# Configuration of Freshwater/Saline-Water Interface and Geologic Controls on Distribution of Freshwater in a Regional Aquifer System, Central Lower Peninsula of Michigan

By D.B. WESTJOHN and T.L. WEAVER

---

U.S. Geological Survey

Water-Resources Investigations Report 94-4242

Lansing, Michigan
1996

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
GORDON P. EATON, Director



---

For additional information write to:

District Chief
U.S. Geological Survey
810 Broadway, Suite 500
Nashville, Tennessee 37203

Copies of this report may be purchased from:

U.S. Geological Survey
Earth Science Information Center
Open-File Reports Section
Box 25286, MS 517
Denver Federal Center
Denver, Colorado 80225

# CONTENTS

## FIGURES



## CONVERSION FACTORS, VERTICAL DATUM, AND ABREVIATIONS

| Multiply | By | To obtain |
|---|---|---|
| foot (ft) | 0.3048 | meter |
| foot (ft) | 30.48 | centimeter |
| mile (mi) | 1.609 | kilometer |
| square mile ($mi^2$) | 2.590 | square kilometer |

**Sea level:** In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

**Abbreviated water-quality units used in this report:** Chemical concentration is given in milligrams per liter (mg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

**Other abbreviations used in this report:**

(cm/s) centimeters per second

(ohm-m) ohm meters

# Configuration of Freshwater/Saline-Water Interface and Geologic Controls on Distribution of Freshwater in a Regional Aquifer System, Central Lower Peninsula of Michigan

*By* D.B. Westjohn *and* T.L. Weaver


## Abstract

Electrical-resistivity logs and water-quality data were used to delineate the freshwater/saline-water interface in a 22,000-square-mile area of the central Michigan Basin, where Mississippian and younger geologic units form a regional system of aquifers and confining units.

Pleistocene glacial deposits in the central Lower Peninsula of Michigan contain freshwater, except in a 1,600-square-mile area within the Saginaw Lowlands, where these deposits typically contain saline water. Pennsylvanian and Mississippian sandstones are freshwater bearing where they subcrop below permeable Pleistocene glacial deposits. Down regional dip from subcrop areas, salinity of ground water progressively increases in Early Pennsylvanian and Mississippian sandstones, and these units contain brine in the central part of the basin. Freshwater is present in Late Pennsylvanian sandstones in the northern and southern parts of the aquifer system. Typically, saline water is present in Pennsylvanian sandstones in the eastern and western parts of the aquifer system.

Relief on the freshwater/saline-water interface is about 500 feet. Altitudes of the interface are low (300 to 400 feet above sea level) along a north-south-trending corridor through the approximate center of the area mapped. In isolated areas in the northern and western parts of the aquifer system, the altitude of the base of freshwater is less than 400 feet, but altitude is typically more than 400 feet. In the southern and northern parts of the aquifer system where Pennsylvanian rocks are thin or absent, altitudes of the base of freshwater range from 700 to 800 feet and from 500 to 700 feet above sea level, respectively.

Geologic controls on distribution of freshwater in the regional aquifer system are (1) direct hydraulic connection of sandstone aquifers and freshwater-bearing, permeable glacial deposits, (2) impedance of upward discharge of saline water from sandstones by lodgement tills, (3) impedance of recharge of freshwater to bedrock (or discharge of saline water from bedrock) by Jurassic red beds, and (4) vertical barriers to ground-water flow within and between sandstone units.

## INTRODUCTION

Unconsolidated Pleistocene glacial deposits, Jurassic red beds, and Pennsylvanian through Mississippian bedrock units form a regional system of aquifers and confining units in the central Lower Peninsula of Michigan. The areal extent of this aquifer system is approximately 22,000 $mi^2$ (fig. 1). This aquifer system was studied during the period from 1986 through 1994, as part of the Regional Aquifer-System Analysis (RASA) program (Mandle, 1986) of the U.S. Geological Survey (USGS). The Michigan Basin RASA project is one of 28 USGS hydrogeologic investigations of regional aquifer systems of the United States (Weeks and Sun, 1987).

The most important aquifers in the Michigan Basin RASA study area are Pleistocene glaciofluvial deposits and Pennsylvanian and Mississippian sandstones. Glaciofluvial aquifers contain freshwater in most areas; however, saline water is present in glacial deposits in the east-central part of the Saginaw Lowlands (fig. 1). Freshwater in Pennsylvanian and Mississippian sandstones is an exception; in most areas of the basin these bedrock units contain saline water or brine. (As referred to in this report: saline water contains a solute concentration greater than 1,000 but less than 100,000 mg/L, and brine contains a solute concentration greater than 100,000 mg/L.)

Saline water is present below freshwater-bearing aquifers everywhere in the Michigan Basin. Depth to saline water can be estimated on the basis of chemical analyses of water sampled from wells in the southern and eastern parts of the aquifer system. However, in the northwestern part, glacial deposits are a shallow source of freshwater, and wells in this area are rarely completed in bedrock. Consequently, water-quality data are few for bedrock aquifers in the northwestern part of the study area, and the position of the freshwater/saline-water interface has been uncertain. Among areas where water-quality data are few, approximately 200 electrical-resistivity logs are available that were run in boreholes drilled before there was a requirement to case boreholes below freshwater-bearing strata. These uncased boreholes were open to glacial deposits and all bedrock units that form the aquifer system (freshwater- and saline-water-bearing aquifers). Electric logs were used to delineate the position of the freshwater/saline-water interface.

The purposes of this report are to delineate the altitude of the freshwater/saline-water interface in bedrock by use of water-quality data and geophysical logs and to relate the position of this interface to geologic units that form the Michigan Basin regional aquifer system.

## HYDROGEOLOGIC SETTING

The Michigan Basin is an intracratonic depression that contains more than 17,000 ft of sedimentary rocks and unconsolidated sediments. The stratigraphic record is nearly complete from Precambrian sedimentary units through Jurassic red beds, except that rocks of Triassic age are not present in the basin. Pleistocene glacial deposits cover bedrock in most areas; knowledge of bedrock geology is almost entirely from geophysical and geologic logs of drill holes.

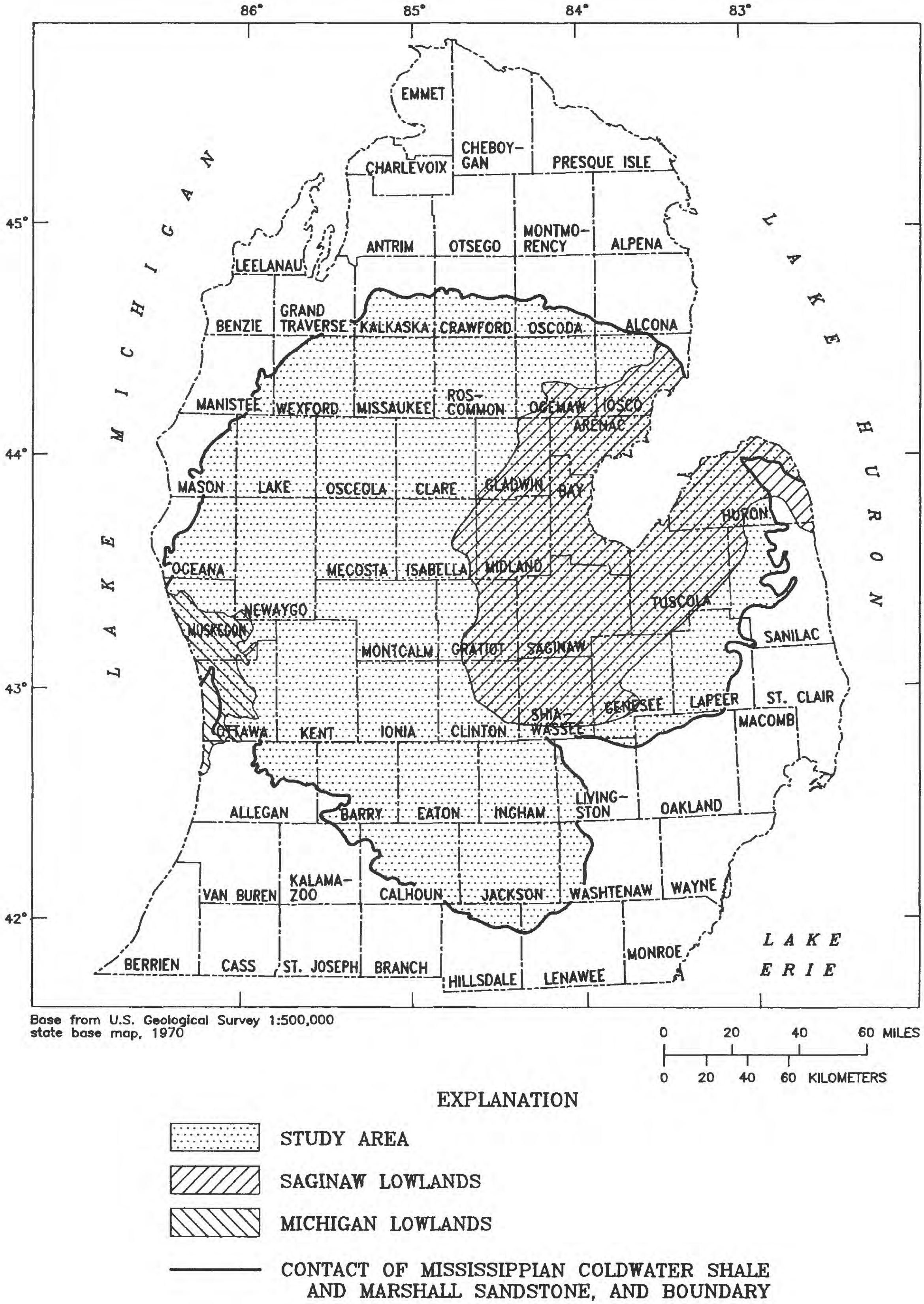



**Figure 1.** Lower Peninsula of Michigan and Michigan Basin Regional Aquifer-System Analysis study area.

### Stratigraphic Units

The geology and hydrology of Mississippian and younger geologic units that form the regional aquifer system are described in a series of Michigan RASA reports (Westjohn and others, 1994; Westjohn and Weaver, 1996a, 1996b). These reports include maps that delineate surface configuration and thicknesses of aquifers and confining units and establish the hydrogeologic framework of the regional aquifer system.

The aquifer system consists of six bedrock formations that have formal stratigraphic names and three geologic units that have informal names (figs. 2 and 3). Formally named units of Mississippian age are the Coldwater Shale, the Marshall Sandstone, the Michigan Formation, and the Bayport Limestone; formally named units of Pennsylvanian age are the Saginaw Formation and the Grand River Formation. Geologic units that have informal names are the Parma sandstone (member of the Saginaw Formation), Jurassic red beds, and Pleistocene glacial deposits. Stratigraphic relations of aquifer-system units are shown in figure 3 and in geologic sections A-A′ and B-B′ (Appendix A).

### Stratigraphic Units in Relation to Aquifers and Confining Units

Commonly used stratigraphic names in relation to hydrogeologic names established for the Michigan Basin RASA study are shown in figure 3. Also shown are lithologic constituents of formations and approximate thicknesses of aquifers and confining units. The boundaries and thicknesses of aquifers and confining units were delineated on the basis of hydraulic properties. Hydrogeologic units include all or part(s) of one or two formations (fig. 3).

Hydrogeologic units that include all or parts of two stratigraphic units are the Saginaw aquifer (sandstones of the Grand River Formation and the Saginaw Formation), the Parma-Bayport aquifer (sandstones and permeable carbonates of the Parma Sandstone and the Bayport Limestone), and the Marshall aquifer (composite of stratigraphically continuous, permeable sandstones of the Michigan Formation, the Napoleon Sandstone, and the Marshall Sandstone). Other hydrogeologic units consist of part or all of a single geologic unit (fig. 3). Stratigraphic names and hydrogeologic-unit nomenclature are used alternately, depending on whether the topic of discussion is geology or hydrogeology. The terms "Mississippian sandstone" and "Pennsylvanian sandstone" are used in a general sense where association of rock units to a specific formation is not relevant.

## METHODS USED TO DELINEATE FRESHWATER/SALINE-WATER INTERFACE

Electrical-resistivity logs of boreholes open to Pleistocene glacial deposits and underlying bedrock units were used to determine depth to saline water. The approximately 200 electrical-resistivity logs of boreholes were examined along with water-quality data to delineate the approximate position of the freshwater/saline-water interface. Applications of these methods are described separately.

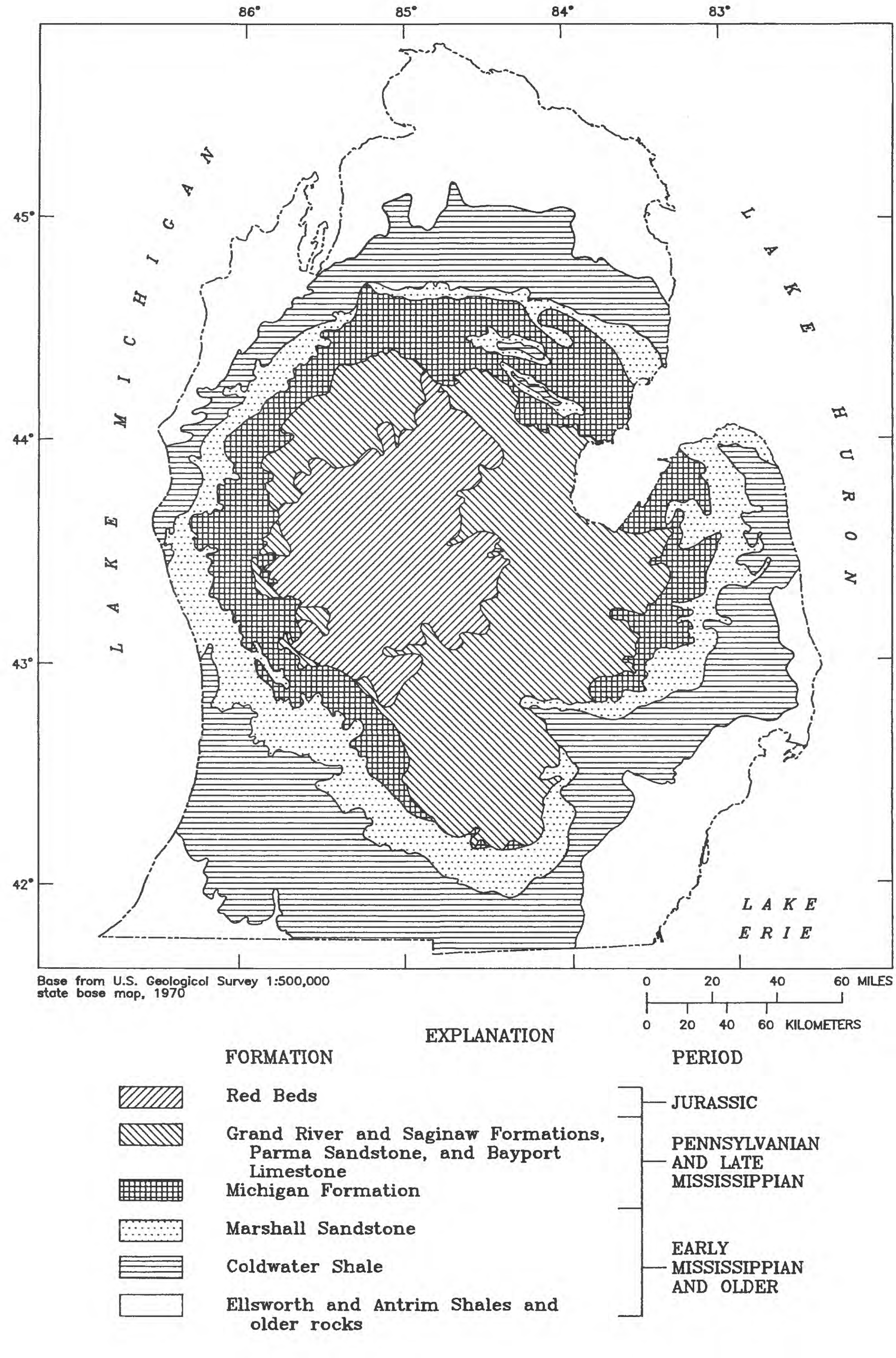



**Figure 2.** Bedrock geology of the Lower Peninsula of Michigan. (Modified from Western Michigan University, 1981, pl. 12; and from Westjohn and others, 1994.)

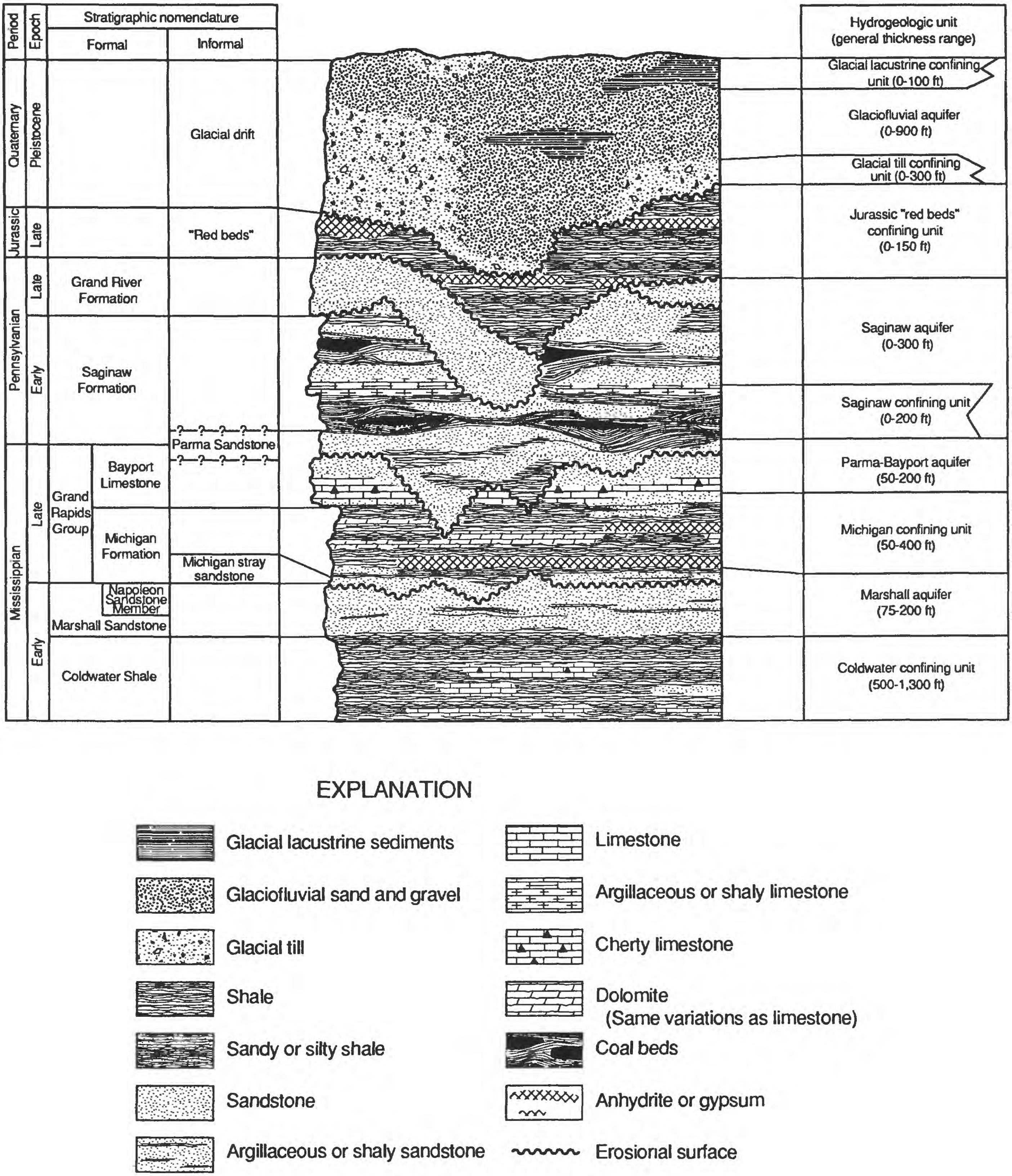



**Figure 3.** Mississippian through Pleistocene stratigraphic nomenclature, hydrogeologic units, and rock units in the central Lower Peninsula of Michigan. (Modified from Michigan Geological Survey, 1964.)

## Compilation and Analysis of Water-Quality Data

Water-quality data were compiled from several sources (Appendix B). These data were used to delineate the approximate altitude of the base of freshwater in the southern and eastern parts of the aquifer system (Appendix C). The altitude of the base of freshwater water was approximated, on the basis of 1,000 mg/L dissolved solids as a maximum solute concentration of freshwater.

The following four factors were identified as potential sources of error—and hence, limitations—in the use of water-quality data for the delineation of the freshwater/saline-water interface:

1. Rocks of Pennsylvanian age in the Michigan Basin consist predominantly of intercalated sandstone, siltstone, and shale. Limestone and coal form a minor part of the Pennsylvanian sedimentary sequence. It is known from geophysical logs that salinity of ground water in Pennsylvanian rocks increases with depth (Westjohn, 1989). Typically, sandstone beds at or near the bedrock/glacial-deposits interface contain freshwater, but sandstone beds successively deeper in the Pennsylvanian rock sequence (which are intercalated with shale) contain progressively higher concentrations of dissolved solids. Water wells completed in Pennsylvanian rocks are commonly open to multiple sandstone beds, and water sampled from these wells is a composite mixture of ground water contributed by different zones. Consequently, a wellbore completed below the freshwater/saline-water interface (open to freshwater- and saline-water-bearing sandstones) may produce ground water with a dissolved-solids concentration of less than 1,000 mg/L.

2. The concentration of dissolved constituents in the producing zone of a particular well can change with time. Changes in water quality related to the encroachment of saline water toward water-supply wells has been reported for several areas in Michigan (Allen, 1977; Stramel and others, 1954; Vanlier, 1963; Wiitala and others, 1963). Water-quality data used to interpret the altitude of the base of freshwater reflect dissolved-solids concentrations at the time that ground water was sampled and analyzed. Composition of ground water could have changed at any of the sampled sites.

3. Some wells that were sampled are probably completed in aquifers above the freshwater/saline-water interface. To minimize this problem, RASA investigators used lowest altitudes of bases of wells that produced freshwater (one per township if possible, and in some areas, two or more per township, see Appendix C) to delineate the position of the freshwater/saline-water interface. Nearby wells (within 1 to 6 mi) completed at lower altitudes that produced saline water were used as an additional constraint to delineate the position of the interface. In most areas, altitudes of the base of wells that produced freshwater and nearby wells that produced saline water differ by less than 50 ft.

4. Freshwater can be present in aquifers that underlie saline-water-bearing units, and this condition has been reported by water-well drillers in some areas of the State (Mark Breithart, Michigan Department of Public Health, oral commun., 1993). Although the presence of freshwater lenses below saline water is an uncommon and highly local phenomenon, it is a limitation of water-quality data that leads to error in determination of the altitude of base of freshwater.

### Collection and Analysis of Geophysical Logs

Electrical-resistivity logs were used to delineate the position of the freshwater/saline-water interface in some parts of the Michigan Basin (Westjohn, 1989, 1994a). Similar studies in other hydrogeologic settings are described by other investigators (Archie, 1942; Keys and MacCary, 1973; Poole and others, 1989; Pryor, 1956).

The electrical-resistivity characteristics of units that form the aquifer system were established by examination of more than 600 electric logs (combination of spontaneous potential/electrical resistivity; see Hilchie, 1979). Electric logs record spontaneous-potential data for lithologic determinations, as well as short-normal, long-normal, and commonly lateral log resistivities for estimation of formation-fluid salinity. Resistivity properties of freshwater-bearing strata were interpreted from resistivity-log traces (lateral log if available, or long normal) of glacial sand and gravel. Such glaciofluvial deposits are assumed to contain freshwater, and they consistently had an electrical resistivity that exceeded 100 ohm-m. Sandstones whose electrical-resistivity characteristics were similar to those of glaciofluvial deposits are interpreted to contain freshwater, on the basis of electrical resistivity of 100 ohm-m or higher.

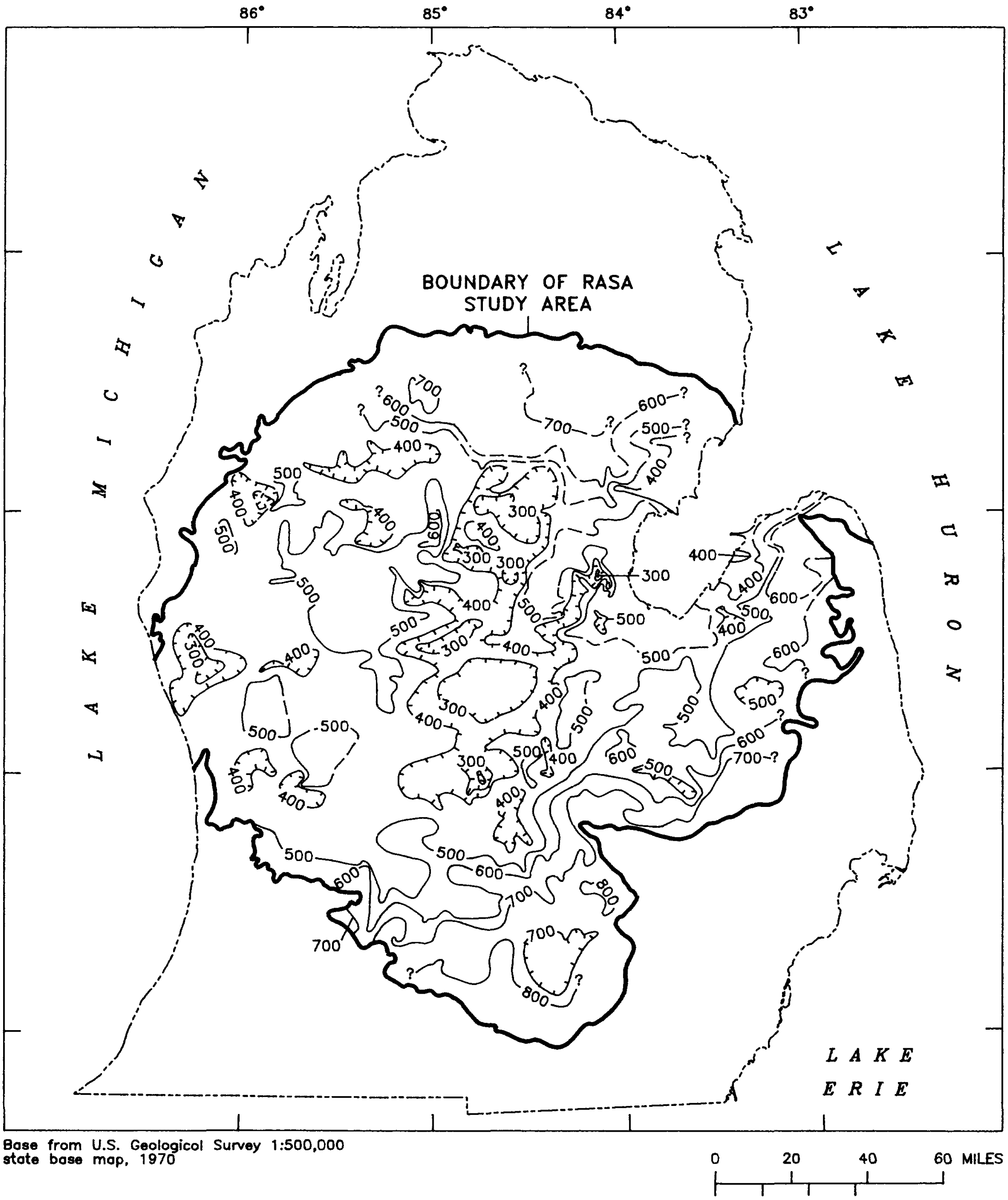
Sandstones that contain brine have a narrow range of electrical resistivity (1 to 4 ohm-m). This geophysical characteristic was established from electrical resistivities measured of Mississippian sandstones in the central part of the Michigan Basin, where chemical analyses of ground water indicate that dissolved-solids concentration exceeds 100,000 mg/L (Western Michigan University, 1981, table 7g). The distribution of brine in Pennsylvanian sandstones was delineated on the basis of the same range of electrical resistivity (1 to 4 ohm-m). Example logs that illustrate the range of resistivities and other geophysical properties of aquifers that contain freshwater, saline water, or brine are given in Appendix D.

The principal source of error in the use of electrical-resistivity logs to delineate altitude of the freshwater/saline-water interface (Appendix E) is their age: the logs were run in boreholes drilled during 1942-56, before the implementation of regulations that required oil and gas exploration/production wells to be cased below freshwater-bearing strata. Geophysical data used to interpret altitude of base of freshwater reflect conditions at the time the borehole was logged. The current depth of the freshwater/saline-water interface may be different at any of the logged sites.

## CONFIGURATION OF FRESHWATER/SALINE-WATER INTERFACE AND GEOLOGIC CONTROLS ON DISTRIBUTION OF FRESHWATER

Configuration of the freshwater/saline-water interface is shown in figure 4. The map is based primarily on water-quality data (612 data points), supplemented with electric-log data (198 data points). (See Appendix C for locations.) The surface configuration is an approximation, and the map depicts only a very generalized trend of the freshwater/saline-water interface.

Relief on the freshwater/saline-water interface is about 500 ft. Altitudes of the interface are low (300 to 400 ft above sea level) along a north-south-trending corridor that extends approximately 100 mi from Gladwin County to Ingham County (fig. 4). In several isolated areas in the northern and




EXPLANATION

——900·—— STRUCTURE CONTOUR--Shows altitude of base of freshwater. Dashed where approximately located. Queried where insufficient data available. Hachures indicate depression. Contour interval is 100 feet. Datum is sea level

**Figure 4.** Altitude of base of freshwater in the central Lower Peninsula of Michigan.

western parts of the aquifer system, the altitude of the base of freshwater is less than 400 ft, but altitude is more than 400 ft in most of the study area. In the southern and northern parts of the aquifer system, where Pennsylvanian rocks are thin or absent, altitudes of the base of freshwater range from 700 to 800 ft and from 500 to 700 ft above sea level, respectively (fig. 4).

The configuration of the freshwater/saline-water interface is primarily a function of geologic controls. These geologic controls on the distribution of freshwater are described by hydrogeologic unit in the section that follows.

### Glacial Deposits

Glacial deposits are absent in isolated areas of the southern and eastern parts of the aquifer system, where Pennsylvanian and Mississippian rocks are exposed. In general, glacial deposits thicken from the southern to the northern part of the study area and are more than 1,000 ft thick (Western Michigan University, 1981, pl. 15) in parts of Wexford and Osceola Counties (fig. 1). Glaciofluvial deposits are the predominant type of glacial material in many areas of the regional aquifer system (Westjohn and others, 1994), and these deposits typically contain freshwater. Glacial deposits within a 1,600-$mi^2$ area of the Saginaw Lowlands (fig. 1) typically contain saline water. This is the only part of the study area where saline water is common in glacial deposits.

Saline water in glacial deposits of the Saginaw Lowlands has been attributed to advection of saline water or diffusion of solutes from underlying bedrock units (Long and others, 1986). That interpretation is supported by hydraulic-head data (Mississippian and Pennsylvanian sandstones) and computer simulation of ground-water flow, which indicate the Saginaw Lowlands is a subregional discharge area (Mandle and Westjohn, 1989).

The Michigan Lowlands (fig. 1) also appears to be a subregional discharge area (Mandle and Westjohn, 1989). However, glacial deposits in this lowland area contain freshwater.

One geologic explanation for the presence of saline water in glacial deposits of the Saginaw Lowlands and not in the Michigan Lowlands is that glacial deposits in the Saginaw Lowlands may be substantially older than previously suggested. Martin (1955) and Farrand and Bell (1982), who compiled maps of surficial deposits of the Saginaw Lowlands, interpreted the surficial materials to be glacial lacustrine sediments that were deposited in Glacial Lake Saginaw about 12,000 to 13,000 years ago (Flint, 1957, p. 347).

Analysis of data collected as part of the Michigan Basin RASA project supports an alternative interpretation regarding age and origin of these surficial deposits. Boreholes were drilled along a 36-mi-long transect from eastern Gratiot County to central Bay County and in other areas of the Saginaw Lowlands (Appendix C). Nine boreholes were drilled to or near bedrock, and split-spoon-core samples of clay-dominant material were collected at 5- to 10-ft intervals. Examination of samples collected from these boreholes indicates that glacial deposits are predominately clay-rich till. Glaciofluvial sand (possibly glaciolacustrine sand) was found at two of the nine sites drilled, but lacustrine clay was not found at any of the sites. The clay-rich till drilled and cored is interpreted to be lodgement till that was deposited at the base of glacial ice. If this interpretation is correct, then glacial deposits in the Saginaw Lowlands must be older than Glacial Lake Saginaw and thus substantially older than previously interpreted.

It is also unusual that glacial deposits of the Saginaw Lowlands contain saline water at altitudes as much as 70 ft above bedrock. This condition is puzzling, because vertical hydraulic conductivity of these tills is very low. Measured vertical hydraulic conductivity of till core samples (seven measurements) ranges from $10^{-9}$ to $10^{-8}$ cm/s (Harold Olsen, U.S. Geological Survey, written commun., 1993). If this clay-dominant lodgement till were older than formerly thought, then the hypothesis of upward migration of saline water into these low-permeability deposits seems more plausible (Westjohn, 1993, 1994b). It is also possible that the differential in hydraulic head between glacial deposits and the underlying Saginaw aquifer was much larger before development of ground-water resources. Such a condition could also lead to substantial vertical migration of saline water into lodgement tills, which have very low vertical hydraulic conductivities.

### Jurassic Red Beds Confining Unit

Jurassic red beds are the youngest bedrock unit in the Michigan Basin; the areal extent of these deposits is approximately 4,000 mi$^2$. Jurassic red beds form a subregional confining unit in the west-central part of the aquifer system (Westjohn and others, 1994). This interpretation is based on examination of geophysical logs, which show that red beds primarily consist of low permeability lithologies (clay, shale, and gypsum).

The areal extent of red beds corresponds spatially to an area where Pennsylvanian rocks that underlie red beds typically contain saline water (fig. 5). One possible geologic control of the spatial relation of saline water in Pennsylvanian rocks to overlying Jurassic red beds is that these deposits may impede discharge of saline water from underlying bedrock. Alternatively, the red beds may impede recharge of freshwater to Pennsylvanian rocks from Pleistocene glacial deposits.

### Saginaw Aquifer

Freshwater is present in the Saginaw aquifer in the northern (areal extent approximately 2,000 mi$^2$) and the southern parts (areal extent approximately 3,000 mi$^2$) of the aquifer system (fig. 5). Typically, the Saginaw aquifer contains freshwater where it is in direct hydraulic connection with permeable glacial deposits. In the east-central part of the study area, saline water in the Saginaw aquifer is spatially related to low permeability lodgement till that seems to impede discharge of saline-ground water. Conditions are similar in the western part of the aquifer, where Jurassic red beds overlie Pennsylvanian rocks.

Distribution of freshwater in the Saginaw aquifer is also controlled by the relative proportion of aquifer- and confining-unit material. The Saginaw aquifer (composite thickness of Pennsylvanian sandstones above the Parma-Bayport aquifer, see fig. 3 and Westjohn and Weaver, 1996a) ranges from 100 ft to more than 300 ft in thickness in most of the northern and southern areas, as well as along the north-south-trending corridor between them. In most of the eastern and western parts of the Saginaw aquifer, composite thickness of sandstones is less than 100 ft. Sandstones in these areas

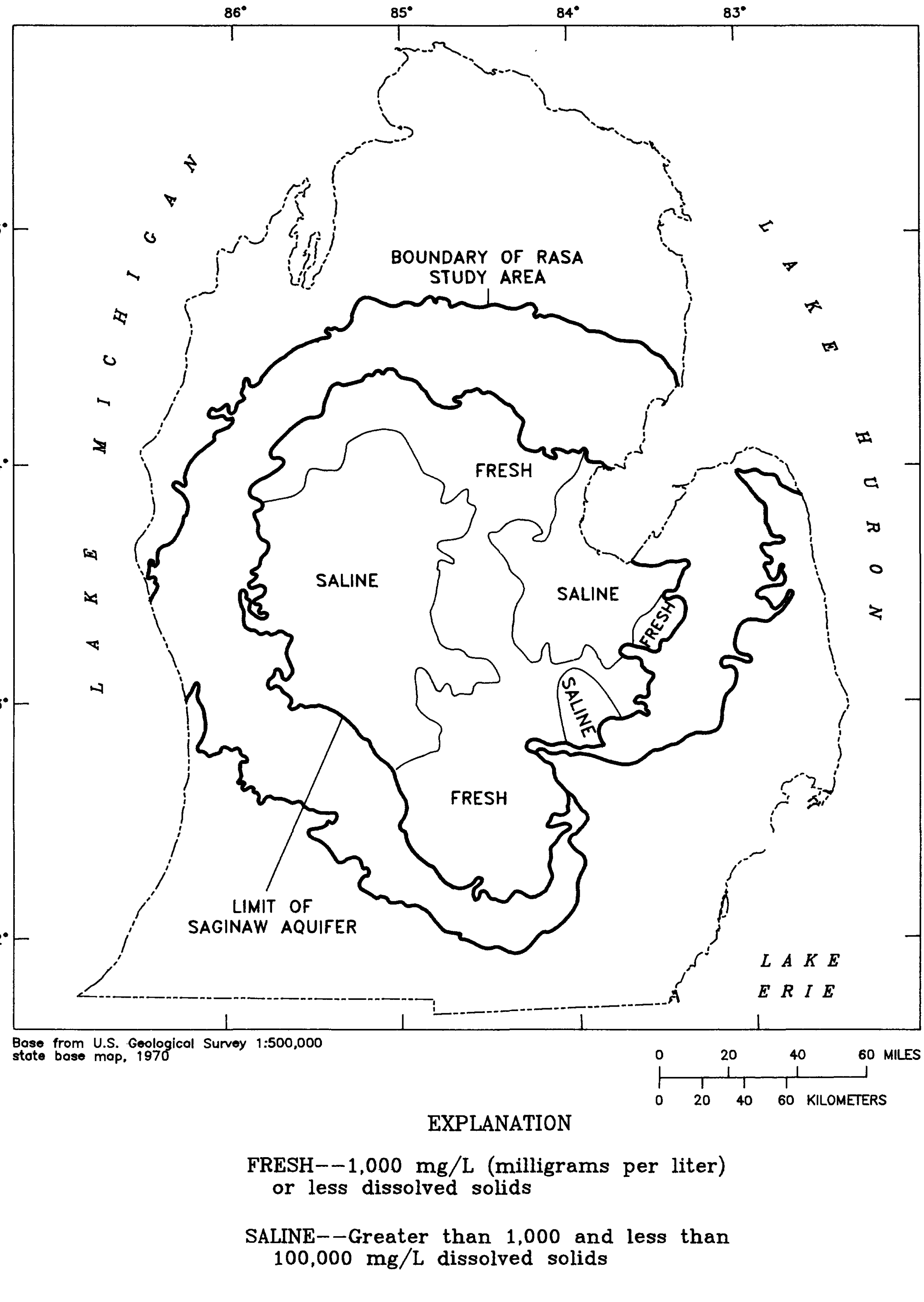



**Figure 5.** Distribution of freshwater and saline water in the Saginaw aquifer, central Lower Peninsula of Michigan.

typically are saline-water bearing and isolated from freshwater-bearing glacial deposits by shale or other confining unit material (Westjohn and Weaver, 1996a).

### Parma-Bayport Aquifer

The distribution of freshwater, saline water, and brine in the Parma-Bayport aquifer is reasonably well delineated in the northern part of the study area on the basis of geophysical logs; water-quality data for this area are limited to two samples (Western Michigan University, 1981, tab. 7h, pl. 24). Water-quality data and geophysical logs are few in the southern part of the aquifer, and no attempt was made to interpret geologic controls of the position of the freshwater/saline-water interface in this area.

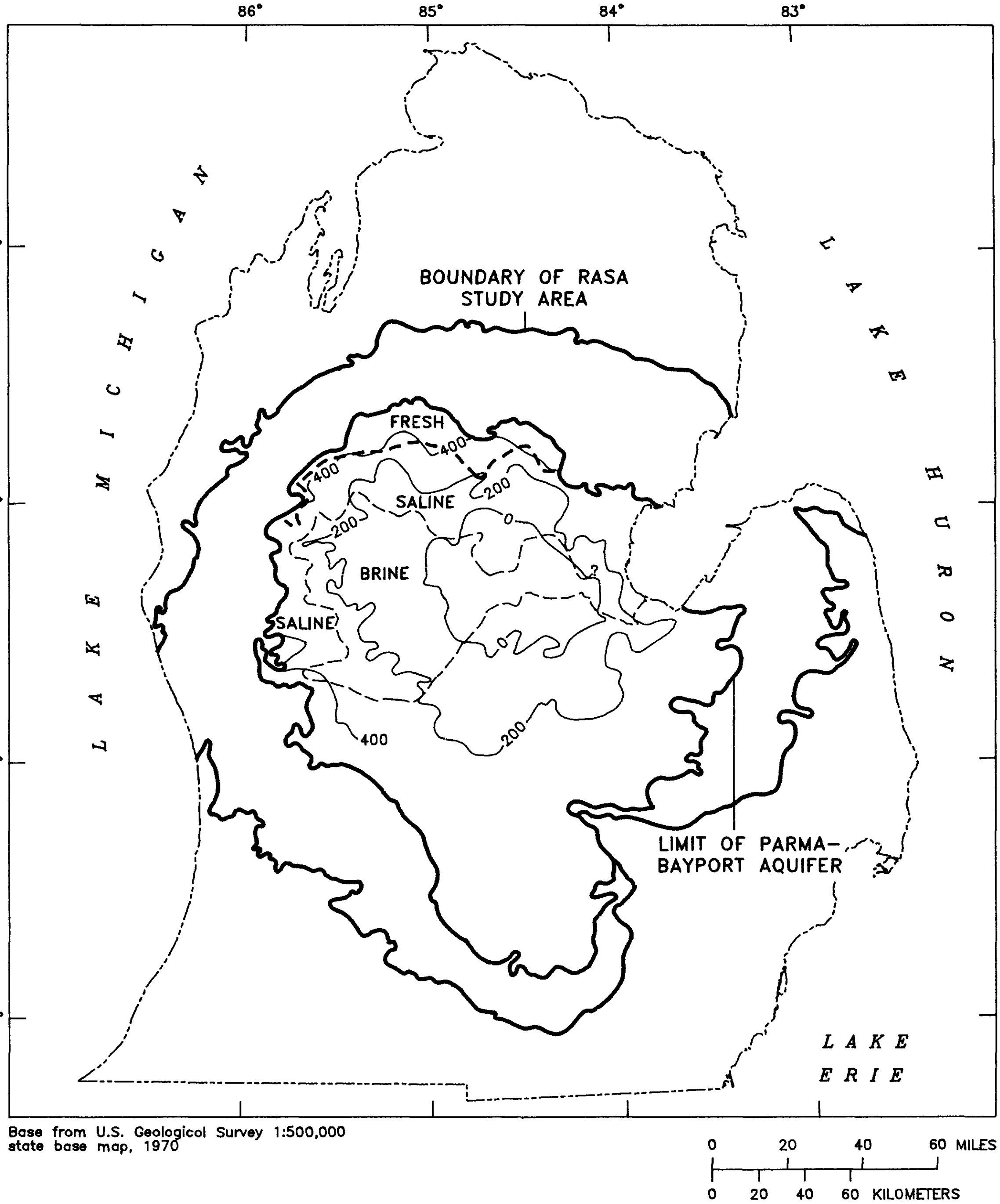
Freshwater is present in the Parma-Bayport aquifer in the northern part of the study area, where the aquifer subcrops beneath Pleistocene glacial deposits (fig. 6). Glacial deposits are predominantly sand and gravel in the northern part of the aquifer system (Westjohn and others, 1994), and freshwater in the Parma-Bayport aquifer seems to be related to direct hydraulic connection with freshwater-bearing glaciofluvial deposits.

Salinity of ground water in the Parma-Bayport aquifer (northern half of the study area) generally increases down regional dip, where the aquifer is confined by overlying Pennsylvanian shale. The transition zone from freshwater to brine is as narrow as 3 mi in the northwest, and broadens toward the northeast (locally more than 30 mi wide). Configuration of the brine-bearing part of the Parma-Bayport aquifer roughly resembles the structural geometry of the basin in the western part of the aquifer, where altitudes of the saline-water/brine interface range from 200 to 400 ft above sea level (fig. 6). All electrical-resistivity logs inside the area delineated as brine-bearing (areal extent 2,300 $mi^2$) show measured electrical resistivities that range from 1 to 4 ohm-m. This interpretation is supported by the only known water-quality data, which indicate that the Parma-Bayport aquifer contains ground water whose dissolved-solids concentration exceeds 225,000 mg/L (Western Michigan University, 1981, tab. 7h, pl. 24).

A narrow tongue of brine in the Parma-Bayport aquifer extends eastward from the main pool of brine, toward Saginaw Bay (fig. 6). This feature is, at present, geologically inexplicable.

### Marshall Aquifer

Regional geologic controls of the distribution of freshwater, saline water, and brine in the Marshall aquifer are related to structural configuration of the aquifer. The Marshall aquifer is freshwater bearing in subcrop areas, where it is in direct hydraulic connection with permeable Pleistocene glacial deposits. Salinity of ground water increases down regional dip toward the center of the basin, where the aquifer is confined by shales, carbonates, and evaporites of the overlying Michigan Formation. The transition zone from freshwater to brine is as narrow as 2 mi in the northwest, but ranges from 15 to 50 mi in width in most areas (fig. 7).




EXPLANATION

—200— STRUCTURE CONTOUR—Shows altitude of top of Marshall aquifer. Absent where data are insufficient. Contour interval 200 feet. Datum is sea level

- - - - - FRESHWATER/SALINE WATER INTERFACE—Absent where data are insufficient

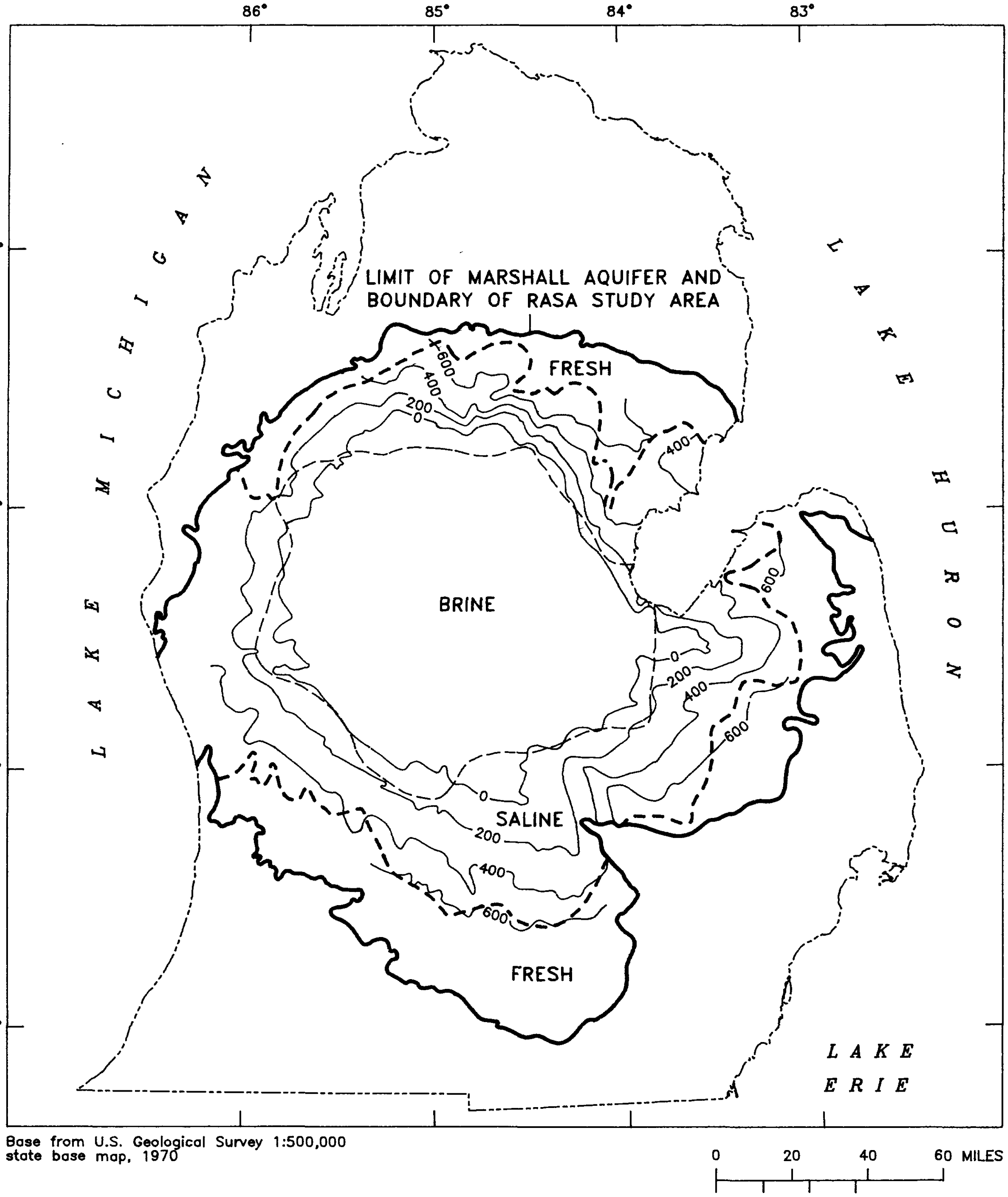
- - - - - SALINE WATER/BRINE INTERFACE—Queried where approximate

FRESH—1,000 mg/L (milligrams per liter) or less dissolved solids

SALINE—Greater than 1,000 and less than 100,000 mg/L dissolved solids

BRINE—100,000 mg/L or more dissolved solids

**Figure 6.** Distribution of freshwater, saline water, and brine in the Parma-Bayport aquifer, central Lower Peninsula of Michigan.




EXPLANATION

—200— STRUCTURE CONTOUR--Shows altitude of top of Marshall aquifer. Absent where data are insufficient. Contour interval 200 feet. Datum is sea level

- - - - - FRESHWATER/SALINE WATER INTERFACE--Absent where data are insufficient

----- SALINE WATER/BRINE INTERFACE

FRESH--1,000 mg/L (milligrams per liter) or less dissolved solids

SALINE--Greater than 1,000 and less than 100,000 mg/L dissolved solids

BRINE--100,000 mg/L or more dissolved solids

**Figure 7.** Distribution of freshwater, saline water, and brine in the Marshall aquifer, central Lower Peninsula of Michigan.

The transition from freshwater to saline water is at an altitude of about 600 ft in the southern and eastern parts of the study area (fig. 7). In the northern subcrop area of the Marshall aquifer, the altitude of the freshwater/saline-water interface ranges from 200 to more than 600 ft above sea level and conforms to relief on the underlying Coldwater confining unit.

The transition from saline water to brine is typically at altitudes between sea level and 200 ft above sea level, although altitudes range from sea level to about 100 ft below sea level in the north-central and south-central parts of the mapped area (fig. 7).

Geophysical logs show that dissolved-solids concentration of ground water increases with depth in the Marshall aquifer. Lithologic irregularities within the sandstones contribute to this condition. For example, layers having especially low vertical hydraulic conductivity have been found among sandstone in the aquifer; these layers seem to be related to mineralogical and stratigraphic barriers (Westjohn, 1991; Westjohn and others, 1991). Vertical hydraulic conductivity is as much as three orders in magnitude lower than horizontal hydraulic conductivity in sandstones that include abundant detrital and authigenic layer-silicate minerals. Detrital layer-silicate minerals that are parallel to bedding seem to impede vertical flow of ground water (Westjohn, 1991). Also within the Marshall aquifer are areas where sandstones are mostly or entirely cemented with carbonate, quartz, or clay; these authigenic minerals partially or entirely occlude pore space and substantially reduce hydraulic conductivity. Areas of well-cemented sandstone seem to be stratiform, and may impede vertical migration of ground water.

Compounding the irregularities within the sandstones is the presence of shale, siltstone, and carbonate layers that separate permeable sandstones of the Marshall aquifer. In the subcrop areas of the Marshall aquifer, sandstones at or near the glacial-deposits/bedrock interface typically have electrical resistivities that indicate the presence of freshwater (greater than 100 ohm-m). In locations where shale or other low permeability material underlies freshwater-bearing sandstone, sandstones underlying this material typically have substantially lower electrical resistivities (10 to 50 ohm-m), indicating the presence of saline water. In many places, low permeability materials seem to divide sandstones into zones that contain waters with very different dissolved-solids concentrations.

Along numerous, minor, northwest-trending anticlines in bedrock, the Michigan confining unit has been eroded, and the Marshall aquifer is in direct hydraulic connection with glacial deposits. The Marshall aquifer contains freshwater along the limbs of these anticlines. Down dip on the limbs of these minor folds (normal to the axial traces), the width of the transition zone from freshwater to brine is narrow and typically ranges from 2 to 4 mi.

## SUMMARY

Unconsolidated Pleistocene glacial deposits, Jurassic red beds, and Pennsylvanian through Mississippian bedrock units form a system of regional aquifers and confining units in the central Lower Peninsula of Michigan. The most important aquifers are Pleistocene glaciofluvial deposits and Pennsylvanian and Mississippian sandstones. Saline water is present below freshwater-bearing aquifers everywhere in the Michigan Basin. The position of the freshwater/saline water interface was delineated on the basis of water-quality data (612 samples) in the southern and eastern parts of the aquifer system. In the northwestern part of the aquifer system where water-quality data are few, electrical-resistivity logs (198 logs) that were run in boreholes open to Pleistocene glacial deposits and bedrock aquifers were used to delineate the position of the interface.

Glacial deposits of Pleistocene age contain freshwater, except in a 1,600 $mi^2$ area within the Saginaw Lowlands, where these deposits typically contain saline water. Pennsylvanian and Mississippian sandstones are typically freshwater-bearing where they are subcrops below permeable Pleistocene glacial deposits. Down regional dip from subcrop areas, salinity of ground water progressively increases in Pennsylvanian and Mississippian sandstones, and these units contain brine in the central part of the basin. Freshwater is present in Pennsylvanian sandstones in the northern (areal extent, approximately 2,000 $mi^2$) and the southern parts (areal extent, approximately 3,000 $mi^2$) of the Saginaw aquifer. Typically, saline water is present in the Saginaw aquifer in the eastern and western parts of the study area.

Relief on freshwater/saline-water interface is approximately 500 ft. Altitudes of the interface are low (300 to 400 ft above sea level) along a north-south-trending corridor that extends through the approximate center of the aquifer system. In isolated areas in the northern and western parts of the aquifer, the altitude of the base of freshwater is less than 400 ft, but altitude is more than 400 ft above sea level in most of the study area. In the southern and northern parts of the aquifer system, where Pennsylvanian rocks are thin or absent, altitudes of the base of freshwater range from 700 to 800 ft and from 500 to 700 ft above sea level, respectively.

Geologic controls of the distribution of freshwater in the regional aquifer system are (1) direct hydraulic connection between sandstone aquifers and freshwater-bearing, permeable glacial deposits; (2) impedance of upward discharge of saline water from sandstones by lodgement tills; (3) impedance of recharge of freshwater to bedrock (or discharge of saline water from bedrock) by Jurassic red beds; and (4) vertical barriers to ground-water flow within and between sandstone units.

## REFERENCES CITED

Allen, W.B., 1977, Flowing wells in Michigan 1974: Michigan Department of Natural Resources, Geological Survey Division, Water Information Series Report 2, 27 p.

Archie, G.E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: American Institute of Mining and Metallurgical Engineers Transactions, v. 146, p. 54-62.

Baltusis, M.A., Quigley, M.F., and Mandle, R.J., 1992, Municipal ground-water development and withdrawals in the central Lower Peninsula of Michigan, 1870-1987: U.S. Geological Survey Open-File Report 91-215, 89 p.

Dannemiller, G.T., and Baltusis, M.A., Jr., 1990, Physical and chemical data for ground water in the Michigan Basin: U.S. Geological Survey Open-File Report 90-368, 155 p.

Farrand, W.R., and Bell, D.L., 1982, Quaternary geology of southern Michigan: Ann Arbor, Mich., Department of Geological Sciences, University of Michigan, scale 1:500,000.

Flint, R.F., 1957, Glacial and Pleistocene geology: New York, John Wiley and Sons, 553 p.

Hilchie, D.W., 1979, Old electric log interpretation: Golden, Colo., D.W. Hilchie, 161 p.

Keys, W.S., and MacCary, L.M., 1973, Location and characteristics of the interface between brine and fresh water from geophysical logs of boreholes in the upper Brazos River basin, Texas: U.S. Geological Survey Professional Paper 809-B, 23 p.

Long, D.T., Rezabek, D.H., Takacs, M.J., and Wilson, T.P., 1986, Geochemistry of groundwaters, Bay County, Michigan: Michigan Department of Public Health, ORD 38553, 251 p.

Mandle, R.J., 1986, Plan of study for the Regional Aquifer Systems Analysis of the Michigan Basin: U.S. Geological Survey Open-File Report 86-493, 23 p.

Mandle, R.J., and Westjohn, D.B., 1989, Geohydrologic framework and ground-water flow in the Michigan Basin, *in* Swain L.A., and Johnson, A.I., eds., Regional aquifer systems of the United States, aquifers of the Midwestern area: American Water Resources Monograph Series no. 13, p. 83-109.

Martin, H.M., comp., 1955, Map of the surface formations of the southern Peninsula of Michigan: Michigan Geological Survey Publication 49, scale 1:500,000.

Michigan Geological Survey, 1964, Stratigraphic succession in Michigan, Paleozoic through recent: Chart 1.

Poole, V.L., Cartwright, Keros, and Leap, Darrell, 1989, Use of geophysical logs to estimate water quality of basal Pennsylvanian sandstones, southwestern Illinois: Ground Water, v. 27, no. 5, p. 682-88.

Pryor, W.A., 1956, Quality of groundwater estimated from electrical resistivity logs: Illinois Geological Survey Circular 215, 15 p.

Stramel, G.J., Wisler, C.O., and Laird, L.B., 1954, Water resources of the Grand Rapids area, Michigan: U.S. Geological Survey Circular 323, 40 p.

Sweat, M.J., 1992, Hydrogeology of Huron County, Michigan: U.S. Geological Survey Water-Resources Investigations Report 91-4133, 76 p.

Vanlier, K.E., 1963, Ground-water resources of the Alma Area, Michigan: U.S. Geological Survey Water-Supply Paper 1619-E, 66 p.

Vanlier, K.E., Wood, W.W., and Brunett, J.O., 1973, Water-supply development and management alternatives for Clinton, Eaton, and Ingham Counties, Michigan: U.S. Geological Survey Water-Supply Paper 1969, 111 p.

Weeks, J.B., and Sun, R.J., 1987, Regional Aquifer-System Analysis Program of the U.S. Geological Survey—bibliography, 1978-86: U.S. Geological Survey Water-Resources Investigation Report 87-4138, 81 p.

Western Michigan University, Department of Geology, 1981, Hydrogeologic atlas of Michigan: U.S. Environmental Protection Agency Underground Injection Control Program Report, 35 pls., scale 1:500,000.

Westjohn, D.B., 1989, Application of geophysics in the delineation of the freshwater/saline water interface in the Michigan Basin, *in* Swain, L.A., and Johnson, A.I., eds., Regional aquifer systems of the United States, Aquifers of the Midwestern area: American Water Resources Association Monograph Series no. 13, p. 111-134.

_____1991, Geophysical and hydraulic properties of Mississippian sandstones from the Michigan Basin, and their relations to mineralogy and stratigraphy [abs.]: Geological Society of America, v. 23, no. 5, p. A26.
_____1993, Geological controls of distribution of freshwater in aquifers of the Michigan basin [abs.], in Michigan—its Geology and Geologic Resources, 3d symposium, Michigan State University, East Lansing, Mich., March 18-19, 1993: Program and abstracts, p. 10.
_____1994a, Use of borehole-geophysical logs to delineate the position of the freshwater/saline-water interface in the Michigan Basin, *in* Paillet, F.L., and Williams, J.H., eds., Proceedings of the U.S. Geological Survey workshop on the applications of borehole geophysics to ground-water investigations: U.S. Geological Survey Water-Resources Investigations Report 94-4103, p. 32-39.
_____1994b, Geologic controls of the distribution of freshwater in a regional aquifer system—central Michigan Basin [abs.]: Geological Society of America v. 26, no. 5, p. 67.
Westjohn, D.B., Sibley, D.F., and Eluskie, J.A., 1991, Authigenic mineral paragenesis in Mississippian and Pennsylvanian sandstone aquifers in the Michigan Basin [abs.]: Geological Society of America Abstracts with Programs, v. 23, no. 5, p. 26.
Westjohn, D.B., and Weaver, T.L., 1996a, Hydrogeologic framework of Pennsylvanian and Late Mississippian rocks in the central Lower Peninsula of Michigan: U.S. Geological Survey Water-Resources Investigations Report 94-4107, 44 p.
_____1996b, Hydrogeologic framework of Mississippian rocks in the central Lower Peninsula of Michigan: U.S. Geological Survey Water-Resources Investigations Report 94-4246, 40 p.
Westjohn, D.B., Weaver, T.L., and Zacharias, K.F., 1994, Hydrogeology of Pleistocene glacial deposits and Jurassic "red beds" in the central Lower Peninsula of Michigan: U.S. Geological Survey Water-Resources Investigation Report 93-4152, 14 p.
Wiitala, S.W., Vanlier, K.E., and Krieger, R.A., 1963, Water Resources of the Flint area, Michigan: U.S. Geological Survey Water-Supply Paper 1499-E, 86 p.

# APPENDIXES

# APPENDIX A. HYDROGEOLOGIC SECTIONS A-A′ and B-B′, MAP SHOWING LOCATIONS OF TRACES OF HYDROGEOLOGIC SECTIONS, AND LIST OF GEOPHYSICAL AND GEOLOGIC LOGS OF WATER WELLS, OIL WELLS, AND GAS WELLS USED TO CONSTRUCT HYDROGEOLOGIC SECTIONS

CONTENTS

**Table A1.** Identification of geophysical and geologic logs used to construct hydrogeologic section A-A', Muskegon County to Crawford County, Michigan

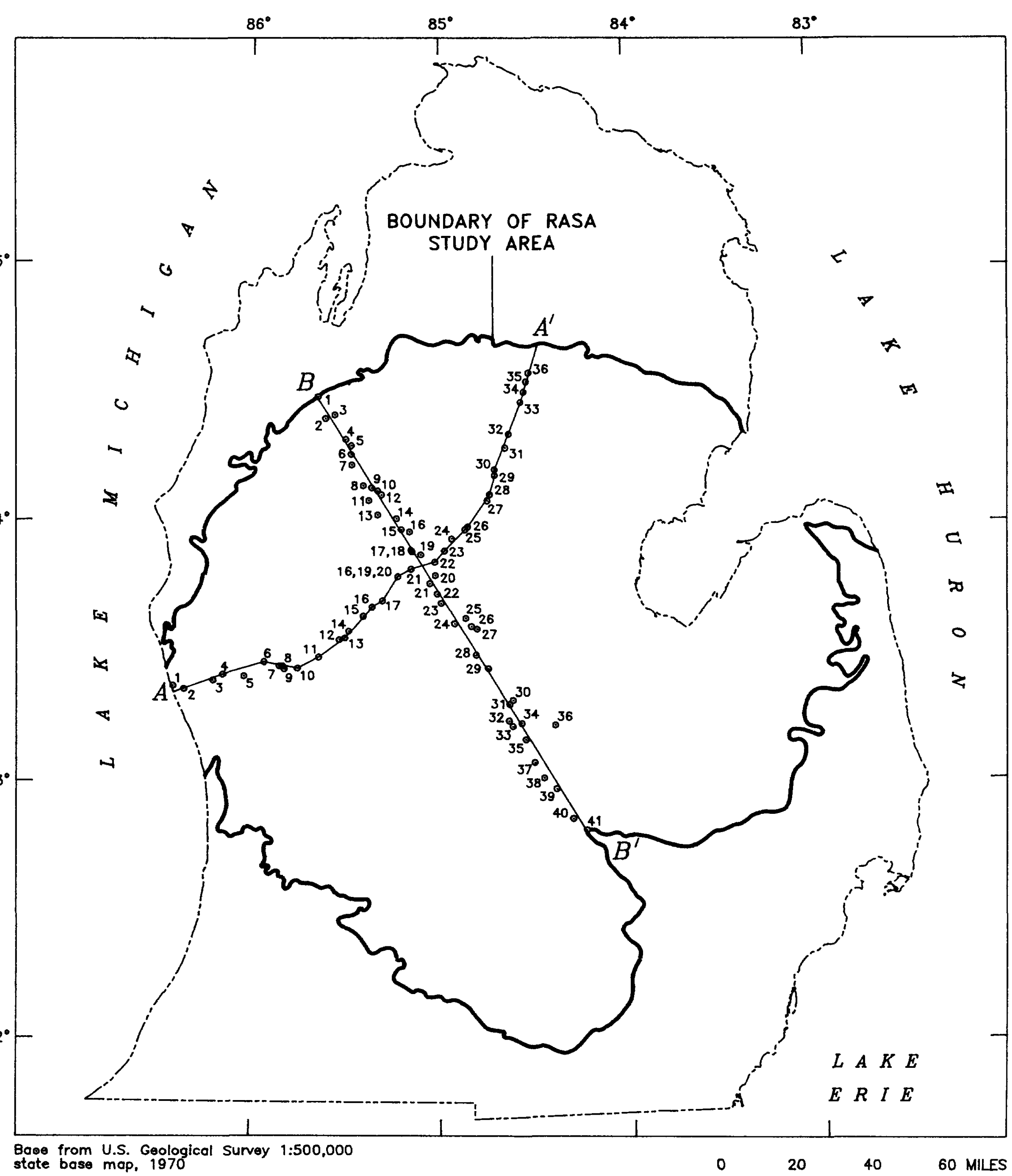
[Permit numbers are assigned to oil and gas wells by Michigan Department of Natural Resources; dashes indicate that no permit number was issued, or that well was used for purposes other than oil or gas exploration or production. U.S. Geological Survey (USGS) identifiers are numbers assigned to logs on file at the USGS, indicating county where well is located, type of well, and type of log]

| Permit number | Number on geologic section | USGS identifier | Section Township Range | Township name, county |
|---|---|---|---|---|
| 18227 | 1 | Mk-g12 | 13-11N-18W | Fruitland, Muskegon |
| — | 2 | Mk-W11 | 16-11N-17W | Fruitland, Muskegon |
| 1499 | 3 | Mk-g9 | 03-11N-16W | Dalton, Muskegon |
| — | 4 | R2 | 30-12N-15W | Holton, Muskegon |
| 217 | 5 | Mk-g16 | 13-12N-15W | Holton, Muskegon |
| 16718 | 6 | Nw-7 | 01-12N-14W | Bridgeton, Newaygo |
| 13520 | 7 | Nw-5 | 10-12N-13W | Garfield, Newaygo |
| 13719 | 8 | Nw-21 | 11-12N-13W | Garfield, Newaygo |
| 13264 | 9 | Nw-25 | 13-12N-13W | Garfield, Newaygo |
| — | 10 | Nw-W3 | 16-12N-12W | Brooks, Newaygo |
| 13146 | 11 | Nw-29 | 33-13N-11W | Big Prairie, Newaygo |
| 16245 | 12 | Mt-32 | 05-13N-10W | Aetna, Mecosta |
| 16305 | 13 | Mt-3 | 03-13N-10W | Aetna, Mecosta |
| 16005 | 14 | Mt-16 | 26-14N-10W | Mecosta, Mecosta |
| 34622 | 15 | Mt-N3 | 04-14N-09W | Austin, Mecosta |
| 11775 | 16 | Mt-5 | 23-15N-09W | Colfax, Mecosta |
| 9806 | 17 | Mt-11 | 17-15N-08W | Martiny, Mecosta |
| 12018 | 19 | Mt-22 | 12-16N-08W | Chippewa, Mecosta |
| 11061 | 20 | Mt-28 | 12-16N-08W | Chippewa, Mecosta |
| 16335 | 21 | Os-6 | 34-17N-07W | Orient, Osceola |
| 12868 | 22 | Cl-13 | 22-17N-06W | Garfield, Clare |
| 10498 | 23 | Cl-10 | 06-17N-05W | Surrey, Clare |
| 31670 | 24 | Cl-N5 | 21-18N-05W | Lincoln, Clare |
| 10795 | 25 | Cl-18 | 12-18N-05W | Lincoln, Clare |
| 11946 | 26 | Cl-20 | 06-18N-04W | Hatton, Clare |
| 14759 | 27 | Cl-17 | 36-20N-04W | Frost, Clare |
| 15433 | 28 | Cl-3 | 19-20N-03W | Franklin, Clare |
| 16985 | 29 | Rc-9 | 29-21N-03W | Roscommon, Roscommon |
| 15702 | 30 | Rc-2 | 20-21N-03W | Roscommon, Roscommon |
| 39826 | 31 | Rc-g3 | 23-22N-03W | Denton, Roscommon |
| 5521 | 32 | Rc-g64 | 06-22N-02W | Bachus, Roscommon |
| 16683 | 33 | Rc-g8 | 21-24N-02W | Higgins, Roscommon |
| — | 34 | Rc-g7 | 02-24N-02W | Higgins, Roscommon |
| 7864 | 35 | Rc-g17 | 36-23N-01W | Richfield, Roscommon |
| — | 36 | R5 | 12-25N-02W | South Branch, Crawford |

**Table A2.** Identification of geophysical and geologic logs used to construct hydrogeologic section B-B', Wexford County to Shiawassee County, Michigan

[Permit numbers are assigned to oil and gas wells by Michigan Department of Natural Resources; dashes indicate that no permit number was issued, or that well was used for purposes other than oil or gas exploration or production. U.S. Geological Survey (USGS) identifiers are numbers assigned to logs on file at the USGS, indicating county where well is located, type of well, and type of log]

| Permit number | Number on geologic section | USGS identifier | Section Township Range | Township name, county |
|---|---|---|---|---|
| 29755 | 1 | Wx-g20 | 16-24N-11W | Hanover, Wexford |
| 10303 | 2 | Wx-3 | 11-23N-11W | Antioch, Wexford |
| 35866 | 3 | Wx-N1 | 05-23N-10W | Colfax, Wexford |
| 12304 | 4 | Wx-4 | 11-22N-10W | Selma, Wexford |
| 10661 | 5 | Wx-g58 | 24-22N-10W | Selma, Wexford |
| 18209 | 6 | Wx-6 | 36-22N-10W | Selma, Wexford |
| 20742 | 7 | Wx-5 | 13-21N-10W | Cherry Grove, Wexford |
| 10754 | 8 | Os-8 | 09-20N-09W | Sherman, Osceola |
| 25007 | 9 | Os-g15 | 14-20N-09W | Sherman, Osceola |
| 15934 | 10 | Os-9 | 19-20N-08W | Highland, Osceola |
| — | 11 | Os-24 | 34-20N-09W | Sherman, Osceola |
| 14591 | 12 | Os-31 | 29-20N-08W | Highland, Osceola |
| 11670 | 13 | Os-1 | 19-19N-08W | Hartwick, Osceola |
| 9039 | 14 | Os-g97 | 25-19N-08W | Hartwick, Osceola |
| 8573 | 15 | Os-g65 | 07-18N-07W | Sylvan, Osceola |
| 14639 | 16 | Os-4 | 09-18N-07W | Sylvan, Osceola |
| 32394 | 17 | Os-N1 | 03-17N-07W | Orient, Osceola |
| 13739 | 18 | Os-12 | 03-17N-07W | Orient, Osceola |
| 12375 | 19 | Os-29 | 12-17N-07W | Orient, Osceola |
| 26256 | 20 | Ib-g45 | 10-16N-06W | Coldwater, Isabella |
| 12911 | 21 | Ib-65 | 20-16N-06W | Coldwater, Isabella |
| 11747 | 22 | Ib-13 | 02-15N-06W | Sherman, Isabella |
| 18330 | 23 | Ib-57 | 13-15N-06W | Sherman, Isabella |
| 23980 | 24 | Ib-L1 | 16-14N-05W | Deerfield, Isabella |
| 15597 | 25 | Ib-6 | 01-14N-05W | Deerfield, Isabella |
| 16275 | 26 | Ib-7 | 17-14N-04W | Union, Isabella |
| — | 27 | Ib-W2 | 27-14N-04W | Union, Isabella |
| 16791 | 28 | Ib-10 | 28-13N-04W | Lincoln, Isabella |
| 9464 | 29 | Gr-g23 | 13-12N-04W | Seville, Gratiot |
| — | 30 | Gr-W11 | 30-11N-02W | Emerson, Gratiot |
| 10536 | 31 | Gr-3 | 36-11N-03W | Arcada, Gratiot |
| 14844 | 32 | Gr-2 | 26-10N-03W | Newark, Gratiot |
| 13920 | 33 | Gr-1 | 36-10N-03W | Newark, Gratiot |
| 33991 | 34 | Gr-NFD-1 | 28-10N-02W | North Star, Gratiot |
| 33382 | 35 | Gr-NFD-4 | 22-09N-02W | Washington, Gratiot |
| 3703 | 36 | Gr-g79 | 36-10N-01W | Hamilton, Gratiot |
| 33313 | 37 | Ct-N2 | 24-08N-02W | Greenbush, Clinton |
| 33321 | 38 | Ct-N1 | 09-07N-01W | Ovid, Clinton |
| 3586 | 39 | Ct-g21 | 25-07N-01W | Ovid, Clinton |
| 1198 | 40 | Sw-g2 | 01-05N-01E | Woodhull, Shiawassee |
| 23376 | 41 | Sw-g9 | 25-05N-02E | Perry, Shiawassee |

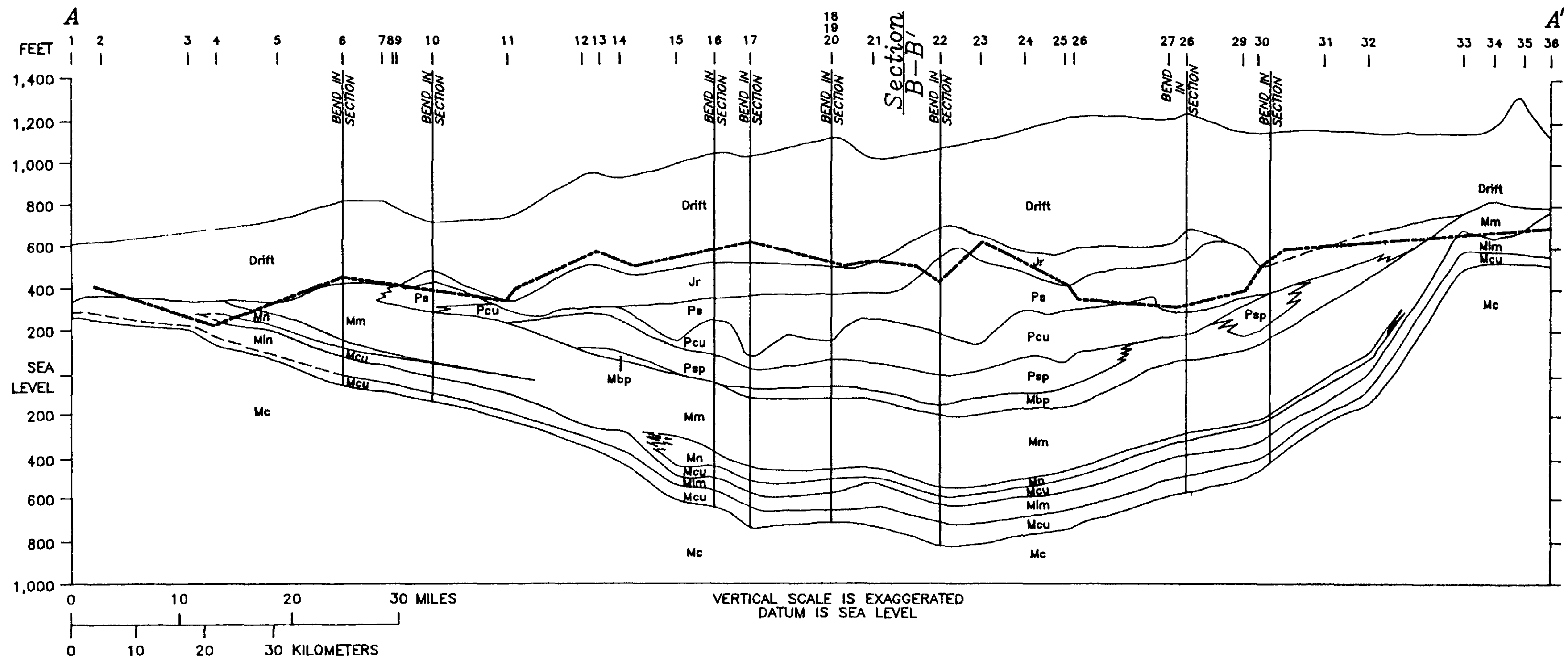



EXPLANATION

B——B′ GEOLOGIC SECTION LINE

41 DATA POINT——Number assigned for reference purposes only. For additional information see tables 1 and 2

**Figure A1.** Location of geophysical and geologic logs used to construct hydrogeologic sections A-A′ and B-B′.




## EXPLANATION

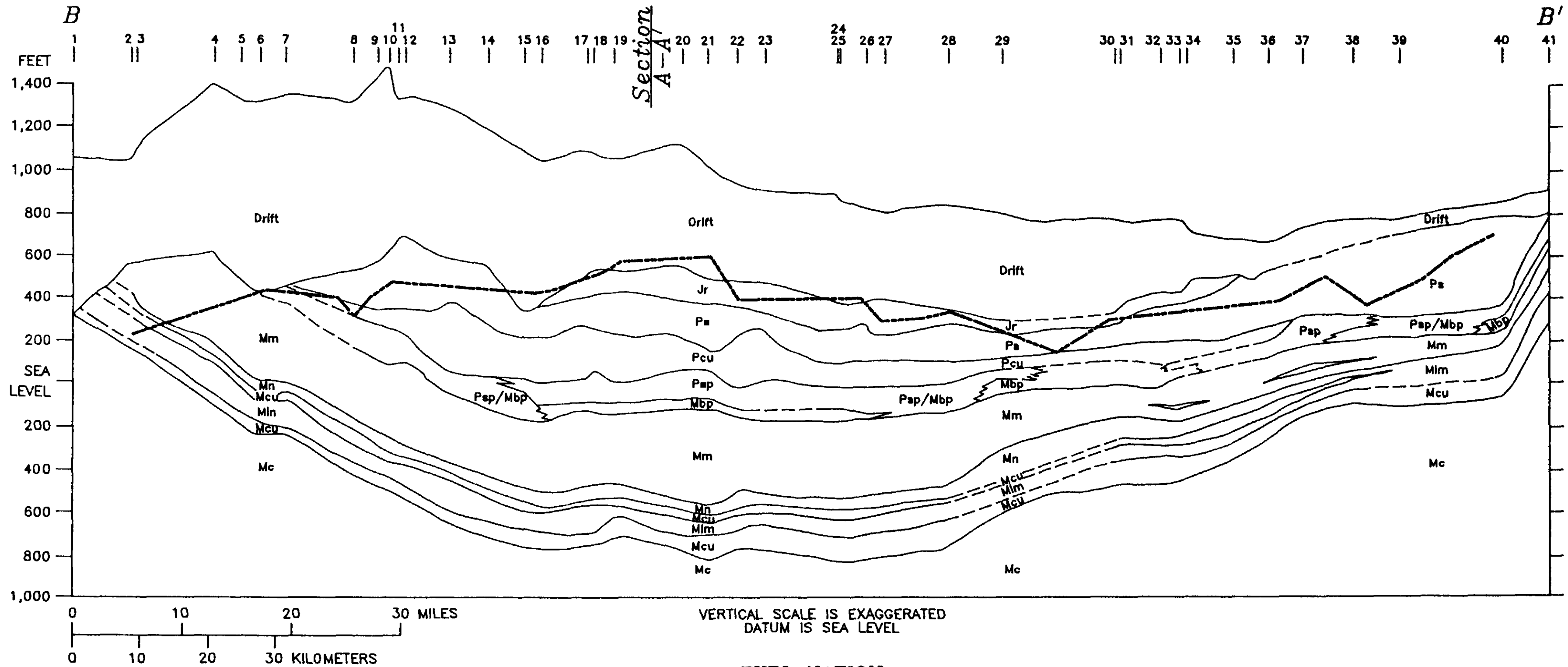
GEOLOGIC CONTACT--Dashed where approximately located

FRESHWATER/SALINE INTERFACE

6 LOCATION OF LOGGED BOREHOLE--Refer to Appendix 1, table 1, column 2

| FORMATION | | PERIOD OR SERIES |
|---|---|---|
| Drift | Drift--Glacial deposits (undifferentiated) | PLEISTOCENE |
| Jr | Red Beds | JURASSIC |
| Ps | Grand River-Saginaw Formations (undifferentiated) | PENNSYLVANIAN |
| Pcu | Saginaw Formation (principally shale) | PENNSYLVANIAN |
| Psp | Parma Sandstone | PENNSYLVANIAN |
| Mbp | Bayport Limestone | MISSISSIPPIAN |
| Mm | Michigan Formation | MISSISSIPPIAN |
| Mn | Marshall Sandstone (Napoleon member) | MISSISSIPPIAN |
| Mlm | Marshall Sandstone (lower Marshall unit) | MISSISSIPPIAN |
| Mcu | Marshall Sandstone (confining unit lithologies) | MISSISSIPPIAN |
| Mc | Coldwater Shale | MISSISSIPPIAN |

**Figure A2.** Generalized hydrogeologic section A-A' showing stratigraphic relations of Mississippian and younger geologic units and position of freshwater/saline-water interface, Muskegon County to Crawford County, central Lower Peninsula of Michigan. (Line of section shown in fig. A1.)




EXPLANATION

| | |
|---|---|
| — — — | GEOLOGIC CONTACT—Dashed where approximately located |
| ▬▬▬ | FRESHWATER/SALINE INTERFACE |
| 6 | LOCATION OF LOGGED BOREHOLE—Refer to Appendix 1, table 2, column 2 |

| FORMATION | | PERIOD OR SERIES |
|---|---|---|
| Drift | Drift—Glacial deposits (undifferentiated) | PLEISTOCENE |
| Jr | Red Beds | JURASSIC |
| Ps | Grand River–Saginaw Formations (undifferentiated) | PENNSYLVANIAN |
| Pcu | Saginaw Formation (principally shale) | PENNSYLVANIAN |
| Psp | Parma Sandstone | PENNSYLVANIAN |
| Mbp | Bayport Limestone | MISSISSIPPIAN |
| Mm | Michigan Formation | MISSISSIPPIAN |
| Mn | Marshall Sandstone (Napoleon member) | MISSISSIPPIAN |
| Mlm | Marshall Sandstone (lower Marshall unit) | MISSISSIPPIAN |
| Mcu | Marshall Sandstone (confining unit lithologies) | MISSISSIPPIAN |
| Mc | Coldwater Shale | MISSISSIPPIAN |

**Figure A3.** Generalized hydrogeologic section B-B′ showing stratigraphic relations of Mississippian and younger geologic units and position of freshwater/saline-water interface, Wexford County to Shiawassee County, central Lower Peninsula of Michigan. (Line of section shown in fig. A1.)

## APPENDIX B. LIST OF SOURCES OF WATER-QUALITY DATA


Breithart, M.S., 1991, Unpublished data, Michigan Department of Public Health.

Dannemiller, G.T., and Baltusis, M.A., Jr., 1990, Physical and chemical data for ground water in the Michigan Basin: U.S. Geological Survey Open-File Report 90-368, 155 p.

Long, D.T., Rezabek, D.H., Takacs, M.J., and Wilson, T.P., 1986, Geochemistry of ground waters, Bay County, Michigan: Michigan Department of Public Health, ORD 38553, 251 p.

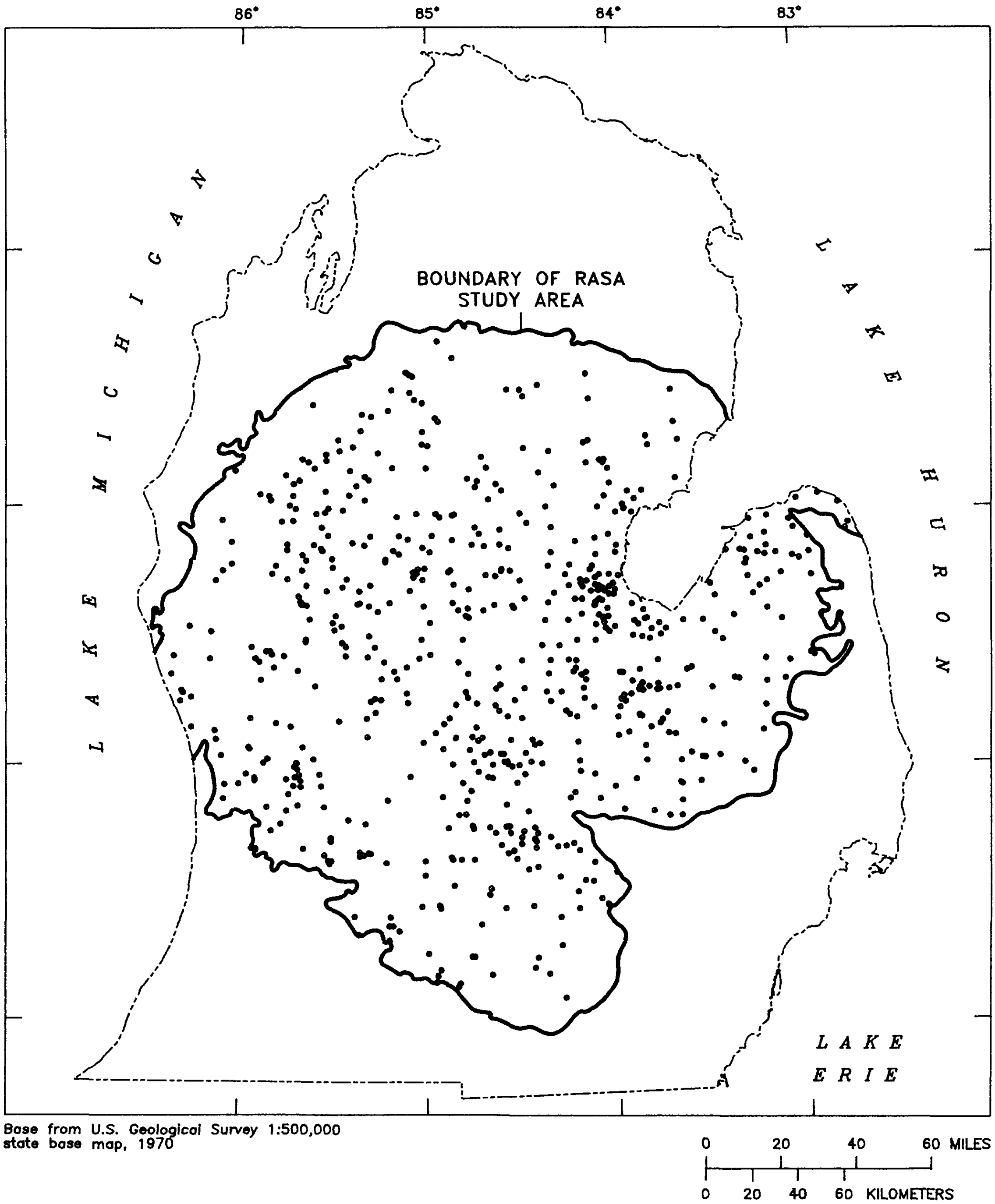
Sweat, M.J., 1992, Hydrogeology of Huron County, Michigan: U.S. Geological Survey Water-Resources Investigations Report 91-4133, 76 p.

Vanlier, K.E., Wood, W.W., and Brunett, J.O., 1973, Water-supply development and management alternatives for Clinton, Eaton, and Ingham Counties, Michigan: U.S. Geological Survey Water-Supply Paper 1969, 111 p.

Western Michigan University, Department of Geology, 1981, Hydrogeologic atlas of Michigan: U.S. Environmental Protection Agency Underground Injection Control Program Report, 35 pls., scale 1:500,000.

# APPENDIX C. LOCATIONS OF BOREHOLES AND LOGS

CONTENTS




EXPLANATION

• DATA POINT--Shows location of boreholes and logs used to construct figure 2

**Figure C1.** Locations of boreholes and logs used to construct altitude of base of freshwater map, central Lower Peninsula of Michigan.

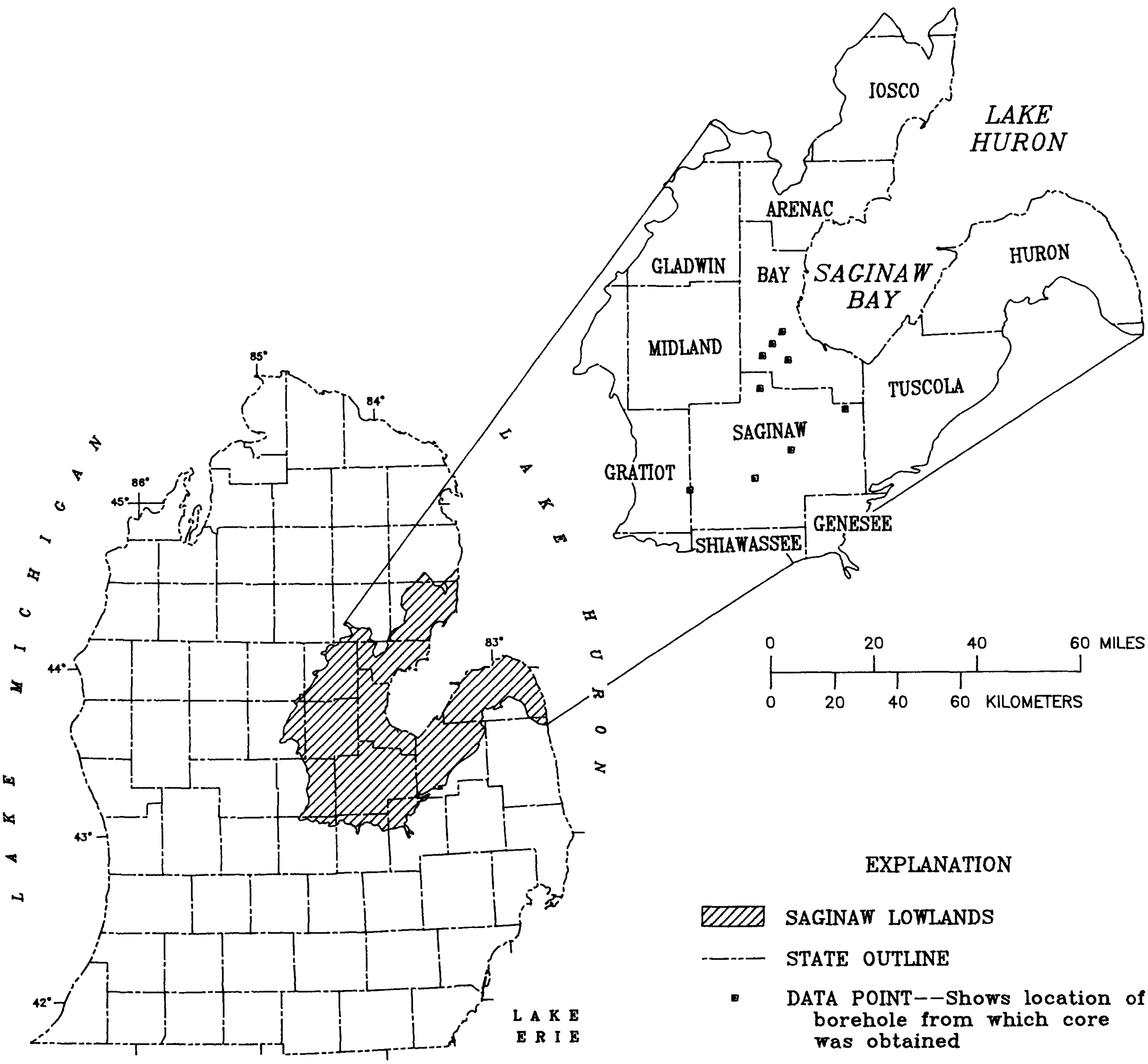



**Figure C2.** Location of cored boreholes, central Lower Peninsula of Michigan. Area shown is the Saginaw Lowlands (Modified from Martin, 1955).

# APPENDIX D. SUITE OF LOGS SHOWING TYPICAL GEOPHYSICAL-LOG TRACES OF FRESHWATER-, SALINE-WATER-, AND BRINE-BEARING AQUIFERS

## CONTENTS

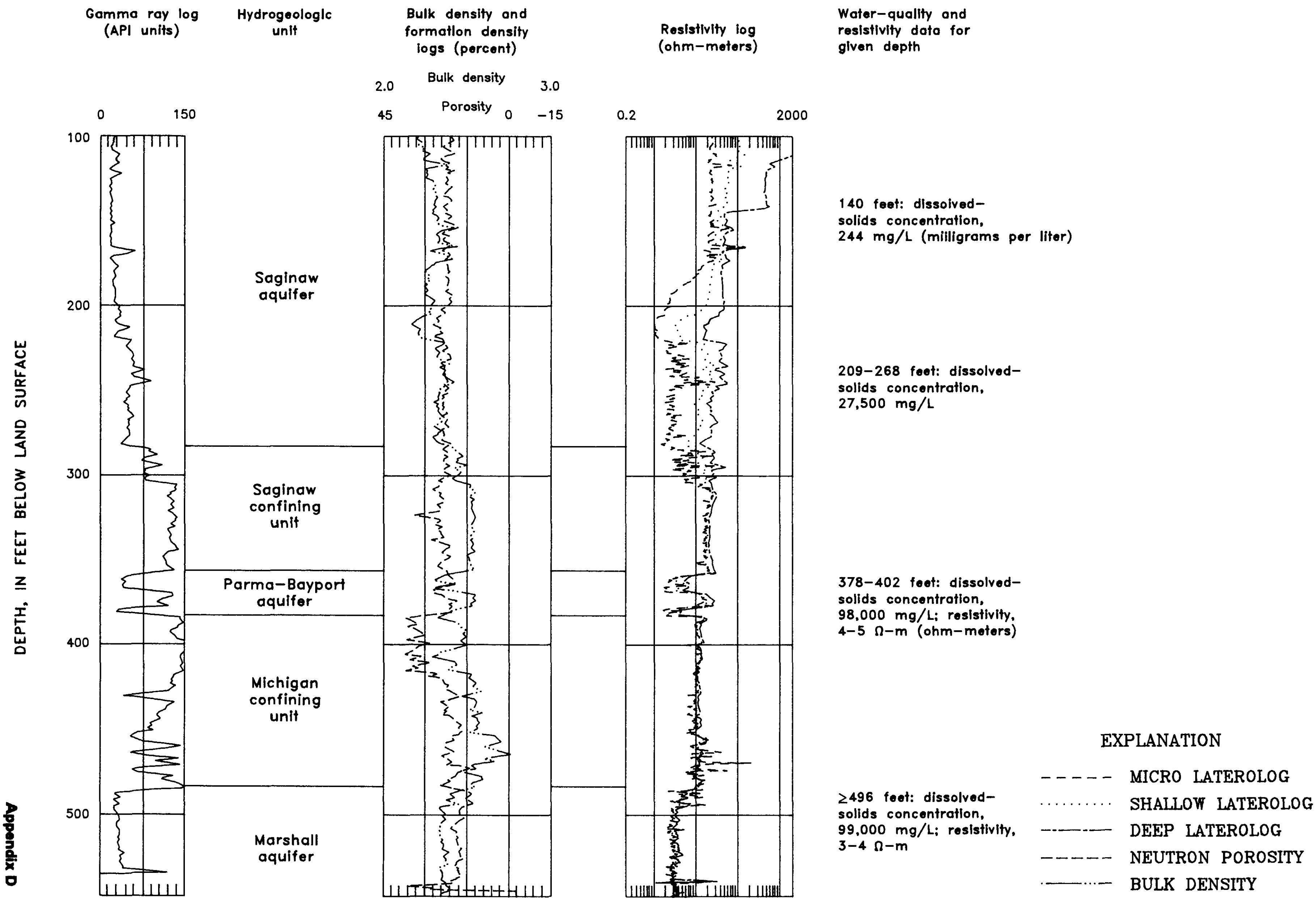



**Figure D1.** Suite of geophysical logs and water-quality data showing typical traces of selected units of Pennsylvanian and Mississippian age, central Lower Peninsula of Michigan.

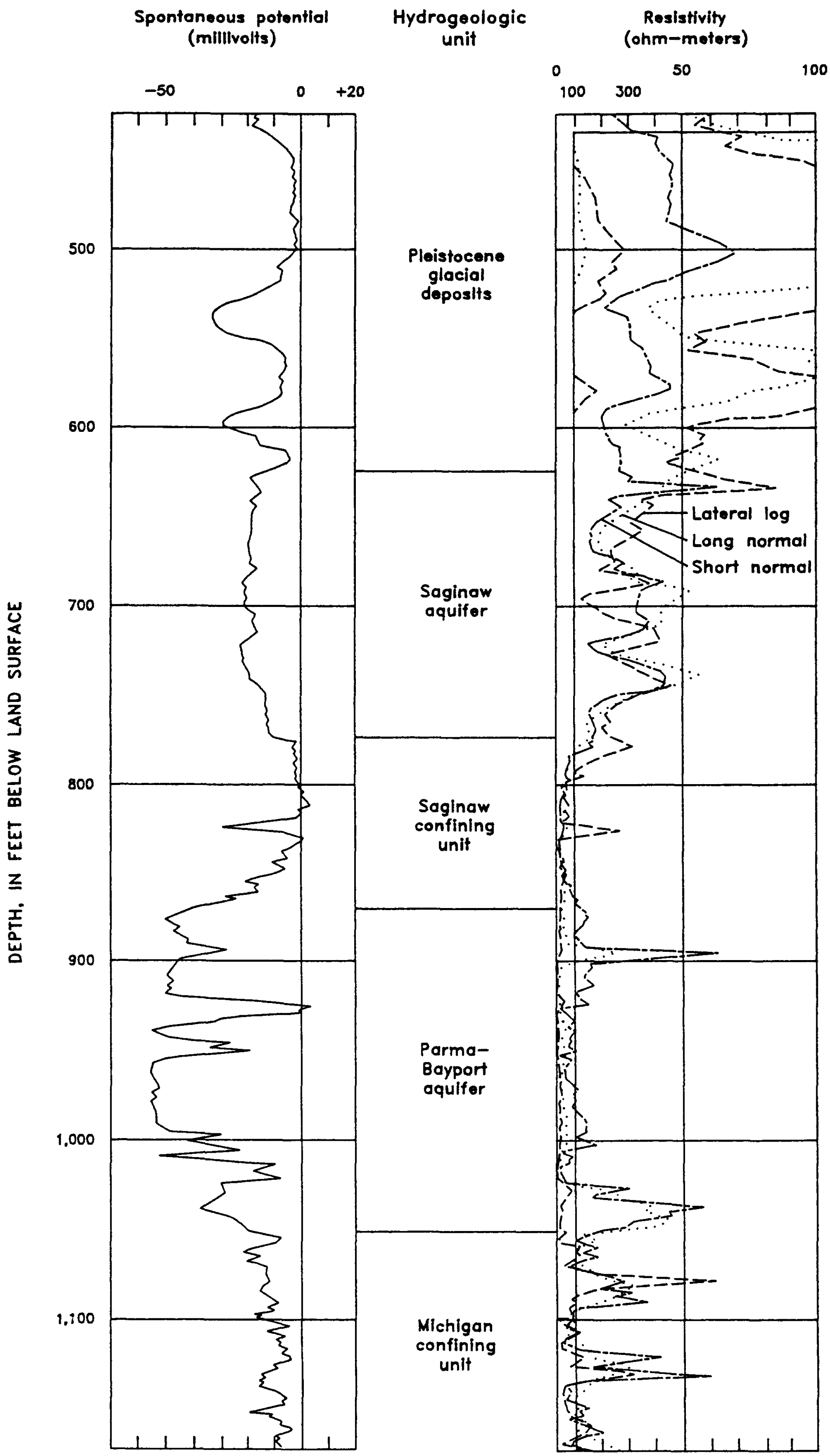



**Figure D2.** Electric log from Newaygo County, Michigan (permit no. 15,300), showing typical traces of Late Mississippian through Pleistocene units.

## APPENDIX E. LIST OF GEOPHYSICAL LOGS USED TO CONSTRUCT FIGURES

**Table E1.** Identification of geophysical logs used to construct figures

[Permit numbers are assigned to oil and gas wells by Michigan Department of Natural Resources; dashes indicate that no permit number was issued, or that well was used for purposes other than oil or gas exploration or production. U.S. Geological Survey (USGS) identifiers are numbers assigned to logs on file at the USGS, indicating county where well is located, type of well, and type of log]

| Permit number | USGS identifier | Section Township Range | Township name, county |
|---|---|---|---|
| 13761 | An-1 | 05-20N-04E | Clayton, Arenac |
| 15218 | An-4 | 35-19N-03E | Adams, Arenac |
| 13764 | An-5 | 18-19N-04E | Deep River, Arenac |
| 14212 | An-6 | 10-18N-04E | Lincoln, Arenac |
| 15510 | An-7 | 36-19N-03E | Adams, Arenac |
| 18542 | Ch-2 | 06-04S-05W | Clarendon, Calhoun |
| 24353 | Ch-3 | 30-03S-05W | Eckford, Calhoun |
| 13814 | Cl-1 | 15-19N-05W | Greenwood, Clare |
| 10498 | Cl-10 | 06-17N-05W | Surrey, Clare |
| 17990 | Cl-11 | 08-19N-03W | Hamilton, Clare |
| 12868 | Cl-13 | 22-17N-06W | Garfield, Clare |
| 14675 | Cl-14 | 06-17N-03W | Sheridan, Clare |
| 16747 | Cl-15 | 02-20N-06W | Winterfield, Clare |
| 17271 | Cl-16 | 12-17N-05W | Surrey, Clare |
| 14759 | Cl-17 | 36-20N-04W | Frost, Clare |
| 10795 | Cl-18 | 12-18N-05W | Lincoln, Clare |
| 13124 | Cl-19 | 36-17N-06W | Garfield, Clare |
| 11946 | Cl-20 | 06-18N-04N | Hatton, Clare |
| 15433 | Cl-3 | 19-20N-03W | Franklin, Clare |
| 16572 | Cl-30 | 04-18N-06W | Freeman, Clare |
| 10329 | Cl-5 | 06-19N-03W | Hamilton, Clare |
| 14463 | Cl-6 | 05-18N-05W | Lincoln, Clare |
| 17181 | Cl-7 | 22-20N-04W | Frost, Clare |
| 10704 | Cl-8 | 25-18N-04W | Hatton, Clare |
| 9483 | Cl-9 | 04-20N-03W | Franklin, Clare |
| 25989 | Cl-D2 | 23-17N-04W | Grant, Clare |
| 18759 | Cl-28 | 25-20N-03W | Franklin, Clare |
| 19272 | Ct-1 | 27-08N-04W | Lebanon, Clinton |
| 19367 | Ct-2 | 02-06N-02W | Olive, Clinton |
| ----- | Et-N7 | 20-03N-04W | Benton, Eaton |
| 13920 | Gr-1 | 36-10N-03W | Newark, Gratiot |
| 14844 | Gr-2 | 26-10N-03W | Newark, Gratiot |
| 10536 | Gr-3 | 36-11N-03W | Arcada, Gratiot |
| 13775 | Gr-4 | 24-10N-04W | New Haven, Gratiot |
| 11241 | Gr-5 | 16-10N-03W | Newark, Gratiot |
| 11201 | Gr-6 | 15-10N-04W | New Haven, Gratiot |
| 19456 | Gr-7 | 04-10N-04W | New Haven, Gratiot |
| 18105 | Gr-8 | 10-11N-04W | Sumner, Gratiot |
| ----- | Gs-N2 | 10-09N-05E | Montrose, Genesee |
| 14276 | Gw-1 | 06-19N-02W | Sage, Gladwin |
| 15490 | Gw-2 | 12-20N-01W | Butman, Gladwin |
| 15243 | Gw-3 | 28-17N-02W | Beaverton, Gladwin |
| 10688 | Gw-4 | 19-17N-02W | Beaverton, Gladwin |
| 13073 | Gw-5 | 31-18N-02W | Grout, Galdwin |
| 18761 | Gw-9 | 13-20N-02W | Sherman, Gladwin |
| ----- | Ia-2 | 16-07N-05W | Lyons, Ionia |
| 11849 | Ib-12 | 25-16N-05W | Gilmore, Isabella |
| 16745 | Ib-15 | 10-14N-06W | Broomfield, Isabella |

Table E1. Identification of geophysical logs used to construct figures—Continued

| Permit number | USGS identifier | Section Township Range | Township name, county |
|---|---|---|---|
| 14813 | Ib-17 | 07-15N-04W | Isabella, Isabella |
| 11785 | Ib-18 | 23-16N-06W | Coldwater, Isabella |
| 10873 | Ib-23 | 33-16N-06W | Coldwater, Isabella |
| 10239 | Ib-25 | 21-16N-06W | Coldwater, Isabella |
| 13014 | Ib-28 | 03-15N-06W | Sherman, Isabella |
| 11337 | Ib-35 | 29-16N-06W | Coldwater, Isabella |
| 14656 | Ib-4 | 01-13N-06W | Rolland, Isabella |
| 15597 | Ib-6 | 01-14N-05W | Deerfield, Isabella |
| 16275 | Ib-7 | 17-14N-04W | Union, Isabella |
| 13116 | Ib-8 | 19-15N-06W | Sherman, Isabella |
| 16743 | Ib-9 | 27-13N-06W | Rolland, Isabella |
| 11853 | Ib-1 | 17-14N-03W | Chippewa, Isabella |
| 12156 | Ib-62 | 05-15N-06W | Sherman, Isabella |
| 16791 | Ib-10 | 28-13N-04W | Lincoln, Isabella |
| 11766 | Ib-68 | 26-16N-05W | Gilmore, Isabella |
| 10639 | Ib-22 | 33-16N-03W | Wise, Isabella |
| 16650 | Kk-1 | 36-25N-07W | Garfield, Kalkaska |
| 15121 | Kk-2 | 17-26N-05W | Bear Lake, Kalkaska |
| 16121 | Kk-3 | 31-25N-06W | Garfield, Kalkaska |
| 14662 | Kk-4 | 12-25N-05W | Garfield, Kalkaska |
| 13103 | Kt-1 | 14-09N-10W | Courtland, Kent |
| 17535 | Kt-2 | 03-05N-09W | Bowne, Kent |
| 17677 | Lk-1 | 07-20N-14W | Elk, Lake |
| 17893 | Lk-11 | 20-18N-12W | Cherry Valley, Lake |
| 12885 | Lk-13 | 02-18N-11W | Pinora, Lake |
| 15016 | Lk-14 | 23-17N-11W | Chase, Lake |
| 16032 | Lk-16 | 23-19N-12W | Newkirk, Lake |
| 13941 | Lk-17 | 22-17N-12W | Yates, Lake |
| 11950 | Lk-19 | 27-17N-12W | Yates, Lake |
| 10392 | Lk-2 | 25-18N-12W | Cherry Valley, Lake |
| 13597 | Lk-20 | 27-19N-12W | Newkirk, Lake |
| 10365 | Lk-21 | 35-20N-11W | Dover, Lake |
| 13565 | Lk-23 | 14-19N-13W | Peacock, Lake |
| 24314 | Lk-28 | 08-19N-13W | Peacock, Lake |
| 10587 | Lk-3 | 30-20N-11W | Dover, Lake |
| 12542 | Lk-4 | 14-18N-12W | Cherry Valley, Lake |
| ----- | Lk-6 | 02-20N-11W | Dover, Lake |
| 13013 | Lk-7 | 16-20N-12W | Newkirk, Lake |
| 17230 | Lk-9 | 14-19N-12W | Newkirk, Lake |
| 20277 | Mc-11 | 06-12N-09W | Winfield, Montcalm |
| 15705 | Mc-12 | 13-12N-06W | Home, Montcalm |
| 19026 | Mc-14 | 08-11N-07W | Douglass, Montcalm |
| 20546 | Mc-15 | 19-12N-09W | Winfield, Montcalm |
| 14110 | Mc-19 | 23-11N-08W | Pine, Montcalm |
| 11730 | Mc-2 | 21-12N-06W | Home, Montcalm |
| 13628 | Mc-21 | 25-12N-08W | Cato, Montcalm |
| 17193 | Mc-3 | 21-11N-07W | Douglass, Montcalm |
| 12254 | Mc-4 | 01-11N-07W | Douglass, Montcalm |
| 14892 | Mc-5 | 19-12N-08W | Cato, Montcalm |
| 12972 | Mc-7 | 04-12N-08W | Cato, Montcalm |
| 13562 | Mc-9 | 14-10N-08W | Montcalm, Montcalm |
| 14836 | Mc-8 | 20-10N-08W | Montcalm, Montcalm |
| 18187 | Mc-17 | 11-10N-07W | Sidney, Montcalm |
| 11113 | Mc-20 | 31-09N-05W | Bloomer, Montcalm |
| 14614 | Ml-1 | 27-16N-02W | Warren, Midland |

Table E1. Identification of geophysical logs used to construct figures—Continued

| Permit number | USGS identifier | Section Township Range | Township name, county |
|---|---|---|---|
| 18590 | Ms-11 | 32-23N-05W | Forest, Missaukee |
| 17785 | Ms-12 | 30-24N-06W | Norwich, Missaukee |
| 18521 | Ms-13 | 04-22N-05W | Butterfield, Missaukee |
| 12836 | Ms-15 | 01-21N-06W | Clam Union, Missaukee |
| 17806 | Ms-16 | 10-23N-06W | West Branch, Missaukee |
| 16220 | Ms-18 | 05-24N-06W | Norwich, Missaukee |
| 11675 | Ms-2 | 19-23N-07W | Forest, Missaukee |
| 11452 | Ms-3 | 15-22N-06W | Aetna, Missaukee |
| 11062 | Ms-4 | 09-21N-07W | Riverside, Missaukee |
| 16995 | Ms-6 | 05-23N-06W | West Branch, Missaukee |
| 12388 | Ms-7 | 28-23N-08W | Caldwell, Missaukee |
| 15488 | Ms-8 | 03-21N-06W | Clam Union, Missaukee |
| 15248 | Ms-9 | 15-21N-08W | Richland, Missaukee |
| 9806 | Mt-11 | 17-15N-08W | Martin, Mecosta |
| 11756 | Mt-15 | 07-14N-08W | Martin, Mecosta |
| 16005 | Mt-16 | 26-14N-10W | Mecosta, Mecosta |
| 15518 | Mt-18 | 20-15N-10W | Big Rapids, Mecosta |
| 13462 | Mt-2 | 18-16N-09W | Grant, Mecosta |
| 12018 | Mt-22 | 12-16N-08W | Chippewa, Mecosta |
| 11663 | Mt-23 | 06-16N-10W | Green, Mecosta |
| 10903 | Mt-24 | 12-16N-08W | Chippewa, Mecosta |
| 20310 | Mt-25 | 36-13N-10W | Aetna, Mecosta |
| 16305 | Mt-3 | 03-13N-10W | Aetna, Mecosta |
| 16226 | Mt-31 | 22-16N-10W | Green, Mecosta |
| 12475 | Mt-4 | 12-13N-10W | Aetna, Mecosta |
| 11775 | Mt-5 | 23-15N-09W | Colfax, Mecosta |
| 11495 | Mt-7 | 06-14N-07W | Wheatland, Mecosta |
| 16278 | Mt-8 | 15-13N-10W | Aetna, Mecosta |
| 32922 | Mt-N7 | 11-14N-09W | Austin, Mecosta |
| 10824 | Mt-1 | 10-16N-10W | Green, Mecosta |
| 13029 | Mt-9 | 22-14N-08W | Morton, Mecosta |
| 12185 | Mt-10 | 02-14N-09W | Austin, Mecosta |
| 18507 | Mt-13 | 20-13N-08W | Hinton, Mecosta |
| 11266 | Mt-27 | 05-15N-09W | Colfax, Mecosta |
| 16226 | Mt-31 | 22-16N-10W | Green, Mecosta |
| 11815 | Nw-1 | 16-15N-11W | Norwich, Newaygo |
| 19331 | Nw-13 | 07-11N-11W | Ensley, Newaygo |
| 21241 | Nw-14 | 01-11N-13W | Ashland, Newaygo |
| 17446 | Nw-15 | 34-14N-11W | Goodwell, Newaygo |
| 14886 | Nw-2 | 28-13N-11W | Big Prairie, Newaygo |
| 13719 | Nw-21 | 11-12N-13W | Garfield, Newaygo |
| 10423 | Nw-22 | 08-14N-11W | Goodwell, Newaygo |
| 13524 | Nw-23 | 09-16N-11W | Barton, Newaygo |
| 10608 | Nw-24 | 06-14N-11W | Goodwell, Newaygo |
| 13264 | Nw-25 | 13-12N-13W | Garfield, Newaygo |
| 10368 | Nw-26 | 09-14N-11W | Garfield, Newaygo |
| 14054 | Nw-28 | 31-15N-11W | Norwich, Newaygo |
| 13146 | Nw-29 | 33-13N-11W | Big Prairie, Newaygo |
| 15300 | Nw-3 | 05-16N-11W | Barton, Newaygo |
| 14194 | Nw-34 | 18-11N-11W | Ensley, Newaygo |
| 10592 | Nw-40 | 29-16N-11W | Barton, Newaygo |
| 13520 | Nw-5 | 10-12N-13W | Garfield, Newaygo |
| 16718 | Nw-7 | 01-12N-14W | Sheridan, Newaygo |
| 15806 | Nw-8 | 19-12N-13W | Garfield, Newaygo |

**Table E1.** Identification of geophysical logs used to construct figures—Continued

| Permit number | USGS identifier | Section Township Range | Township name, county |
|---|---|---|---|
| 14092 | Nw-9 | 19-16N-12W | Home, Newaygo |
| 15649 | Nw-10 | 18-16N-14W | Troy, Newaygo |
| 10649 | Nw-11 | 03-15N-12W | Monroe, Newaygo |
| 15438 | Nw-12 | 36-16N-13W | Lilley, Newaygo |
| 10683 | Nw-35 | 07-14N-11W | Goodwell, Newaygo |
| 12952 | Nw-18 | 29-12N-13W | Garfield, Newaygo |
| 18483 | Oa-11 | 27-16N-15W | Colfax, Oceana |
| 17522 | Oa-13 | 18-13N-15W | Greenwood, Oceana |
| 11367 | Oa-2 | 07-13N-16W | Otto, Oceana |
| 12267 | Om-3 | 08-21N-01E | Edwards, Ogemaw |
| 15966 | Om-4 | 36-22N-02E | West Branch, Ogemaw |
| 11670 | Os-1 | 19-19N-08W | Hartwick, Osceola |
| 10657 | Os-10 | 35-19N-09W | Rose Lake, Osceola |
| 12379 | Os-11 | 33-19N-10W | LeRoy, Osceola |
| 9815 | Os-13 | 04-17N-10W | Richmond, Osceola |
| 16400 | Os-14 | 31-19N-09W | Rose Lake, Osceola |
| 13134 | Os-15 | 10-18N-09W | Cedar, Osceola |
| 12865 | Os-18 | 16-17N-09W | Hersey, Osceola |
| 11610 | Os-19 | 05-18N-10W | Lincoln, Osceola |
| 15193 | Os-2 | 08-19N-09W | Rose Lake, Osceola |
| 10479 | Os-21 | 02-20N-08W | Highland, Osceola |
| 8733 | Os-22 | 30-18N-10W | Lincoln, Osceola |
| 16317 | Os-23 | 05-20N-07W | Marion, Osceola |
| ----- | Os-24 | 35-20N-09W | Sherman, Osceola |
| 19697 | Os-27 | 29-17N-07W | Orient, Osceola |
| 14958 | Os-28 | 30-17N-10W | Richmond, Osceola |
| 10584 | Os-3 | 30-17N-10W | Richmond, Osceola |
| 12640 | Os-30 | 36-20N-07W | Marion, Osceola |
| 14591 | Os-31 | 29-20N-08W | Highland, Osceola |
| 19822 | Os-32 | 05-17N-08W | Evart, Osceola |
| 14639 | Os-4 | 09-18N-07W | Sylvan, Osceola |
| 11312 | Os-7 | 05-19N-10W | LeRoy, Osceola |
| 10754 | Os-8 | 09-20N-09W | Sherman, Osceola |
| 15934 | Os-9 | 19-20N-08W | Highland, Osceola |
| 16335 | Os-6 | 34-17N-07W | Orient, Osceola |
| 13739 | Os-12 | 03-17N-07W | Orient, Osceola |
| 11902 | Os-17 | 19-17N-08W | Evart, Osceola |
| 12375 | Os-29 | 12-17N-07W | Orient, Osceola |
| 14589 | Rc-1 | 05-21N-01W | Nester, Roscommon |
| 9674 | Rc-10 | 29-24N-01W | AuSable, Roscommon |
| 15702 | Rc-2 | 20-21N-03W | Roscommon, Roscommon |
| 16611 | Rc-4 | 19-24N-01W | AuSable, Roscommon |
| 16683 | Rc-8 | 21-24N-02W | Higgins, Roscommon |
| 10052 | Rc-5 | 13-24N-01W | AuSable, Roscommon |
| 10381 | Wx-1 | 34-21N-11W | Henderson, Wexford |
| 12515 | Wx-2 | 28-21N-10W | Cherry Grove, Wexford |
| 10303 | Wx-3 | 11-23N-11W | Antioch, Wexford |
| 12304 | Wx-4 | 11-22N-10W | Selma, Wexford |
| 20742 | Wx-5 | 12-21N-10W | Cherry Grove, Wexford |
| 18209 | Wx-6 | 36-22N-10W | Selma, Wexford |
| 17794 | Wx-7 | 34-21N-10W | Cherry Grove, Wexford |
| 17109 | Wx-8 | 13-22N-09W | Haring, Wexford |
| 11755 | Wx-9 | 21-21N-10W | Cherry Grove, Wexford |
| 15757 | Wx-10 | 25-23N-09W | Cedar Creek, Wexford |
| 10841 | Wx-11 | 10-21N-09W | Clam Lake, Wexford |
| 10181 | Wx-12 | 29-21N-11W | Henderson, Wexford |