PATTERNS OF REGIONAL SUBSURFACE FLUID MOVEMENT IN THE MICHIGAN BASIN

by

Raymond Vugrinovich
Geological Survey Division
Michigan Department of Natural Resources

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ABSTRACT

Hydrologic information in the form of subsurface pressure measurements or static water level measurements, associated surface elevations and depth measurements, and water analyses, is abundant for many aquifers in the Michigan Basin. The data was used to generate hydraulic head maps, pressure-vs depth graphs, dP-D-Z charts, and hypsographic distributions of hydraulic head and surface elevations for 11 aquifers in rocks ranging in age from Cambrian to Pennsylvanian. The resulting maps and charts were then interpreted in terms of fluid flow patterns.

Aquifers in rocks of the Saginaw Group (Pennsylvanian P1 aquifer), Marshall Sandstone (Mississippian M2 aquifer), Traverse Group (Devonian D3 aquifer), Dundee Limestone (Devonian D2 aquifer), and Detroit River Group (Devonian D1 aquifer) are regionally unconfined and that flow in these aquifers occurs in response to surface elevation differences. Regional topographic highs act as recharge regions and regional topographic lows act as discharge regions. Cross-formational fluid flow, even across aquitards, probably supplies most of the recharge. Except for the P1 aquifer, the aquifers are not in complete equilibrium with either the present land surface or bedrock surface. The aquifer in the Dundee Limestone is notable for a pronounced hydraulic low centered over the Lower Peninsula. Hydrocarbon production is believed to be the cause of the hydraulic low.

The Berea Sandstone (Mississippian Ml aquifer), the Silurian age A-2 carbonate (Silurian S3 aquifer), A-1 carbonate (Silurian S2 aquifer), and Niagara and Clinton Groups (Silurian S1 aquifer) host aquifers which are totally confined in the central basin. Moderate to severe overpressuring occurs in the confined portions of the aquifers while nominal to subnominal pressure is observed in the unconfined portions. Where the aquifers are unconfined, they display many of the characteristics of the previously-discussed group of aquifers. The Silurian S2 and S1 aquifers are marked by hydraulic lows in the southern part of the Lower Peninsula. The origin of the hydraulic lows is not known.

Aquifers in rocks of the Trenton and Black River Groups of Ordovician age (Ordovician O2 aquifer), the St. Peter Sandstone and Prairie du Chien Group (Ordovician O1 aquifer) and the Mt. Simon Sandstone (Cambrian C1 aquifer) are characterized by subnominal pressures at all but the shallowest depths. Present-day topography has only minor, if any, influence on flow patterns. The aquifers receive recharge at the outcrops. The O1 aquifer may discharge into the underlying C1 aquifer, but sparse data for the latter aquifer make this conclusion speculative. The aquifer in sub-Black River rocks exhibits a hydraulic low of unknown origin in the central portion of Michigan's Lower Peninsula.

Nothing is known of hydraulic properties of the Keeweenawan clastic rocks that underlie the Mt. Simon in the Lower Peninsula. The pre-Keeweenawan basement is assumed to be the lower limit of effective permeability.

INTRODUCTION

The movement of deep groundwater influences or has influenced many aspects of sedimentary basins. An understanding of the present day hydrology of deep groundwater serves as the basis for understanding the paleogeohydrology and its effects during basin evolution. Patterns of regional subsurface water movement are also of importance in planning for subsurface waste disposal.

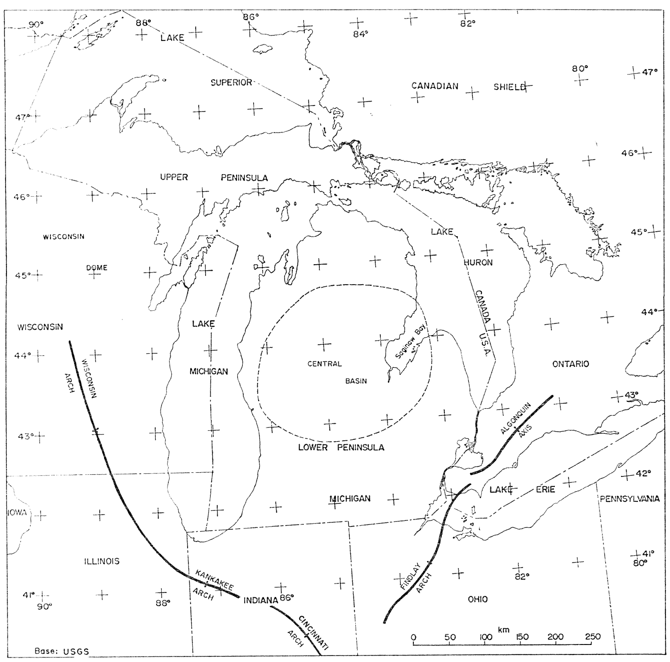
Several energy-related characteristics of aquifers are useful in determining regional patterns of subsurface water movement. These include (1) regional petterns of hydraulic head, (2) vertical subsurface pressure-depth gradients (referred to in the body of this paper as “pressure gradients”), (3) water table elevation, (4) the relationship between the dynamic pressure increment, surface elevation and depth, (5) hypsographic distribution of surface elevation and hydraulic head, (6) the degree of correlation between pressure gradients and elevation (Toth, 1978, 1979). The present study makes use of these characteristics to document the movement of deep groundwater and to show the occurrence of gravity-driven groundwater movement in the Michigan Basin.

THE MICHIGAN BASIN - REGIONAL SETTING

The Michigan Basin (figure 1) lies beneath the Lower Peninsula of Michigan and extends into Michigan's Upper Peninsula, the neighboring states of Illinois, Indiana, Ohio, Wisconsin, and the Province of Ontario, Canada. On the west, south, and east, the Michigan Basin is bounded respectively by the Wisconsin Dome and the Wisconsin Arch, the Kankakee, Cincinnati, and Findlay Arches, and the Algonquin Axis. Precambrian rocks of the Canadian Shield occur to the north.

Elevations in the study area range from less than 60 meters above sea level to more than 500 meters above sea level (figure 2). The bedrock surface mirrors the surface topography and is generally from 50 to 100 meters lower than the surface (figure 3).

FIGURE 1



Aquifers and aquitards are named for the geologic system in which the rocks occur, using the first letter of the system name followed by a number (for aquifers) or a lower-case letter (for aquitards) (figure 4). Lower numbers indicate stratigraphically lower units in a given system. The letter “a” represents the stratigraphically lowest aquitard within a system, “b” the next highest, and so forth. Figure 4 is not a stratigraphic chart. Contact relationships, stratigraphic sequence, and correlations between Michigan rock units and rock units outside of Michigan are as shown by the American Association of Petroleum Geologists (1985).

FIGURE 2

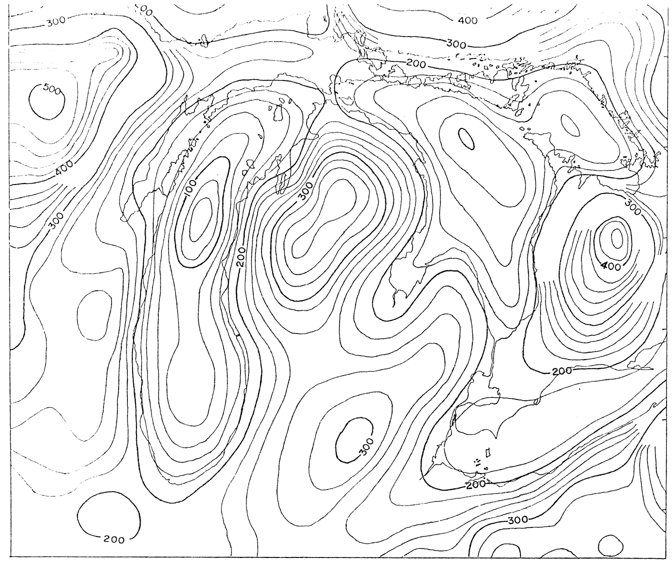
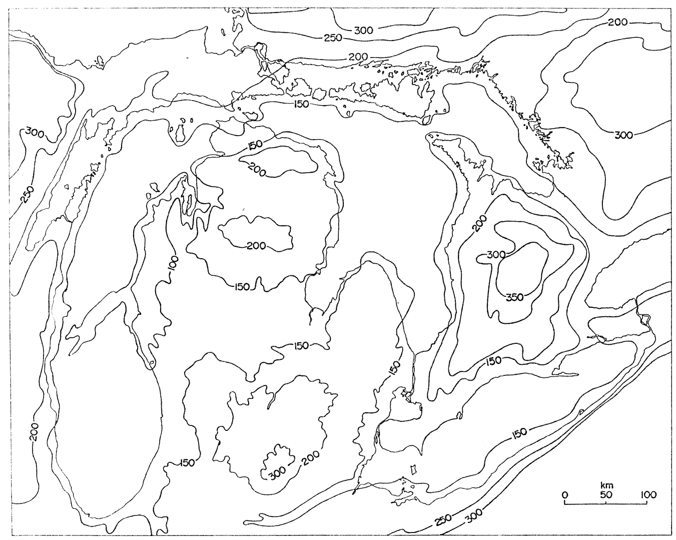


FIGURE 3



In this study, basement rocks are any rocks of pre-Keeweenawan age. Basement rocks outcrop only in the northern portion of the study area (figure 5). The geohydrology of the basement rocks of the Lower Peninsula is not known; basement rocks are assumed to be the lower limit of effective permeability.

The maximum thickness of Keeweenawan rocks in the Lower Peninsula is not known from drilling; COCORP seismic studies suggest a thickness of more than 9 km (Brown and others, 1982). The hydrologic conditions of the Keeweenawan rocks of the Lower Peninsula is also unknown.

The maximum thickness of Paleozoic rocks probably exceeds 4500 m in the central part of the Lower Peninsula (Hinze and others, 1975, Brown and others, 1982). The Paleozoic rocks can be divided into three groups:

1) Sandstones, sandy dolomites, dolomites and shales of Cambrian age. The C1 aquifer and Ca aquitard are in this group.

2) A sequence of Ordovician to Middle Devonian age consisting of carbonate rocks interbedded with evaporites, shaly carbonate rocks, shales and minor sandstones. Aquifers occupy the carbonates and sandstones; rocks of other lithologies form aquitards. This group contains the O1, O2, S1, S2, S3, D1, D2 and D3 aquifers and the Oa, SOa, Sa, Sb, SDa, Da and Db aquitards.

3) A Late Devonian to Pennsylvanian sequence consisting predominantly of shale with interbeds of sandstone, siltstone, and thin beds of carbonate rocks and evaporites. The M1, M2 and P1 aquifers occupy sandstone or siltstone beds. Shales constitute the Dc, Ma and Mb aquitards.

Figure 4

PERIOD	HYDROGEOLOGIC DESIGNATION	LITHOLOGY	MICHIGAN ROCK UNITS	THICKNESS (m)
Pennsylvanian	P1	SS ST SH ls	Saginaw Gp.	120
	Mb	SH ls do an gy	Michigan Fm. Bayport Fm.	180
Mississippian	M2	SS sh	Marshall Ss.	90
	Ma	SH st ls	Coldwater Sh./ Ellsworth Sh.	560
	M1	SS sh	Berea Ss.	30
	Dc	SH st	Bedford Sh./ Antrim Sh.	270
	D3	LS do sh an	Traverse Gp. (exc. Bell Sh.)	250
Devonian	Db	SH ls	Bell Sh.	35
	D2	LS do	Dundee Ls.	75
	Da	DO HA AH ls	Upper Detroit River Gp.	360
	D1	LS DO ss	Lower Detroit River Gp.	160
Silurian/ Devonian	SDa	LS DO SH HA AN	Bois Blanc/ upper Salina Gp.	850
	S3	LS DO	A-2 carbonate	55
	Sb	HA AN do	A-2 evaporite	150
Silurian	S2	LS DO	A-1 carbonate	40
	Sa	HA AN do	A-1 evaporite	150
	S1	LS DO	Niagara Gp./ Clinton Gp.	280
Silurian/ Ordovician	SOa	SH DO	Cabot Head Sh./ Utica Sh.	245
	O2	LS do sh	Trenton Gp./ Black River Gp.	320
Ordovician	Oa	SH st	Glenwood	8
	O1	SS DO sh an	St. Peter Ss./ Prairie Du Chien Gp.	450
	Ca	DO SS sh	Trempeleau Fm./ Eau Claire Fm.	650
Cambrian	C1	SS st	Mt. Simon Ss.	300

Thin sediments of Jurassic age were deposited following a post-Pennsylvanian erosional episode. Unconsolidated sediments up to 250 meters thick were deposited by Pleistocene glacers. The aquifers in these sediments are not considered in this study.

The P1 aquifer occurs in the Saginaw Group, a series of interbedded shales, siltstones, sandstones, and thin limestones and coals, confined to the Lower Peninsula. Porosities in the sandstones commonly exceed 25 percent. No core analyses have been made, but aquifer characteristics suggest high permeability (Western Michigan University, 1981).

The Mb aquitard consists of shale interbedded with thin beds of carbonate rock, anhydrite and sandstone. No hydrologic data is available for the unit beyond the observation that the carbonate rocks and sandstones may be locally water productive. The unit is treated as an aquitard because of its gross lithology.

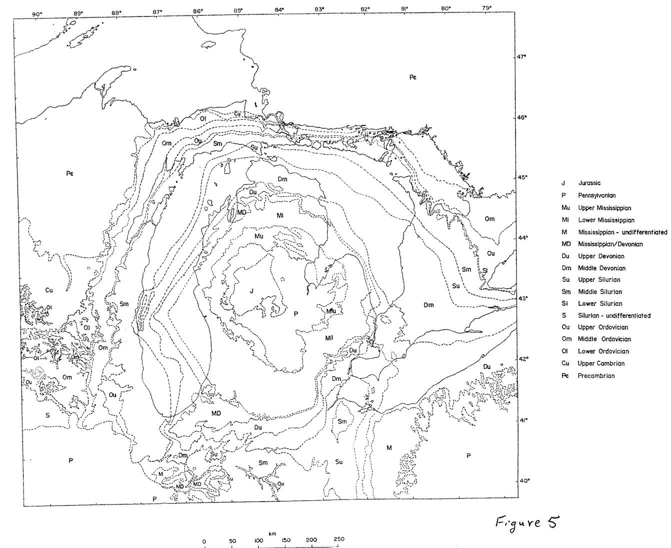


Figure 5

The Mississippian M2 aquifer occurs in the Marshall Sandstone which is confined entirely to the Lower Peninsula. The Marshall Sandstone is of high porosity. Producing characteristics and drillstem tests of the overlying so-called “Stray” sandstone (lithologically similar to the Marshall) suggest high permeabilities.

The Ma and Dc aquitards consist predominantly of shale. Thin beds of siltstone or limestone within the shales are water-bearing and the shales will yield water and hydrocarbons where fracturing occurs, but because of the gross lithology the units are considered to be aquitards. Permeability measurements on cores from the Antrim Shale (the stratigraphically lowest formation in the aquitard) do not exceed 2 millidarcies, with most of the permeabilities being lower than 0.01 millidarcy (Hockings and others, 1979).

The M1 aquifer, found in the Berea Sandstone, is almost entirely confined to the eastern half of the Lower Peninsula. Porosity in the Berea Sandstone ranges as high as 20 percent with positive correlation between porosity and permeability. Permeability is high where the sandstone is not shaly.

Limestones, dolomites, shales and shaly carbonate rocks form the Traverse Group of upper Middle Devonian age. The D3 aquifer occurs in these rocks. Porosity in the Traverse carbonate rocks varies widely over short vertical distances, although zones of similar porosity can be traced laterally over long distances (Lilienthal, 1978). Porosity is highest in the western and extreme southeastern Lower Peninsula of Michigan and decreases toward the central basin area. Fracture and vugular porosity is well-developed in some areas. Permeabilities as high as 1,100 millidarcies occur in the well-developed vugular zones. In Ontario and the central eastern part of the Lower Peninsula permeabilities of Traverse rocks are regionally low, although the presence of small oil fields in Traverse rocks of the eastern Lower Peninsula suggest the local development of moderate permeability.

The Db aquitard, the stratigraphically lowest formation of the Traverse Group, consists of shale. Permeability of the aquitard has never been measured on core samples. A single drillstem test conducted entirely in the aquitard indicated little or no permeability. Low permeability is also suggested by the observation that the shales serve as cap rocks for many of the oil fields in the underlying Dundee Limestone of the central basin.

The Middle Devonian Dundee Limestone is a stratum of carbonate rocks which hosts the D2 aquifer. Over much of the study area Dundee rocks have high porosity. Intercrystalline, fracture and vugular porosities are all present in Dundee rocks. Permeabilities as high as 650 millidarcies have been measured. Porosity shows no direct relationship to permeability.

The Da aquitard, the upper part of the Detroit River Group, consists of a sequence of anhydrite, bedded halite, limestone and dolomite. The salt beds, of which there are eight (Gardner, 1974) are present only in the northern portion of the Lower Peninsula. The permeability of undisturbed bedded salt is less than 0.5 x 10 exp -4 millidarcy (Jenks and Claiborne 1981). Drillstem tests and core analyses show that the carbonate rocks of the Da aquitard are regionally of low permeability. Locally high permeabilities may develop in the so-called "sour zone" which is productive of hydrocarbons in the central basin.

The D1 aquifer occurs in carbonate rocks and sandstones of the lower part of the Detroit River Group. Wireline logs and core analyses agree in showing regionally low porosity for the Detroit River carbonate rocks. Core analyses of the Richfield Member of the lower portion of the Detroit River Group show that permeability of carbonate rocks is commonly less than 1 millidarcy. Permeabilities of 820 millidarcies have been measured but these are rare. The Sylvania Sandstone, the lowest member of the Detroit River Group, has high porosity and high permeability.

The Sc aquitard consists of interbedded shales, dolomitic shales, dolomites anhydrites and halites. Locally the dolomites have sufficient permeability to serve as aquifers. Thus, the E unit is an aquifer in parts of southwestern Ontario and southwestern Michigan. Regionally the gross lithology suggests that the Sa rocks act as an aquitard.

Bedded halite makes up the bulk of the Sa and Sb aquitards of Silurian age. Thin (2-5 cm) laminae of dolomite occur within the salt (Mesolella and others 1974). Any porosity that may have existed in the dolomite laminae is probably salt plugged, making the Salina salts of low permeability.

The S2 aquifer occurs in rocks of the A-1 Carbonate. Core permeabilities for the Salina A-1 carbonate are not available. Fluid recovery and drillstem tests show that the rocks are regionally of low permeability. The relationship between porosity and permeability is not known, although wireline logs show high porosities in areas where the permeability from drillstem tests is known to be low.

Carbonate rocks of the Niagara Group and Clinton Group underlie the Salina Group and host the S1 aquifer. The Niagara Group is well known for the occurrence of hydrocarbon-bearing pinnacle reefs. Within the pinnacle reefs, porosity and permeability can vary considerably over short distances. However the reefs are not typical of the bulk of the aquifer rocks. Porosity in the non-reef facies of the Niagara rocks and the Clinton rocks of Michigan is generally low. Core analyses are unavailable. Drillstem tests suggest regionally low permeability.

The SOa aquitard consists of shale, dolomitic shale, and shaly dolomite. The dolomite units may have locally developed porosity and permeability. No direct information about the permeability of the aquitard is available. A permeability of 0.027 millidarcy was calculated for the Maquoketa Shale of northeastern Illinois (the stratigraphically lowest formation of the aquitard) using flow net analysis (Walton 1984). This value is believed to be typical of the rocks in the aquitard.

Limestones and dolomites of the Trenton and Black River Groups of Middle Ordovician host the O2 aquifer. The rocks have low porosity except where they have been locally secondarily dolomitized. Core analyses show that the low porosities correspond to low permeabilities. Permeabilities of the limestones are commonly less than 0.1 millidarcy while permeabilities as high as 400 millidarcies have been measured in the dolomite sections. Low permeabilities of the limestone sections are also often shown by drillstem tests and by lack of fluid recovery in cable-tool wells. The lack of porosity and permeability persist into the outcrop and is reflected by low yields of water from wells drilled for domestic use except where jointing and fracturing have occurred (for example Brueckmann and Bergstrom, 1958, Visocky and others, 1985).

Hydrologic information is not available for the Oa aquitard which consists of a series of interbedded shales, siltstones and carbonate rocks. The unit is treated as an aquitard based on gross lithology.

The O1 aquifer is found in dolomites and sandstones of Chazyan and Canadian age. While porosity is locally moderately high, permeability of these rocks is low: only 2 of 59 measurements on one core exceeded 1.0 millidarcy. Drillstem tests and water production rates in cable tool wells of the carbonate rocks also show low permeabilities.

Upper Cambrian silty dolomites, dolomitic sandstones and shales make up the Ca aquitard. Hydrologic information for these rocks is lacking. Gross lithology and lack of fluid recovery in wells which penetrate the rocks suggest that the rocks function as a regional aquitard.

The Mt. Simon Sandstone is the base of the Paleozoic section in the Michigan Basin and is host to the C1 aquifer. Porosity in the Mt. Simon is quite high in some areas near the rim of the basin. Core analyses show high permeabilities. The only drillstem test of the Mt. Simon in the central basin indicated low permeability over approximately 94 meters of section.

DATA BASE

The data used in this study consist of drillstem test results, initial bottomhole pressure surveys of discovery wells, initial shutin wellhead pressures of discovery wells in gas fields, water level measurements, related depth and surface elevation measurements, water analyses, and permeability and porosity measurements.

Drillstem test reports were obtained from files of the Michigan Geological Survey, the Indiana Geological Survey (D. Sullivan, personal communication) and industry. Bottomhole pressure, surface pressure, and fluid level measurements were obtained from files of the Michigan Geological Survey and publications of the Michigan Geological Survey (Sinclair, 1959, 1960, Vanlier, 1959, 1963a, 1963b, Vanlier and Deutsch, 1958), the Ontario Ministry of Natural Resources (Ontario Department of Energy and Resources, 1967, Ontario Department of Energy and Resources Management, 1968, 1969, Ontario Department of Mines and Northern Affairs, 1972, Ontario Ministry of Natural Resources, 1972, 1973a, 1973b, 1974, 1975, 1976, 1977, 1978, 1979, Palonen, and others, 1981, Booth-Horst and Rybansky, 1982, Rybansky and Trevail, 1983, Habib and Trevail, 1984), the Illinois State Geological Survey (Visocky and others, 1985), The Wisconsin Geological and Natural History Survey (Borman, 1976, Young and Batten, 1980), and the U. S. Geological Survey (Leverett and others, 1906, 1907, Drescher, 1953, Berkstresser, 1964, Allen, 1977, Twenter and Cummings, 1985), and Clifford (1973).

Wireline geophysical logs and core porosity-permeability analysis reports were obtained from the files of the Michigan Geological Survey.

Water analyses are available from publications of the geological surveys of Illinois (Anderson, 1919 and Lamar, 1938), Indiana (Blatchley, 1902 and Keller, 1983), Ohio (Stout and Lamborn, 1932, Lamborn, 1952), Wisconsin (Ryling, 1961), the U. S. Geological Survey (Cummings, 1980, Handy, 1982) and the files of the Ontario Ministry of Natural Resources (R. Trevail, 1984, personal communication), the Michigan Department of Public Health and the Michigan Geological Survey.

DATA REDUCTION

Stabilized subsurface pressures were estimated from drillstem tests and from unstabilized bottomhole pressures using the method of Horner (1951). For a small number of wells pressure buildup data was not available. For such wells the highest measured pressure was presumed to be stable if the pressure gradient calculated using this pressure was similar to pressure gradients in nearby wells for which a stabilized pressure was available. For discovery wells in gas fields initial shutin wellhead pressures were used to estimate bottomhole pressures by using the following relationship (Craft and Hawkins, 1959):

$$BHP = WHP + (D/100 \times WHP/100) \times 0.25 \quad (1)$$

where

BHP = bottomhole pressure
WHP = measured wellhead pressure
D= depth of gas zone.

The stabilized pressures were used to calculate hydraulic heads using the following relation:

$$H = Z + P/Rg \quad (2).$$

Where:

H = Hydraulic head
Z = Elevation above sea level of the point at which the pressure was measured.
P = Stabilized pressure
R = water density
g = acceleration of gravity

Many driller's logs of cable tool wells contain measurements of the wellbore water levels. Nonstabilized values were eliminated by comparison of the hydraulic heads and pressure gradients (estimated using equation 2) with hydraulic heads and pressure gradients calculated from nearby drillstem tests or bottomhole pressure surveys. Water-level measurements from shallow observation wells and domestic and municipal water supply wells were presumed to be stabilized.

Water analyses were screened to eliminate those from aquifers affected by subsurface disposal, secondary recovery or pressure maintenance operations. Specific gravities from the remaining analyses were mapped and used to estimate specific gravities as required for use in equation 2. Specific gravities were also used in the determination of dynamic pressure increments as discussed below.

The dynamic pressure increment (“dP” in the body of this paper) is the difference between the measured subsurface pressure and the nominal pressure. The nominal pressure is the pressure exerted by a static column of water of a height equal to the depth at which the pressure measurement is made (Toth, 1978, 1979). To calculate nominal pressures, the relationship between water density and depth must be determined. For 50-meter depth intervals, beginning at the surface, the density of water was assumed to be the median of the analyses available from the interval and to remain constant within the interval. The pressure at the bottom of the interval was then calculated using the pressure gradient corresponding to the specific gravity of the water. The nominal pressures for the bottoms of 50-meter intervals were tabulated and plotted versus depth (figure 6); nominal pressures at intermediate depths were determined by interpolation.

Standard crossplot techniques (Schlumberger 1972, 1974, 1984) were used to calculate in-situ porosity from wireline well logs. Corrections for shale content and the presence of gas were made as necessary. Permeability estimates were obtained from core analyses, and drill stem tests. Qualitative permeability estimates were made using water production rates in cable tool wells.

REGIONAL GEOHYDROLOGY

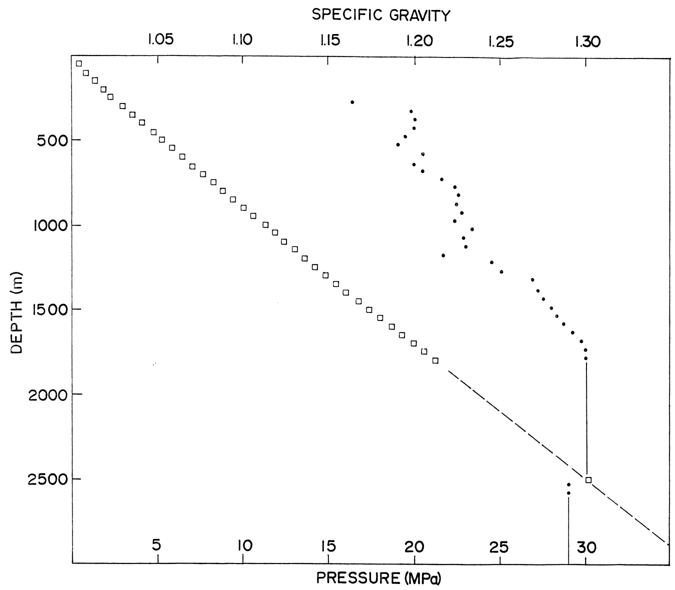
Pennsylvanian P1 aquifer

Flow in the P1 aquifer is from hydraulic and topographic highs in the northwest, west and south toward the hydraulic and topographic low near Saginaw Bay (figure 7a). Negative dynamic pressure increments beneath the highest elevations, increasing to positive beneath lowest elevations (figure 7b), predominantly subnominal pressures (figure 7c), and close correspondence between topography and the equipotential surface, indicate gravity-driven flow. Hydraulic head is always above the top of the aquifer, indicating a saturated condition. The dP-Z-D diagram indicates a simple, continuous, homogeneous basin. Looping iso-dP contours correspond to intraformational permeability barriers. Present-day topography provides the energy to drive flow; the aquifer is in equilibrium with the present-day land surface as indicated by hypsographic distributions of surface elevation and hydraulic head (figure 7d). Topographic control of flow patterns suggests a regionally unconfined system. The occurrence of artesian flow (Allen, 1977, Leverett and others, 1906, 1907) indicates that the system is not completely unconfined.

Mississippian M2 aquifer

The equipotential surface of the M2 aquifer shows flow from hydraulic and topographic highs in the north, northwest and south toward lows near Saginaw Bay and in the southwest (figure 8a). The overall pattern of the dP-Z-D graph suggests a simple, homogeneous basin influenced by the overlying Ma aquitard (figure 8b). About half of the aquifer is receiving recharge; the remainder is in a discharging state. Local flow systems controlled by local topography are indicated by the areas of negative dP in the field of positive dP. The hypsographic curve of hydraulic head is displaced downward 25-50 meters with respect to the hypsographic curve of surface elevation (figure 8c) implying that the present pattern of flow is generated by a topography 25-50 meters lower than the present surface. The bedrock surface is generally 50-100 meters below the land surface suggesting incomplete reequilibration of the aquifer following deposition of the glacial drift. Pressures range from subnominal to supernominal at all depths (figure 8d).

FIGURE 6



Topography controls flow in the M2 aquifer. Recharge areas occupy topographic highs; discharge occurs beneath topographic lows. There is negative correlation between surface elevation and pressure gradient: the correlation coeffecient (V in the body of the paper) has a value of -0.38. The moderate negative value indicates that the aquifer is partially confined and illustrates both the confining nature of the Ma and Mb aquitards and that both are leaky aquitards. Potential differences between the P1 and M2 aquifers indicate downward flow from P1 to M2 except near Saginaw Bay where flow direction is reversed.

Mississippian M1 aquifer

The MI aquifer provides the first instance of substantial overpressuring in the Michigan Basin; only at the shallowest depths are pressures nominal or subnominal (figure 9a). The aquifer is almost completely confined: r = -0.08. Thus the relative efficiency of the Ma and Dc aquitards is illustrated. Hydraulic head mimics topography (figure 9b) but potential differences preclude recharge from the overlying M2 aquifer. Abnormally high sonic transit times indicate undercompaction of the Antrim Shale (the stratigraphically lowest member of the Dc aquitard) in the central basin. The associated high pressure would be expected to leak into the more permeable sandstones of the M1 aquifer. The pattern of dP reflects the overpressuring (figure 9c). The lack of correspondence with type patterns indicates that flow in the MI aquifer is not gravity-driven. Nevertheless discharge occurs in the vicinity of Saginaw Bay and other topographically low areas in central eastern and southeastern Michigan, reflecting some influence of regional topography on regional flow patterns. Hypsographic distributions of surface elevation and hydraulic head also reflect overpressuring, particularly under the highest surface elevations, and provide additional evidence that flow is not gravity-driven (figure 9d).

FIGURE 7

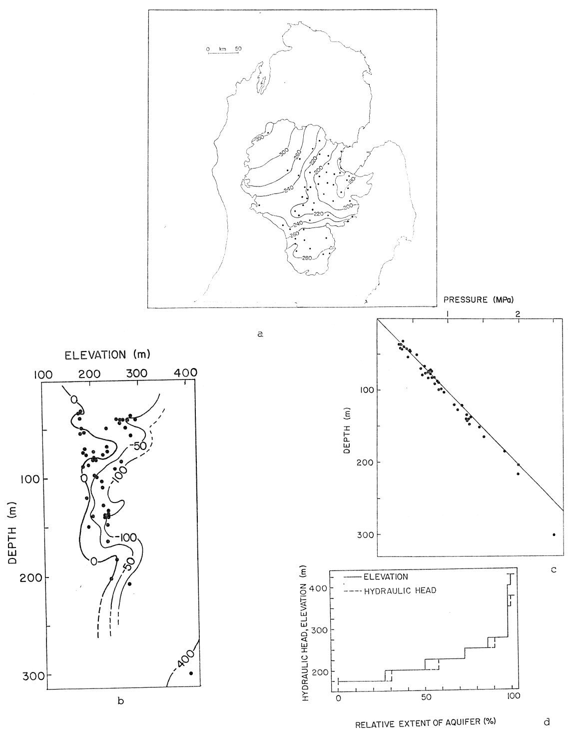


FIGURE 8

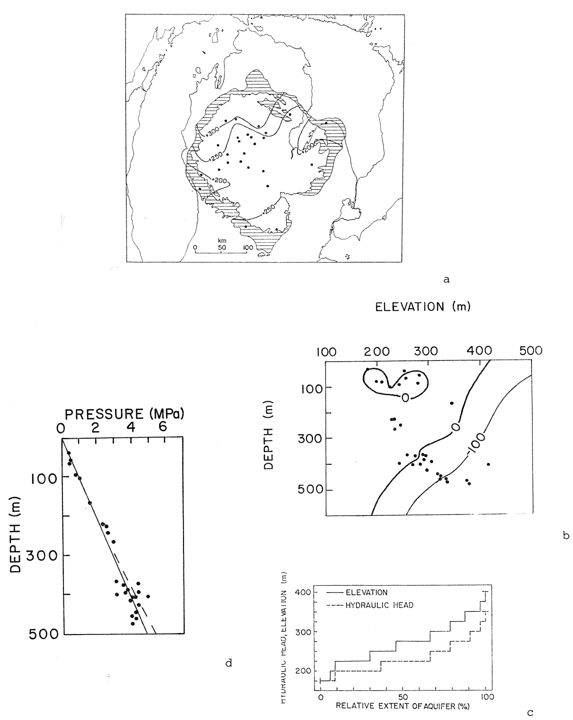


FIGURE 9

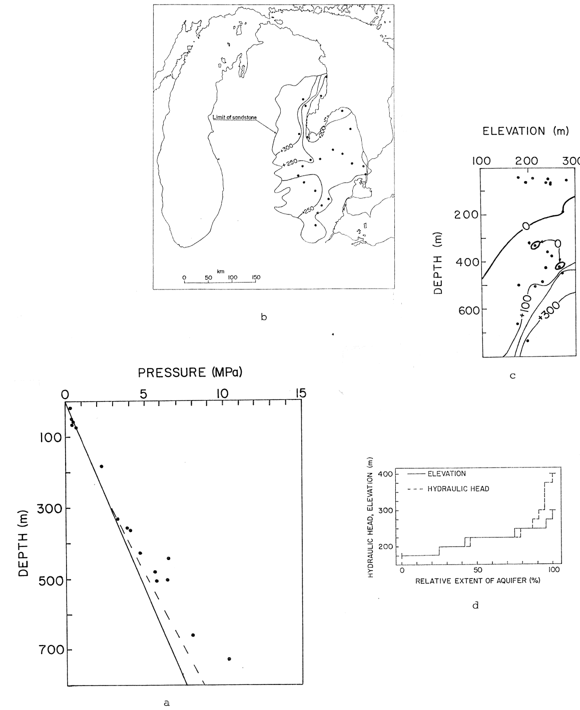
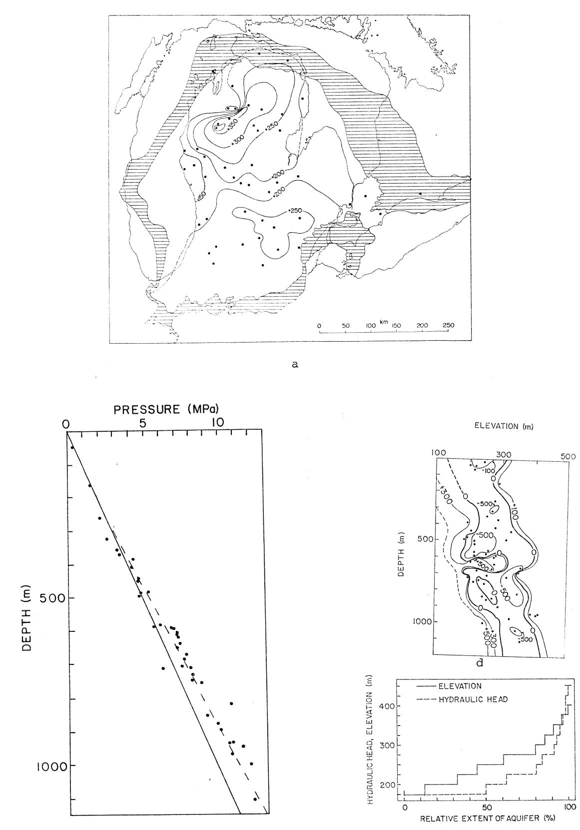


FIGURE 10



Devonian D3 aquifer

Hydraulic head again mimics surface topography (figure 10a) but hypsographic distributions of surface elevation and hydraulic head show evidence of supernominal pressures - reflected by high hydraulic heads - beneath the highest elevations (figure 10b). Hypsographic curves also show 25 to 50 meters between the land surface and the hydraulic heads over much of the aquifer, indicating incomplete equilibration of the aquifer with present-day topography, yet energies too high to be generated by bedrock topography. Hydraulic heads above the top of the aquifer indicate a saturated condition. Recharge of the aquifer occurs beneath topographic highs. Flow is directed toward topographic lows and outcrops beneath Lakes Huron, Michigan and Erie. Outcrops in Ontario and the southern study area are recharge areas. The high negative value of r (-0.05) indicates a regionally confined aquifer. However recharge is believed to occur from the overlying, overpressured Dc aquitard, which is in direct contact with the D3 aquifer over much of the study area and which probably is the source of the supernominal pressures found below about 500 meters (figure 10c). The pattern of dP-Z-D indicates a multiple homogeneous basin. Tortuosity of the iso-dP contours indicates intraformational permeability variations. The small areas of positive dP in the negative dP field suggests the occurrence of local flow systems probably responding to local variations in topography (figure 10d).

Devonian D2 aquifer

The D2 aquifer is characterized by subnominal pressures (figure 11a), negative values of dP as low as 3200 kPa (figure lib) and a pronounced hydraulic low in the central basin (figure lie). The aquifer is only partially confined (r = -0.34); recharge is probably from both the D1 and D3 aquifers. The moderate negative value suggests that both the Da and Db aquitards are leaky aquitards. Recharge regions occupy almost the entire aquifer; discharge occurs at the hydraulic low in the central basin. The pattern of the dP-Z-D graph suggests a simple, continuous basin with some intraformational permeability barriers. However, as discussed below, the present energy levels in the aquifer may have been artificially lowered and do not represent of conditions before the disturbance of the aquifer. There is reason to believe that energy levels were at one time more similar to those in the D3 aquifer.

The central basin hydraulic low is probably caused by artificial discharge from the aquifer through wells drilled for hydrocarbons. Three lines of reasoning support such an origin. First, since 1927 more than 469 million cubic meters of fluids have been withdrawn from an aquifer known to be of high porosity and presumably high permeability (Michigan Geological Survey, 1984). Second, water levels measured in the 1930's, before significant hydrocarbon production had occurred, indicate hydraulic heads of as much as 250 meters in the central basin. Some of the older water level measurements are from wells located very close to more recent wells in which subnominal bottomhole pressures were measured in the 1960's and later. Third, the present hydraulic low coincides with the area of major hydrocarbon production from the D2 aquifer. The presence of a hydraulic low and subnominal pressures is difficult to reconcile with reported oil production figures from the 1930's which ranged as high as 400 cubic meters per day per well without artificial lift. These lines of reasoning indicate that artificial discharge has created the hydraulic low in the central basin.

Devonian D1 aquifer

A recharge area covering most of the northern Lower Peninsula and extending to the northeastern outcrop zone in Ontario dominates the D1 aquifer (figure 12a). Recharge conditions occur in roughly half of the aquifer; discharge occurs over the remaining half (figure 12b). Pressures range from subnominal to supernominal at all depths (figure 12c). Hydraulic head and topography (both surface and bedrock) show good correspondence north of the 200-meter isopotential contour. In the southern and central Lower Peninsula, correspondence is not so pronounced. The hydraulic head is generally 25 to 50 meters below land surface (figure 12d). The D1 is the first aquifer to show a preferential flow direction: predominantly to the south. The pattern of dynamic pressure increments suggests a simple, continuous, homogeneous basin with some intraformational permeability variation. The aquifer is partly unconfined (r = -0.20), recharge occurring primarily beneath the topographic highs in the northern Lower Peninsula and Ontario.

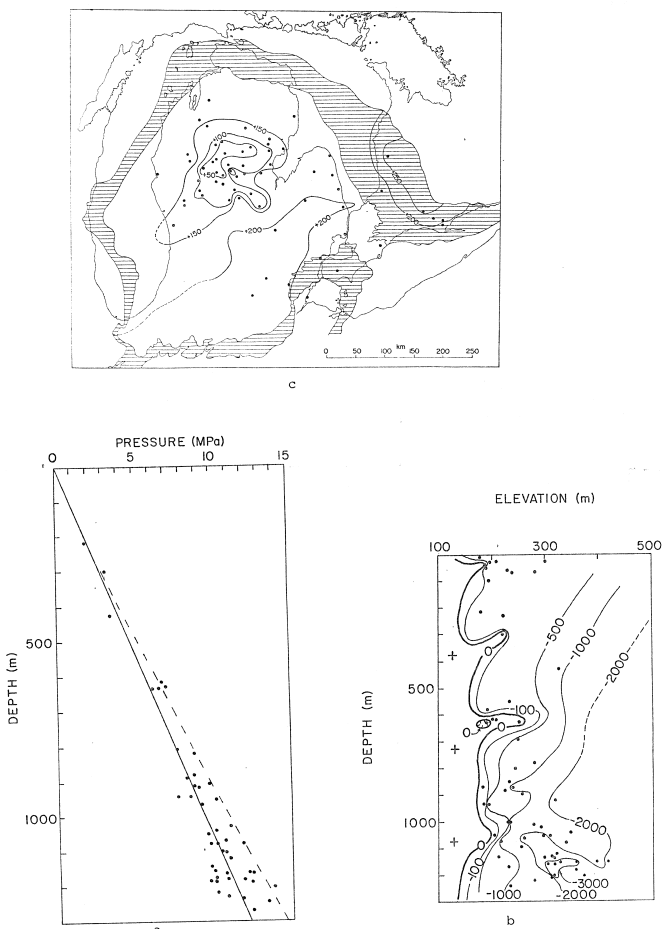
Silurian S3 Aquifer

The Silurian S3 aquifer occupies rocks of the Salina A-2 carbonate and will not be discussed in detail because of lack of data. The general lack of fluid recovery from the aquifer during drilling suggests that the rocks are regionally of low permeability. A few drillstem tests, a single bottomhole pressure from a central basin gas field, and gas encountered during drilling indicate that part of the aquifer is overpressured. The area of overpressuring occupies about the same portion of the aquifer as does the area of overpressuring in the underlying S2 aquifer. The pattern of individual occurrences of high pressure bears no apparent relationship to the pattern in the underlying S2 aquifer.

Silurian S2 aquifer

The S2 aquifer is characterized by the most severe overpressuring found in the Michigan Basin (figure 13a). Overpressuring is confined to the central basin where hydraulic head locally exceeds 2000 meters (figure 13b). At depths of 1000 meters or less pressures range from nominal to subnominal. The sharp diffraction of the iso-dP contours at about this depth reflects a regional permeability barrier (figure 13c). Drillstem test results also suggest such a permeability barrier. That portion of the aquifer in which hydraulic heads exceed 300 meters is confined (r = +0.12), undoubtedly by the thick salts of the subjacent and superjacent Sa and Sb aquitards and the intraformational region of low permeability. The remainder of the aquifer is only partially confined (r = -0.41). In the unconfined parts of the aquifer subsurface pressures, the pattern of dynamic pressure increments, and correspondence between surface topography and the equipotential surface indicate gravity-driven, topographically-generated flow. Flow is from recharge areas at outcrops toward discharge areas located both in the southern Lower Peninsula area and beneath Lakes Michigan, Huron and Erie. The southern Lower Peninsula is the site of a poorly-defined hydraulic low which mirrors the hydraulic low in the underlying S1 aquifer.

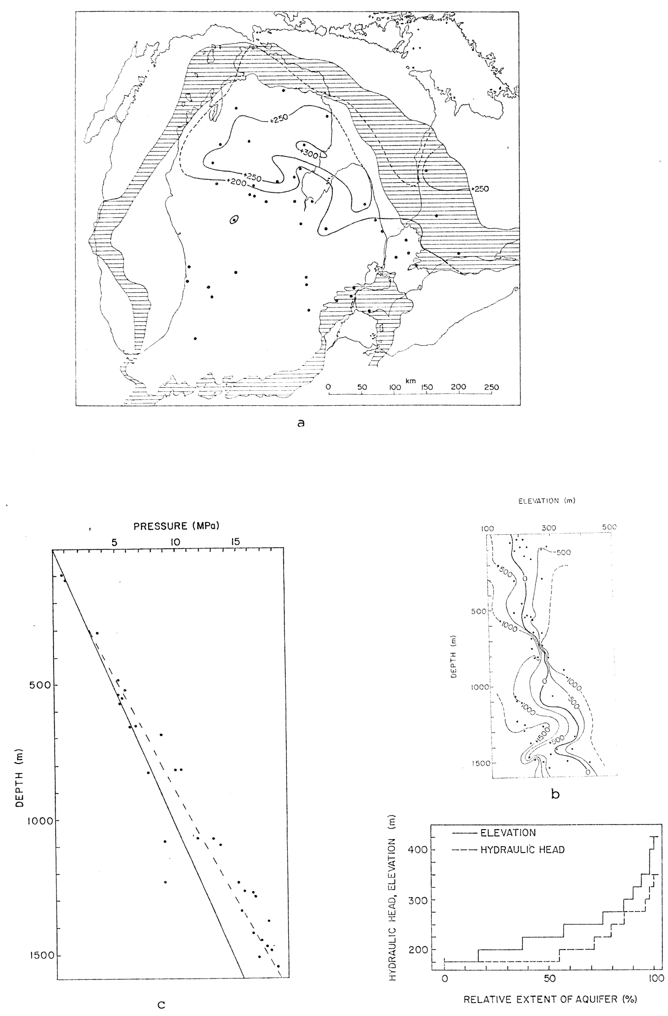
FIGURE 11



Silurian S1 aquifer

The extreme overpressuring of the S2 and S3 aquifers is not found in the S1 aquifer although supernominal pressures do occur at depths greater than 1250 meters (figure 14a). The southern Lower Peninsula is the site of a major discharge area, toward which flow moves from outcrops in the southern half of the study area and from the topographic and hydraulic high in the northern Lower Peninsula (figure 14b). Despite the overpressuring, hydraulic head is generally below land surface (except at the highest elevations) by the 25 to 50 meter value typical of shallower aquifers (figure 14c). A regional permeability barrier is evident at about 1250 meters depth, the aquifer below this depth being in a generally discharging state. Above this depth, recharge areas predominate. Intraformational permeability barriers above 1250 meters are also indicated by the tortuosity of the iso-dP contours (figure 14d). Above 1250 meters depth the aquifer behaves as a simple, homogeneous continuous system in which flow is gravity-driven with flow patterns controlled by surface topography. Insufficient information is available to determine whether vertical flow between the S1 and S2 aquifers occurs in the area of the hydraulic low.

FIGURE 12



Ordovician O2 aquifer

Energy deficiency characterizes the O2 aquifer at all depths (figure 15a). Recharge occurs at outcrops and the flow is toward the central basin (figure 15b). Flow may continue to the south out of the study area but lack of data for Ohio, Indiana and Illinois make any such statements speculative. Values of dP are zero or negative at nearly all elevations, reaching values as low as -2900 kPa below the highest elevations (figure 15c). The sole exception occurs at the point labelled “152” in figure 15b. This occurrence of positive dP may indicate regional recharge from the overlying S1 aquifer, or an isolated local flow system. The available data do not allow a choice between these alternatives to be made. The aquifer is saturated and nearly totally confined (r = -0.009), suggesting that the positive dP point reflects a local flow system and that the SOa and Oa aquitards are not leaky aquitards. Hydraulic head is generally 100 meters below surface elevation (figure 15d).

Ordovician O1 aquifer

Aquifer energies continue to be low (figure 16a). Flow is directed entirely toward the central basin hydraulic low and toward a secondary hydraulic low near southern Lake Michigan (figure 16b). The secondary hydraulic low is caused by withdrawal of water from the aquifer (Visocky and others, 1985).

The aquifer appears to be completely confined (r = +0.22), suggesting that the overlying Oa aquitard is an efficient barrier to cross-formational fluid flow. The pattern of dynamic pressure increment suggests a hydraulically continuous, homogeneous, simple basin (figure 16c). Hydraulic heads are generally 150 to 200 meters below surface elevation (figure 16d) and are generally lower than bedrock surface elevation. Recharge occurs at outcrops. Because of the difference in potential, discharge cannot occur into the O2 aquifer in the central basin. Discharge is believed to be downward into the C1 aquifer. In the southern Lower Peninsula the aquifer appears to be unconfined (r = -0.83) and locally upward-directed discharge may occur.

Cambrian C1 aquifer

Low energies characterize the C1 aquifer at depths of less than 2500 meters (figure 17a); below this depth no information is available. Hydraulic heads indicate flow from the recharge area at the outcrop toward the southeast. An area of local recharge occurs in southwestern Ontario (figure 17b). The origin of the high hydraulic heads in this small area is unknown. Recharge from the overlying O1 aquifer may occur in the central basin although lack of data for the C1 aquifer makes such a statement speculative. Hydraulic heads are generally only 25 meters below land surface, although the distance may exceed 75 meters (figure 17c). The aquifer is regionally unconfined (r = -0.56). The pattern of dynamic pressure increments indicates a hydraulically continuous, simple, homogeneous basin (figure 17d.) Discharge areas are presumed to lie outside the study area.

DISCUSSION

The regional aquifers in the Michigan Basin may be divided into 3 categories.

1) Flow systems which display good correspondence with surface topography. Pressures range from slightly subnominal to slightly supernominal. Topography drives the regional flow system: recharge occurs beneath topographic highs while discharge occurs beneath topographic lows. Aquifers are saturated and regionally unconfined to varying degrees. The distribution of hydraulic head generally parallels the distribution of surface elevation; the two surfaces commonly are separated by 25 to 75 meters. Gravity-driven flow and recharge occurring by downward movement of fluid from overlying strata characterize the flow systems. The P1, M2, D3, D2, and D1 aquifers fall into this group.

2) Aquifers which display slight to extreme overpressuring at greatest depths. The overpressured areas of the aquifers are nearly totally confined and dP-D-Z patterns commonly indicate regional permeability barriers affecting flow systems. At intermediate to shallow depths, the aquifers display most of the characteristics of aquifers in Group 1. The M1, S3, S2 and S1 aquifers fall into this group.

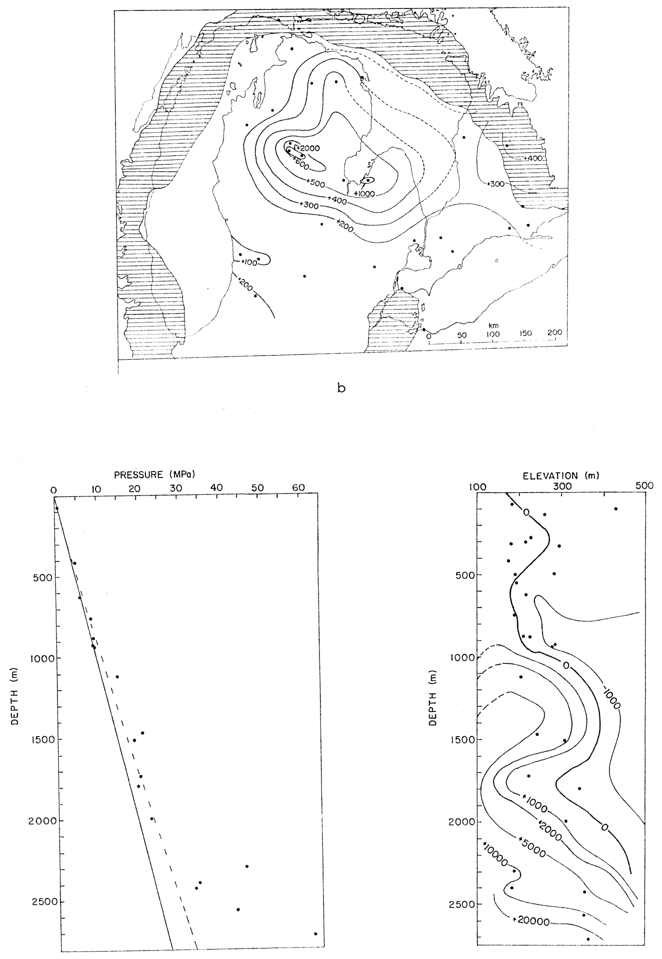
3) Aquifers characterized by generally deficient energy levels. Recharge occurs at outcrops and discharge regions are commonly located outside the study area. Low energy levels are generally reflected by subnominal pressures, hydraulic heads lying up to 100 and more meters beneath the land surface elevation, and negative values of dynamic pressure increment. The dP-Z-D pattern is of a simple, continuous, through-flowing basin with few intraformational permeability barriers. The O2, O1 and C1 aquafers belong in this group.

The differing characteristics of each group probably reflect differing histories for the aquifers in each group. Aquifers in Group 1 are apparently in the process of establishing equilibrium with the present day, recently established land surface. Before the Pleistocene glaciation they were presumably in equilibrium with the existing land surface, which would have approximated the present bedrock surface. For what length of time the equilibrium had persisted is not certain.

Group 2 aquifers may at one time have been more similar to Group 1 aquifers. The aquifers are associated with thick sequences of low-permeability rock; only the S1 aquifer is not completely enclosed by such permeability barriers. Overpressuring in the M1 aquifer can be attributed to the underlying overpressured shales of the Dc aquitard. Overpressuring in the Silurian aquifers is probably due to in-situ generation of gas accompanied by low hydrocarbon loss rates through the low permeability rock (Momper, 1980, Meissner, 1984, Law and Dickinson, 1985). This explanation is particularly attractive for the Silurian aquifers because all hydrocarbon production to date from overpressured

Silurian central basin fields has been dry gas with few or no associated liquids.

FIGURE 13



Subnominal pressures have been attributed to removal of overburden (Russel, 1972, Dickey and Cox, 1977). It is difficult to accept this explanation for the low energies of the Ordovician and Cambrian aquifers. Although as much as 1000 meters of overburden have been removed from the Michigan Basin, the removal was completed before Jurassic time (Cercone, 1984); equilibrium would have been reestablished in the ensuing 150 million years. Low rates of recharge through the regionally low permeability aquifer rock appears to be a better explanation. This explanation becomes more attractive when one considers that near the outcrops, where permeability has been enhanced by solution by meteoric water, pressures may be nominal or slightly supernominal. This suggests that continued movement of water into the rock is impeded by permeability barriers.

The data presented in this paper are interpreted to indicate that subsurface water movement is occuring in the Michigan Basin and that cross-formational water movement occurs even across rocks considered to be aquitards. The existence of the present circulation systems raises questions about their genesis, duration, relationship to previously-existing flow systems, and the effects these have had on the evolving Michigan Basin. Detailed discussion of these questions is beyond the scope of this study. Future work will examine the relationship between fluid flow in the Michigan Basin and such aspects as the distribution of subsurface temperatures, the occurrence of hydrocarbons, and the evolution of the present-day flow systems.

FIGURE 14

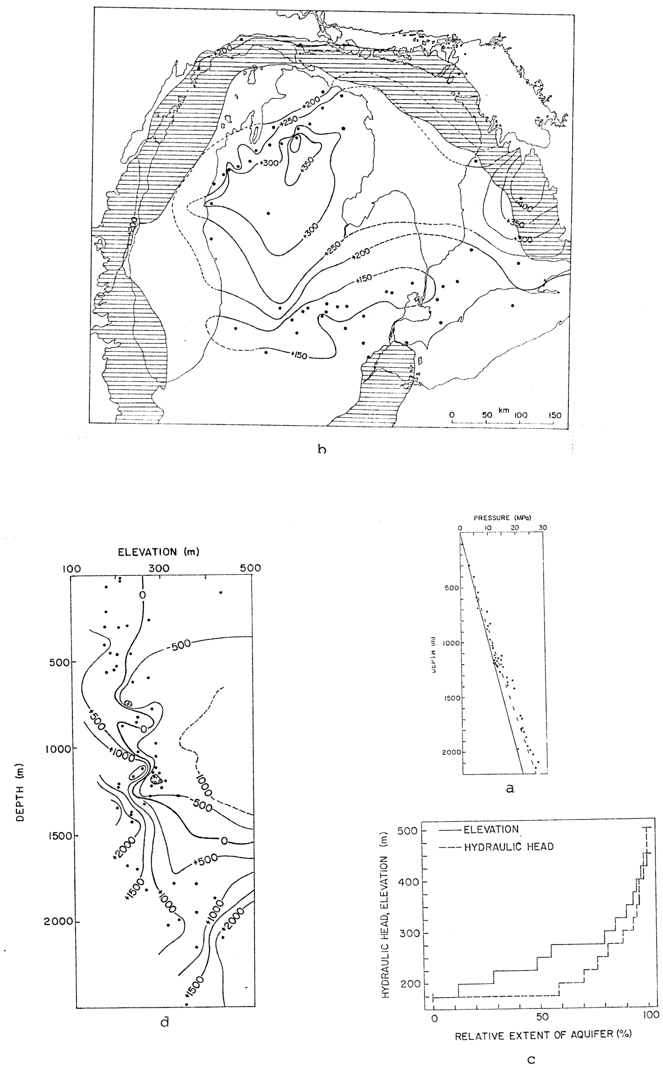
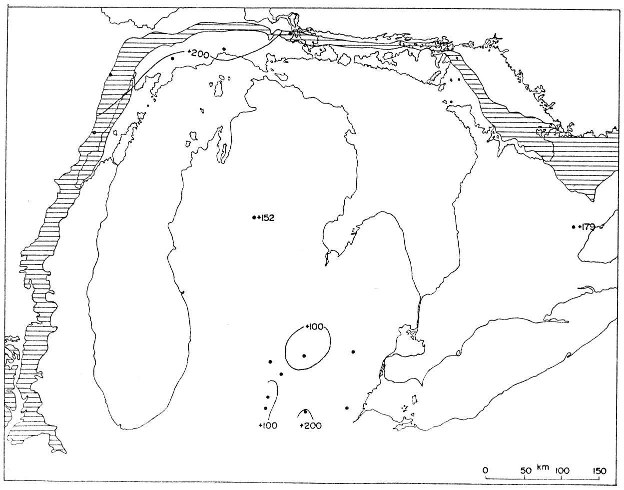
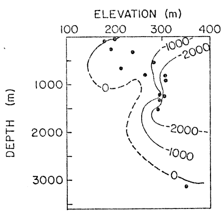


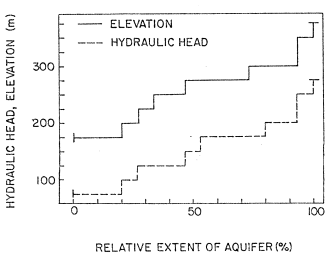
FIGURE 15



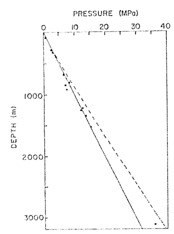
b



c

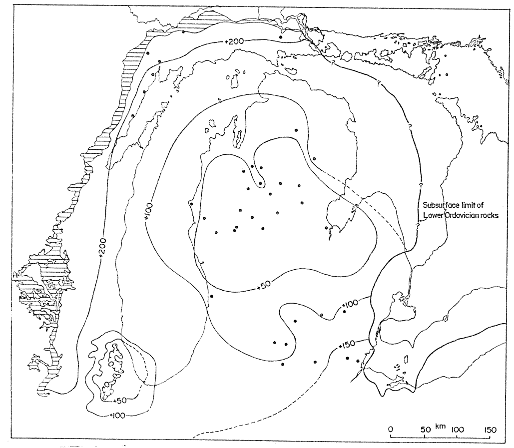


d



a

FIGURE 16



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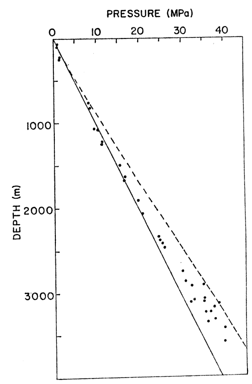
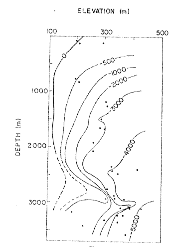


a



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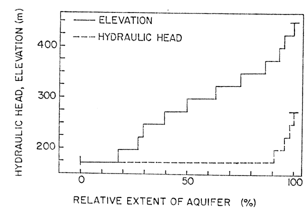

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FIGURE 17

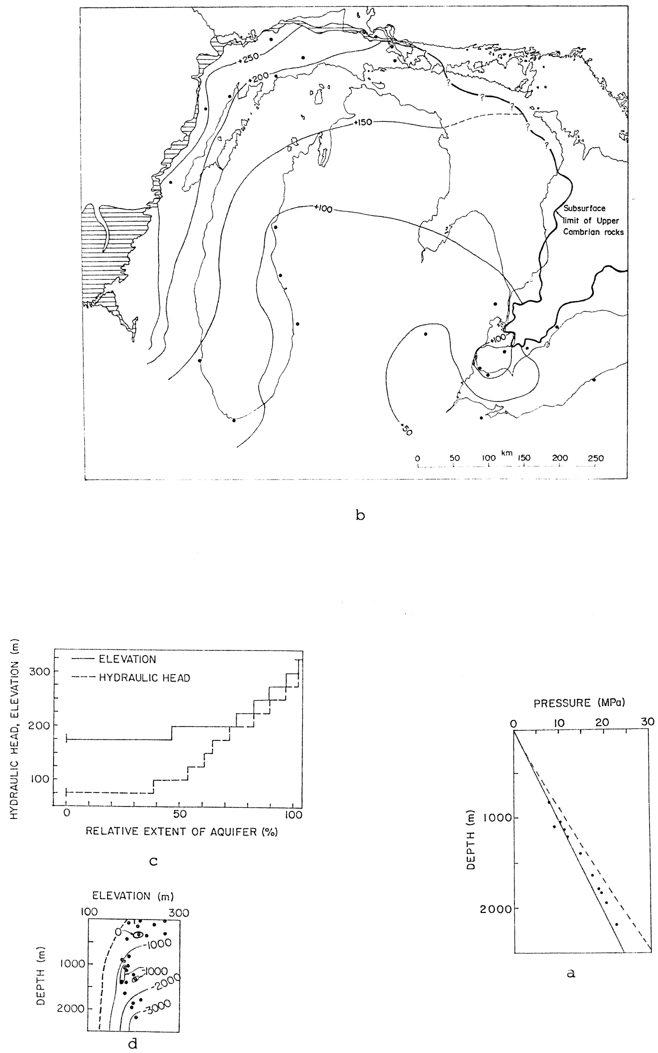

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FIGURE CAPTIONS

Figure 1 Regional structural and political setting of the Michigan Basin. Compiled and modified from Ostrom (1966), Ells, (1969), Doheny and others (1975) and Prouty (1983).

Figure 2 Average surface elevation in the Michigan Basin region Contours are in meters above sea level; variable contour interval. After Diment and Urban (1981).

Figure 3 Generalized bedrock topography in the Michigan Basin region. Compiled from Horberg and Anderson (1956), Sommers (1977), and Wold and others (1981).

Figure 4 Hydrogeologic and stratigraphic units in the Michigan Basin. The following abbreviations are used: an - anhydrite, do - dolomite, gy - gypsum, ha -halite, ls - limestone, sh - shale, ss - sandstone, st - siltstone. Capital letters indicate major lithologies. Thicknesses from AAPG (1985).

Figure 5 Bedrock geology of the Michigan Basin region Compiled from Craig and others (1979), Hewitt (1966), Illinois State Geological Survey (1967) Iowa State Geological Survey (1962), Janssens (1972, 1977), Kelly (1968), Liberty (1978), Pinsak and Shaver (1964), Rickard (1984), Wisconsin Geological and Natural History Survey (1981), and Wold and others(1981).

Figure 6 Variation of water specific gravity and nominal pressure with depth in the Michigan Basin. Dots represent median values of water specific gravity for 50-meter depth intervals. Squares represent the nominal pressures at the bottoms of 50-meter depth intervals.

Figure 7 Pennsylvanian P1 aquifer.

- a Hydraulic head. Contours are in meters above sea level.
- b dP-Z-D diagram. Contours are in kilopascals.
- c Pressure-vs-depth diagram.
- d Hypsographic distribution of surface elevation and hydraulic head.

Figure 8 Mississippian M2 aquifer.

- a Hydraulic head. Contours in meters above sea level.
- b dP-Z-D pattern. Contours in kilopascals.
- c Hypsographic distributions of surface elevation and hydraulic head.
- d Pressure-vs-depth diagram. The solid line on this and following pressure-depth diagrams is the pressure-depth curve for fresh water (specific gravity = 1.000). The dashed line is the nominal pressure curve from figure 6.

Figure 9 Mississippian Ml aquifer.

- a Pressure-vs-depth diagram.
- b Hydraulic head. Contours are in meters above sea level.
- c dP-Z-D pattern. Contours in kilopascals.
- d Hypsographic distributions of surface elevation and hydraulic head.

Figure 10 Devonian D3 aquifer.

- a Hydraulic head. Contours are in meters above sea level.
- b Hypsographic distributions of surface elevation and hydraulic head.
- c Pressure-vs-depth diagram.
- d dP-Z-D pattern. Contours in kilopascals.

Figure 11 Devonian D2 aquifer.

- a Pressure-vs-depth diagram.
- b dP-Z-D pattern. Contours in kilopascals.
- c Hydraulic head. Contours are in meters above sea level.

Figure 12 Devonian D1 aquifer.

- a Hydraulic head. Contours are in meters above sea level.
- b dP-Z-D pattern. Contours in kilopascals.
- c Pressure-vs-depth diagram.
- d Hypsographic distributions of surface elevation and hydraulic head.

Figure 13 Silurian S2 aquifer.

- a Pressure-vs-depth diagram.
- b Hydraulic head. Contours are in meters above sea level.
- c dP-Z-D pattern. Contours in kilopascals.

Figure 14 Silurian S1 aquifer.

- a Pressure-vs-depth diagram.
- b Hydraulic head. Contours are in meters above sea level.
- c Hypsographic distributions of surface elevation and hydraulic head.
- d dP-Z-D pattern. Contours in kilopascals.

Figure 15 Ordovician O2 aquifer.

- a Pressure-vs-depth diagram.
- b Hydraulic head. Contours are in meters above sea level.
- c dP-Z-D pattern. Contours in kilopascals.
- d Hypsographic distributions of surface elevation and hydraulic head.

Figure 16 Ordovician O1 aquifer.

- a Pressure-vs-depth diagram.
- b Hydraulic head. Contours are in meters above sea level.
- c dP-Z-D pattern. Contours in kilopascals.
- d Hypsographic distributions of surface elevation and hydraulic head.

Figure 17 Cambrian C1 aquifer.

- a Pressure-vs-depth diagram.
- b Hydraulic head. Contours are in meters above sea level.
- c Hypsographic distributions of surface elevation and hydraulic head.
- d dP-Z-D pattern. Contours in kilopascals.

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