Hydrodynamic Character of the Dundee Limestone in the Central Michigan Basin

Ann Carol Little
Western Michigan University

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HYDRODYNAMIC CHARACTER OF THE DUNDEE LIMESTONE
IN THE CENTRAL MICHIGAN BASIN

by

Ann Carol Little

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
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HYDRODYNAMIC CHARACTER OF THE DUNDEE LIMESTONE
IN THE CENTRAL MICHIGAN BASIN

Ann Carol Little
Western Michigan University, 1986

The Middle Devonian Dundee Limestone underlies most of the Lower Peninsula of Michigan. A potentiometric surface constructed of the formation, utilizing pressure data was compared to local and regional structure, permeability trends, specific gravity of the brines, oil accumulations, and surficial topography.

The data were distributed mainly in the central basin area, with information becoming more sparse around the basin margins. This created difficulties in the determination of the extent of control imparted by each of the factors in flow direction. Surficial topography, on a regional scale, is likely the most influential of the controls, with the Dundee Limestone brines flowing toward outcrops in Lake Michigan. Lake Michigan is acting as a potentiometric low. Lack of data in the eastern portion of the state resulted in a lack of definition of the potentiometric surface in this area; therefore, no relationship could be determined between flow direction and Lake Huron.
ACKNOWLEDGEMENTS

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Special thanks go to my family for their belief in my abilities, to Steve for his constant encouragement, and to all my friends of the department for making this journey more bearable.

Ann Carol Little
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INTRODUCTION

The deep aquifer characteristics of the Michigan basin are not known. Although many shallow local aquifer studies have been conducted in fresh water zones, the regional circulation of the basin remains a mystery. A greater understanding of the regional ground water flow is necessary to form a more integrated view of the ground-water system of the entire basin. The knowledge of the hydrodynamic characteristics of deep aquifers of the basin is also an invaluable tool for the continued exploration of oil and gas as easily found reserves are exhausted. Petroleum explorationists have traditionally focused their attention on the rock framework, and have done little work to determine the hydrodynamic environment through which oil and gas migrate. This environment is a dominant influence in the entrapment process. (Dahlberg, 1982; Hubbert, 1953; McNeal, 1961).

When studying fluid flow of large sedimentary basins, it is imperative to understand that one is working with a system in a state of hydrodynamic equilibrium. "It may be assumed that a relatively steady state has been reached. This does not imply static
conditions, but rather that any recharge [and discharge] to the flow regime is negligible in relation to the vast amount of fluid in the system." (Hitchon, 1969a, p. 186).

This thesis addresses a portion of the central Michigan basin to determine the feasibility of various methods in defining the hydrodynamic environment of the Middle Devonian Dundee Limestone. Data generated by the petroleum industry such as drillstem test (DST) results, fill-up data from wells drilled with cable-tools, brine chemistry and density, and drillers logs were used in the attempt to define the system parameters. A potentiometric surface was constructed utilizing formation pressure data obtained from DSTs. Flow lines and potentiometric gradients were compared to structure, petroleum accumulation, surficial topography, and specific gravity trends of the brines. Cable-tool fill-up data were used to determine generalized permeability trends.

As will be illustrated, the methodology used to construct the potentiometric surface is not entirely reliable on a relatively small scale, and this study makes it clear that a basin-wide, multi-formational study is needed to fully determine regional trends. A significant problem encountered in the study of the hydrodynamics of the Michigan basin is the tendency for
petroleum exploration to occur along trends. This leads to a disproportionate distribution of the data in terms of geographical position. Data were investigated in counties outside of the study area to enhance the local results. Few tests with reliable test data were found. Specific gravity of the Dundee brines were plotted and contoured in an area surrounding the study area to determine its relationship to depth and distance from the basin center, and the potentiometric surface.

Study Area Location

The study area is located in an area included in Osceola, Mecosta, Clare, and Isabella Counties of the Central Michigan basin Province, encompassing 1764 square miles (Figure 1). The Middle Devonian Dundee Limestone was chosen as the formation of interest because of the large amount of petroleum exploration in and production from that unit.

Literature Review

Several studies have been conducted utilizing drillstem tests (DSTs) to determine the hydrodynamics of sedimentary basins on regional scales. Hitchon (1969a,b) used DST data to study fluid flow in the western Canada sedimentary basin. His study included flow nets for 27
Figure 1. Study Area Location.
stratigraphic units in which he compared the individual effects of geology and topography on the flow patterns. Hitchon found that both major and minor topographic features exerted an important control on the regional and local flow systems. Major upland topographic features corresponded with areas of recharge and associated high potentials. He also observed that these high potentials were close in value to the potentials at the surface in these areas. Regions of low topography were found to act as discharge zones with the potentials at depth again close to those found at the surface. Hanshaw and Hill (1969) conducted a geochemical and hydrodynamic study of the Paradox basin region using DSTs, water well records, and an electric analog model of the entire basin. Hitchon and Hays (1971) utilized DSTs and static water levels in boreholes to determine the hydrodynamic environment of the Surat basin, Queensland, Australia. Bond (1972) did a comprehensive analysis of the Illinois basin using DSTs, static water levels, and geochemical evaluations. Basset and Bentley (1982) utilized DSTs to study the Palo Duro and Dalhart basins located in Texas, to determine the hydrodynamics in regard to burial of high-level radioactive wastes. Bair (1985) utilized incomplete DST records to conduct a hydrodynamic study of the Palo Duro basin area.
Previous investigations of the hydrodynamic character of the Michigan basin are few in number. Newcombe (1933) collected brine data about the Dundee and other formations of the basin and related the chemistry to local and regional structural trends. Newcombe also studied the occurrences of the first water zones encountered in many of the oil fields located in the basin. Graf, Meents, Friedman, and Shimp (1966) conducted a study on the geochemical properties of the Michigan and Illinois basins in the attempt to discern the origin of the brines. They concluded that the flow through the Michigan basin was of a much greater volume than that of the Illinois basin due to steeper hydraulic gradients present in the Michigan basin, and the brines were composed of a mixture of sea and fresh waters. The workers also concluded that an upward movement of fluids was occurring near the center of the Michigan basin, and undergoing ultrafiltration by the shale formations. Graf et al. (1966) also stated that the outcrop belt of the Silurian Salina Formation, which is now covered by Lake Michigan, is a potentiometric low and has been in such a state since most of post-Salina time.

Black (1983) studied the hydrologic character of Devonian carbonates which outcrop in northern lower Michigan and the resultant karstic terrain. Black
observed a regional flow system influenced by Lake Huron which was clearly separate from the local, surficial aquifer system. Prouty (1983) observed the correspondence between ground-water flow and open faults and fractures in the Devonian carbonates in the same area.
REGIONAL GEOLOGY

The Michigan basin is a structurally controlled depositional province centered in the Southern Peninsula of Michigan. The basin is relatively shallow in comparison to sedimentary basins of more active tectonic regimes, with thicknesses of Phanerozoic sediments reaching an estimated maximum of 15,000 feet (Hinze and Merritt, 1969). The Michigan basin encompasses the entire Southern Peninsula and the eastern portion of the Northern Peninsula of Michigan, eastern Wisconsin, the northeast corner of Illinois, northern Indiana, northwest Ohio and parts of Ontario bordering Lake Huron, Lake St. Clair and the western end of Lake Erie (Cohee and Landes, 1958). The Michigan basin is bordered on the west and northwest by the Wisconsin Arch and Wisconsin Dome, to the north by the Canadian Shield, to the east and southeast by the Algonquin and Findley Arches, and to the southwest by the Kankakee Arch (Figure 2). This study is concerned only with that part of the structural basin that is located in the Southern Peninsula of Michigan and its outcrop areas in the Great Lakes.
Figure 2. Structural Features Associated With the Michigan Basin (From Ells, 1969).
The Michigan basin contains sedimentary rocks of Precambrian, Paleozoic and younger age. The rocks are downwarped toward the center of the basin, and outcrop and subcrop in a roughly circular pattern above and below Pleistocene glacial drift. The youngest consolidated rocks present in the basin are deeply eroded Jurassic beds located in central to west-central Michigan. Progressively older rocks ranging from Pennsylvanian to Precambrian outcrop in bands surrounding the basin center (Figure 3). Approximately 47 percent of the sedimentary rock volume in the basin is carbonate, 41 percent sandstone and shales and 12 percent is salt, anhydrite, and gypsum (Cohee and Landes, 1958).

The Michigan basin is believed to have originated during Late Precambrian time, with continued subsidence through the Pennsylvanian Period. This is reflected in the general basinward thickening of most formations. Major periods of evaporite deposition occurred during the Silurian and Devonian periods, resulting in the thick sections of the Salina and Detroit River Formations (Lilienthal, 1978).
Figure 3. Generalized Geologic and Tectonic Map of the Michigan Basin and Surrounding Area (From Gardner, 1974).
Stratigraphy

The regional stratigraphy of the Michigan basin has been studied by several authors (Fisher, 1969b; Lilienthal, 1978; Newcombe, 1933). The oil and gas industry of the basin which began in 1925, and continues today, has also provided a vast amount of information essential to the definition of the stratigraphic column. The stratigraphic succession of the Michigan basin is represented by a Precambrian basement complex and sedimentary section, a complete Paleozoic section with the exception of Permian strata, a small remnant of Mesozoic strata, and a mantle of Pleistocene glacial drift ranging from 0 to 1250 feet in thickness (Figure 4).

Devonian Strata

The Devonian section of the Michigan basin is represented by Middle and Upper Devonian sequences, whereas Lower Devonian beds are generally absent. The only remnant of Lower Devonian deposition is the deeply eroded Garden Island Formation (Lilienthal, 1978). In ascending order the Middle Devonian formations of the Michigan basin are the Bois Blanc Formation, Detroit River Group, Dundee Limestone, and the Traverse Group.
Figure 4. Generalized Stratigraphic Column of the Michigan Basin (After Lilienthal, 1978).
Upper Devonian formations include the Antrim Shale and Ellsworth Shale. The Detroit River Group underlies the Dundee Limestone and is composed of sandy limestone, fossiliferous limestone, shaly limestone, anhydrite and gypsum (Newcombe, 1933). The Dundee Limestone underlies most of the Southern Peninsula, except for the extreme southwestern portions of the state. The Dundee Limestone is directly below the glacial drift in Wayne and Monroe Counties of southeast Michigan (Lilienthal, 1978). The greatest thicknesses are in the Saginaw Bay area, thinning toward the west and south. It is predominately a buff to brownish gray, fine to coarsely crystalline limestone (Lilienthal, 1978). In the western and southwestern portions of the state, the Dundee is dolomitic and anhydritic. In the central part of the basin, a mixture of limestone and dolomite is present. The base of the formation is generally dolomite with some sandy zones (Newcombe, 1933). The Dundee Limestone will be further discussed in a subsequent section. The Bell Shale, a member of the Traverse Group, directly overlies the Dundee Limestone. The Bell Shale is greater than 100 feet thick in the Saginaw Bay area, generally 60 to 70 feet thick in the central basin, and pinches out towards the south (Lilienthal, 1978). The Bell Shale seems to be conformable with the Dundee Limestone in the central
basin area, although an angular unconformity has been reported between the two formations at the Rogers City quarry in Presque Isle County in northeast Michigan (Addison, 1940). The Traverse Group is an alternating sequence of limestone and shale units that have been named from the Alpena area. The shales thin to the southwest and are generally absent in southwestern Michigan. In this area the several formations of the Traverse Group have not been distinguished. The Traverse Group is predominantly shale toward the east and becomes a relatively pure limestone westward, with reefs found in the limestone facies. The upper Devonian Antrim Shale is a dark gray to black and brown, carbonaceous shale with an lower member identified as the Traverse Formation. The overlying Ellsworth Shale is green with some gray and greenish-gray occurrences near the Antrim contact (Lilienthal, 1978). The Ellsworth Shale is present only on the western side of the state, occupying the same stratigraphic position as the Berea Shale, Bedford Sandstone and Upper Antrim to the east.

**Dundee Limestone**

Newcombe (1933) designated the section of rocks between the Bell Shale and the Detroit River Group the Dundee Limestone. Newcombe described the formation as a
gray to buff, cherty, crystalline, fossiliferous limestone usually of high purity. He reported frequently encountered bituminous, stylolitic, and porous zones. The porous zones were described as of extreme importance as oil and gas reservoirs. Numerous seams of secondary crystalline calcite were observed to be the result of extensive solution activity. Ehlers and Radabaugh (1933) differentiated the Dundee into two formations, (1) the upper Rogers City Limestone and the lower Dundee Limestone. This differentiation was based upon faunal succession, lithologic variation, and color. Addison (1940) substantiated the division of the Dundee Limestone into two formations in his work on the Buckeye Field, Gladwin County. He described the Rogers City to be about 55 to 65 feet thick, consisting of dense brown limestone with a waxy or vitreous appearance. The Dundee was easily differentiated by its light gray to buff appearance with textures ranging from crystalline to lithographic (Addison, 1940). Landes (1944) also differentiated the Dundee Limestone into two formations, stressing the importance of this distinction because of the common occurrence of oil reservoirs within the porous zone between the two formations. Landes described the Rogers City Limestone as a dark brown limestone with a resinous luster. The Dundee Limestone was described as a
yellow, tan, or buff limestone in the Porter Oil field in Midland County.

Lilienthal (1978) considered this differentiation to be of minor significance since overall, the Rogers City and Dundee were not readily separable with electric logs, which was his method of study. He combined the two, designating the formation the Dundee Limestone. Lilienthal described the Dundee as a buff to brownish, gray crystalline limestone except where dolomitic in the western portions of the state.

Gardner (1974) divided the Dundee Formation into the Rogers City Member and the Reed City Member. In this classification, the Reed City was recognized as the first continuous anhydrite layer underlying the Dundee in western Michigan, pinching out towards the east (Figure 5). Gardner's (1974) description of the Dundee Limestone, which he delineated as the Rogers City Member, depicts a massive uniform limestone with a persistent character over much of the basin, except where it is dolomitized in the west. Gardner also described a tendency for dolomitization to occur along structural highs in the western half of Michigan, with an eastward alteration to impermeable limestone. He reported that where the Dundee is not highly dolomitized, it is typically a brown, biocalcarenite wackestone containing
Figure 5. Thickness-Lithofacies Map of the Dundee Limestone (From Gardner, 1974).
brachiopods, corals, and crinoidal debris with bioturbation common.

In western Michigan the Dundee has been reported to be dolomite where the underlying Reed City is dolomite, and generally limestone where the Reed City anhydrite is compact and continuous. Knapp (1947) hypothesized that the Reed City Dolomite had long served as an aquifer for the Dundee Limestone, providing dolomitizing fluids which migrated upwards along fractures and other permeable routes in response to hydrodynamic forces. A detailed study of the origin of the dolomite would need to be done to determine the feasibility of this hypothesis.

Bush (1983) divided the strata between the Bell Shale and the Detroit River Group into the Rogers City and Dundee Formations. The Rogers City was described as typically a dark colored, brownish buff, dolomitic limestone or dolomite with dolomitization strongly associated with structural highs. The Dundee Formation was described as a typically brown, biocalcarenite wackestone or packstone with brachiopods, corals, stromatoporoids, and crinoidal debris. Bush reported that the Dundee was fine to medium grained, tan to dark gray, locally dolomitized limestone in the central basin area. Scattered stylolites parallel to bedding containing black residue were also reported.
In this study, the Dundee Limestone will be considered to be all strata between the Bell Shale and the Detroit River Group. The Reed City Anhydrite and Dolomite are not included in this classification.

The Dundee Limestone reaches its greatest thickness in the Saginaw Bay area where it is as much as 475 feet thick (Figure 5). In most of West Michigan the formation is less than 100 feet thick, with much of the formation less than 40 feet thick (Lilienthal, 1978). The Dundee Limestone is absent from the extreme southwestern portion of the state, and outcrops in the northern Southern Peninsula of Michigan (Figure 5). In northern Michigan the Dundee is utilized as an aquifer, where flow occurs through solution channels in the karstic terrain. The formation is very susceptible to pollution in these areas. In the study area it attains thicknesses of approximately 350 feet in the extreme eastern edge of the area, and thins to about 200 feet towards the west.

The Dundee has been observed to be thickest on structural highs and thinnest in structural troughs. Possible mechanisms for this phenomenon include: sediment loading, local tectonic activity, changes in the depositional or marine environment, reefing, or a combination of these processes (Bush, 1983). A popular concept is the reefing process, where slightly positive
areas serve as points of reefal growth, further accentuating the positive areas. The lithology on the structural highs tends to support this hypothesis. Porous and fossiliferous carbonates are observed in these zones, and may represent a biohermal or biostromal deposit (Bush, 1983).
REGIONAL STRUCTURE

The Michigan basin is dominated by a northwest to southeast trend of en echelon, broad subparallel anticlinal and synclinal folds and associated faults. A minor axis of deformation trending approximately perpendicular to the major axis in a northwest-southeast direction is also present (Figure 6). The structural geology of the basin has been studied by many workers. Pirtle (1932) concluded that the structures found in the Michigan basin were a reflection of structural weaknesses in the Precambrian basement, with a subsequent occurrence of horizontal stress. Newcombe (1933) observed a rotational shear aspect to some faults. He attributed this to basinal stresses due to subsidence. Hinze and Merritt (1969) interpreted the major northwest-trending structures to be associated with basement zones of weakness along the rift zone believed to be related to the Mid-Continent gravity anomaly. He also stated that the rejuvenation of these zones occurred due to basin sinking or externally applied stress fields. Prouty (1983) developed a shear model of deformation for the basin by observing thousands of azimuths of joints and fractures in outcrops around the basin margins. A shear
Figure 6. Major Fold Trends of the Michigan Basin (From Prouty, 1983).
model was used to explain the nearly vertical joints and fractures, and lateral movement observed on several of the faults. This vertical nature implied a regional stress acting upon the basin, rather than localized intrabasinal stresses (Prouty, 1983). Most workers hypothesize that faulting probably originated in Precambrian rocks, but not necessarily in Precambrian time. This would account for the regional character of stresses, which could be transferred through the competent Precambrian basement (Prouty, 1983). The most popular theory for the time of deformation of the basin, is one of intermittent development of structures throughout the Paleozoic, with major deformation occurring during the Late Mississippian period (Ells 1969; Newcombe, 1933; Prouty, 1983). This corresponds with a major Appalachian deformation to the east.

The possible presence of faults associated with the folds is important to a study of hydrodynamics, because such features could serve as conduits for basinal fluids, including oil, gas and ground water. Faults have often been described as channelways for dolomitizing fluids in locally dolomitized formations such as the Dundee Limestone. Many workers have theorized that Dundee production is controlled in some structures by dolomitized porosity zones along fractures within the
structure.

Central Michigan Structure

The central Michigan basin is dominated by several northwest-to-southeast-trending highs. The Broomfield High extends from Evart and Orient Townships of Osceola County toward Sherman Township in Isabella County. The Greendale High extends from Grant Township in Clare County southeastward into Midland County. The Mt. Pleasant oil field is located along this high. A portion of the Headquarters-Bentley Trend is in the study area, extending from Franklin Township, Clare County southeastward toward Bentley Township, Gladwin County. The origin of these highs is probably related to vertical tectonics originating in the Precambrian basement.

Dundee Structure

The center of the Dundee structural basin is located west of the Saginaw Bay area in the northern central basin (Figure 7). The regional dip is fairly uniform in all directions surrounding the structural center. The Dundee outcrops in northern Michigan at an elevation of approximately 800 feet above sea level. The outcrop level in Lake Michigan is between 180 and 280 feet above sea level (Figure 8).
Figure 7. Structure Map on the Dundee Limestone (From Gardner, 1974).

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Figure 8. Schematic Cross-Section of the Michigan Basin Illustrating Outcrop Areas of the Devonian Carbonates in the Great Lakes (From Hough, 1958).
The producing fields of the Dundee Limestone within the study area consist of two distinct types. The larger structures have a strong northwest to southeast trend and are probably related to basement movements. An example of this type of field is the Mt. Pleasant structure (Plate I). The second type of structure is more circular in plan view with nearly equal displacement in all directions. This could be due to cross-buckling of the Dundee (Newcombe, 1933) or due to reefal build-up (Bush, 1983). Examples of this type of structure are the Evart and Fork oil fields. The majority of the fields are assymetric, with a steeply dipping southwest flank.
THE CONCEPT OF POTENTIAL

Potential Energy

When one wishes to determine the nature of ground-water flow in a rock medium at every point within that flow system, the nature of the fluid and the properties of the framework medium must be known. When utilizing Darcy's Law to derive fluid flow, three parameters are analyzed: (1) the discharge, (2) a coefficient of permeability (K), and (3) the hydraulic gradient (dh/dl), which is defined as the fall in head (dh) over a distance (dl):

\[ Q = -K \left( \frac{dh}{dl} \right) \]

Darcy's Law is derived from classical hydrodynamic equations which deal with frictionless fluids (Hubbert, 1940). While the law of conservation of matter has been acknowledged, the first and second laws of thermodynamics have not. In the past, many workers attempted to employ a substitution into Darcy's Law utilizing pressure data to determine flow direction:

\[ Q = -K \left( \frac{dp}{dl} \right) \]
where \((dp/dl)\) is the differential of the fall of pressure \((dp)\) over a distance \((dl)\). It was generally assumed that fluids would flow from a high pressure zone towards a low pressure zone, and that equations (1) and (2) were equivalent.

M.K. Hubbert demonstrated in his 1940 classic paper on fluid flow that this assumption was not valid. He concluded that a fluid could flow from a region of high pressure to a region of low pressure, or vice versa quite arbitrarily. Hubbert (1940) showed that not only was pressure not the controlling factor in the direction of fluid flow, but neither was the tilt of the formation nor the elevation. What was needed was a physical quantity that could be measured at every point in the system where flow would occur from high values to low values regardless of direction in space (Hubbert, 1940). This value corresponds to the physical manifestation of the hydraulic head.

The Second Law of Thermodynamics states in general that "any material transformation which involves friction or its equivalent, is unidirectional and irreversible in character meaning that, once the process has taken place, by no method whatsoever can it be undone again." (Hubbert, 1940, p. 796). Since friction is a major component of ground water movement through the pore
spaces of a rock, this constitutes a unidirectional process where mechanical energy is transformed to thermal energy by friction. This satisfies the law of the conservation of energy. This process continues toward mechanical equilibrium, where kinetic energy is zero and potential energy is at a minimum compatible with the constraints of the system (Hubbert, 1940). The mechanical energy the fluid possesses is equivalent to the fluid or hydraulic potential ($\Phi$). In hydrodynamic studies, the hydraulic potential is defined as "the energy possessed by a unit mass at a given point, which in the subsurface environment is basically induced by the forces of gravity and pressure." (Dahlberg, 1982, p. 6). Numerically, the potential is calculated as:

$$\Phi = gh$$

where $g$ equals the acceleration of gravity, and $h$ is equal to the hydraulic head in feet above a reference datum.

Dahlberg (1982) illustrated the concept of fluid potential with a simplified model (Figure 9). A marble, representing a fluid particle, will roll down an inclined, undulating surface given an initial horizontal force and the force of gravity. The undulating surface represents the relative energy potential. The marble
Figure 9. Model Illustrating the Concept of Potential Energy Minimums and Barriers (From Dahlberg, 1982).
will roll down the surface until it becomes trapped in one of the troughs: A, B, C, or D. In this position, the marble possesses zero kinetic energy and a minimum of potential energy compatible with the constraints of the system, which in this case is an energy barrier. The marble is thus trapped in a zone of low potential with respect to the surrounding system. If the original horizontal force is increased or tilting occurs, the marble could again gain kinetic energy. The contour traces on Figure 9 illustrate the energy surface.

Dahlberg (1982) inverted the model (Figure 9) to portray an environment containing two or more fluids of differing densities. The most common type of environment encountered in the subsurface is one containing brine, oil, and/or gas. In this case, where oil and gas are less dense than the water component, the gravity effect is inverted—resulting in a gravity induced buoyancy directed upward, with the marble representing a globule of oil or gas. The troughs A, B, C, and D are still regions of low potential with respect to the water medium. Oil and gas are trapped within the potential lows until enough energy becomes stored to enable the particles to overcome local energy barriers (Dahlberg, 1982). When hydrodynamic theory is utilized for petroleum exploration, variations in fluid potential are
mapped on regional or local stratigraphic scales and related to the structure. This model illustrates that the potential of a fluid is a function of gravity and the height above a datum, local pressures, and the density of the fluid. It also demonstrates that the system is in a state of hydrodynamic equilibrium.

The Potentiometric Surface

A potentiometric surface represents the height to which water will rise in wells cased into an aquifer. The hydraulic head is an approximation of fluid potential. It is determined primarily by formation pressure and to a lesser degree by fluid density (Dahlberg, 1982.) A potentiometric surface is a two-dimensional display of isopotential lines representing concentric surfaces of equal potential in three-dimensional space.

The potentiometric map is constructed on the basis of an equivalent fresh water head, or $H^{1.0}$. If $H^{1.0}$ has a value of $N$, $N$ is equal to the feet above or below sea level to which water with a relative density of 1.00 would rise in a well opened to the surface (Bair, O'Donnel, & Picking, 1985; Bond, 1972). Saline waters, such as those in the Dundee Limestone in the study area, will not rise to the same height under the same pressure.
as fresh water. This is due to a smaller pressure being required to equalize the system with a denser fluid (Dahlberg, 1982; McNeal, 1965). In order for a potentiometric surface to be constructed with densities taken into account, corrections must be made, not only at the point of observation,

but also by computing a composite of the densities of waters up dip the potentiometric surface from that well. Other problems are that unless the correction factor is given at each datum point, another person using the data will not be able to incorporate the same corrections into new data on the map, at a later date, and as additional water data are obtained the corrections must be revised. (McNeal, 1965, p. 309)

Bond (1972) warned, however, that a sloping potentiometric surface constructed for a layer with fluids of variable densities, may not be showing flow direction. A simple model of flow from a high potential to a low potential may become extremely complex if a formation contains ground water of variable concentrations of dissolved solids. A difference in densities may be sufficient to cause a difference in potentials at two opposing points, while not signifying flow between these two points. Areal changes in salinity over the study area are minimal and drastic changes in the flow paths are unlikely. However, the possibility of this phenomenon must be considered.
Utilizing equivalent fresh-water heads is the common method to represent potential in aquifers with variable densities. On a regional scale, this method is acceptable to determine regional flow patterns and hydraulic gradients (Bair et al., 1985; Hitchon, 1969a,b; McNeal, 1965).

Flow paths are oriented perpendicular to isopotential lines, pointing to zones of low potential. If a potential surface is horizontal, the potential energy of the water within the formation of interest will be constant and no flow will occur. If the surface is tilted, water will flow toward lower potentials "with the horizontal component of flow in the approximate direction of the steepest downward slope of the surface." (Hubbert, 1953, p. 1974). One must be cautious not to assume that the magnitude of the flow is proportional to the potential gradient (Hubbert, 1953). Some type of flow, even if it is of a very small magnitude with the water in a quasi-static state, should be expected in all ground water regimes (Hubbert, 1940). Calculation of H requires formation pressure data most often acquired from drillstem tests.
Tilted Oil-Water Contacts

Tilted oil-water contacts are the most commonly encountered evidence of hydrodynamic properties in sedimentary environments. The attitude of the potentiometric surface bears a direct relationship to the orientation of the hydrocarbon interface in associated reservoirs (Dahlberg, 1982; Hubbert, 1953). This relationship is primarily dependent on density differences of the subsurface fluids. Hubbert (1953) described the relationship between water potentiometric surfaces and hydrocarbon potentiometric surfaces, and developed an equation for determining the slope of the oil-water interface when the potentiometric surface of the water is known. Hubbert utilized a "tilt-amplification factor," which is defined as the ratio of the water density to the difference between the water density and hydrocarbon density:

\[ \frac{Z}{\Delta X} = \frac{D_w}{(D_w - D_h)} \times \frac{H_w}{\Delta X} \]

where \( \frac{Z}{\Delta X} \) represents the slope of the hydrocarbon-water interface over a distance \( X \), \( \frac{H}{\Delta X} \) is the change in the hydraulic head over the same distance \( X \), and \( \frac{D_w}{(D_w - D_h)} \) is the tilt amplification factor, where \( D_w \) equals the density of the water and \( D_h \) is the hydrocarbon density.
If the potentiometric surface of the ground-water environment is known, the oil-water interface slope may be predicted. With this method, petroleum accumulations may be discovered in unclosed structural noses, and structural closures may be determined to be flushed, without the expense of drilling an exploratory well in an unproductive area.

Tilted oil-water interfaces have been reported for individual oil fields of the Michigan basin. In his study of the Buckeye oil field in Gladwin County, Addison (1940) constructed a structural contour map of the producing zones. A tilted oil-water interface can be observed, with oil production occurring farther down-dip on the structure towards the northwest in the Dundee producing zone. Landes (1944) illustrated a tilted oil-water interface in the Porter oil field located in Midland County, in the Dundee. The oil in this field also occurs farther down-dip toward the northwest. The Deerfield oil field in Monroe County, produces from the Trenton Group. Lindberg (1948) reported a non-productive area on the crest of the anticlinal structure was "caused by a greater westward dip of the oil zone than of the Trenton Formation" (Lindberg, 1948, p. 305). Cohee and Landes (1958) reported tilted oil-water interfaces in the Traverse Group. An attempt was made to map the interface
orientations in wells producing in southwestern Michigan to determine if a regional trend could be observed. Unfortunately, the oil-water interfaces appeared to be randomly oriented throughout the Group.

Drillstem Tests

Drillstem tests are an important but expensive procedure utilized by the petroleum industry to determine reservoir parameters. Undisturbed formation pressure and a coefficient of permeability can be determined. A sample of formation fluids can also be obtained. A drillstem test enables the formation of interest to be isolated by the use of packers attached to the drill string allowing production of formation fluids under the natural formation head (Bredehoeft, 1965). The drillstem test string (Figure 10) is described in detail by VanPoolen and Bateman (1958).

In a typical test, the drill pipe is emptied of all circulating fluids. The operator opens the tester valve allowing the formation access to atmospheric pressure (Figure 10). Production of the fluids within the formation is then possible given adequate permeability. This flow period is generally 30 minutes to two hours in length (Bredehoeft, 1965) and is reported as the initial flow pressure (IFP). The tester valve is then closed.
Figure 10. Typical Drillstem Test String (From Bredehoeft, 1965).
causing the formation pressure to recover. The pressure response is recorded throughout this shut-in period with the pressure gauge located near the bottom of the drill string. The resultant pressure is recorded as the initial shut-in pressure (ISIP), and should represent the undisturbed formation pressure. This sequence is repeated, recording a final flow pressure (FFP) and a final shut-in pressure (FSIP). The repetition insures that the tool is in proper working condition.

Pressure Charts

Drillstem test results are displayed on charts showing pressure response versus time (Figure 11). The test is divided into five parts:

(1) The first segment of the chart (curve A-B), is the response of the pressure gauge as the tool is lowered into the hole. The noisy appearance is due to the addition of joints and pipe to the drill string (Bredehoeft, 1965).

(2) When the string is lowered to the desired depth, the packer assembly is set, isolating the interval of interest. The tester valve is then opened for a short period (point B), allowing the formation to approach atmospheric pressure (point C) and produce formational fluids.
Figure 11. Pressure-Response Curve From Drillstem Test (Modified From Dahlberg, 1982).
The tester valve is then closed, giving the pressure sufficient time to recover to undisturbed conditions (curve C-D). The undisturbed formation pressure is approached asymptotically (point D), and recorded as the ISIP. The ratio of shut-in pressure time to flow time should generally be at least equal to 1.5 to 2.0 (Vanpoolen and Bateman, 1958). In zones of low permeability, the initial shut-in time (ISIT), should be as long as possible to insure pressure recovery.

(3) The tester valve is opened following the ISIT, causing the formation pressure to again drop to about one atmosphere (point E). Production occurs throughout this period. As the column of fluids and/or gas begins to rise in the drill pipe, a greater pressure is exerted on the pressure gauge (curve E-F).

(4) The tester valve is closed (point F) for a final shut-in time (FSIT), causing isolation of the zone of interest and pressure recovery (curve F-G).

(5) The packer is unseated (point G), and the pressure returns to that of the weight of the drilling mud (point H), or the hydrostatic mud pressure (Bredehoeft, 1965). Curve H-J is a record of the pressure reduction as the tool is pulled out of the hole.
If the entire pressure chart is available for use, data for permeability measurements may be derived by a method developed by Horner (1951) which utilizes a mathematical formula similar to the Theis recovery method (Bredehoeft, 1965; VanPoolen and Bateman, 1958). However, complete DST pressure charts may not be available. For example, the Petroleum Information Corporation (PI) distributes incomplete DST data in the form of scout tickets which are available to most industries, universities, and interested individuals. Incomplete data cannot be used to derive permeabilities of the tested formation.

Incomplete Drillstem Records

Incomplete DST data do not show continuous pressure changes during the flow and shut in periods of the test. They often do record the ISIP, ISIT, FSIP, FSIT, and recovery data (Bair et al., 1985). Incomplete data such as these can be useful to a hydrodynamic study if used with care. Scout tickets and drillers logs are the most common source of such data for the Michigan basin. Pertinent information needed from each of the DSTs includes the following: (1) location—state, county, township, range, and section, (2) operator and lessee, (3) well completion date, (4) elevation, (5) depth of tested
interval, (6) geologic unit of tested interval, and (7) test data: ISIP, ISIT, FSIP, FSIT, and recovery information.

In order to determine if a drillstem test is reliable, the available data must be carefully studied. The time allotted to the shut-in periods must be sufficient to allow the formation to fully recover in order for the undisturbed formation pressure to be recorded. The test must be conducted on the water leg of the formation fluids. If a large amount of oil, gas or mud is recovered during the test, pressures will not reflect the ground-water environment. The recovery should also be of sufficient quantity to assure that the formation is permeable enough to recover during the shut-in periods.

ISIP values were used to calculate the equivalent fresh-water heads needed for the potentiometric surface; and a classification and culling process of the DST data was employed to omit anomalous pressure readings. This culling process will be further elaborated in the discussion of investigative methods.
Brine Data

Newcombe (1933) reported that the chemical composition of the brines of the Michigan basin were influenced by both local and regional trends. Newcombe illustrated an increase in the concentrations of calcium chloride (CaCl$_2$), potassium chloride (KCl), and bromine (Br$_2$) with depth and nearness to the structural center of the basin. A corresponding decrease in the amount of sodium chloride (NaCl) was also observed in this direction. The differentiation of Devonian brines was also described by Newcombe (1933). The Traverse brines were described as having higher specific gravities and higher concentrations CaCl$_2$ and Br$^-$ than Dundee brines. Brines of the Detroit River Group were described as having greater concentrations of CaCl$_2$ and Br$^-$ than either Traverse or Dundee brines, with the Br$^-$ concentration almost twice that of the Dundee. Newcombe hypothesized that the "composition of the brines indicates they are connate waters which have been reconcentrated by leaching and modified by chemical interchange of radicals." (Newcombe, 1933, p. 189).

During 1930 and 1931, the Dow Chemical Company conducted many studies of the Mississippian Marshall Sandstone brines since the brines were a major source of
Figure 12. Contour Map of Equal Static Water Head in the Marshall Sandstone (From Newcombe, 1933).
chemicals for the company. Static head levels were carefully observed to determine what effect the structure had on the hydraulic head. Static water levels were mapped along the west side of the Greendale high by the Mt. Pleasant oil field (Figure 12). The heads measured were quite variable, ranging from 190 feet above sea level to almost 600 feet above sea level (Newcombe, 1933). A definite relationship between structure and hydraulic head was observed in the Marshall Sandstone. It was also discovered that the bromine content on structural highs was much less than in synclinal areas. These principles were then employed by Dow Chemical in a manner similar to hydrocarbon exploration for determining the maximum recovery of both bromine and other contained chemicals (Newcombe, 1933).

Traverse brines are not generally located on structural highs, and if present are easily exhausted. Dundee brines have often created difficulties in oil recovery because of their encroachment tendencies. The edgewater around the fields is often the limiting factor defining the edges of production. Edgewater encroachment of the Dundee brines can significantly reduce the production potential of a field (Newcombe, 1933).
INVESTIGATIVE METHODS

Drillstem Test Classification

Drillers' logs and scout tickets were examined for drillstem test data within the Dundee Limestone. Using incomplete DST records, such as those found on scout tickets, requires careful examination of the pressure data. In order to determine data reliability, a classification scheme modified after Bair et al. (1985) was employed. The ISIP was the value used for calculating equivalent fresh-water heads and constructing the potentiometric surface. If the ISIP and FSIP were found to be equal, the pressure was taken to be a good estimate of true formation pressure (Bond, 1972; Dahlberg, 1982). In cases such as this, the aquifer is large enough so that ground-water barriers do not affect the data (Negalia, 1979). If a discrepancy exists between the ISIP and FSIP, the ISIP is commonly the higher of the two and is the best estimate of actual pressures. When this occurred, the time of the shut-in periods became extremely important in determining the reliability of the test. A hydrostatic head of one pound per square inch (psi) corresponds to 2.2 feet of water. Therefore, if the pressure reading is ±5 percent
reliable, the maximum error can be as great as 10 psi or 22 feet of water (VanPoolen and Bateman, 1958).

The classification scheme for the DST data was modified after Bair et al. (1985). Five categories were used for classification according to test reliability:

Class 1: Includes all complete DSTs with pressure response curves.

Class 2: The ISIT and FSIT must be greater than or equal to 60 minutes; and the FSIP must be within +5% of the ISIP.

Class 3: The ISIT and FSIT must be greater than or equal to 30 minutes; and the FSIP must be within +5% of the ISIP, but not qualifying for Class 2.

Class 4: The ISIP must be equal to the FSIP, but no shut-in times were reported.

Class 5: All remaining test data that did not qualify for Class 1, 2, 3, or 4.

Bair et al. (1985) reported potentiometric mounds were produced when Class 1 data were used along with lower classified data. Since no Class 1 data were found in the study area, this problem did not have to be addressed. Class 5 data were excluded on the basis of their questionable reliability.
Several bottom-hole pressure (BHP) values were included and plotted on the pressure-depth diagrams to evaluate their usefulness in defining the potentiometric surface. BHP data are obtained from drill-stem tests in which there is only one flow and shut-in period. As a consequence, there is no second pressure reading with which to compare results. All BHP data had 30 minute or greater shut-in times. These data are identified with a numerical symbol on the potentiometric surface and should be recognized as deficient in quality relative to the DST values. In a more regional study, data of this type would need to be excluded.

The study area is relatively small in areal extent, and the number of high quality data was proportional in size. Because of this, a search was done for DST data from counties surrounding the study area to accentuate local results. Considering that many workers have worked with much less control when constructing potentiometric surfaces of other sedimentary basins, the number of control points was considered satisfactory. Hitchon (1969a,b) utilized, on the average, one fluid potential datum point per 200 cubic miles of sedimentary rock in the well explored western Canada sedimentary basin. In the Surat basin, Queensland, Australia one fluid potential measurement per approximately 500 cubic miles
of sedimentary rock was used to construct a potentiometric surface (Hitchon and Hays, 1971).

**Pressure-Depth Gradient Diagrams**

Formation pressure is equal to the "hydrostatic pressure exerted by a column of water extending from its potentiometric level down to the point of measurement" (Bair et al., 1985). Hydrostatic pressure gradients are dependent on fluid density (Figure 13). This method is a simple way to determine the hydrostatic gradients of the water system. For example, the hydrostatic gradient of fresh or brackish waters is approximately 0.433 psi/ft, brines with total dissolved solids concentrations of 200,000 mg/l have a hydrostatic pressure gradient of 0.465 psi/ft, and heavy oil has a gradient of 0.404 psi/ft (Bair et al., 1985).

After the DST data were classified according to reliability, pressure-depth diagrams were constructed. The data can be further culled if aberrant points do not lie along the general trend of the majority of the data. Overpressured and underpressured points on the diagrams do not infer hydrodynamic connotations (Bair et al., 1985).
Figure 13. Pressure-Depth Gradient Plot for Various Fluids (From Dahlberg, 1982).
Calculation Of $H^{\text{iso}}$

To determine $H^{\text{iso}}$ from drillstem test results, the pressure of the formation must be known at some elevation. The recovery of fluids should also be observed. The pressures of DSTs are reported most often in pounds per square inch as gauge pressure (psig) with the elevation of the tested interval specified. Because the tested zone frequently spans several or tens of feet, the mid-point of each tested interval was used as the elevation of the test. The pressures were converted to equivalent feet of fresh-water by multiplying by the factor of 2.31 (Bond, 1972). Thus:

$$H^{\text{iso}} = \text{elev} + [(\text{equiv feet fresh-water head}) - (\text{gauge depth})].$$

The equivalent fresh-water heads were contoured, creating a potentiometric surface of the study area. Because it could not be determined if the resultant potentiometric surface was representative of regional or local trends, DST data from outside of the study area were investigated. The number of reliable data found outside of the study area limits was small, but these data were included in the final analysis.
Permeability Trends

Thousands of drillers logs were inspected for water information within the Dundee Limestone. Production from the Dundee began during the early thirties and attained a maximum level during the 1940s. The vast majority of the wells used to explore and produce the Dundee were drilled with cable-tool rigs. This allowed for the formation to be tested for fluid recovery. When the formation was opened to the surface, porous zones saturated with water would begin to produce into the well under the natural formation head. The amount of fill-up was recorded most often in feet of head, along with the duration the well operator allowed this process to take place. Because of the low probability that the fill-up would achieve hydraulic equilibrium in the amount of time most operators allowed for down-rig time, the recorded heads could not be used as hydraulic head approximations. Nonetheless, an attempt was made to determine equivalent fresh-water heads for fill-up data given twelve or more hours to equilibrate. An equation from Bond (1972) to determine equivalent fresh-water heads from static water levels in saline aquifers did not produce plausible conclusions.
In terms of the amount of fill-up versus time, a relative permeability profile can be estimated. For example, if 2000 feet of fill-up were recorded in one well during a five-hour period, while in another well only 300 feet were reported in the same amount of time, a relative permeability difference is indicated. The fill-up data were classified both in terms of the amount of fill-up and the time allotted to the process. In the first division, (I), all data with the times equal to or less than five hours were compared on the basis of feet of fill-up. Class A wells had fill-ups of 0-500 feet of water in the hole. Class B wells ranged from 501-1000 feet of fill-up, while Class C had fill-ups exceeding 1000 feet of head.

Wells that were allowed to produce formation waters within the range of 5-12 hours were placed in Division II, and Division III wells were allowed to go toward equilibrium for 13 or more hours. Division IV wells did not report any time information.

The vast majority of the data fell into Division I and Division IV categories. Division I wells were used to contour the permeability trends (Plate I). Division II, III, and IV wells were used as general indicators of the extent of the permeable or non-permeable zones adjacent to Division I control points. The resulting
permeability trends were then related to the potentiometric gradient and structure.

Structure Contour Map

A structural contour map was constructed of the study area on the base of the Bell Shale (Plate II). The structural trends were defined using 709 control points and a 50-foot contour interval. The control points are not a representation of all wells in the area, but a majority of those located in the study area are identified. Dry holes and producers are signified only for the Dundee. Production from other formations were not labeled. Oil accumulations of the Dundee were identified, and regional trends analyzed. The relationships between the structure and oil fields to the potentiometric surface were observed. Structure was also related to specific gravity trends and permeability.
RESULTS

Drillstem Classification Results

Twenty-two (see Appendix A) of the most promising DSTs found among the drillers' logs and scout tickets were classified according to the writer's modified classification scheme. Three tests qualified for Class 2: L, N, and Q. Seven tests qualified for Class 3: F, G, H, J, P, and V. Seven tests fell into Class 4: B, C, P, I, M, and O; five tests were classified as Class 5: K, R, S, T, and U. Class 5 data were disqualified for use in constructing the potentiometric surface.

The DSTs were then plotted on a pressure-depth diagram (Figure 14). Although tests M and Q plotted along the trend of the majority of the data, their recoveries of mud and gas were the basis for their disqualification. Of the remaining data, N, O, P, and V were disqualified on the basis of recoveries and anomalous pressure readings.

The continuity exhibited by the data, when points at a wide range of depths and at different geographic locations throughout the central and western portions of the basin are plotted, reveals that a hydraulic connection exists. DST tests K and J up dip from the...
Figure 14. Pressure-Depth Gradient Plot for Dundee Limestone Brines. Pressures Acquired From Drillstem Tests.
majority of the data also fall on the hydrostatic trend. This is further evidence of a hydraulic connection between the western flank of the basin and the central basin area.

BHP data (see Appendix A) was also included in the pressure-depth plotting. Fluid recoveries and shut-in times were carefully examined. It was hoped that these data would give a general indication of flow in areas away from the study area, and further define the potentiometric surface in areas of more control. Five BHP readings within the study area were calculated for equivalent fresh-water heads. One data point located in Lake County was found to be accurate enough to be included in the interpretation outside of the study area.

Many other BHP data were examined and disqualified on the basis of shut-in times, recovery, lack of permeability, and placement on the pressure-depth diagram. The writer was most confident of the six BHP data-points included in the interpretation. Only these points are shown on the pressure-depth diagram. It is interesting to note that BHP number six is equal to DST F in hydraulic head. Both tests are located in section 30, T15N, R6W of Isabella County, but they are from different wells. Test F was recorded at a depth of -2744 feet below sea level and BHP 6 was recorded at a depth of
-2957 feet below sea level. These data support the conclusion that the permeable zones in the Dundee are hydraulically connected.

Sixteen hydraulic head calculations were used to construct the potentiometric surface, with the majority of the control points located within or close to the study area boundaries (Figure 15). A potentiometric high is located in the northern half of Clare County with a decrease in head southwestward. The lack of control to the south, east, and north of the study area creates difficulty in determining the regional flow of the basin. The proximity of the study area to the structural center of the basin may also be revealing some local effects. This may account for the rather anomalous shape of the surface in the study area.

The maximum equivalent fresh-water head is located in section 3, T19N, R5W of Clare County with a value of 704 feet above sea level. The lowest equivalent fresh-water head calculated is located in section 36, T15N, R17W of Oceana County with a value of 457 feet above sea level. The total drop in potential was calculated to be approximately 250 feet from near the center of the basin in Clare County to the center of Oceana County. It is important to remember that the resulting potentiometric gradient is only a qualitative
Figure 15. Potentiometric Surface of the Dundee Limestone. Contour Interval 50 Feet; Datum Sea Level.
description of the fall in potential over the area. The resulting heads should not be assumed to be quantitative in character.

The hydraulic gradient is steeper near the center of the study area with an abrupt drop from a head of 650 feet to a head of 550 feet in approximately 12 miles. Toward the southwest, the gradient seems to be more gentle in nature; however, the lack of control makes it difficult to calculate a true hydraulic gradient.

If the potentials recorded are correct, a change in flow direction may be present along the potentiometric nose that plunges toward the southwest within the study area bounds. Under these conditions flow would occur toward the west and southwest on the western side of the nose, and towards the east on the eastern flank. An east-west tilt of the oil interface in the Mt. Pleasant field of Isabella and Midland counties has been reported. This would correspond to the potential contours with flow paths directed toward the east in this area.

Toward the southwest, more control is available, and flow seems to be toward the outcrop area of the Dundee under Lake Michigan (Figure 8).
Specific Gravity Results

Dundee brine data (Appendix B) from around the central basin province were collected and plotted on a depth versus specific gravity profile (Figure 16). An increase in specific gravity is apparent with an increase in depth. The specific gravity data from within the study area were also plotted to illustrate the variations in density within the bounds of the area (Figure 17). The specific gravity generally does not show a great variability within the study area and does not seem to be of great enough magnitude to alter flow directions.

The specific gravities from the study area and the surrounding province were then contoured to illustrate the regional trends relative to the structural center of the basin and the potentiometric surface (Figure 18). High and low, or anomalous points were not culled because there should not be as great a possibility of recording an inaccurate test result as with a drillstem test. Also, high specific gravity values, corresponding to a greater salinity of the ground water, tend to occur in conjunction with oil accumulations in stratigraphic traps (McNeal, 1965).
Figure 16. Specific Gravity Versus Depth of the Dundee Limestone Brines of the Central Michigan Basin Province.
Figure 17. Specific Gravity Versus Depth of the Dundee Limestone in the Study Area.
Figure 18. Contour Map of Specific Gravities of the Dundee Limestone Brines Contour Interval .010.
Specific Gravity Trends

The specific gravity of the Dundee brine tend to increase with depth and nearness to the structural center of the basin. The northwest trending nose of low salinity brines on the southeastern edge of the specific gravity contours is directly related to the Howell Anticline. The general trends, when contoured, correlate fairly well in a regional sense to the potentiometric surface. A nose of low salinity in the northern half of Clare County correlates closely with the high potentiometric nose in the same area. This could signify the vertical inflow of water into the Dundee from a formation with a lower specific gravity and higher pressure. Faults are also present in this area (Figure 6), and may act as channelways for basinal fluids. The Na/Cl ratios of the brine samples within the study area were plotted to determine if they were characteristic of waters which had undergone halite dissolution (Figure 19). Most points were gathered close to the ratio for a sea water origin. Graf et al. (1966) concluded that the brines of the Michigan basin were a mixture of sea water and fresh waters, with evidence of dissolved bedded salts present along the margins of the basin where salts in the Silurian Salina Group have been dissolved. If water
Figure 19. Illustration of Na/Cl Ratio in Brine Samples of the Dundee Limestone.
was passing upward in the central basin area, it is doubtful if the chemical nature of the fluid would allow solution of the evaporites in the deep basin environment.

Permeability Trends

The permeability of the Dundee can be related to structural highs within the study area (Plate I, Plate II). Low permeability zones correspond to the synclinal structure which trends northwestward through the study area (Plate II). In zones of petroleum production along structural highs, the permeability of the formation increases. The petroleum accumulations do not however define the entire extent of the permeable zones, since there are zones of high permeability with no oil accumulation. There are also zones of low permeability along the structural highs. The permeability is variable on the Broomfield high, most likely due to changes in lithology such as an alteration of limestone to dolomite. The more permeable areas around the edges of the study area may be directly related to the regional dip of the Dundee with an increase approximately coincident with the -2850 structural contour in the northern portion of the study area, and with the -2600 contour towards the south.
Relation To Potential Gradient

The potential gradient becomes steeper along an arcuate band extending from the Broomfield High northeastward. It has been reported that variable permeabilities may cause anomalies in the potentiometric surface. Hitchon (1969b) recognized that rapid changes in lithology and thus permeability are commonly associated with steep hydraulic gradients. He also observed a tendency of some formations of the western Canada sedimentary basin to produce oil only in zones of steep hydraulic gradients. In the study area, it is interesting to note that the majority of the oil accumulations are located in the region of the steep hydraulic gradient (Plate II). This may be due to the fact that the flow is much more stagnant throughout this area, thus producing an environment favorable to hydrocarbon accumulation.

Structural Relationships

Plate II displays the structural contour map on the top of the Dundee Limestone. 709 control points were used to define the structure within the study area. Local structure does not seem to be a major influence on flow patterns. A more detailed study of the potential
variations however, might show more local distortions of the potentiometric surface as is seen in the Marshall Sandstone (Figure 12).

The regional structure may influence the flow direction with flow occurring up dip, away from the structural center of the basin, at least in the area of data control. This may correspond to an upward movement of fluids in this area which is the argument expoused by Graf et al. (1966). However, without data surrounding the basin center, it is difficult to discern if the regional structure is a controlling factor.

The areas of petroleum accumulation shown on Plate II appear to be preferentially distributed in the area of steep hydraulic gradient. The writer believes this to be due to the geology of the area, rather than the effect of structure.

Effect of Topography

The physiography of the Southern Peninsula may offer the most convincing argument as to the control of flow direction. The Southern Peninsula is divided into four major topographic provinces (Figure 20). The Northern Upland attains the highest average elevation ranging from 1100 to 1300 feet above sea level (Newcombe, 1933). The highest elevations in the area are located in Osceola,
Figure 20. Physiographic Provinces of the Lower Peninsula of Michigan (From Newcombe, 1933).
Wexford, Missaukee, Crawford, and Otsego Counties. The other topographically high province is located in the Thumb Upland with elevations between 800 and 1000 feet above sea level (Newcombe, 1933). Two low areas are present in the Lower Peninsula: the Saginaw Lowland and the Michigan Lowland. The Michigan Lowland is located along the western edge of the state and is generally at an attitude of 700 to 900 feet in elevation, while the Saginaw Lowland ranges between 600 and 800 feet above sea level (Newcombe, 1933).

It is interesting to note that the potentiometric surface illustrates flow occurring toward both lowland areas, with the flow divide located approximately in the area where the two lowlands meet (Figure 20). The high potential values may also be influenced by the Northern Upland, which is not only topographically high, but also the location of Dundee outcrops. The potentials decrease toward Lake Michigan as expected, with an outcrop elevation of the Dundee at about 180 to 280 feet above sea level.

This hypothesis corresponds to Hitchon's (1969a) work dealing with the effect of topography on fluid direction. Unfortunately, no data are available to discern the nature of the flow east and south of the study area. If topography is a major control on flow
direction in the Michigan basin, the Thumb Upland should also impart an influence.
CONCLUSIONS

A potentiometric surface was constructed for the central basin area of the Michigan basin with pressure readings from the Dundee Limestone. The quality of the data used to construct the surface was generally poor due to testing procedures employed by the petroleum industry. The importance of pressure data in evaluating reservoir parameters is just beginning to be recognized. Unfortunately, this has not always been the case. More data of better quality will no doubt require that sizeable changes be made in the potentiometric surface as drawn for this study. Given the existing data base, however, the general trend of water moving toward the potential low of Lake Michigan on the western half of the state seems reasonable.

Pressure data were screened and culled to insure that the readings were not anomalous in nature, and so that a regional flow net could be constructed. The potentiometric surface was then compared to specific gravity trends, structure, permeability, and regional topography.
The specific gravity trends did not seem to exert an appreciable effect on the potential, although the regional decreases in each did correspond. In no place was the density contrast sufficient to cause a reversal of flow directions due to variable densities of the brine. Specific gravity varied as a function of depth and structure.

The steep hydraulic gradient located near the center of the study area may reflect changes in permeability in the Dundee. Steeper gradients are commonly associated with areas of variable or reduced permeabilities (Hitchon, 1969b). This may be beneficial as a trapping mechanism, producing more stagnant conditions throughout this arcuate belt of high potential gradient.

Without further data surrounding the structural center of the basin, it is difficult to ascertain if the regional dip of the Dundee is a controlling factor in water movement. Graf et al. (1966) proposed that ground water is moving upward near the basin center, and the high potential in this area may be a result of this process. The local structures in the central basin area do not seem to affect the regional flow pattern, as isopotential lines generally cross structural contour lines. A more detailed study may prove that local structures do exert some effect on flow direction. Local
effects such as these, however, are often considered to be anomalous in nature in regional studies.

The regional surficial topography of the Southern Peninsula may produce the most influence upon flow directions in the Dundee Limestone. High areas in the northern Southern Peninsula also correspond to outcrop areas of the Dundee. Lake Michigan has been reported to be a potentiometric low (Graf et al., 1966), and the Dundee Limestone is at its lowest outcrop elevation on the Lake floor (Figure 8). The divide between the two topographic lowlands, the Michigan Lowland and the Saginaw Lowland, corresponds closely with the divide on the potentiometric surface.

In order to gain a better understanding of the flow patterns of the Michigan basin, it would be necessary to conduct a basin-wide multi-formational study to determine where and how vertical flow occurs between formations, and what effect surficial features impart at depth to flow circulation. This study was based on the assumption of horizontal flow, approximately parallel to the bedding planes of only one formation. It becomes obvious that similar studies of formations with more recent exploration and production activity would greatly contribute to the understanding of the migration of fluids in the basin. Geochemical studies would also be
invaluable in determining the relationships between formations and directions of fluid flow.
Appendix A

Drillstem Test And Bottom-Hole Pressure Data
<table>
<thead>
<tr>
<th>OPERATOR &amp; LESEE</th>
<th>LOCATION</th>
<th>ELEVATION (FT)</th>
<th>ELEV TEST (FT)</th>
<th>ISIP (psig)</th>
<th>FSIP (psig)</th>
<th>RECOVERY</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Tartan Oil C. Barker</td>
<td>15-17N-8W</td>
<td>1150</td>
<td>-2761</td>
<td>1439</td>
<td>1439</td>
<td>200' blk muddy salt wtr</td>
</tr>
<tr>
<td>B. Coy Oil</td>
<td>14-18N-10W</td>
<td>1163K</td>
<td>-2511</td>
<td>1313</td>
<td>1313</td>
<td>60' muddy blk wtr + 1200' blk wtr</td>
</tr>
<tr>
<td>C. Hevel &amp; the MOCO</td>
<td>23-17N-6W</td>
<td>856</td>
<td>-2974</td>
<td>1559</td>
<td>1559</td>
<td>3530' brackish wtr</td>
</tr>
<tr>
<td>D. Paul G Neuhart</td>
<td>3-19N-6W</td>
<td>1153K</td>
<td>-2867</td>
<td>1546</td>
<td>1546</td>
<td>1580' alt wtr</td>
</tr>
<tr>
<td>E. Billy G Ellis</td>
<td>21-19N-6W</td>
<td>1055K</td>
<td>-2837</td>
<td>1510</td>
<td>1508</td>
<td>650' alt wtr</td>
</tr>
<tr>
<td>F. JV Wicklund, Jr</td>
<td>30-15N-6W</td>
<td>1040K</td>
<td>-2744</td>
<td>1440</td>
<td>1440</td>
<td>582' 100' drlg mud + 540' blk alt wtr</td>
</tr>
<tr>
<td>G. DJ Hall &amp; the MOCO</td>
<td>26-16N-5W</td>
<td>905K</td>
<td>-3133</td>
<td>1632</td>
<td>1632</td>
<td>637' 80' mud + 540' alt wtr</td>
</tr>
<tr>
<td>H. Jack Hall Oil Co</td>
<td>10-16N-6W</td>
<td>1117R</td>
<td>-2882</td>
<td>1536</td>
<td>1536</td>
<td>666' 45' gas + 445' alt wtr</td>
</tr>
<tr>
<td>I. Slagter Prod.</td>
<td>17-20N-8W</td>
<td>1372K</td>
<td>-2705</td>
<td>1430</td>
<td>1430</td>
<td>598' 86' sly drlg fluid + 170' sly wtr</td>
</tr>
<tr>
<td>J. Pure Oil</td>
<td>36-15N-17W</td>
<td>733R</td>
<td>-1698</td>
<td>933</td>
<td>925</td>
<td>457' 630' muddy alt wtr + trace oil</td>
</tr>
<tr>
<td>K. Consumers Power et al</td>
<td>15-10N-17W</td>
<td>633K</td>
<td>-1444</td>
<td>779</td>
<td>769</td>
<td>355' 300' gas + 180' sly o-gem + 240' muddy alt wtr</td>
</tr>
</tbody>
</table>

<p>| L. Coy Oil               | 23-15N-8W  | 1067          | -2766         | 1435        | 1435        | 540' gas + 310' o-gem + 143' o-gem sly wtr |
| M. Mountain Oil &amp; Gas    | 22-19N-10W | 1233          | -2475         | 1280        | 1280        | 482' 70' o-gem + 90' sly wtr + 3' muddy alt wtr + 765' gas |
| N. McLure Oil &amp; Gas      | 27-13N-4W  | 836K          | -2772         | 1579        | 1579        | 875' 628' drlg mud + sho brine + few gas bubbles |
| O. CJ Moskowitz Raldon Pasc #1 | 13-15N-5W | 847K | -2953 | 1629 | 1629 | 810' 1550' alt wtr |
| P. Don Yohe Enterp. Lake Isabella Corp #1-9 | 9-14N-6W | 1036K | -2718 | 1576 | 1576 | 923' 1922' gas + 1600' oil + 100' drlg fluid |
| Q. Mich Consol Gas Leach #1 | 4-17N-9W | 1059R | -2613 | 1403 | 1403 | 549' gas to surf 7min, flowed oil cut mud |
| R. Leonard Oil WI Roundtree et ux #1 | 29-17N-7W | 1125 | -2008 | 1442 | 1426 | 523' 1380' gc muddy sly wtr + 1650' gc sly wtr |
| S. GE Organek Sager #1 | 11-18N-9W  | 1326          | -2610         | 1420        | 1420        | 670' 300' gas + 555' sly wtr |
| T. Don Yohe Enterp. G McArthur #1-9 | 9-14N-6W | 1024K | -2721 | 1562 | 1562 | 887' 645' drlg fluid |
| U. Lud Segerslund P Ruehi #1 | 11-19N-5W | 1190R | -2893 | 1494 | 1494 | 558' 2730' blk alt wtr |
| V. Sun Oil Jacobson Unit #3 | 14-18N-17W | 708K | -1517 | 804 | 793 | 340' 1740' gas + 90' sly sulphur wtr + 175' o-gem + sho oil |</p>
<table>
<thead>
<tr>
<th>OPERATOR &amp; LESEE</th>
<th>LOCATION</th>
<th>ELEVATION</th>
<th>ELEV TEST (MIDPOINT)</th>
<th>SIT</th>
<th>H</th>
<th>RECOVERY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sun Oil State-Evart A #1</td>
<td>6-17N-8W</td>
<td>1059'</td>
<td>-2740'</td>
<td>1402psi</td>
<td>499'</td>
<td>840' muddy alt wtr + 1915' alt wtr</td>
</tr>
<tr>
<td>2. Coy Oil Fleming Estate #1</td>
<td>5-17N-8W</td>
<td>1000RB</td>
<td>-2754</td>
<td>1437</td>
<td>565</td>
<td>365' muddy alt wtr + 825' blk wtr</td>
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<tr>
<td>3. Farmers Pet Cooper Patty Ann Pederson #1</td>
<td>3-15N-8W</td>
<td>1033RB</td>
<td>-2756</td>
<td>1430</td>
<td>547</td>
<td>125' mud + 120' alt wtr</td>
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<tr>
<td>4. Taggart Co. Alvil Moore #1</td>
<td>5-16N-6W</td>
<td>1123RB</td>
<td>-2865</td>
<td>1543</td>
<td>699</td>
<td>240' muddy alt wtr</td>
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<tr>
<td>5. WW Mesel/ The MOCO Ira Hoover et al #1</td>
<td>14-19N-12W</td>
<td>967RB</td>
<td>-2205</td>
<td>1193</td>
<td>551</td>
<td>50' mud + 150' fluid 175' alt wtr</td>
</tr>
</tbody>
</table>
Appendix B

Brine Data
<table>
<thead>
<tr>
<th>LOCATION</th>
<th>TDS-PPM</th>
<th>SPEC.GRAV.</th>
<th>ELEV. TEST</th>
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<tr>
<td>Arenac Co.</td>
<td>34-12U-1E</td>
<td>258,000</td>
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<tr>
<td></td>
<td>11-20U-2E</td>
<td>276,000</td>
<td>1.193</td>
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<tr>
<td></td>
<td>4-20U-2E</td>
<td>272,000</td>
<td>1.197</td>
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<tr>
<td>Bay Co.</td>
<td>10-14U-3E</td>
<td>313,000</td>
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<td>Clare Co.</td>
<td>6-17U-3I</td>
<td>208,000</td>
<td>1.203</td>
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<td></td>
<td>14-10U-6H</td>
<td>293,000</td>
<td>1.212</td>
</tr>
<tr>
<td></td>
<td>12-19U-3I</td>
<td>263,000</td>
<td>1.199</td>
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<td></td>
<td>29-20U-6H</td>
<td>291,000</td>
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<td>Clinton Co.</td>
<td>18-5U-2I</td>
<td>277,000</td>
<td>1.200</td>
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<td></td>
<td>12-5U-2I</td>
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<tr>
<td></td>
<td>19-6U-2I</td>
<td>292,000</td>
<td>1.211</td>
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<tr>
<td></td>
<td>32-7U-1I</td>
<td>274,000</td>
<td>1.199</td>
</tr>
<tr>
<td></td>
<td>22-8U-2I</td>
<td>292,000</td>
<td>1.211</td>
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<tr>
<td>Genessee Co.</td>
<td>31-7U-6E</td>
<td>251,000</td>
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<td>5-9U-8E</td>
<td>301,000</td>
<td>1.217</td>
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<td>Gladwin Co.</td>
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<td>295,000</td>
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<td>301,000</td>
<td>1.217</td>
</tr>
<tr>
<td>Gratiot Co.</td>
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<td>25-12U-2H</td>
<td>298,000</td>
<td>1.214</td>
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<td>6-12U-2H</td>
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<td>1.215</td>
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<tr>
<td></td>
<td>6-12U-1H</td>
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<td>1.209</td>
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<tr>
<td></td>
<td>6-12U-1W</td>
<td>309,000</td>
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<tr>
<td>Huron Co.</td>
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</tr>
<tr>
<td></td>
<td>32-15U-12E</td>
<td>271,000</td>
<td>1.196</td>
</tr>
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</table>
BIBLIOGRAPHY


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PLATE I

GENERAL PERMEABILITY TRENDS OF THE DUNDEE LIMESTONE
CLASS A
0-500 feet fill-up

CLASS B
501-1000 feet fill-up

CLASS C
1000 feet fill-up

DIVISION I (5hrs)

DIVISIONS II, III, IV

feet fill-up – time (hrs)

ISOPOTENTIAL CONTOUR

POTENTIAL CONTOUR

INTERVAL

50 FEET

SCALE

1:10,000

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CLASS A
0-500 feet fill-up

CLASS B
501-1000 feet fill-up

CLASS C
1000 feet fill-up

DIVISION I (5hrs)

DIVISIONS II, III, IV

100-3 feet fill-up – time (hrs.)

ISOPOTENTIAL CONTOUR

POTENTIAL CONTOUR

INTERVAL

50 FEET

SCALE

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STRUCTURE CONTOUR ON THE DUNDEE LIMESTONE AND POTENTIOMETRIC SURFACE
STRUCTURE CONT
DUNDEE LIMES:
POTENTIOMETRIC

STRUCTURAL CONT
INTERVAL
50 FEET

POTENTIAL COI
INTERVAL
50 FEET

SCALE
1:48,000

KEY
Dundee Dry H

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