tops are depicted in Figure 2.

In locations where well logs were not available, drillers' records were utilized. The quality and reliability of the drillers' records varied. In some instances, good drilling records were kept with careful sample analysis. These records generally yielded tops and thicknesses in line with surrounding well log data, and were included in the study. The records which appeared unreliable or that differed greatly with the surrounding data were omitted. Some subjective judgement and common sense was used in deciding which records were to be included in this study.

Interpretation and contouring of the data is also a subjective process. Contouring is an individual interpretation of the data concerning the thickness and character of a rock unit. Variations in the control pattern, reliability of data, and the interpreter may lead to very different results.

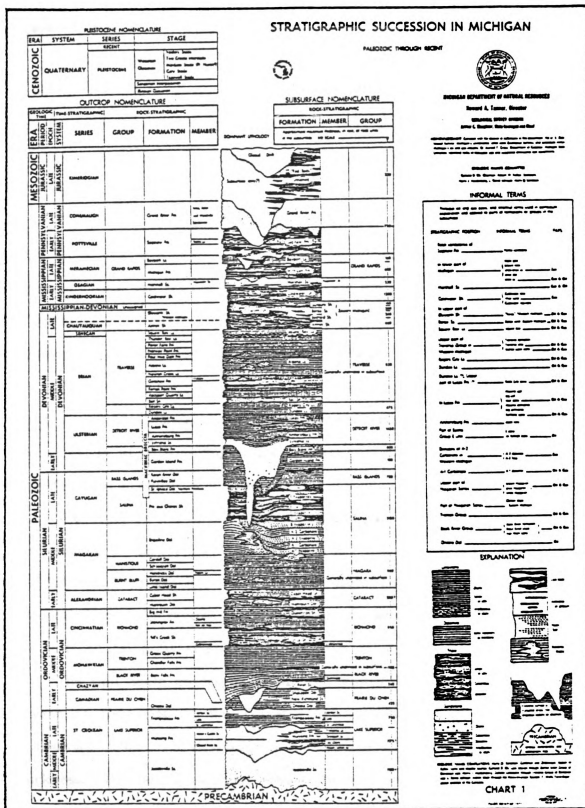


Figure 9. Stratigraphic succession in Michigan.

Traverse Group

The Traverse Group of the Michigan Basin is commonly divided into three units for subsurface work. These three units are: the Traverse Formation, Traverse Limestone, and the Bell Shale (Figure 10). The Group varies in thickness, from about 800' in the north to less than 100' in the southwest corner of Michigan (Lilienthal, 1978).

The Traverse Formation is a gray shale near the top of the interval. This gray shale gradually becomes lighter colored and calcareous lower in the interval. Near the base of the formation the shale grades into a light colored argillaceous limestone. This gradational lithology, from gray, pure shale to a lighter, argillaceous limestone, can make correlation in the subsurface difficult.

The Traverse Limestone has a variable lithology as well. It is primarily a shale in eastern Michigan, with a progressive increase in limestone occurring to the west. In western Michigan, the Traverse Limestone is predominantly pure limestone and dolomitic limestone.

The Traverse Limestone produces oil and gas in Michigan. Through 1979, the Geological Survey of Michigan reported 106,665,092 barrels of oil and 9,048,289 MCF of gas had been produced from Traverse pools. Most of the production occurs in southwestern Michigan. A variety of trap types have been encountered, bioherms, stratigraphic pinchouts, collapse features, and anticlines.

The Bell Shale covers much of the central Michigan Basin. It is the lowermost formation of the Traverse Group, and is predominantly a shale (Lilienthal, 1978). It is generally 60' to 70' thick, but may locally exceed 100' in thickness. The Bell Shale thins toward the southwest corner of Michigan and eventually pinches out. Bloomer (1969) noted this trend of thickening and suggested a source to the north or northeast of the area of study for the Bell Shale.

System	Group	Formation
D	Traverse	Traverse Unit
E		Traverse Limestone
V		Bell Shale
O		
N	Detroit River	Rogers City
I		Dundee
A		
N		Lucas
		Amherstburg
		Sylvania Sandstone

Figure 10. Subsurface nomenclature common to the Michigan Basin Devonian System (Lilienthal, 1978; Tinklepaugh, 1957).

In the central Michigan Basin, the Bell Shale is typically a dark gray to black shale. It is often calcareous, and crinoids seem to be the dominant fossil types. These crinoid fragments usually occur in thin beds, somewhat size sorted, with partings parallel to bedding.

An isopach map of the Bell Shale was constructed (Plate 2). Well coverage of the Bell was good, with many of the wells in the area targeted to the Dundee. Drillers' records were less accurate, a large number of which were recorded prior to 1950. Lithologic descriptions in these older records are often limited to shale or shale and shells.

Thicknesses of the Bell Shale interval varies from 35 feet to 75 feet in the area of study. A general thickening to the northeast and east is observed. This correlates with the regional thickening toward the Devonian depocenter northwest of Saginaw Bay. The thinnest interval of the Bell occurs in southern Isabella County. Gradual variation in Bell thickness is most common in the region. A few anomalous areas can be seen, notably the thickening near the Bentley field in Gladwin County and the Broomfield field in Isabella County.

The area around the Broomfield structure also has a thicker Dundee interval. This suggests the Broomfield area may have been a local depocenter in Devonian Bell time, with a greater accumulation of sediment.

In some areas, the thickness of the Bell exhibits subparallel trends to the structural surface of the Dundee (Plate 1). One example of this is the Cranberry Lake field in Clare County. Thinning of the Bell occurs over the positive Dundee structure. This suggests at least some degree of positive relief in the Dundee existed at the time of Bell Shale deposition. A more detailed study of the Bell Shale and other younger horizons may determine the control of the Dundee topography upon the configuration of the Bell. The geologic history of the Dundee and the Bell Shale could be more accurately determined.

The Bell Shale overlies the Dundee Formation. Gardner (1974) found a parallelism of bedding above and below the Bell-Dundee contact. In some areas, the Bell grades lithologically into the Dundee (Ten Have, 1979). The Bell shale may unconformably overlie the Dundee in the extreme southwest area of the state. In this area, the Dundee may have been exposed to aerial erosion prior to Bell deposition (Lilienthal, 1978). The contact between the Bell and the Dundee is considered conformable in the central Michigan Basin.

Dundee Formation

The Dundee Formation underlies much of the southern peninsula of Michigan. The term Dundee was first used by Lane in 1895 while describing an outcrop near Dundee, Michigan. Several outcrops of Dundee occur in Michigan. Notably good exposures are present in the Sibley Quarry in Wayne County and along the Mason Creek in Monroe County. These outcrops allow detailed surface work on the lithology and the paleontology of the Dundee. The correlation of these stratigraphic details to the central part of the basin is not fully understood.

The Dundee is a formation of variable thickness in the basin. The greatest accumulation occurs in the Saginaw Bay area, with thicknesses up to 475 feet.

In the past, the Dundee Formation has been separated on the basis of surface work into two units: the Rogers City unit and the Dundee unit (Cohee and Underwood, 1945). Ehlers and Radabough (1938) divided the Dundee on the basis of faunal succession and slight differences in lithology. These terms are still used by some geologists working in the Michigan Basin. However, the similar lithology of the two units make them indistinguishable in the subsurface (Ten Have, 1979). The Dundee Formation in this study will combine the two units into one for the purpose of subsurface mapping.

An isopach map was constructed for the Dundee Formation (Plate 3). Thicknesses were obtained from well logs where possible, and supplemented with drillers' logs. Wells penetrating the entire Dundee interval were normally confined to deeper tests on a known Dundee structure. This led to a grouping of the data points, with less control between.

On a regional level, the Dundee thickens to the northeast. This corresponds to the position of the Devonian depocenter northwest of Saginaw Bay. Noses of thick Dundee sections alternate with noses of thinner sections. The areas of alternating thickness trend somewhat northwest to southeast. This pattern may be in part due to early movements along structural trends and subsequent thickening or thinning along these zones.

Thickness of the Dundee interval in the area of study ranges from 200 feet to 400 feet. The thinnest spot occurs in Sheridan Township, Clare County, where the Dundee is only 184 feet thick. The trends in thickness observed are due in a large part to the topography of the surface of the Detroit River Group's surface, and to a lesser extent to the mechanics of marine deposition.

Thinning is observed in Hamilton Township, Clare County, and in Edenville Township, Midland County. The areas of thinning are located within deep structural troughs in the Dundee surface (Plate 1). Some areas of local thickening occur over structurally positive areas in the Dundee. Evidence is observed in Winterfield Township, Clare County, Hay Township in Gladwin County, and Wise Township in Isabella County. Variations in the thickness of the Dundee may be due to any of a number of mechanisms.

Some authors have suggested dolomitization of the Dundee took place at the expense of the interval present, resulting in a decreased thickness (Syrjamacki, 1977; Richey, 1981). If this were the case in the area of study, thin areas should show a strong relationship to areas of intense dolomitization. No

such relationship is observed, therefore, this model is not considered applicable to this area.

Erosion could also create great variability in the thickness of the Dundee interval. Slight differences in lithology could create a difference in resistance to weathering. Preferential erosion would remove the less resistant beds and create thin areas. This process requires exposure of the Dundee at the surface for long periods of time. The resultant pattern of thick and thin areas would reflect the lithologic distribution of the Dundee. No such pattern is observed in the area of study. Furthermore, the contact of the Dundee with the overlying Bell Shale has been shown to be conformable in the central Michigan Basin (Gardner, 1974; Ten Have, 1979). The Dundee was not exposed for long periods of time in the central basin and erosion did not take place on a large scale.

The local areas of variable thickness may also suggest structural inversion has taken place. Structural inversion is the development of inverted relief, whereby anticlines become negative features and synclines become positive features. The mechanisms for inversion can be sediment loading, local tectonic activity along zones of weakness, changes in the depositional or marine environment, or any combination of these processes. Zones of weakness are present in the Precambrian in the Michigan Basin. These faults and fractures have been active intermittantly throughout geologic time. Figure 11 represents the response of rock to changing tectonic forces. In schematic A, forces in one direction create a graben and horst configuration. Subsequent changes in the direction of force may invert the structure as shown in schematic B, resulting in structural inversion. It is possible such forces acted upon the Precambrian and overlying strata in the Michigan Basin. This process may have some correlation in the area of study. Thick zones in the Dundee correlate with present day positive structures and thin zones with present day deep troughs. The thick

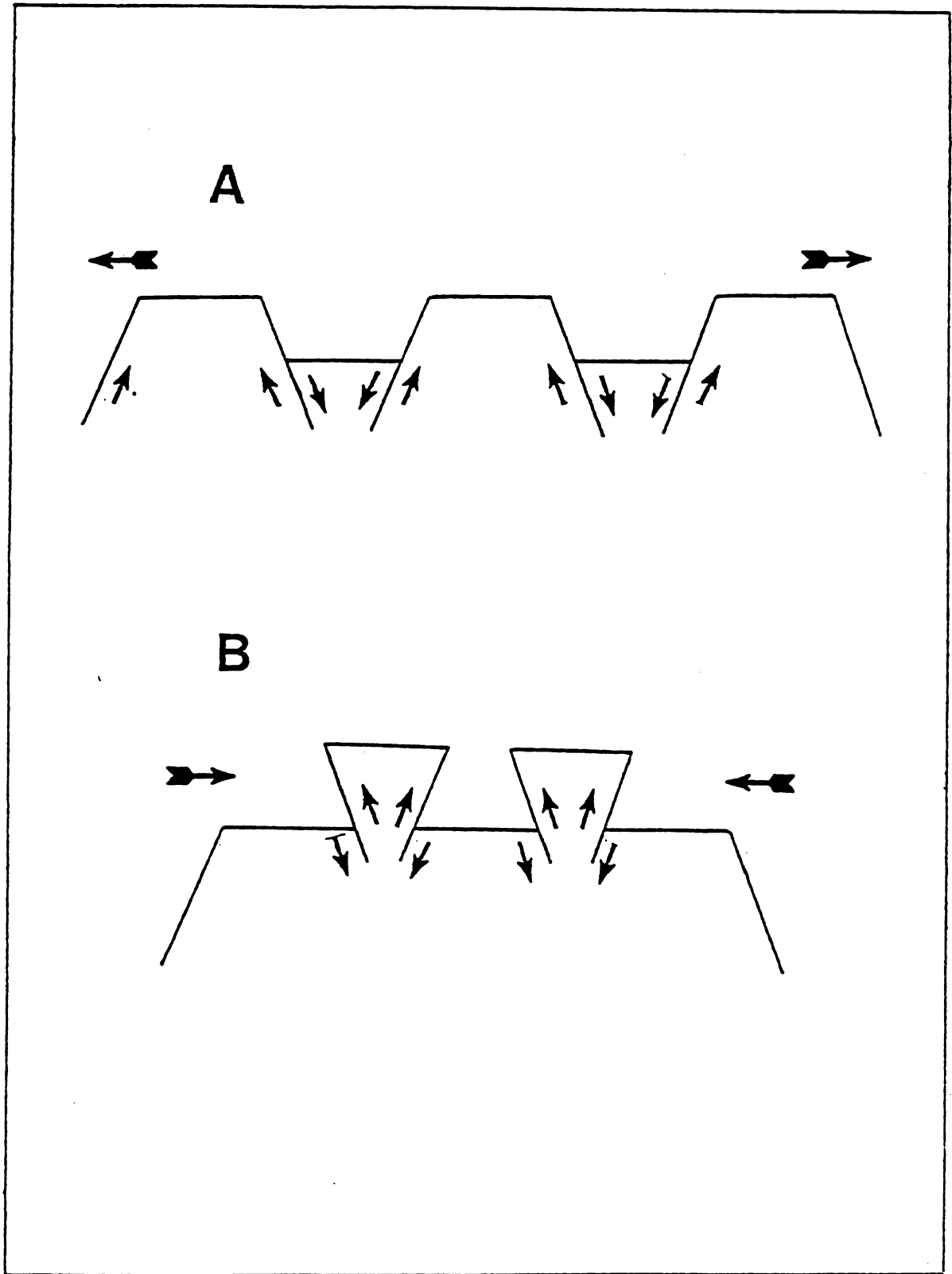


Figure 11. Mechanics of structural inversion.

areas may represent former local depocenters which received greater sediment accumulations. Subsequent structural inversion then created the configuration observed today.

The process which best explains the variable thickness in the Dundee Formation is the process of "reefing". The anomalous areas of thick accumulations may represent reefal buildup. This buildup began on areas that were slightly positive with respect to the surrounding Dundee topography. These positive areas acted to effectively shallow the water depth and promoted more rapid reefal growth than the lower lying, deeper water areas. These deeper water areas would experience slower carbonate deposition. The result is a relative thickening of the positive areas compared to the negative areas. Later structural activity accentuated these slight positive areas and the thick areas associated with them. This hypothesis is supported by the type of carbonates found in the thick areas. The carbonates tend to have a higher porosity and be fossiliferous. Where detailed lithologic descriptions are available, the Dundee in the thick areas would be classified as a bioherm or biostrome deposit. The idea of reefal buildup, and to a minor extent the idea of structural inversion, best explain the present configuration of thickness of the Dundee in the central Michigan Basin.

Detroit River Group

The Detroit River Group unconformably underlies the Dundee Formation in the area of study. For the purpose of subsurface work, the Detroit River Group is divided into three formations: the Lucas Formation, the Amherstburg Formation, and the Sylvania Sandstone (Figure 10).

The uppermost member of the Detroit River Group is the Lucas Formation. Ehlers (1950) defined the Lucas dolomite as a formation "in the upper part of the Detroit River Group of the Middle Devonian Age". In the central Michigan

Basin, the Lucas Formation is composed of dolomites, anhydrites, salts, limestones, and sandstones (Landes, 1951).

The contact between the Dundee and the Lucas Formation is not easily recognized in the subsurface. As discussed earlier, many methods of picking the contact are used in the Michigan Basin (See Methods of Study). The most practical and reliable method in the area of study places the contact at the top of the first anhydrite occurrence.

Several oil and gas zones occur in the Detroit River Group. Two of the most prolific are the Richfield zone and the "sour" zone. The Richfield zone produces sweet crude from the lower Lucas Formation. As in the Dundee, most production is associated with anticlinal structures in the central Michigan Basin. Many wells targeted to the Detroit River Group are located over known or projected Dundee structures in the hope of finding a multiple pay oil well.

The Amherstburg is essentially a brown to black fossiliferous carbonate which is more often limestone than dolomite (Lilienthal, 1978). Many geologists refer to the Amherstburg as the "Black Lime" due to the dark coloration.

The Sylvania Sandstone is the basal formation in the Detroit River Group. The sandstone is fine to medium grained, predominantly well sorted, with minor amounts of silt, chert and carbonate. The formation is present over much of the central basin. In some areas, the Sylvania is an important brine producer.

LITHOLOGY OF THE DUNDEE

The Dundee Formation outcrops in many locations in Michigan. Detailed lithologic and stratigraphic studies have been conducted on these exposures. The Dundee is sometimes broken down into two units: the Dundee Limestone and the Rogers City Limestone.

The Rogers City Limestone is typically a dark colored brownish buff dolomitic limestone or dolomite (Cohee, 1948). The unit shows a persistent massive and uniform limestone character over most of the basin, except where dolomitized in western Michigan. In areas of dolomitization, there is a strong association with anticlinal structures (Knapp, 1947). Ehman (1964) noted that the marginal occurrences of the Rogers City Limestone were lighter in color than the carbonates in the central basin.

The Dundee unit is typically a brown biocalcarenitic wackestone or packstone. Fossil types include brachiopods, corals, stromatoporoids, and crinoidal debris. In much of the basin, it is composed of limestone and dolomite with minor anhydrite beds (Fisher, J. A., 1981). In the extreme west and southwest areas of the basin, the Dundee is almost entirely dolomite (Lilienthal, 1978).

In the area of study, lithologic descriptions of the Dundee were obtained from drilling records, sample descriptions and previous work done on petrology. Detailed petrographic descriptions are, for the most part, restricted to studies conducted on various Dundee oil and gas fields in Michigan. Although these studies provide valuable information, the carbonate sequences they describe are atypical of the regional Dundee lithology and may not be applicable to the basin in general.

In the central Michigan Basin, the Dundee Formation is a fine to medium grained, tan to dark gray, locally dolomitized limestone. Tinklepaugh (1957) classifies the Dundee as a marine limestone that contains fossils including stromatoporoids, brachiopods, and crinoids. Scattered groups of stylolites, many containing a black residue, occur roughly parallel to the bedding. The Dundee in some areas becomes heavily fractured and brecciated (Bloomer, 1969). Bloomer describes the matrix as dark finely crystalline dolomite, with the clast in the breccia being composed of lighter coarser dolomite. Anhydrite nodules and some tabular gypsum have been observed in Dundee cores. A typical well is described lithologically in Appendix II.

A map of the Dundee Formation lithology was constructed for the area of study (Plate 4). Only wells which penetrated the entire thickness of the Dundee were included in the data for mapping. To include wells which only penetrated part of the Dundee would have biased the data toward lithologies more common to the upper Dundee and negated those that occur more commonly in the lower Dundee.

Two methods were used to identify the lithology of the Dundee Formation at each location. The first method utilized drillers' logs and lithologic descriptions to determine the percent dolomite in the Dundee. Relative footages of dolomite and limestone at each location were recorded. An example of a drillers' record is given in Appendix II. In places where the records were suspect, or where lithologic descriptions were vague, surrounding well locations were used to correlate lithologies. The percent dolomite at each of the well locations could be determined by the following formula:

$$\text{Percent Dolomite} = \frac{\text{feet of dolomite in the Dundee interval}}{\text{total thickness of the Dundee interval}} \times 100$$

The second method utilized density and neutron logs to determine the lithology of the Dundee at each location, particularly Schlumberger Compensated Formation Density logs (FDC) and the Compensated Dual Spacing Neutron logs (CNL). This method is used at the Michigan Geological Survey to aid in lithology determinations.

The combination of CNL and FDC curves recorded on the same porosity index scale can be an excellent lithologic indicator on well logs (Figure 12). Where the formation is 100% limestone, the CNL and FDC curves will track or overlay one another. If the formation is 50% limestone and 50% dolomite, the curves will be separated by approximately 3 divisions (9% porosity) on the apparent porosity index scale. When the formation is 100% dolomite, the curves will be separated by approximately 6 divisions (18% porosity) on the apparent porosity index scale (Michigan Geological Survey, 1982).

At some locations, data was not available for one or both of the methods. However, when possible, both methods were used on each well location. Comparison of the values obtained at well sites using both methods correlated well. In some locations, the two methods yielded almost identical dolomite percentages. In instances where the values did not agree well, the value considered to be based on the most reliable data was used.

The map based on these values reflected the relative distribution of limestone and dolomite mineralogies in the Dundee interval. Several trends can be observed on the map.

Areas of highest percent dolomite, with up to 100% dolomite, are located over or adjacent to positive Dundee structures. Examples of this are the Broomfield field, the Freeman-Lincoln field, and others. The strong association of dolomite with structure is anticipated from conclusions reached in previous studies conducted on the dolomitization patterns in the Dundee (Ten Have, 1979;

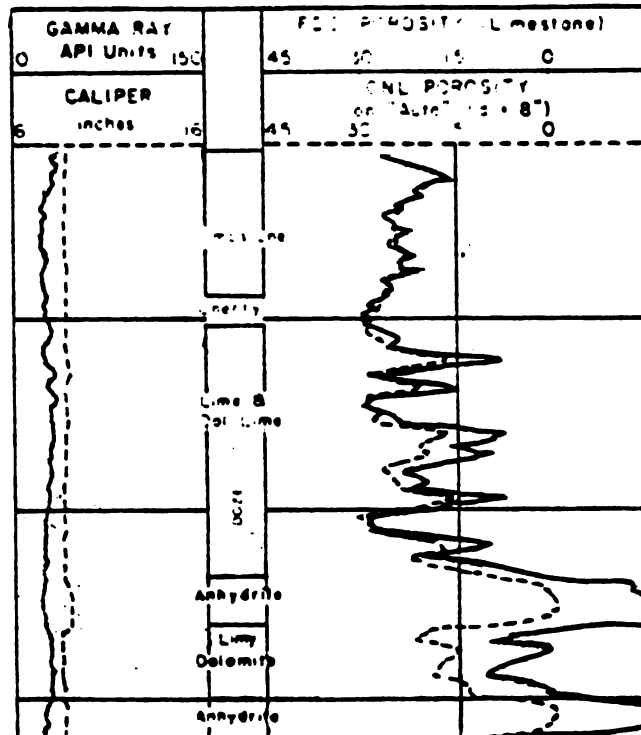


Figure 12. Typical well log and lithology analysis using the FDC-CNL method of track comparison.

Richey, 1981; Hyde, 1979; Jackson, 1958; Tinklepaugh, 1957; and others). Most of the studies have indicated that dolomitization as well as zones of porosity are strongly controlled by fracture and fault systems developed during folding.

Ten Have (1979) studied the lateral and vertical dolomite variation in the Dundee of the West Branch oil field, Ogemaw County. The vertical variation in the dolomite was controlled primarily by porosity. High dolomite occurrence correlates with high porosity zones. He also showed that lateral variation is closely related to the axes of the structure and decreases off structure. This suggests epigenetic dolomite formed along faults, fractures, and porosity zones in the Dundee during or after the structure began forming.

Detailed lithologic mapping on a smaller interval, a 20 foot interval for example, may yield a better location of faults and fractures than can be determined by the use of structure contour or isopach maps. Areas with drastic increases in the dolomite content would be related to faults and fractures. Such a project is beyond the scope of this study.

Not all positive structures are dolomitized in the central Michigan Basin. Some of the producing Dundee fields are of limestone lithologies. The lack of dolomite may be in part due to the lack of an adequately connected system of faults and fractures. Production may be from zones of primary porosity present in the Dundee.

In locations where lithologic descriptions were used, the accuracy of the dolomite percentages were directly related to the accuracy of the drillers' records. A cross check with CNL-FDC values enabled better control of the data.

Data were for the most part grouped near known structures, with few control points off these structures. The problem is twofold. Wells that are located over structures are more likely to test dolomite enriched Dundee

intervals, biasing the data. Secondly, contouring of groups of data points yielded contour patterns which may not reflect the regional dolomite percentage values in the area.

Since a large percent of the hydrocarbon production from carbonates is from dolomitic reservoirs, the location of dolomite occurrence has important exploration value. Previous studies have indicated dolomites generally have higher porosity than limestones. Detailed mapping of the dolomite percent could outline areas of economic interest.

POROSITY DEVELOPMENT

Porosity in any carbonate sequence may be divided into one of two types, primary or secondary. While both occur in the Dundee Formation, most studies have centered on anticlinal structures with well developed secondary porosity (Ten Have, 1979; Richey, 1981; etc.). In the following discussion, the major controls on primary and on secondary porosity development will be outlined and related to the porosity trends observed in the Dundee.

Primary Porosity

"Primary porosity includes pore types which result from depositional processes and which have later been only slightly modified by compaction, pressure solution, simple pore filling cement or by dissolution alteration" (Murray 1960).

Three common types of carbonate sediments exhibit primary porosity: framework sediments, carbonate mud sediments, and sand sediments (Moore, 1979). The textural characteristics of a carbonate sediment controls the resultant primary porosity and permeability. These characteristics include grain size, grain shape, and most importantly, grain orientation and packing. All of these textural properties are in turn controlled by the depositional environment. Each depositional environment has a distinct set of processes which result in sedimentary structures and textures related directly to that environment.

Dunham (1962) classified carbonate rocks according to their "depositional texture". This classification scheme makes a distinction between grain supported sediments and those with grains floating in a matrix of mud (Figure 13). The idea of classification according to depositional texture has

DUNHAM'S CLASSIFICATION ACCORDING TO DEPOSITIONAL TEXTURE

Depositional texture recognizable				Depositional texture not recognizable
Original components not bound together during deposition				
Contains mud (Particles of clay and fine silt size)		Lacks mud		Original components were bound together during deposition... as shown by intergrown, skeletal matter, lamination contrary to gravity, or sediment-flooring cavities that are rooted over by organic or questionably organic matter and are too large to be later added. <i>Boundstone</i>
Mud supported		Grain supported		
Less than 10% grains	More than 10% grains			
<i>Mudstone</i>	<i>Wackestone</i>	<i>Packstone</i>	<i>Grainstone</i>	Subdivide according to classifications designed to bear on physical texture or diagenesis. <i>Cryotalline carbonate</i>

Figure 13. Dunham's classification scheme (1962).

important applications in exploration. The prediction of the occurrence and areal extent of the most porous facies in a region may become possible.

Certain depositional environments create carbonate sequences which are most favorable for primary porosity formation. For example, reef deposits, with the associated steep slopes and clastic reef material have great potential for primary porosity. These framework sediments are originally a rigid or semirigid system with finer sediment filling in between. Incomplete filling and winnowing of the finer sediments by currents often leads to the formation of high primary porosity.

Generalizations concerning relationships of primary porosity can be seen in Figure 14. Each specific depositional environment is depicted, along with the textural response, the bed form response, and the primary porosity response. Classification in this manner allows evaluation of a particular facies based on depositional environment and prediction of the sediments characteristics.

In order to be useful as an exploration tool, the concept of depositional classification requires preservation of at least some of the primary porosity during and after burial. However, primary porosity preservation is the exception rather than the rule. Most porosity is associated with chemical diagenetic processes, not with physical depositional processes (Moore, 1974).

Loss of primary porosity occurs by varied mechanisms: compaction, cementation, pressure solution, and dissolution alteration. These diagenetic environments were outlined by Choquette and Pray (1970). Figure 15 shows that porosity can be destroyed or created as the sediments are subjected to various diagenetic environments.

Schmoker and Halley (1982) suggest preservation of primary porosity occurs more frequently than previously believed. Rather than early cementation destroying primary porosity, the authors suggest that compaction and pressure

Figure 14. Depositional process-product relationship showing primary porosity response to depositional processes (after Moore, 1979).

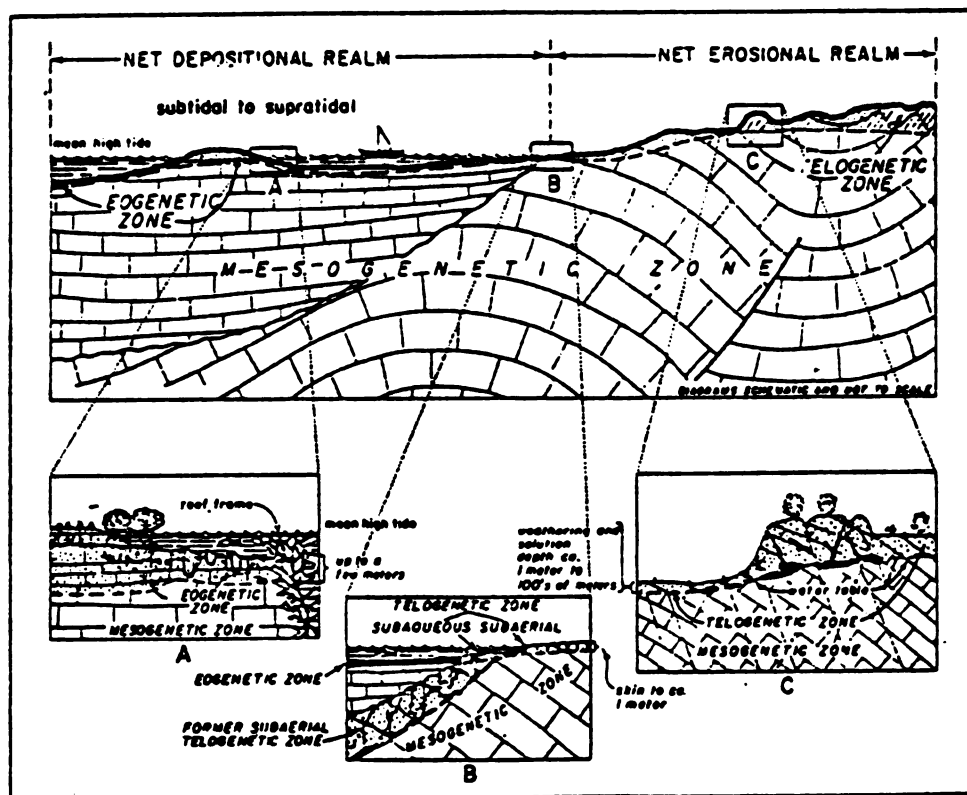
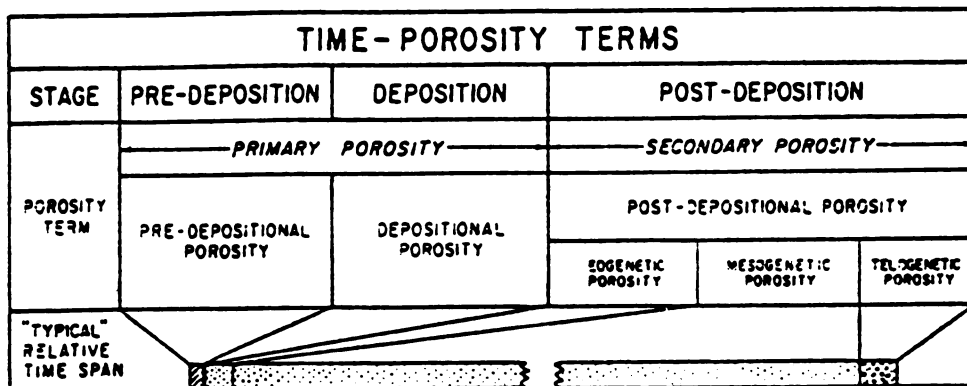


Figure 15. Zones of creation and destruction of porosity in sedimentary carbonates (Choquette and Pray, 1970).

solution much later in the diagenetic history of the sediment destroys the porosity.

The loss of porosity is generally related to depth of burial and to a minor extent to time. The authors conducted the study on a regional level, using macroscopic techniques of sampling and measuring. Their results indicate that primary porosity may be preserved until late in the diagenetic history of the sediment and that it may actually be common. This idea would have many applications to exploration in carbonate sequences if the chance of finding primary porosity is present.

Primary porosity helps control the formation of secondary porosity by providing more porous and permeable horizons. This means that even if the preservation of primary porosity is uncommon, it plays an important part in the formation of secondary porosity required for a favorable carbonate reservoir.

Secondary Porosity

"Secondary porosity is created by the modification of an original carbonate sediment after deposition" (Murray, 1960). After a carbonate sediment is deposited, it may be subjected to a wide range of physical and chemical environments. Characteristics which were important in the original sediment may become negligible or obliterated with time. An entirely different array of processes interact in a complicated fashion and produce the final carbonate sequence. Understanding these processes and their effect is basic to the prediction of the diagenetic environment.

The textural characteristics of the sediment play an important role in the early development of secondary porosity (Sibley, 1980). If primary porosity is present, it may provide an avenue for easier fluid flow and subsequent secondary porosity formation. The presence of porosity in a dolomite reservoir rock is normally attributed to secondary porosity (Chilingar, 1960). The texture is

controlled by the facies of the rock present, i.e., a grainstone vs. a mudstone. Interpretation of the original carbonate texture and fossil content may become difficult if there is a high degree of recrystallization, alteration or leaching during diagenesis (Thomas, 1962).

Certain textures and facies may aid or hinder early diagenetic processes. The presence of carbonate mud, for example, inhibits the formation of submarine cement (Bathurst, 1975). As diagenesis continues, the influence of the original sediment texture declines. Fossil fragments and matrix are both susceptible to removal and replacement.

The alteration of the original sediment normally exhibits fabric selectivity (Bebout, 1975). This means that certain mineralogies and morphologies are preferentially altered. Chemical and mechanical processes create secondary porosity. The mineralogy and texture of the sediment are important in the diagenetic response to these processes (Choquette and Pray, 1970).

General trends in carbonate sequences allow predictions of the diagenetic response of the sediment. Aragonite and magnesium calcite make up the bulk of shallow water carbonate sediments (Choquette and Pray, 1970). The response of these minerals in particular chemical environments have been studied intensely. Aragonite is susceptible to solution in fresh water (Land, 1973) and may dissolve to form secondary moldic porosity.

The response of a mineral to a process relies on two factors: the texture of the sediment and the chemical environment encountered. Textural responses have already been discussed. A grainstone with aragonite fragments may lead to a good reservoir with high porosity and permeability upon solution of the aragonite. A mudstone, however, may yield ineffective and unconnected porosity and permeability.

The chemical environment to which a carbonate is subjected to during diagenesis is a function of the geology. From a simple point of view, three main chemical environments are common: the meteoric zone, the marine zone, and the subsurface zone (Folk, 1974). These environments are shown in Figure 16.

The meteoric environment includes areas of subaerial exposure and intermediate depths below the water table. The pore fluids are normally low in ionic concentration, often to the point of being potable. Many modern meteoric zones have been studied for ground water chemistry and characteristics.

A large degree of cementation is often attributed to this zone. The meteoric zone may represent the most dynamic of the three zones in rates of cementation. The lower Mg^{+2} ion concentration and slow CO_2 degassing rates favor the formation of larger crystal sizes. Sparry calcite is the dominant cement formed (Folk, 1974). The amount, type, and distribution of porosity present in a sediment may undergo a change in the meteoric zone. Solution of unstable sediments, such as aragonite, may create moldic porosity. At the same time, cementation of existing porosity may occur. Both solution and precipitation occur rapidly in the meteoric zone (Land, 1967).

The marine zone is characteristic of the lower intertidal and the subtidal environments. The pore waters encountered in the marine zone are similar to the large reservoir of ocean water in constant contact with the zone. Ionic concentrations reflect that of seawater and are generally high. Aragonite and magnesium calcite are the mineral phases precipitated as cement from marine waters (Folk, 1974).

Cementation does occur in the marine zone, but it is limited and normally occurs only in beachrock and hardground formation (Bathurst, 1975). Most marine sediments are not heavily cemented. Sediments that are buried under the influence of marine waters typically retain the original porosity until later

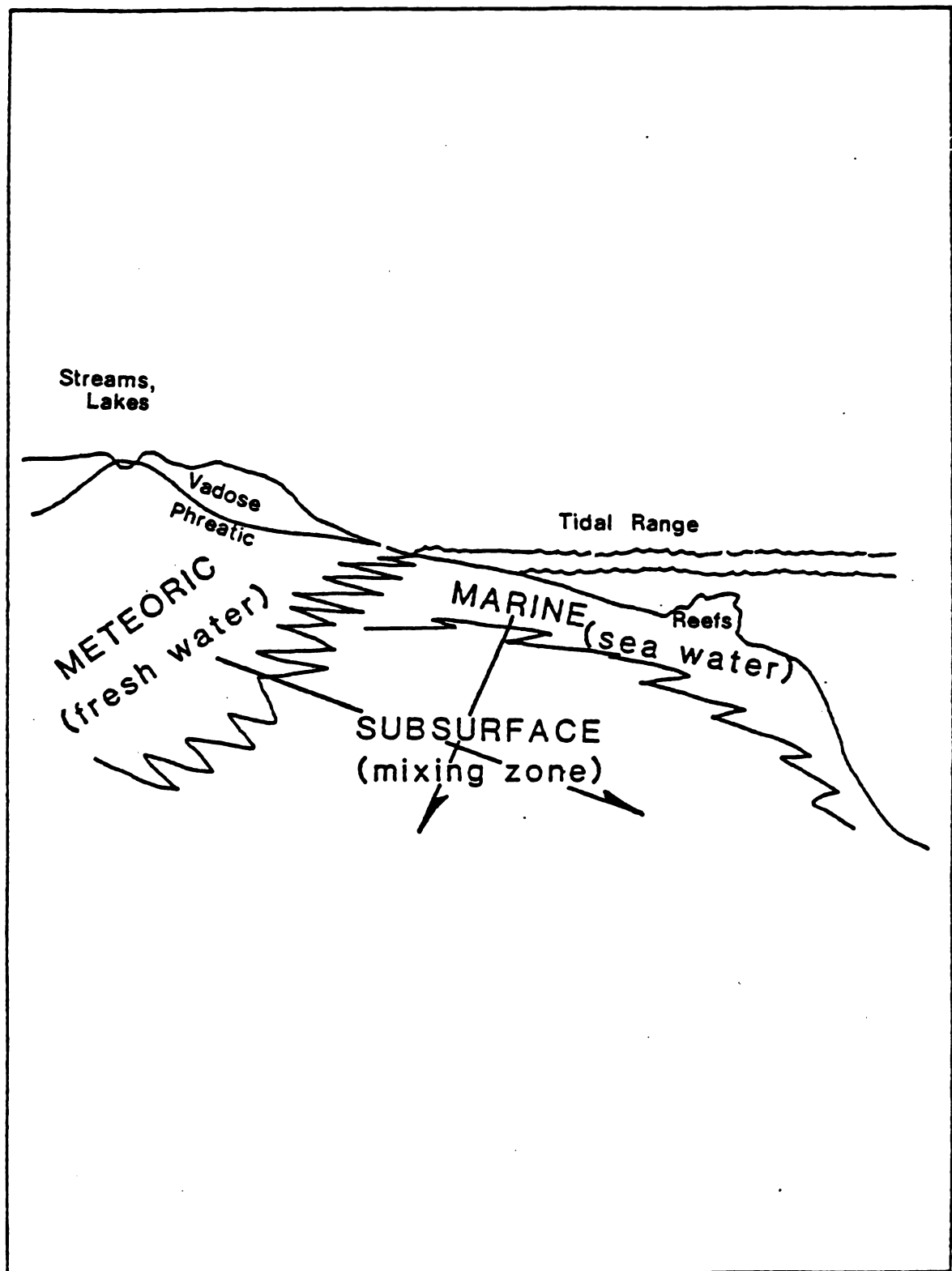


Figure 16. Diagenetic realms and carbonate crystal morphology (Folk, 1974).

diagenesis. Secondary porosity will be developed in the marine sediment if they become exposed to fresh, meteoric water. Unstable mineral phases of aragonite and magnesium calcite will dissolve forming moldic porosity.

The final chemical environment is perhaps the least understood and the most complex, the subsurface zone. In the subsurface zone, sediments are exposed to increasing temperature and pressure. In addition to these changes, the chemistry of the pore fluids may change drastically through the mechanism of leaching, mineral phase changes, ion exchanges, or membrane filtration (Bebout, 1975).

Mechanical compaction, pressure solution and late cementation can also occur in the subsurface zone. The effect of mechanical compaction during burial on porosity is related to the textural characteristics of the sediment. Carbonate sediments may have a porosity of up to 70% at the time of deposition (Choquette and Pray, 1970). Compaction of these sediments with burial can reduce porosity by up to 35% (Sibley, personal communication). The texture of the sediment plays an important part in the response to mechanical compaction. Fine grained sediments lose a significant amount of porosity, primarily during dewatering of the sediment. Grain supported carbonates do not seem to be as affected by compaction, especially if the sediment was previously cemented (Buxton and Sibley, 1980).

Once mechanical compaction brings the sediment grains into contact, further compaction will lead to pressure solution. Pressure solution is "the solution of grains at their contacts while under lithostatic forces" (Bebout, 1977). Fine grained sediments are much more susceptible to pressure solution than coarse grained sediments. It is difficult to observe pressure solution in fine grained samples in the laboratory, therefore most work is conducted on coarser grained samples. Other factors include compaction of the sediment, grain shape,

grain packing, and degree of cementation. Cementation homogenizes the sediments into one unit, of which all parts respond equally to stresses applied. Well cemented sediments resist pressure solution and the formation of stylolites.

If the formation of stylolites occurs, pathways are provided through which carbonate species may migrate into other areas of the rock and reprecipitate. Pressure solution is a porosity reducing process in the subsurface zone. Figure 17 demonstrates that with only a small amount of pressure solution, large amounts of porosity may be destroyed. It becomes obvious that a large initial porosity value is needed if the resultant rock is to have any remaining porosity.

Murray (1960) suggests any porosity remaining after early diagenesis will be lost with further burial by a combination of mechanical and chemical processes. There are mechanisms, however, which may create porosity late in the diagenetic history of the sediment. Land (1975) and Bebout (1975) suggest late secondary porosity formation from brines associated with hydrocarbon generation, late mineral phase changes, and dolomitization. The most important porosity producing process in the Dundee seems to be dolomitization.

Dolomitization and Porosity

Dolomite occurs throughout the Dundee interval in the area of study. The nature and origin of dolomite has been the subject of many discussions. Many theories for the formation of dolomite have been presented, with a select few gaining some degree of acceptance. Only the theories which apply to dolomitization and porosity in the area of study will be discussed. The understanding of dolomite formation and its extent will aid in the prediction of possible reservoirs.

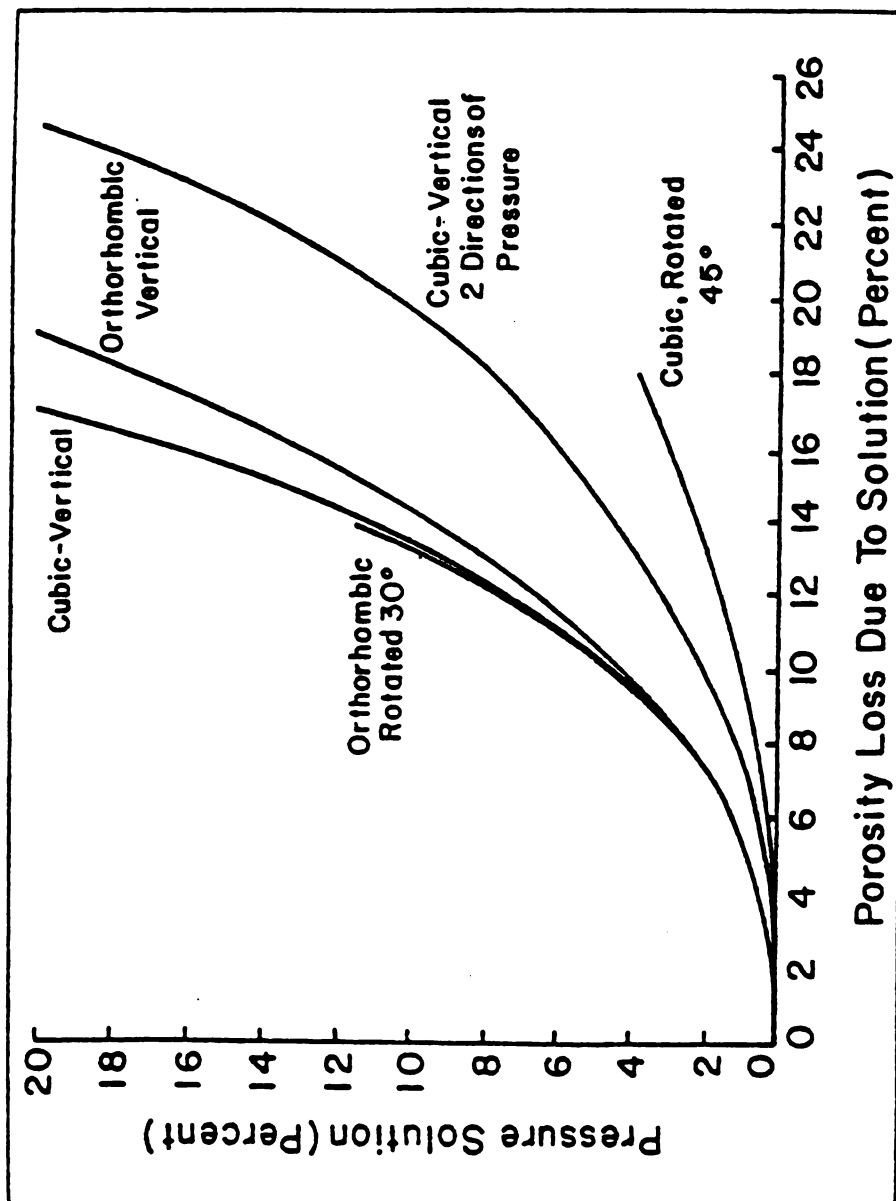


Figure 17. Response of porosity to pressure solution.

There are certain conditions which are necessary for dolomitization to take place (Wilson, 1975);

- 1) a fluid of the correct chemical composition to react with the sediment, capable of dissolving CaCO_3 and releasing Mg,
- 2) a carbonate sediment of sufficient porosity and permeability to act as a host during Mg replacement,
- 3) a long enduring supply of Mg, and
- 4) a hydrodynamic head to force large volumes of water through the sediment.

Dolomite can be either primary or secondary. Primary dolomite is formed by the penecontemporaneous replacement of unconsolidated carbonate sediments (Bathurst, 1975). These types of dolomites are typical of the supratidal environment and are often associated with evaporites, mud cracks, and algal mats. Secondary dolomite forms by the replacement of pre-existing carbonates. These forms of dolomite include diagenetic and epigenetic dolomite. Both of these occur in the Dundee Formation.

Diagenetic dolomite forms relatively early in the history of a sediment. Tinklepaugh (1957) describes this dolomite as "forming lenses or layers with obscure stratification". Porosity in these dolomites is slight and they are generally fine grained. Fossils remain as molds and relict structures are common (Chilingar, 1958).

Epigenetic dolomite is formed later in the sediment history by the alteration of completely lithified limestone. Replacement dolomite shows strong fabric selectivity (Sibley, 1980). A number of factors determine the response of a carbonate to replacement by dolomite. Grain size is an important control. Fine grained sediments are preferentially dolomitized, such as the mud based matrix in a packstone. Composition is also important, aragonite being replaced before low magnesium calcite.

Various mechanisms have been presented for the formation of diagenetic and epigenetic dolomite. Most models are based upon processes observed in Recent carbonate sediments. Some are, however, based on trends observed in ancient carbonate sequences, petrology, and chemistry of the dolomites in these sequences. The present concern with Recent dolomite formation and the difficulty in determining ancient processes is a problem which still lacks a solution. The effects of post burial processes are not yet understood. There may be an important relationship between burial history and dolomite occurrence, hydrocarbon generation, and entrapment (Landes, 1946).

The Evaporative Reflux (Seepage Refluxion) model is based on evaporation of sea water in a restricted environment to produce a Mg-rich brine (Adams and Rhodes, 1960; Deffeyes, et al., 1965; Illing, 1965). Precipitation of gypsum and anhydrite raises the Mg concentration relative to the Ca concentration. The evaporites are deposited on tidal flats in supratidal areas. The solution with the high Mg:Ca ratio moves downward through the carbonate sediment and dolomitization occurs.

A similar model, called the Capillary Concentration model, relies on the simple concentration of the pore fluids by evaporation, the precipitation of gypsum, and the subsequent increase in the Mg:Ca ratio. Recharge of the system occurs during unusually high tides (Carpenter, 1980).

Some studies conducted on the Michigan Basin have proposed dolomitization by Seepage Refluxion (Bloomer, 1969). Dolomite formed by this mechanism would be associated with evaporites in a supratidal environment, which may have existed on the west side of the state in Devonian Dundee time (Gardener, 1974). These dolomites are of limited extent in the basin.

Carbonate sequences exposed to seepage refluxion are generally heavily altered to dolomite. A high percentage of the original sediment is converted to

dolomite, with a much lesser amount remaining as the original material. These dolomites are associated with areas that were once emergent and which had a restricted marine environment.

Mixed-water models have been proposed by Hanshaw (1971), Badiozamani (1973), Folk and Land (1975), and others. The model proposed by Badiozamani, termed the "Dorag" model has gained wide acceptance. The "Schizohaline" model presented by Folk and Land is very similar to the Dorag model. Interaction of a lense of fresh water with an underlying mass of sea water is the basis for these models. The interface between the two water masses is gradational, with a zone of brackish water occurring. Badiozamani (1973) estimated that fresh water mixed with between 5% and 30% sea water yielded a solution undersaturated with respect to calcite and many times supersaturated with respect to dolomite. It is in this zone of mixing that dolomitization occurs. Mixing in of the sea water supplies the necessary Mg.

Fluctuation of this zone of mixing can happen for many reasons: change in the rate of recharge of the fresh water lense, seasonal changes in the level of waters, local evaporation of the fresh water at the surface, and tectonic activity in the area of the sediment. Fluctuation of the zone of mixing allows great thicknesses of the sediment to be exposed to dolomitization. This model is often used to explain regional dolomites that have no associated evaporites.

Dolomitization of the Dundee Formation by the Dorag model would yield regional dolomites associated with areas that were emergent in Dundee time. These emergent areas would allow formation of a fresh water lense and a zone of mixing. Prediction of the areas that were emergent in Dundee time could be accomplished by observing erosion of the Dundee on positive structures.

Emergent areas of the Dundee may have been present on the extreme west and southwest areas of the state. The Dorag model of dolomitization may in

fact have been active in these areas. In the area of study, the Bell Shale and the Dundee have been shown to be conformable. No areas of emergence existed during Devonian Dundee time in the central basin. The Dorag model of dolomitization is not applicable to the area of study.

Shale dewatering has been presented as a mechanism for dolomite formation. Dolomitization of existing limestones by connate water expelled during compaction of shales adjacent to or within the Dundee has been proposed (Illing, 1959, 1965). Metals may be derived from the sediment during dewatering, serving as a source of magnesium from Mg-calcite muds. Illing suggests dolomitization may occur as progressive burial releases water from the shales. This water, he suggests, may be more or less saline than the water in the limestone. This aspect of the model has similarities to the Dorag model, with mixing of waters controlling dolomite formation.

If this model is applied to the area of study, the Bell Shale would typify the source of the water. Connate waters derived from the Bell would move downward into porous horizons of the Dundee and dolomitization would ensue. No major studies have been conducted on the relationship of the Dundee to the Bell Shale in terms of dolomite percent and chemical similarities.

Richey (1980) believes shale dewatering accounts for little of the dolomite present in the Dundee. Less than 5% dolomite is found in the 20 foot interval of the Dundee next to the Bell Shale. A greater iron content occurs in the top 5 feet of the Dundee, which may indicate some of the iron was derived from the Bell (Tinklepaugh, 1957). Ten Have (1979) also found the largest iron content in the top 20 feet of the Dundee. This could mean waters moved downward from the Bell or that the Bell Shale acted as an impermeable horizon to upward moving fluids. Much more detailed work is necessary before a solution can be determined.

In many of the producing Dundee fields, dolomite percentage has been shown to vary greatly over short distances, both vertically and horizontally (Richey, 1980; Ten Have, 1979; Hyde, 1979; Hamrick, 1978; and Jackson, 1958). These studies have suggested structurally controlled dolomitization along fractures and joints which formed epigenetic dolomite. The highest occurrence of dolomite is generally along the axes of the fields and associated with minor cross faults.

Richey (1980) believes the dolomitizing fluids originated in horizons below the Dundee. The non-ferroan character of the dolomite and the increasing dolomitization with depth support this.

Hyde (1979), using core samples, showed dolomite occurrence followed natural porosity zones present in the Dundee. Ten Have (1979) and Hamrick (1979) also suggested dolomitization along the porous zones in the Dundee, somewhat parallel to bedding. Most likely, these zones of dolomite followed previously porous zones rather than creating the porosity through dolomitization as some have suggested.

The resultant epigenetic dolomites are lower in dolomite percentages than those formed by evaporative reflux on the west side of the state. Ten Have (1979) found a maximum of 43% dolomite in his study of the West Branch Field. Averages of 10% to 30% are common in a 20 foot interval of a producing field. Unlike the dolomite on the west side of the state, the epigenetic dolomite controlled by structure lacks lateral continuity (Gardner, 1974).

A close relationship exists between porosity and dolomite occurrence. Of the carbonate hydrocarbon reservoirs in North America, nearly 80% are dolomite mineralogies (Blatt, et al., 1975). The location of porosity and the presence of dolomite are essential for successful exploration in carbonate sequences.

The relative proportion of lime mud and coarser grains in the original sediment affects the porosity development. Lucia (1962) showed sediments remaining as limestones had higher proportions of crinoidal material and less than 35% lime mud. Sediments that were dolomitized, however, had higher proportions of lime mud and less coarser material.

In Devonian sediments that are limestones, the best porosity is in rocks that were originally 5-20% lime mud. These sediments has a supporting framework which resisted compaction, and the lime mud inhibited the formation of cement (Bathurst, 1975). As the amount of lime mud increased over 20%, the porosity decreased, probably through compaction of the sediment. Schmoker and Halley (1982) suggested limestones are less resistant to the effects of compaction, and the associated increase in temperature and pressure with burial.

The relationship between porosity and dolomitized sediments is complex. The majority of carbonate petrologists agree that dolomite formation give rise to porosity providing a solid framework is present which will minimize the effects of compaction (Chilingar, 1972). Weyl (1960) suggested a local source for carbonates involved in dolomite formation. Dolomite formation took place at the expense of nearby dissolved carbonates. The resultant dolomite would occupy a 12-13% smaller volume than the limestone it replaced. The difference in volume is reduced by compaction of the sediment until a solid framework of the dolomite crystals is formed. Dolomites are generally more resistant to the porosity reducing effects of temperature and pressure than limestones. Ten Have (1979) showed that Dundee dolomites have an increased porosity. He did not conclude whether the dolomitization created the porosity or the dolomite formed where there was higher original porosity. He suggested that much of the dolomite formed in zones of initial porosity which provided porous avenues for transport of the fluids.

Bloomer (1969) identified five types of porosity in the Dundee dolomites: 1) angular vugs lined with white dolomite crystals formed by the solution of breccia clasts, 2) solution of clasts without the dolomite lining, 3) vugs formed by solution of fossil fragments, 4) voids formed by the solution of anhydrite nodules, and 5) solution of replacement anhydrite.

Studies have been done which investigate the role of fabric and texture selectivity during dolomitization. It has been shown that a fine grained material is more susceptible to replacement by dolomite than coarser grained material. The porosity and permeability of a dolomitized sediment varies intensely with the degree of dolomitization. Murray (1960) conducted studies on a number of samples of various percent dolomite. He found that for between 0% and 50% dolomite, a slight decrease in porosity occurred. For dolomite percentages between 50% and 80%, the porosity values increased rapidly to a maximum value of 30% porosity at 80% dolomite percent. The pore size and porosity increased with the increasing dolomitization.

Dolomitization is an important mechanism for the formation and preservation of porosity in carbonate sequences. Successful hydrocarbon exploration depends on the location and knowledge of porosity trends. Dolomitization in the Dundee Formation controls the distribution of most of the production. The studies conducted on Michigan oil and gas fields have shown Dundee production to be from predominantly dolomite reservoirs. In the next section, the porosity trends in the Dundee are outlined and related to production in the area of study.

Porosity in the Dundee

Porosity values were calculated for the Dundee interval in the area of study. Porosity data were collected from suites of neutron, sonic, and density logs run by Schlumberger. The readings of the sonic, neutron, and density logs

depend not only on porosity, but also on the formation lithology and the fluid content. These logs respond differently and independently to the different matrix compositions, and to the presence of light oils or gas. A limestone matrix is the basis for all calibration of log runs in the central Michigan Dundee Formation. The combination of these logs can furnish more accurate information than can be supplied by a single log.

The most common neutron logs run by Schlumberger in Michigan are the Sidewall Neutron Porosity log (SNP) and the Compensated Neutron Log (CNL). The Borehole Compensated Sonic log (BHC-Sonic) is the most common sonic log. Crossplots of two porosity logs are convenient to display both porosity and lithology characteristics. These crossplots place the bulk density (ρ_b) or sonic transit time (t) against a correlated porosity value (ϕ_{CNL} or ϕ_{SNP}). Corrections to the porosity value measured on the logs are required for lithology, mud cake thickness, borehole salinity, mud weight, depth of measurement, and borehole temperature. These corrections are accomplished by the use of a Schlumberger nomograph (Figure 18) by one of the two following methods:

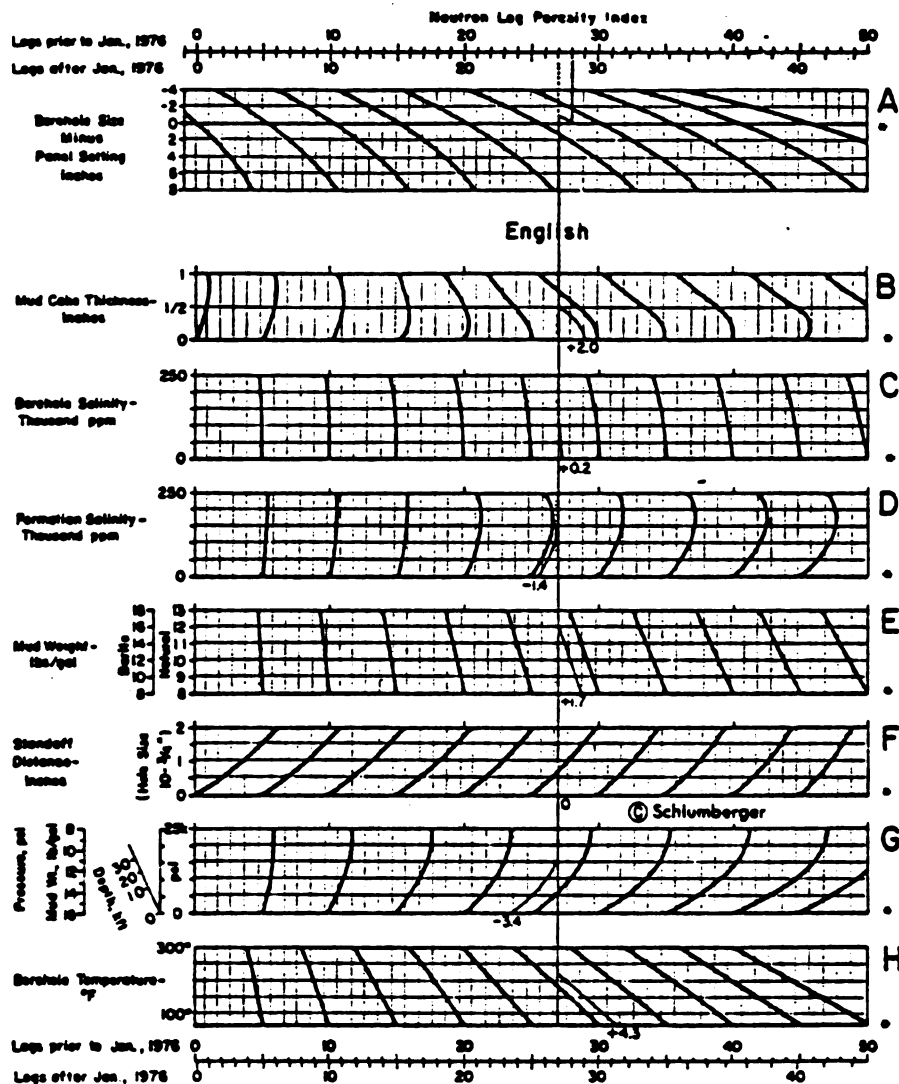
1) Log run with automatic caliper.

"Back out" the caliper correction to find the "chart base" porosity. Go down to Reference (*), Block A, and follow trend lines to "Borehole Size Minus Panel Setting". This value is the chart base porosity. Draw a vertical line through all chart blocks at this value, as the one on Figure 18.

If "Borehole Size Minus Panel Setting" is negative, as in the example, normally assume that it is caused by mud cake. Do not make both borehole size (Block A) and mud cake (Block B) corrections. Beginning at Block B, find corrections for each block and add the algebraic total to the chart base porosity. This is the environmentally corrected CNL porosity.

Schlumberger

DUAL SPACING NEUTRON LOG (CNL*) CORRECTION NOMOGRAPH FOR OPEN HOLE⁵



EXAMPLE 1. Auto. Collar (in red)

GIVEN:

CNL Rdg. 28 p.u.
(corr. for bh)
Mud Wt. 12 lb/gal
 h_m 1/2 in.
 T_m 225°F
Salinity (bh) 100 kppm
Salinity (fm) 150 kppm
Standoff 0
Depth 21,000 ft

SOLUTION:

Enter at 28 p.u.
Go to Index, Block A
Follow trend lines to 1/2 in.
Draw chart-base line at this point (27 p.u.)
Find corrections as shown:
 $3.26 = +2.0 + 0.2 - 1.4 +$
 $1.7 - 3.4 + 4.3 = 3.4$
 $d_m = 27 + 3.4 = 30.4 \text{ p.u.}$

EXAMPLE 2. Separate Collar

GIVEN:

CNL Rdg. 30 p.u.
(corr. for bh)
"BH - Cal." 4 in.
Mud Wt. 9.3 lb/gal
 T_m 175°F
Salinity (bh) 30 kppm
Salinity (fm) 150 kppm
Standoff 0
Depth 12,500 ft

SOLUTION:

Enter at 30 p.u.
Draw chart-base porosity line
through all blocks.
Find corrections as shown
(skip Block B)
 $3.36 = -4.0 + 0 - 1.5 +$
 $0.7 - 0 - 2.5 + 3.3 = -4.0$
 $d_m = 30 - 4.0 = 26 \text{ p.u.}$

*Mark of Schlumberger

Per-14b

Figure 18. Correction nomograph for porosity value adjustment (Schlumberger, 1979).

If "Borehole Size Minus Panel Setting" is positive, normally assume that the hole is washed out and mud cake thickness, if any, is indeterminate. Beginning with Block A, but skipping Block B, find corrections and proceed as above.

2) Log not run with automatic caliper.

Draw a vertical line through all the blocks at the corrected CNL reading.

If "Borehole Size Minus Panel Setting" is positive, begin at Block A and find corrected CNL porosity as above. Do not use both Block A and B.

If "Borehole Size Minus Panel Setting" is negative, begin at Block B and find corrected CNL porosity as above.

The value obtained after the nonograph corrections is an environmentally corrected porosity value. These values can now be used in any one of the proper crossplots.

Neutron-Density crossplots are one type used. Figure 19 is an example of the crossplot. A Compensated Formation Density log (FDC) measures the bulk density of the rock (ρ_b). This is plotted against a corrected porosity value $(\phi_{\text{CNL}})_{\text{cor}}$ or $(\phi_{\text{SNP}})_{\text{cor}}$. The location of the crossplotted points determines the porosity value.

In the example shown on Figure 19, $\rho_b = 2.62$ and $(\phi_{\text{CNL}})_{\text{cor}} = 13.5\%$. This defines point P, lying between the limestone and dolomite curves and falling near a line connecting the 10% porosity gradations on the two curves. Assuming the matrix is limestone and dolomite, by proportioning the distance between the two curves, the point is found to correspond to about 45% dolomite and 55% limestone.

Sonic-Neutron crossplots are another type of plot used (Figure 20). The procedure is the same as for the Neutron-Density crossplot, but sonic transit time (t) is used instead of bulk density.

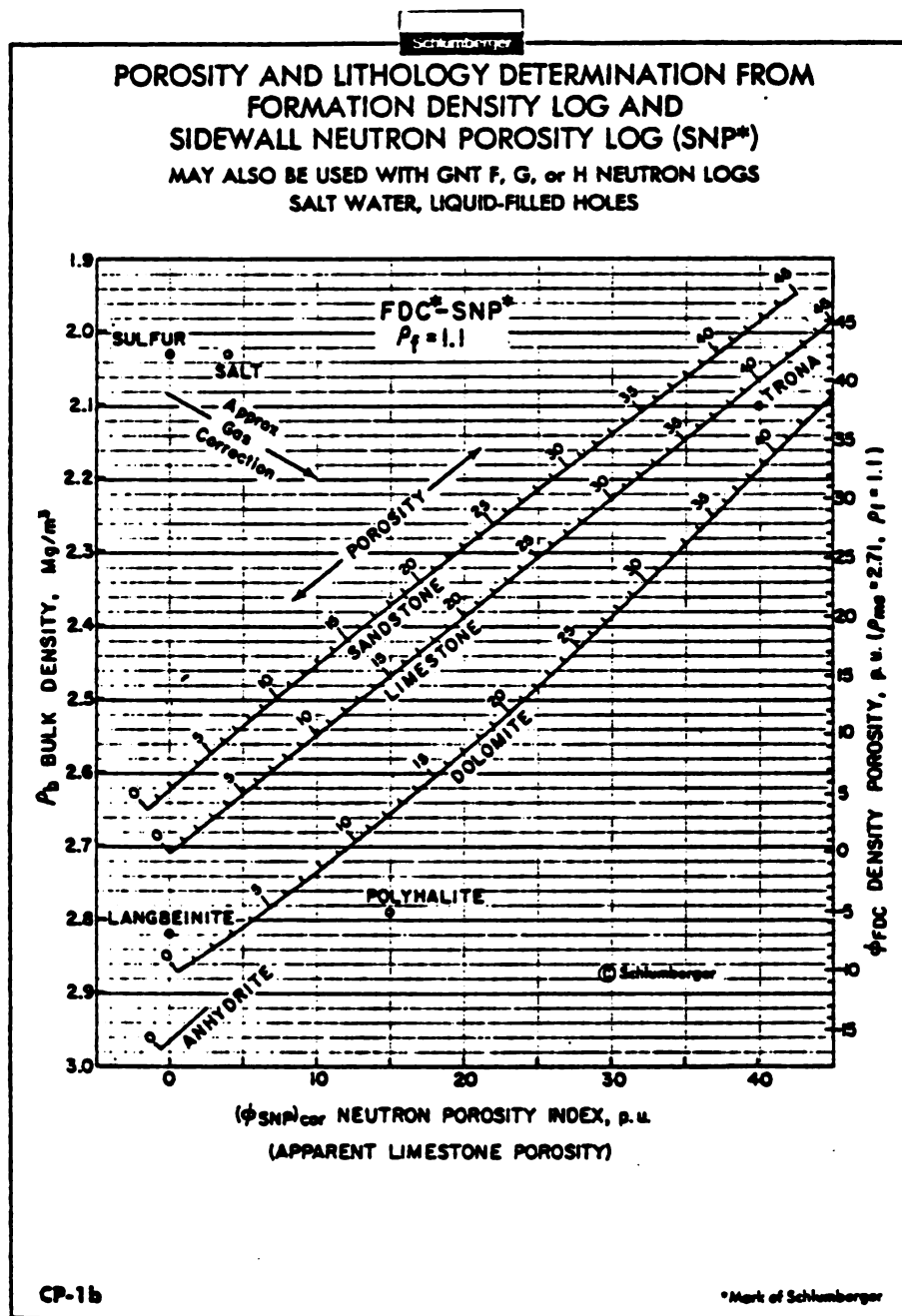


Figure 19. Crossplot of CNL porosity and FDC bulk density for a corrected porosity determination (Schlumberger, 1979).

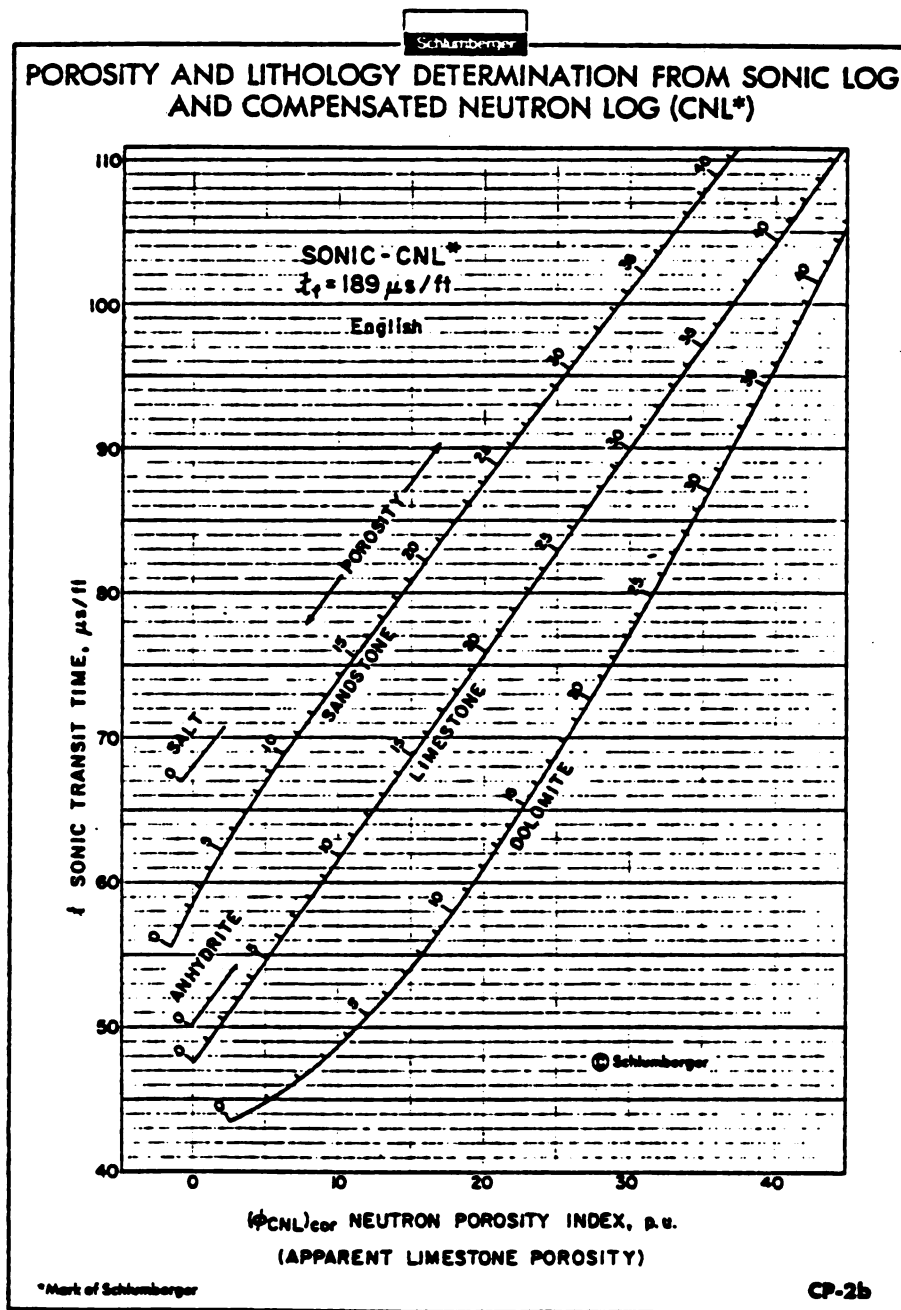


Figure 20. Crossplot of sonic transit time (t) and CNL porosity for a corrected porosity determination (Schlumberger, 1979).

These crossplotted porosity values were placed on a map (Plate 5). Even though the number of wells useful in the crossplot method were limited, enough were available to develop some distinct trends.

Zones of highest average porosity correlated well with areas which were structurally positive. Examples of this are found in the Winterfield and Cranberry Lake fields in Clare County, and along the Porter field in Midland County. The association of high porosity zones with positive structures has been determined in a number of field studies conducted on the Dundee in Michigan.

These positive features are generally also associated with a higher dolomite percentage. Porosity in these zones may be in part due to faulting and fracturing, but it is primarily due to the effects of dolomitization. Murray (1960), and others, have found that increased porosity is related to the degree of dolomitization. The greatest increase in porosity occurs in the range between 50% and 80%. A decrease or redistribution of initial porosity occurs along with the process. This is more than compensated for by the replacement or dissolution of other fragments in the sediment which creates porosity.

The high degree of lateral and vertical dolomite variability suggests that dolomites associated with positive structures are predominantly epigenetic. As one moves off structures in the area, dolomites and limestones which represent a more general regional Dundee Formation are encountered. This has been supported by previous studies as well (Powell, 1959; Jodry, 1954; Tinklepaugh, 1957; Egleston, 1957; Jackson, 1958; Paris, 1977; Dastanpour, 1977; Hamrick, 1978; Ten Have, 1979; and Richey, 1980).

A large area of low porosity occurs in the northern half of Midland County. This area corresponds with the area of low dolomite percentage (Plate 4). This indicates that at least in this location, preservation of primary porosity in the Dundee as a whole is not common. Zones and patches of higher porosity do occur

within the interval, but as a whole, the interval has very low porosity. These more porous zones are the avenues along which dolomitizing fluids would more should the proper structural and chemical environment develop.

In general, a strong correlation exists between porosity, dolomite content, and structure. Recurring associations of porosity with high dolomite percentages and positive structures make these types of conditions most desirable as a prospective hydrocarbon reservoir. The association of these characteristics are the typical fields studied in the previous work in the Michigan Basin.

Other types of reservoir conditions may exist which may be just as important. Detailed mapping of the porosity zones over smaller areas may locate porosity traps not located directly over positive relief structures. Some of the zones of porosity may be primary or early diagenetic, which were present in the rock before folding. The coincidental location near a forming positive structure can create a porosity trap on the flanks of the structure. Dolomitization need not occur in order for porosity to be present. The idea of initial zones of porosity not associated with dolomitization has important uses in exploration of the Dundee. In order to delineate these porous zones and trace them across an area, careful log to log correlation of various zones would be required, which is beyond the scope of this study. Such a study would yield important information regarding the type and distribution of porosity in the Dundee.

Detailed petrographic work needs yet to be conducted on the Dundee interval where it is not associated with structures. Studies of the Dundee off structure could determine regional textural and lithologic characteristics. These regional characteristics in turn control the response of the Dundee to dolomitization. A composite of these studies would form a detailed history of porosity in the Dundee and allow prediction of possible economic reserves.

PRODUCTION IN THE DUNDEE

The Dundee Formation is the most prolific oil producing zone in Michigan. Production was first established in the Muskegon field on the west side of the state. Large scale production in the central Michigan Basin began with the discovery of the Mount Pleasant field in 1928. Since that time, over 200 oil and gas fields have been discovered in Michigan. The Dundee Formation reached maximum production in the late 1940's and has been steadily declining since then.

According to figures published by the Michigan Geological Survey, the Dundee has produced 341,229,283 barrels of oil and 41,527,206 MCF of gas through 1979 (Ann. Stat. Summary 32).

Many of the fields lie in a broad sweeping band that runs from west to east across the central lower peninsula, including the central basin area (Figure 21). Dundee fields, with the exception of a few, occur in a small central portion of the basin. A number of factors may contribute to this pattern.

Ten Have (1979) suggests a correlation between the occurrence of the Bell Shale and production in the Dundee. The Bell Shale is fairly continuous over the basin and pinches out in the southwest corner of the state (Figure 21). Most areas in which the Bell Shale is absent represent shallow depths to the Dundee Formation, usually less than 1300' (Bloomer, 1969). Hydrocarbon loss can occur easily as this shallow depth and large accumulations are rarely found. Even at greater depths, in the absence of the Bell Shale, no cap rock existed, and hydrocarbons were probably lost to upper horizons.

The source of the hydrocarbons may be the organic rich beds in the Dundee or deeper horizons in the stratigraphic column. The dynamic bottom drive



Figure 21. Dundee oil and gas fields in the Michigan Basin.

hydrologic systems prevalent in the Dundee fields suggests that the hydrocarbons or the hydrocarbon precursors were moved upward into porous zones of the Dundee in much the same way as the hydrothermal brines moves upward.

The movement of brines and hydrocarbons into the Dundee determines the regional extent of production. A study of the oil field waters and hydrocarbon characteristics may determine a correlation between the chemical environment and the occurrence of oil and gas. Specific chemical environments may be found to occur only in the central Michigan Basin which limit the development and movement of hydrocarbons into the Dundee. These chemical environments will not only depend on the Dundee, but on deeper horizons as well.

Prouty (personal communication) has suggested brines present in the Dundee originate in the Prairie du Chien Group. These upwelling Prairie du Chien brines may control the location of hydrocarbon occurrence. A detailed study of the central Michigan Basin crudes and oil field waters could yield data for predictions of favorable conditions for hydrocarbon accumulation.

The crude present in the Dundee is generally high gravity and paraffin based. Gravities range from 35° API to 45° API and average around 40° API (Newcombe, 1933). Variation in the sulfur content occurs, typically increasing downdip, as does the API gravity of the oil.

The Dundee crudes are found in two major types of traps. Bell, Witherspoon, and Hautau (1956) categorized the type of traps on the basis of the structure, the location, and the type of porosity in the pay section.

One type is anticlinal fields with localized sheet porosity. This sheet porosity may occur on several zones, but is normally best developed near the top of the pay. In several other fields, almost vertical lenses of well developed secondary porosity exist. The porosity development and hydrocarbon accumulation are controlled by a complex fracture porosity system, such as in

the Deep River field in Arenac County. Most of the fields have efficient bottom water drives and show high potential. Both of these trap types are found in the Dundee in the area of study.

RECENT ACTIVITY

Dundee exploration has been primarily limited to development of known structures. Of the wells drilled in Michigan, 7% are targeted to the Dundee. In the area of study, about 6% of the permits issued are for wells targeted to the Dundee. Permit locations have been issued for a number of well sites, but not all of these locations will actually be drilled. Permitting patterns can help to identify the areas of interest.

In a recent State of Michigan oil and gas lease sale, tracts of land were offered in Clare County. Bidding on the parcels ranged from the minimum of \$4 per acre to \$220 per acre. The highest bids were for tracts close to known producing oil fields. Several tracts within or adjacent to the Headquarters and Skeels fields in Clare County brought bids of over \$150 per acre. Both of these fields have more than one pay horizon, including the Dundee and Richfield.

Dundee discoveries have been limited in the past few years. In 1979, Don Yohe Enterprises made a Dundee pool discovery, the Lake Isabella Corporation #1-9, in the Broomfield field. The well was good for an initial production of 15 BOPD and 15 BWPD. Production is from approximately a 3 foot section of dolomite at a depth of 3752 feet. Also in 1979, the Chase Oil Company discovered a Dundee pay with the Wonsey #1-24 in Rolland Township, Isabella County. Initial production was 25 BOPD and 25 BWPD from 6 feet of dolomite. These two discoveries are the latest in the area of study.

Drilling activity in the four county area has concentrated on development of the two new Dundee pools and extensions of existing pools. The Dundee completions for 1981 and the first quarter of 1982 are given in Appendix III.

Only one well, the Muskegon Development Company Pohl #1-36 was classified as exploratory, with all other Dundee wells classified as development.

The most active area is in Isabella County. The Broomfield Dundee discovery kicked off a series of wells in the area. In all, 7 wells were completed in 1981, and 9 have been completed so far in 1982. Of these 16 wells, 12 have produced Dundee oil and 4 have been dry. The combined production in the new Broomfield field is about 300 BOPD.

Other existing fields in Isabella County experienced continued development, notably the Rolland field. This field had 4 development wells drilled during 1981, with 3 finding oil. Development wells were also completed in the Vernon, Leaton, and Mount Pleasant fields.

Clare County did not have any wells completed in the Dundee Formation during 1981. A number of wells were completed to deeper horizons and will be discussed later. Drilling activity was also low in Midland County, centering on the Porter field.

Development drilling in Gladwin County centered on the North and South Buckeye fields. The Wiser Oil Company drilled all of the wells in these fields during 1981 and 1982. In the South Buckeye field, 4 wells were completed for oil in the Dundee, and one oil producer was completed in the North Buckeye field. Horizon Oil and Gas struck oil in the Beaverton field with the Cingano #1-36.

In all, 23 wells were drilled to the Dundee during 1981 in the area of study. In the first 5 months of 1982, 11 wells were drilled to the Dundee. Of these 34 wells, 25 have produced oil for a success ration of 73.5%. The Dundee well depths range from 3600 feet to about 3800 feet.

Average production from these Dundee wells is about 25 BOPD. The Dundee Formation is nonprorated in Michigan, with no limit placed on the

maximum daily production. As of August 1, 1982, oil produced from the Dundee yielded \$31 per barrel.

Figures published recently outlined the cost of drilling and completing a Dundee well in the central Michigan Basin during 1981. Drilling a 3900' well costs an average of \$160,875, and completion costs an additional \$151,875, for a total cost of \$312,750 per well. On a per foot basis, drilling and completion in the Dundee costs about \$80.19 per foot. These costs have increased drastically in the last few years. The values given above represent a 37% increase in drilling costs and a 14% increase in completion costs of 1979 prices (Oil and Gas News, 1982).

Drilling activity to other horizons continued in the area of study. A Prairie du Chien test, the Hunt Winterfield Unit A-1, struck gas in commercial quantities in Clare County. Other deep tests to the Prairie du Chien have proven dry, and interest in the horizon is dwindling in the area of study. To the west, activity in the Prairie Du Chien is somewhat more stable.

Many of the Richfield development wells drilled during 1981 were located over Dundee structures. A common practice of locating deeper tests over known Dundee structures has had great success in the basin. The possibility of striking oil may exist in more than one horizon. Most of the Richfield wells were confined to development. A discovery in the Richfield occurred in the Leaton field in Isabella County.

The Traverse Lime and the Berea continued to be targets in the area, with 5 wells to the Traverse and 7 to the Berea. Two Berea discoveries occurred in 1981, the Burgess Traverso #1, and the Union Mary Narmore #46, both in Midland County.

CONCLUSIONS

From the maps prepared and from data obtained from various sources, certain conclusions may be made concerning the Middle Devonian Dundee in the central Michigan Basin.

Distinct structural trends exist in the central basin. A strong northwest-southeast lineament is observed, with a weaker northeast-southwest lineament. Configuration of these structures is controlled by vertical tectonics. The Precambrian rock surface is believed to be heavily faulted and fractured, with relief created by the relative vertical movement of adjacent blocks. The faulting observed in the Canadian Shield to the north may continue into the Michigan Basin and control the structural trends in the central basin.

These structures occur en echelon and create oil field traps by folding and crossfolding of the overlying strata. Two types of Dundee fields are commonly created in the area of study: circular fields and linear, somewhat arcuate fields. Both of these field types are normally asymmetrical

The Bell Shale thickens to the northeast in the central basin. This thickening corresponds to the position of the Devonian depocenter northwest of Saginaw Bay. The Bell Shale is a transgressive shale which onlapped the Dundee surface from the east and northeast. A source for the shale would also be to the east or northeast.

The isopach map of the Bell (Plate 2) shows some areas of minor thinning or thickening in subparallel trends to the Dundee structures. This suggests that the surface of the Dundee had at least some relief as the Bell was being deposited. A gently undulating submarine surface may have been present at the close of Dundee time.

Local areas of variable thickness are also observed in the Dundee interval (Plate 3). A variety of mechanisms may control the thickness of the Dundee. The configuration of the Detroit River surface created areas more favorable to carbonate buildup. These slightly positive Detroit River structures shallowed the water and effectively promoted reef growth. Carbonate buildup occurs more rapidly on these areas relative to the deeper water areas. This process of "reefing" best explains the location of thick Dundee intervals on the top of structural highs.

Later structural activity can accentuate the positive structures. Studies conducted on the central Michigan Basin suggests a major period of deformation occurred in Pre-Marshall Mississippian time.

The Dundee in the area of study is typically a brown to gray biocalcarenitic wackestone or packstone. Fossil types include corals, brachiopods, stromatoporoids, and crinoidal debris. Scattered groups of stylolites are found, many containing a black residue, and they occur roughly parallel to bedding. In some areas the Dundee becomes heavily brecciated and fractured.

The Dundee is locally dolomitized in the basin, and distribution of the dolomite follows distinct trends. The highest percent dolomite in the Dundee interval is typically over or directly adjacent to the positive structure. The wide variation in the dolomite percentages over these structures indicates epigenetic dolomite. This dolomite is strongly associated with the structure, usually decreasing rapidly off structure. Epigenetic dolomitization occurs along faults, fractures, and porous zones within the Dundee.

These porous zones in the Dundee may be a primary porosity zone in the carbonate or porosity formed during an earlier diagenetic process. When dolomitization does occur, these porous horizons are preferentially dolomitized. This creates the strong association of dolomite with porosity zones.

Dolomite can form in the Dundee without an associated structure. Dolomite that is not associated with a positive structure may be an early diagenetic dolomite. This diagenetic dolomite forms lenses or layers with obscure stratification. Porosity in these dolomites is generally slight and they are fine grained. Location of these diagenetic dolomites can be off structure or over structure, since they were formed before the folding of the strata.

Dolomite formation in the area of study proceeded by one of three mechanisms. The dolomite associated with structures, epigenetic dolomite, formed by fluids moving through the rock along fractures and faults, and porous zones as stated earlier. These types of dolomites are associated with much of the Dundee production in Michigan.

Diagenetic dolomite was formed much earlier in the history of the Dundee strata. These patches of dolomite are controlled by both primary porosity and textural characteristics.

Shale dewatering, to a minor extent, may be responsible for a small percentage of the dolomite formed in the Dundee. Dolomite formed in this way is normally confined to the upper horizons of the Dundee. More detailed petrographic and geochemical work is needed to determine the importance of this mechanism.

Porosity and increasing dolomite percentages in the Dundee follows many of the same trends. Dolomitization of a carbonate creates porosity when the rock is altered to greater than 50% dolomite. This trend is observed in the central basin, with areas of greatest porosity often corresponding to areas of high dolomite percent and structure. This trend has been outlined in a number of previous studies of carbonate sequences.

Dolomites not located over structures are representative of the regional dolomites in the Dundee. These dolomites are typically low in porosity and have

a lower percent dolomite content. The low porosity values normally obtained for these regional dolomites suggest that porosity is not well preserved in the Dundee. Northern Midland County is an example of an area of regional diagenetic dolomite.

While it is true that the regional dolomites do not have as high an overall porosity value as epigenetic dolomites, porosity zones can exist within the interval. Diagenetic dolomites that have had later structural activity may create hydrocarbon traps.

The best reservoirs are positive structures, faulted and fractured, with associated high dolomitization and increased porosity. Cranberry Lake and Winterfield fields are good examples of this type. Dolomite distribution in these fields is strongly controlled by structure and production will be from these horizons.

Porosity which is not related to structure, formed prior to the folding, may create traps off structures or on the flanks of structures. This concept has interesting applications in the central basin. Positive structures which have been tested on the axis and have proven nonproductive may in fact produce from diagenetic porosity traps on the flanks.

Production from the Dundee interval will continue exploration interest in the area. While it is believed few large fields remain to be discovered, many small fields likely await discovery. The lower cost of Dundee wells and the shallower drilling depth make Dundee wells a way to establish regular production in the area. The drilling of development wells and the deeper drilling of known structures will dominate the Dundee exploration programs in the Michigan Basin.

Another interest will lie in the exploration of older fields and previous tests which were considered noncommercial. Advances in recovery techniques, and knowledge of the productions trends, may create new interest in horizons

once thought nonproductive. Many of the older Dundee tests drilled only a few feet into the formation and stopped after production was not obtained at the Dundee-Bell contact. These areas represent locations in which deeper testing may find hydrocarbons.

SUGGESTIONS FOR FURTHER STUDY

Information is far from complete concerning the Middle Devonian formation in the central basin. In order to clarify the relationships that exist between dolomitization, porosity, structure, lithology, and production the following suggestions are made:

1. A study of the Bell Shale to determine the chemical, structural, and physical relationship to the Dundee. The relationship of the Bell shale to production in the Dundee may be determined, as well as the relationship of dolomite percent in the Dundee.
2. A detailed petrographic study of the Dundee Formation, primarily the intervals present off structure. This may yield a typical regional dolomite and aid in the exploration for traps not associated with epigenetic dolomites on structure.
3. A study of the oil fields brines and hydrocarbons may allow the determination of the source of the fluids and oils. This would shed light on the controls and mechanisms of dolomite formation.
4. Detailed mapping of the porosity zones present in the Dundee interval. These patchy, noncontinuous zones are related to initial porosity and porosity developed much later in the diagenetic history. Mapping of the units on cross-sections may determine porosity traps off structure.

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APPENDIX I

20 WATERFIELD	5 SUMMERFIELD	4 FROST	3 FRANKLIN	2 SHERMAN	1W BUTMAN	1E CLEMENT	2 BOURRET
19 REDDING	GREENWOOD	HAYES	HAMILTON	SAGE	GLADWIN	SECOR	SHERIDAN
18 FREE-MAN	CLARE LINCOLN	MATTON	ART-MUR	GLADWIN	GROUT	BUCKEYE	GRIM
17 GARFIELD	SURREY	GRANT	SHERIDAN	DEWERTON	TOBACCO	BILLINGS	BENTLEY
16 COLDWATER	GILMORE	VEP-NON	WISE	WARREN	EDENVILLE	HOPE	MILLS
15 SHERMAN	NOTTAWA	ISABELLA	DENVER	GENEVA	JEROME	LINCOLN	LARKIN
14 BROOKFIELD	MT. PLEASANT DEERFIELD	UNION	CHIPPEWA	GREENDALE	LEE	HOMER	MIDLAND
13 ROLLAND	FREMONT	LINCOLN	COE	JASPER	PORTER	MOUNT MALEY	INGERSOLL

Figure 22. Index map of township names and locations.

Appendix I. Locations of key wells used in study.

Township/ Range	Section	Location	Operation	Farm	Well Number	Permit Number	Elev. Ref.	Top Bell	Top Dundee	Top D.R.
13N 1W	10	NESESW	Union	Narmore	46	32513	681	3330	3379	
	15	S½NENE	Pure	Narmore	44	24067	683	3332	3380	
	21	CNENE	Pure	Emery	1	26793	695	3300	3364	3702
	27	CNENE	Tope	Williams	1-BDW	33025	687	3344	3398	3708
13N 4W	22	NENENE	McClure	Childs	1-22	29916	810	3574	3620	
	28	NENESE	McClure	Recker	1-28	30208	831	3533	3579	
	30	SESENW	McClure	Bigelow	1-30	30404	874	3586	3631	
14N 5W	17	SWNENE	Dow	Causer	1	23905	888	3600	3650	3864
14N 6W	4	CWSWSE	Trendwell	McClintic	1-4	34481	956	3624	3669	
	8	SENE	Yohe	McNeel	1-8	34425	1107	3770	3816	
	10	SWNWSW	Hunt	Lk. Isabella	1-10A	35068	933	3588	3632	
	16	SENE	Dart	Badgley	1-16	33770	1000	3669	3719	
	25	SWNWNW	Dow	Pendell	1	24206	994	3674	3722	3922
15N 2W	4	NENESW	McClure	Clarke	2-4	31192	719	3640	3706	

Appendix I (Continued).

Township/ Range	Section	Location	Operation	Farm	Well Number	Permit Number	Elev. Ref.	Top Bell	Top Dundee	Top D.R.
15N 2W	15	SESWSE	Consumers	Middleton	1	30457	691	3655	3728	3950
	29	NESESW	Glavin	McClintic	1	19542	707	3575	3655	3686
	33	SESENW	Glavin	Henry	1	19098	696	3520	3596	3830
15N 3W	19	SESWSW	Dart	Wezensky	1-19	35206	759	3552	3609	3861
15N 4W	1	NWSWNW	Apollo	McGuire	1-1	35380	791	3610	3668	3918
	1	NWNWNW	Tope	Tope	A-2	35303	786	3606	3665	3912
	2	NWSESE	Tope	Pappas	1	34960	793	3613	3670	3896
	10	SWNWSE	Merril	Sheahan	1	31621	892	3795	3850	
16N 1W	5	E½NWNW	Yohe	Bower	1	34575	725	3718	3782	4060
	5	W½NWNW	Yohe	Bower	3-5	35237	723	3716	3783	4054
	6	CNENE	Muskegon	Staley	1-6	35338	721	3722	3792	4063
16N 2W	13	SENE	Wicklund	Neal	1	22902	704	3750	3826	4081
16N 3W	17	CNWSE	Quadro	Paisley	1-B	34572	799	3588	3663	3931
	21	SWSWSW	Citles	McNerney	3	19693	770	3602	3648	3930

Appendix I (Continued).

Township/ Range	Section	Location	Operation	Farm	Well Number	Permit Number	Elev. Ref.	Top Bell	Top Dundee	Top D.R.
16N 4W	24	NWSESW	Pure	Stough	1-24	35607	804	3680	3736	3998
	26	SWSESW	Neyer	McGuire	1-26	35091	822	3655	3722	3976
	26	SESENW	Rayburn	House	1	20801	817	3645	3719	3970
	35	NWSESE	Tope	McGuire	2	33262	793	3616	3674	3921
	36	NWSWSW	MOCO	McGuire	1	27405	785	3602	3659	3900
16N 6W	4	SWSESW	Merrill	Scott	1-4	33998	1126	3931	3985	
	7	NENENW	NADCO	Carey	1	27193	1078	3884	3940	4099
	16	NENENW	Merrill	Yats	1	31027	1074	3854	3906	
17N 1W	30	SESENE	MI Petro	Killian	1-30	35200	734	3749	3816	4088
	31	CSESE	Hobson	Pointek	1-31	35284	732	3755	3822	4058
17N 2W	11	NWNWSE	Roberts	Welker	1	24333	734	3777	3842	4168
	18	SESWE	Peake	State	C-1	24165	756	3787	3850	
17N 3W	8	NWNWSW	Dart	Harrington	1-8	32546	939	3923	3984	4168
17N 4W	6	SWSENE	Atha	McKay	1	21102	960	3828	3888	4146

Appendix I (Continued).

Township/ Range	Section	Location	Operation	Farm	Well Number	Permit Number	Elev. Ref.	Top Bell	Top Dundee	Top D.R.
17N 4W	7	NWNWNE	Dart	Gallagher	1-7	33097	993	3855	3914	4175
	7	NENENE	JEM	Weingartz	1-7	34611	1004	3860	3919	4176
	36	SWNENE	Mall	Johson	1	31106	824	3712	3772	
17N 6W	34	SWNW	Dome	Brandt	1-34	34790	1121	3946	4003	4232
18N 1W	10	CNENW	Sun	Buckey-4	7	31979	772	3503	3566	3900
	11	CSESW	Wiser	Brenner	1-11	34674	764	3482	3546	
	14	NWNE	Wiser	Buckeye	8-6	32780	753	3480	3548	
	35	CSWSE	Wiser	Nash	1	33846	733	3475	3540	
18N 2W	4	NENESE	Sun	Mills	1	20714	850	3758	3818	4103
	10	NESESE	Sun	Cameron	3	20346	844	3715	3774	4083
	11	NESWSW	Sun	Cameron	B-1	20407	824	3688	3750	4081
	14	NENWNW	Sun	Ogg	1	20456	837	3704	3764	4077
	15	NENENE	Sun	Ogg	C-1	20308	839	3697	3759	4065
18N 3W	5	NENENW	Trico	Emery	1	30039	983	4012	4076	4236

Appendix I (Continued).

Township/ Range	Section	Location	Operation	Farm	Well Number	Permit Number	Elev. Ref.	Top Bell	Top Dundee	Top D.R.
18N 3W	8	S½SWSW	American	Cornwell	1	8029	905	4015	4086	4450
	19	SWNW	Sibley	Cornwell	1	24821	892	3995	4061	
	22	NWNWNW	Stewart	Shull	1	19257	890	3945	4013	4269
18N 5W	1	SESENE	Harvey	Kirkpat	1	20618	1275	4140	4201	4590
	12	NESWSW	Dart	Audrey	1-12	32930	1237	4084	4143	4432
	18	SESENE	Dart	Frackelton	1-18	33526	1129	3917	3973	4254
	20	SENWSE	Dart	Frackelton	1-20	32858	1144	3941	3998	4257
19N 1W	22	NWNWNW	Tribal	Graver	1-22	29065	804	3677	3743	4065
19N 2W	1	S½SESE	Hill	White	1	28835	853	3825	3892	4186
	13	SWNWE	Tribal	Gertz	1-13	29097	863	3800	3863	4160
19N 3W	5	NWSWSW	Sun	Iutzi	1	17382	1134	3900	3962	4239
	6	SENESE	Sun	Hamilton	12-3	34331	1162	3920	3984	4262
	6	NWSWSE	Sun	Iutzi	B-2	19266	1141	3899	3965	4235
	7	SENESE	Sun	Hamilton	18-3	34330	1092	3874	3936	4204

Appendix I (Continued).

Township/ Range	Section	Location	Operation	Farm	Well Number	Permit Number	Elev. Ref.	Top Bell	Top Dundee	Top D.R.
19N 3W	25	NWNESW	Reef	Shea	1-25	30563	944	3757	3818	4103
19N 5W	3	SESESE	Benedum	Corleco	1	27390	1153	3946	4003	
	35	SWSWNE	Wood	Dicks	1-35	34326	1239	4137	4195	4377
19N 6W	1	CNENE	Muskegon	Redding	1-1	32461	1107	3755	3812	4180
	21	SWNWSE	Ellis	Redding	1	26649	1053	3808	3860	
20N 1W	11	NESESE	Bell	Hilts	1	17288	846	3495	3563	3884
20N 3W	3	NNWSE	Pure	Thompson	1	9590	1195	3935	4013	4280
	3	NSESW	Pure	Trubell	4	18880	1149	3867	3951	4279
	4	SSWSW	Sun	State	A-1	7339	1163	3945	4008	4283
	10	NNENW	Farmers	Heirs	1	18710	1164	3914	3970	4323
	10	NNESE	Farmers	Stafford	2	18940	1147	3917	3948	4286
	25	CNSESE	Rayburn	Townsend	1	19209	1034	3790	3850	4115
	25	CNNESE	Rayburn	Townsend	2	19277	1036	3735	3855	4127
	36	CNSESW	Farmers	Wallace	2	21884	994	3766	3826	4094

Appendix I (Continued).

Township/ Range	Section	Location	Operation	Farm	Well Number	Permit Number	Elev. Ref.	Top Bell	Top Dundee	Top D.R.
20N 4W	21	SWSWNW	Sun	Yake	1	24669	1219	3972	4032	4328
	35	NWSESE	Sun	Coskey	B-2	18923	1190	3930	3982	4370
20N 5W	7	NWNWNW	Hunt	Summerfield	2-7	34698	1137	3736	3792	4080
	8	NESWSW	Sun	Summerfield	A-2	25290	1104	3685	3742	4040
	17	NENWNE	Sun	Summerfield	B-2	25475	1108	3696	3753	4050
20N 6W	2	SESESE	Lease Mgt.	State	A-2	33508	1128	3718	3774	4052
	12	NWNWNW	Lease Mgt.	Blaney	2-12	31654	1139	3753	3812	4073
	19	SESESE	Dark	Blackledge	1-19	32334	1148	3736	3793	4063
	20	SESWSE	Oklahoma	Blackledge	2-20	34493	1116	3752	3808	4084
	29	SENENW	Dart	Blackledge	4-29	32296	1149	3757	3817	4083
	30	SENWSE	Dart	Barhitte	6-30	32902	1144	3705	3762	4025
	31	CNNENE	Hunt	Benchley	1-31	32880	1191	3678	3734	4007
	32	NESWNW	Dart	Fox	3-32	32971	1107	3666	3723	3994
13N 1E	5	SWNENE	Dow	Dow Chem.	33	BD112	630	3500	3556	3870

Appendix I (Continued).

Township/ Range	Section	Location	Operation	Farm	Well Number	Permit Number	Elev. Ref.	Top Bell	Top Dundee	Top D.R.
14N 1E	34	SESWNW	Dow	Dow Chem.	35	BD110	640	3510	3558	3900
	36	SESWNE	Dow	Dow Chem.	34	BD111	637	3510	3583	3896
14N 2E	21	SESWSW	Dow	Dow Chem.	8	BD121	609	3553	3615	3920
	36	SWSWSE	Dow	Ames	1	11718	621	3470	3530	3851
15N 2E	12	NENESW	McClure	Draves	1-12	30378	676	3583	3648	3988
	14	SWSWNE	Dow	Dow Chem.	39	BD109	678	3690	3760	4100
16N 1E	14	NENENW	Kughn	Kobisa	1-14	35187	714	3707	3796	4142
	15	SWNWNE	Con. Power	Marsh	1	32029	697	3706	3774	4032
17N 1E	3	SESENE	Hunt	McCrandell	1-3	34374	728	3417	3486	3860
18N 1E	34	SWSWNW	Kughn	Ried	1-34	33180	746	3456	3528	3828

APPENDIX II

Appendix II. Sample well description.

Exploratory
Dry Hole
TD 4081 in Detroit River

22-19N-1W
Gladwin Twp. (Gladwin Co.)

Tribal Oil Company

Permit No. 29065

James S. Graver No. 1-22

Location: NW ¼ NW ¼ NW ¼ Section 22, T.19N., R.1W.
330 feet from North and 330 feet from West line of quarter
section.

Elevations: 803.7 Kelly Bushing

BELL SHALE

3577-3738 Shale: gray, soft, fossiliferous

CORE No. 1 13738-3798 Recovered 31.66/60.0' (3741-3801
drillers measure)

3738-3741 Lost on connection

3741-3742.3 Shale: dark gray

3742.3-3742.95 Shale: dark gray, calcareous, hard, crinoidal

DUNDEE

3742.95-3745.0 Limestone: dark gray, fine crystalline, argillaceous, crinoidal,
some horizontal banding

3745.0-3756.0 Limestone: dark gray-brown to brown-gray, fine crystalline,
mottled, churned, slightly crinoidal, dense, some medium
irregular, dolomite filled voids, stylolite at 3746.7, crinoidal
band at 3745.2, numerous corals 3748-3750

(Core dropped on rig floor from 3751-3772.66, pieces out of
order)

3756.0-3772.66 Limestone: as above becoming gray-brown, less mottled on
surface

3772.66-3798 Lost in hole. Drilled with rock bit 3708-TD

3798-3803 No samples

3803-3816 Limestone: brown, fine crystalline, slightly porous, no show.
Poor samples to 3820-30 sample

Appendix II (Continued).

- 3816-3874 Limestone: light brown to buff, fine to very fine crystalline matrix, occasional coarse crystal, partly fragmental "reworked", some small vugs, pyritic, trace limestone: brown, fine crystalline, tight, some medium-coarse, white dolomite crystals, some scattered, "dead" carbonaceous stain 3837-3843, no fluorescence, no gas show
- 3874-3901 Limestone: as above, fragmental, spotted porous, no show and Dolomite: light brown to brown, fine-medium crystalline to partly sucrosic
- 3901-3930 Limestone: brown and dark brown, fine crystalline, slightly argillaceous, some white dolomite infilling, some vugy porosity, some Dolomite: light brown, fine-medium crystalline, spotted porosity, no show
- 3930-3946 Dolomite: brown and dark brown, fine-medium crystalline to partly coarse crystalline, partly calcareous, porous
- 3946-3952 Limestone: dark brown to gray-brown, fine crystalline, argillaceous, tight and Dolomite: brown, fine-medium crystalline, some white dolomite infilling
- 3952-3985 Dolomite: brown to dark brown, fine-medium crystalline, occasional dead stain, slightly argillaceous in part
- 3985-4033 Dolomite: brown with some light brown to buff, fine-medium crystalline, partly argillaceous, some white dolomite infilling, spotted vugy porosity
- 4033-4050 Limestone: brown to slightly gray-brown, fine crystalline, partly dolomitic, some Dolomite: as above, some white dolomite infilling, some Dolomite: dark brown, fine crystalline, argillaceous
- 4050-4055 Dolomite: brown, very fine sucrosic, porous
- 4055-4065 Dolomite: as above, trace Limestone: gray-brown, fine crystalline, tight, with Anhydrite: white to light brown

DETROIT RIVER ANHYDRITE

- 4065-4076 Dolomite: brown, very fine sucrosic, Dolomite: light brown, very fine sucrosic, anhydritic, with Anhydrite: white to light brown
- 4076-4081 Limestone: light brown and light gray-brown, fine crystalline, tight, some Dolomite: as above
- 4081 Total Depth Schlumberger - 4092 TD Driller

APPENDIX III

Appendix III. Dundee well completions, January 1, 1981 through June 31, 1982.

Permit Number	Operator	Farm	TRS	Location	Pool Name	Classification	Production	T.D.
34674	Wiser	Brenner 1-11	18N/1W/11	CSESW	N. Buckeye	Development	Oil	3805
35263	Horizon	Cingano 1-36	17N/2W/36	NWSENE	Beaverton	Development	Oil	3841
33846	Wiser	Nash-Lom #1	18N/1W/35	CSWSE	S. Buckeye	Development	Oil	3753
33815	Wiser	Wineman #2	17N/1E/9	SWSENW	S. Buckeye	Development	Oil	3795
34465	Wiser	Woodward #1	17N/1E/9	CNENW	S. Buckeye	Development	Oil	3800
34449	Wiser	Smith et al., #3	17N/1E/9	CNWNE	S. Buckeye	Development	Oil	3800
34866	Hunt	Lk. Isabella 1-9A	14N/6W/9	NWSENE	Broomfield	Development	Oil	3683
34867	Hunt	Lk. Isabella 2-9A	14N/6W/9	SESENE	Broomfield	Development	Oil	3650
35068	Hunt	Lk. Isabella 1-10A	14N/6W/10	SWNWSW	Broomfield	Development	D+A	3632
35329	Dart	Bagley 3-9	14N/6W/9	SENESE	Broomfield	Development	Oil	3701
34922	Yohe	C. Estates 1-5	14N/6W/5	SESWSW	Broomfield	Development	Oil	3786
35252	Sun	McClintic #1	14N/3W/11	SWSENE	Mt. Pleasant	Development	Oil	3670

Appendix III (Continued).

Permit Number	Operator	Farm	TRS	Location	Pool Name	Classification	Production	T.D.
35298	Tope	Moggenberg #2	15N/3W/19	NWNWSE	Leaton	Development	Oil	3893
34572	Quadro	Paisley #1-B	16N/3W/17	CNWSE	Wise	Development	Oil	4871
35019	Yohe	McNeel #2-8	14N/6W/8	NWNENE	Broomfield	Development	Oil	3877
35260	Trendwell	McArthur 4-9	14N/6W/9	NWSWSE	Broomfield	Development	D+A	3770
34261	Dart	Bagley 1-9	14N/6W/9	NWNESE	Broomfield	Development	Oil	3674
34166	Musk. Dev.	Pohl 1-36	15N/5W/36	SESENW		Exploration	D+A	3899
34307	Woods	Moss 1-24	13N/6W/24	SWNESW	Rolland	Development	Oil	3630
34450	Woods	Moss 4-24	13N/6W/24	SWSENW	Rolland	Development	Oil	3631
34488	Woods	Cooper 1-24	13N/6W/24	SWNWSE	Rolland	Development	Oil	3618
34577	Dart	Bagley 2-9	14N/6W/9	NWSESE	Broomfield	Development	Oil	3747
34697	Woods	Armstrong 1-24	13N/6W/24	SWSESW	Rolland	Development	D+A	3615
34711	Sibley	Young 1-16	14N/6W/16	NWNWNE	Broomfield	Development	D+A	3787

Appendix III (Continued).

Permit Number	Operator	Farm	TRS	Location	Pool Name	Classification	Production	T.D.
34426	Yohe	Lk. Isabella 4-9	14N/6W/9	SESWNE	Broomfield	Development	Oil	3672
34581	Yohe	McArthur 2-9	14N/6W/9	NWNWSE	Broomfield	Development	Oil	3685
34425	Yohe	McNeel 1-8	14N/6W/8	SENE	Broomfield	Development	Oil	3822
34881	Yohe	Lk. Isabella 5-9	14N/6W/9	SESENW	Broomfield	Development	Oil	3732
34781	Tope	Moggenberg 1	15N/3W/9	NWSWSE	Leaton	Development	Oil	3735
34560	Cent. Mi. Exp. Beatty 1		16N/4W/22	CSENE	Vernon	Development	D+A	3768
34481	Trendwell	McClintic 1-4	14N/6W/4	CSWSE	Broomfield	Development	D+A	3672
34703	Tope	Wolfgang #1	13N/1W/21	CSWSE	Porter	Development	Oil	3493

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