HYDROGEOLOGIC FRAMEWORK OF THE MICHIGAN BASIN REGIONAL AQUIFER SYSTEM

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Hydrogeologic Framework of the Michigan Basin Regional Aquifer System

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

REGIONAL AQUIFER-SYSTEM ANALYSIS—
MICHIGAN BASIN AQUIFER SYSTEM

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1418

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which, in aggregate, underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and, accordingly, transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number beginning with Professional Paper 1400.

Thomas J. Casadevall

Thomas J. Casadevall
Acting Director

CONTENTS

ILLUSTRATIONS

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

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
gallon (gal)	0.003785	cubic meter
feet per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.0929	meter squared per day
gallon per day per foot [(gal/d)/ft]	0.01242	meter squared per day
million gallons per day (Mgal/d)	3,785	cubic meter per day

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of 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) or micrograms per liter (µg/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. One thousand micrograms per liter is equivalent to one milligram per liter. 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 are: centimeters per second (cm/s) and ohms per meter (ohm-m).

REGIONAL AQUIFER-SYSTEM ANALYSIS—MICHIGAN BASIN AQUIFER SYSTEM

HYDROGEOLOGIC FRAMEWORK OF THE MICHIGAN BASIN REGIONAL AQUIFER SYSTEM

BY D.B. WESTJOHN AND T.L. WEAVER

ABSTRACT

Mississippian and younger geologic units form a regional system of aquifers and confining units in the central Lower Peninsula of Michigan. The area of the regional aquifer system is about 22,000 square miles. The aquifer system consists of three bedrock aquifers, which are separated by confining units. Bedrock aquifers and confining units are overlain by surficial glaciofluvial aquifers, which are complexly intercalated with confining beds composed of glacial till and fine-grained lacustrine deposits.

Geophysical and geologic logs were used to characterize the hydrogeologic framework of this regional aquifer system and to delineate and map boundaries of aquifers and confining units. Geophysical logs and water-quality data were used to delineate the base of freshwater within the aquifer system and to determine geologic controls on the distribution of freshwater in the aquifer-system units.

Pleistocene glaciofluvial deposits are the largest reservoir of fresh ground water in the mapped region, and the thickness of this aquifer unit exceeds 900 feet in some areas. The Saginaw aquifer, the composite of sandstones of Pennsylvanian age, typically ranges in thickness from 100 to 350 feet in areas where this unit is used for water supply. In the western part of the aquifer system, the Saginaw aquifer is separated from glacial deposits by 100 to 150 feet of Jurassic "red beds." "Red beds" are a confining unit, and the Saginaw aquifer contains saline water where it is overlain by these deposits. The Saginaw confining unit, which is principally shale, separates the Saginaw aquifer from the underlying Parma-Bayport aquifer. Thickness of the Saginaw confining unit is about 50 feet in the eastern and the southern parts of the aquifer system, about 100 feet in the north, and 100 to 250 feet in the west. The Parma-Bayport aquifer, which consists mostly of permeable sandstones and carbonates, is 100 to 150 feet thick in most areas. The Parma-Bayport aquifer contains freshwater only in subcrop areas where it is in direct hydraulic connection with glacial deposits. Dissolved-solids concentration of ground water increases down regional dip in the Parma-Bayport aquifer, and saline water or brine is present in this aquifer where it is overlain by the Saginaw confining unit.

The Michigan confining unit, which is about 300 to 400 feet thick in most of the area mapped, is primarily interbedded shale, carbonate, and evaporite. This confining unit overlies the Marshall aquifer, which consists of one or more stratigraphically continuous sandstones of Mississippian age. Composite thickness of blanket sandstones that form the Marshall aquifer is typically 75 to 200 feet. Freshwater is present in the Marshall aquifer only in areas where it is a subcrop beneath glacial deposits. Dissolved-solids concentration of ground water in the Marshall aquifer increases down regional dip, and saline water or brine is present in this unit where it underlies beds of the Michigan confining unit. The Mississippian Coldwater Shale forms the base of the regional aquifer system.

Relief on the base of freshwater is about 600 feet. Altitudes of the base of freshwater are low (200 to 400 feet) along a 30- to 45-mile-wide north-south-trending corridor near the center of the aquifer system. The trend of this corridor corresponds to an area where thickness of the Saginaw aquifer ranges from 100 to 370 feet. In isolated areas in the northern and the western parts of the aquifer system, the altitude of the base of freshwater is below 400 feet; however, the altitude is above 400 feet in most of the mapped area. In the southern and the northern parts of the aquifer system, where the Saginaw aquifer is thin or absent, altitudes of the base of freshwater range from 700 to 800 feet and from 500 to 700 feet, respectively.

Geologic controls on 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 lodgment tills with very low permeability; (3) impedance of recharge of freshwater to bedrock (or discharge of saline water from bedrock) by very low permeability Jurassic "red beds"; and (4) the presence of units characterized by very low vertical-hydraulic-conductivity, which are within and between sandstone units.

INTRODUCTION

In 1978, the U.S. Geological Survey (USGS) began the Regional Aquifer-Systems Analysis (RASA) of groundwater resources in 25 regions of the United States (Sun and Johnston, 1994). Detailed information on geology, hydrology, and geochemistry of aquifer systems in these regions was needed to understand regional groundwater-flow regimes and to develop management plans for the Nation's most important ground-water resources. A regional system of aquifers and confining units (Mississippian and younger geologic units) in the central part of the Michigan Basin was studied from 1986 through 1994 as part of the nationwide RASA program (Mandle, 1986).

The hydrogeologic framework of the multilayered aquifer system in the Michigan Basin was characterized by use of geophysical and geologic logs of oil, gas, and water wells. Also, a petrographic study of thin sections of cores and drill cutting was made to classify sandstones according to texture and mineralogy (Westjohn, 1994c; Zacharias, 1992; Zacharias and others, 1994). The hydrogeologic framework is depicted in this report on maps and geologic sections, which delineate boundaries of aquifers and confining units. The report also includes delineation of the position of the freshwater/saline-water interface, and a description of geologic controls of distribution of freshwater.

Other reports from the Michigan Basin RASA study describe various aspects of the hydrogeology. Geochemistry of ground water in the central part of the Michigan Basin was described by Ging and others (1996), Meissner and others (1996), and Wahrer and others (1996). Simulation of ground-water flow was discussed by Mandle and Westjohn (1989), and estimates of ground-water recharge were made by Holtschlag (1997).

The purposes of this hydrogeologic framework report are to:

- Describe the geologic and hydrogeologic units that form the Michigan Basin regional aquifer system.
- Delineate boundaries of aquifers and confining units by use of geologic sections, thickness maps, and surface-configuration maps.
- Describe hydraulic properties of aquifers and confining units used as parameters for computer simulation of ground-water flow.
- Delineate the configuration of the base of freshwater and approximate the boundary between saline water and brine by use of water-quality data and geophysical logs.
- Describe the geologic controls on the position of the transition zone between freshwater and saline water.

REGIONAL GEOLOGIC SETTING

The Michigan Basin is an intracratonic depression containing a sequence of sedimentary rocks and unconsolidated sediments that is more than 17,000 ft thick (Lilienthal, 1978; see McClure/Sparks, Eckelbarger, and Whightsil well 1–8). The geographic center of the Lower Peninsula of Michigan is the approximate center of the basin (fig. 1). The north edge of the basin is in the Upper Peninsula of Michigan, where Precambrian sandstones at the base of the sedimentary-rock sequence overlie Proterozoic or Archean metamorphic and crystalline rocks. Margins of the southern half of the Michigan Basin extend outside the State: east into Lake Huron and Ontario, Canada; south into Ohio and Indiana; and west into Wisconsin. Margins of the southern half of the basin are formed by the Algonquin, Findlay, Kankakee, and Wisconsin Arches (fig. 1). Area of the basin is about 122,000 mi^2 (Cohee, 1965).

PREVIOUS GEOLOGIC INVESTIGATIONS

Various aspects of Michigan's geology have been described in numerous reports. Dorr and Eschman (1970) summarize the geology of Michigan in a general textbook. Their more than 200 cited references are the basis for a summary of historical geology (Archean to Holocene), stratigraphy, paleontology, and economic geology. Many reports on the regional geology of Michigan are the result of investigations by the Michigan Geological Survey, and an extensive list of references that resulted primarily from these activities was compiled by Martin and Straight (1956). Updates of the Martin and Straight bibliography have been published (Currie, 1978; Michigan Geological Survey, 1992). Descriptions of geologic units that form the Michigan Basin regional aquifer system are summarized from data collected by RASA investigators and from published and unpublished (theses and dissertations) literature.

DEPOSITIONAL SETTING

Continuous subsidence of the Michigan Basin has resulted in deposition of a nearly complete stratigraphic sequence of sedimentary rocks from Precambrian units through Jurassic "red beds," the youngest bedrock unit in the basin (Michigan Geological Survey, 1964). One notable hiatus in the stratigraphic sequence is the absence of Triassic rocks. Because Pleistocene glacial deposits cover bedrock in most areas, knowledge of bedrock geology is primarily from geophysical and geologic logs of drill holes.

The depositional history and stratigraphy of rock units in the Michigan Basin are complex. At least 49 units have been formally named (Michigan Geological Survey, 1964), and interpretations of stratigraphy continue to evolve as data from hydrocarbon-exploration boreholes become available. Readers interested in details of basin stratigraphy and depositional setting can refer to a series of papers in Catacosinos and Daniels (1991), which is an update on sedimentary evolution of the basin. Catacosinos and Daniels (1991) also contains comprehensive lists of references of previous geological investigations; most of the current understanding of geology of the basin can be credited to these investigations.

Time stratigraphic units in the Michigan Basin can be grouped by dominant sedimentary facies, as a means to simplify description of geology and depositional setting.

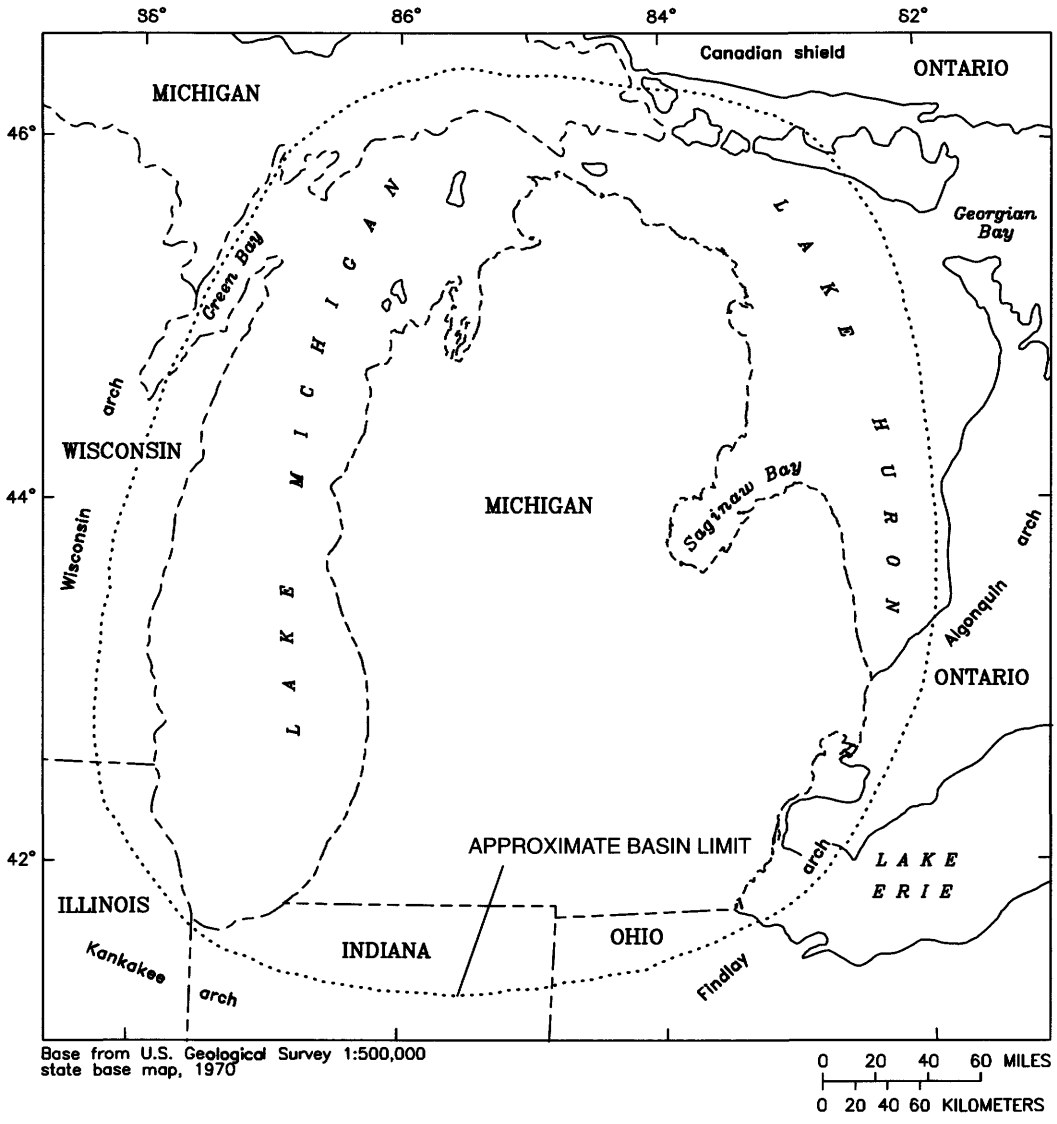


FIGURE 1.—Michigan Basin and surrounding region. (Modified from Catacosinos and Daniels, 1991.)

In general, the base of the stratigraphic section consists of sandstones of Precambrian and Cambrian age, which overlie Precambrian crystalline rocks. Ordovician through Devonian strata consist mostly of carbonate rocks and lesser amounts of shale, evaporite, and sandstone. Geologic units of Cambrian through Devonian age constitute approximately 90 percent of the sedimentary sequence. Mississippian and younger geologic units, which form the Michigan Basin regional aquifer system, constitute the upper 10 percent of the sedimentary fill in the basin.

STRUCTURES

The largest structural feature within the Michigan Basin is the southeast-trending arm of the Precambrian Midcontinent Rift System (fig. 2). This arm of the rift system extends from the Keweenaw Peninsula (Upper Peninsula of Michigan) southeast beneath Phanerozoic rocks (Chase and Gilmer, 1973; Hinze and others, 1971, 1975), which constitute the sedimentary fill of the Michigan Basin. The southwest trending arm of the rift system extends south-southwest from the Keweenaw Peninsula, but elsewhere these volcanic rocks are covered by younger sedimentary deposits. The southeast and southwest extensions of the Midcontinent Rift System are delineated by belts of magnetic and gravity highs. These geophysical anomalies are probably the result of dense magnetic basalts, which were extruded during opening of the rift system (Hinze and others, 1975; Van Schmus and Hinze, 1985).

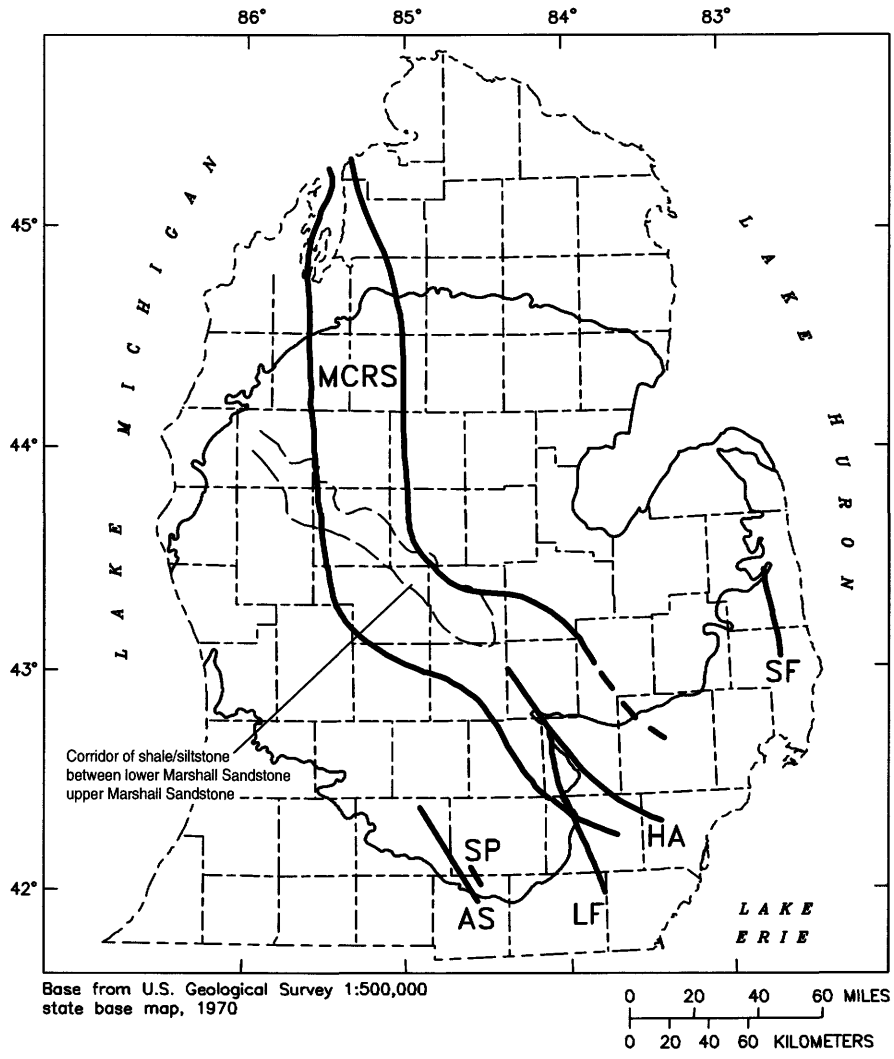


FIGURE 2.—Major structures of the Lower Peninsula of Michigan. (Modified from Budai and Wilson, 1991, and Fisher, 1981.)

Many northwest-southeast trending anticlines in the Michigan Basin are former or current oil and natural-gas reservoirs. Most of these folds are gentle and relief on these structures is typically tens of feet over closure distances of a few miles (Newcombe, 1933; Rawlins and Schellhardt, 1936; Wollensak, 1991).

Numerous northwest-southeast trending faults parallel dominant-fold trends. These faults are typically steep and offset is minor. Most of these structures are normal faults, but some are reverse faults (Fisher and others, 1988). Although offset of most faults is relatively minor, vertical offsets of three faults exceed 500 ft (Fisher, 1981). These structures (the Lucas fault, the Sanilac fault, and Howell Anticline) are in the southeastern part of the State (fig. 2).

Strike-slip faults also are present, and these features are related to some of the largest hydrocarbon reservoirs in Michigan. The Albion-Scipio trend (fig. 2), which

parallels a major oil field of the same name, is probably the largest structure of this type in the basin (Fisher and others, 1988). Many faults appear to have been reactivated several times during subsidence of the basin; the peak of the activity was probably during Late Mississippian time (Fisher and others, 1988).

GEOLOGY OF MISSISSIPPIAN AND YOUNGER GEOLOGIC UNITS

Geologic units in the Michigan Basin regional aquifer system consist of Early Mississippian through Jurassic bedrock units and unconsolidated Pleistocene glacial deposits. The area of this aquifer system is about 22,000 mi^2 (fig. 3).

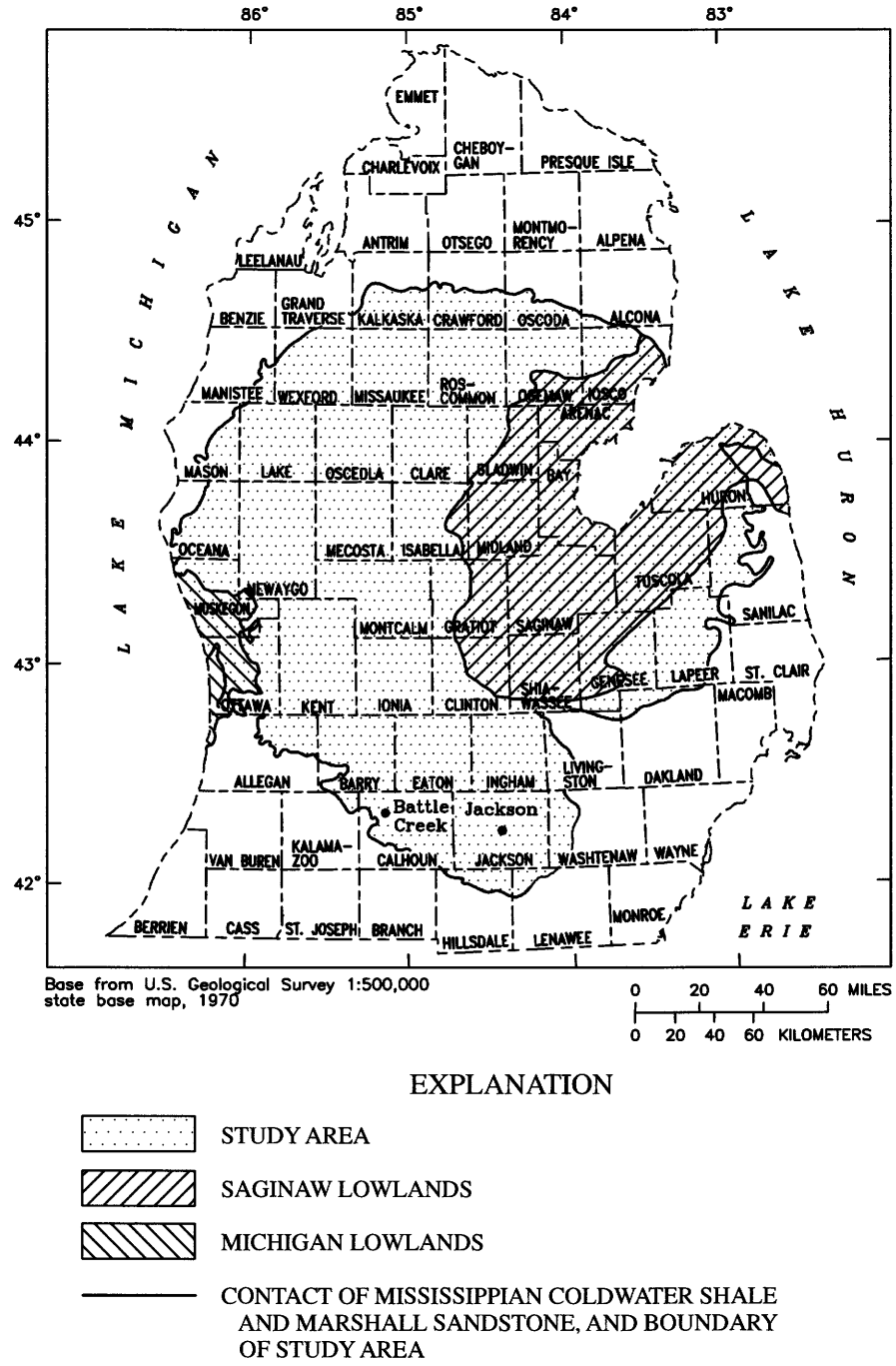


FIGURE 3.—Lower Peninsula of Michigan and Michigan Basin Regional Aquifer-System Analysis study area.

The aquifer system consists of six formally named formations and three informally named geologic units (figs. 4, 5). 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 do not have formal names are the Parma sandstone, Jurassic "red beds," and Pleistocene glacial deposits. Stratigraphic relations of geologic units in the Michigan Basin regional aquifer system are shown in generalized hydrogeologic sections (figs. 6, 7). The locations of the sections (fig. 4) are along trends that are parallel and perpendicular to trends of major structural features (fig. 2).

COLDWATER SHALE

The Coldwater Shale of Early Mississippian age is the basal unit of the Michigan Basin regional aquifer system. The Coldwater Shale consists primarily of gray to dark-gray shale. Other lithologies include red fossiliferous or nonfossiliferous shale, carbonate, siltstone, and sandstone (Cohee, 1979; Hale, 1941; Monnett, 1948). Fossil assemblages in samples from the Coldwater Shale indicate the formation is marine in origin (Chung, 1973; Driscoll, 1965, 1969; Hale, 1941; Miller and Garner, 1953; Oden, 1952), and the Coldwater sequence appears to be part of a southwest-prograded deltaic complex (Cohee, 1979).

The distribution of sandstone, siltstone, and carbonate beds within the Coldwater Shale in the eastern part differs from that in the western part of the Lower Peninsula of Michigan. The formation is typically subdivided into eastern and western facies (Monnett, 1948). The eastern facies is distinguished by sandstone and siltstone beds, which are intercalated with shales in the upper part of the formation. These coarser clastic interbeds are present in the eastern facies because the source area for the Coldwater Shale and overlying clastic sedimentary rocks of Mississippian age is near—in southwestern Ontario (Potter and Pryor, 1961). In the Thumb Area of Michigan (fig. 8), which is nearest the sediment source, cumulative thickness of sandstone beds in the Coldwater Shale ranges from 223 to 275 ft (Cohee, 1979). Sandstone beds thin to the west and are absent in most of the western facies. The western facies is distinguished by one or more carbonate beds, which are intercalated with shale. The Coldwater "lime" (informal name) is a distinct geophysical marker horizon that can be traced over much of the western half of the Lower Peninsula of Michigan (Monnett, 1948). Thickness of the Coldwater Shale ranges from 500 ft in the west (Cohee, 1979) to more than 1,300 ft in the east (John Esch, Michigan Department of Natural Resources, written commun., 1994).

Subjects of previous investigations of the Coldwater Shale include economic geology (Cohee and others, 1951; Newcombe, 1933), general geology (Dorr and Eschman, 1970; Ells, 1979; Wooten, 1951), paleontology (Driscoll, 1969), paleotectonic setting (Cohee, 1979), palynology (See, 1980), and sedimentology and stratigraphy (Chung, 1973; Harrell and others, 1991; Kropschot, 1953; Lilienthal, 1978; Potter and Pryor, 1961; Shaver, 1985; Tarbell, 1941). Martin and Straight (1956) provide a bibliography of early investigations and a historic account of development of stratigraphic nomenclature for the Coldwater Shale.

MARSHALL SANDSTONE

The Marshall Sandstone of Early Mississippian age overlies the Coldwater Shale (fig. 5). This sandstone is sparsely fossiliferous in most areas of the basin, although parts of the formation contain a diverse assemblage of fossils (Winchell, 1861; Driscoll, 1965, 1969; Harrell and others, 1991). Sedimentological features and fossil remains indicate the Marshall Sandstone was deposited in a shallow marine environment (Harrell and others, 1991). Sandstone forms only part of the formation. Limestone, dolomite, siltstone, and shale are interbedded with sandstones of the Marshall sedimentary sequence in different parts of the basin. The composite thickness of units that form the Marshall Sandstone ranges from 130 to 360 ft (Ells, 1979; Harrell and others, 1991; Monnett, 1948).

Two relatively thick, stratigraphically continuous, blanket sandstones constitute the bulk of the formation in most areas. The upper sandstone is formally named the Napoleon Sandstone Member (commonly referred to as the "upper Marshall sandstone"); the lower sandstone has no formal name. The terms Napoleon Sandstone and lower Marshall sandstone are used when reference is made to stratigraphic position of these two sandstones of Mississippian age.

Lithofacies trends are mappable within the Marshall Sandstone. In figure 9 for example, geophysical-log signatures are observable for several strata that form the Marshall Sandstone in one area of the basin. Lithofacies trends are useful in characterization of hydrogeology. (See the "Hydrogeology of Aquifers and Confining Units" section.) Results of a petrographic study of thin sections of cores and drill cuttings, which are representative of mappable lithofacies, indicate that each lithofacies has distinctive texture, and detrital and authigenic mineralogy (Eluskie and others, 1991; Westjohn, 1991a; Westjohn and Sibley, 1991; Zacharias, 1992; Zacharias and others, 1994). Clastic-rock units that form most of the Marshall sedimentary sequence are described by use

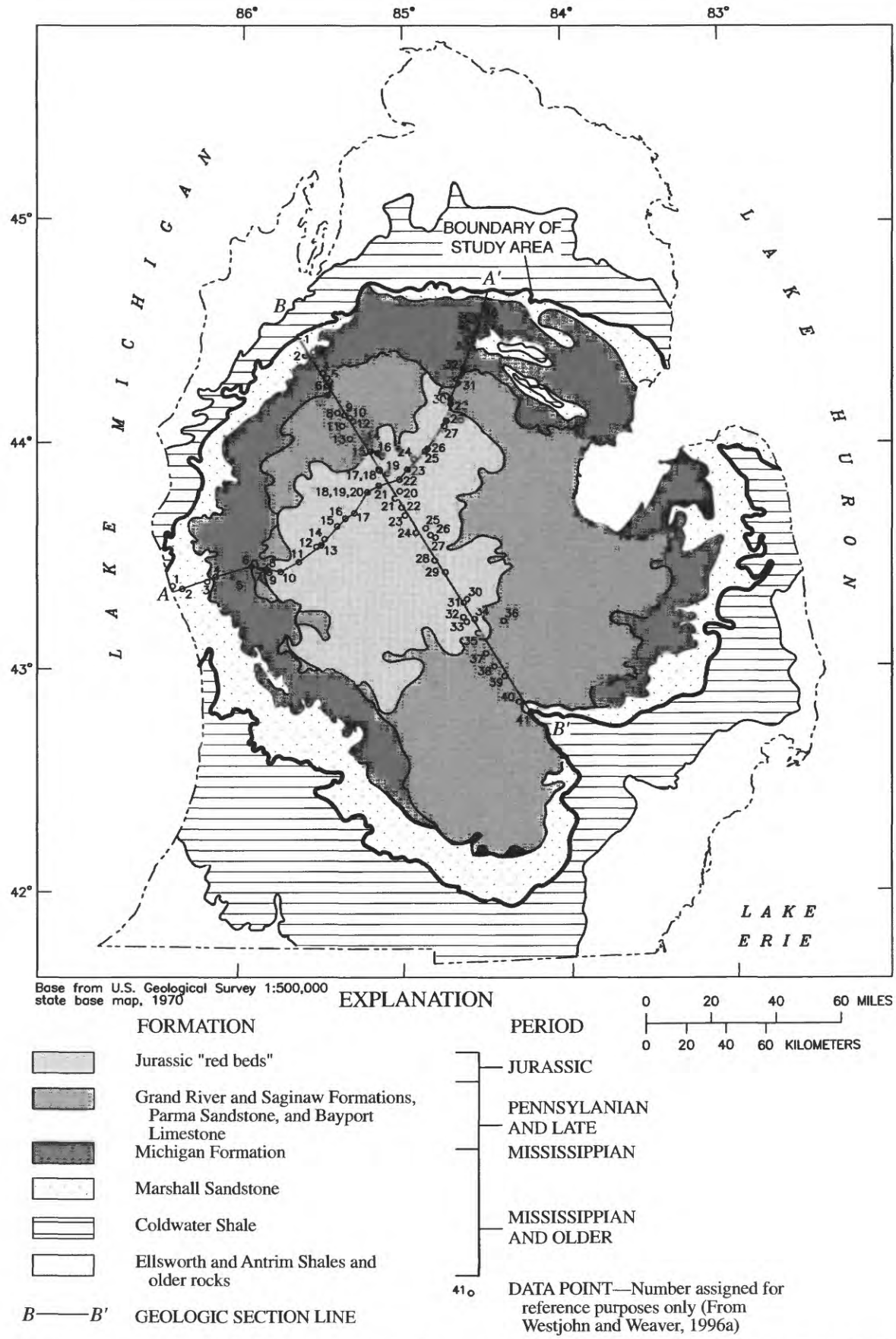
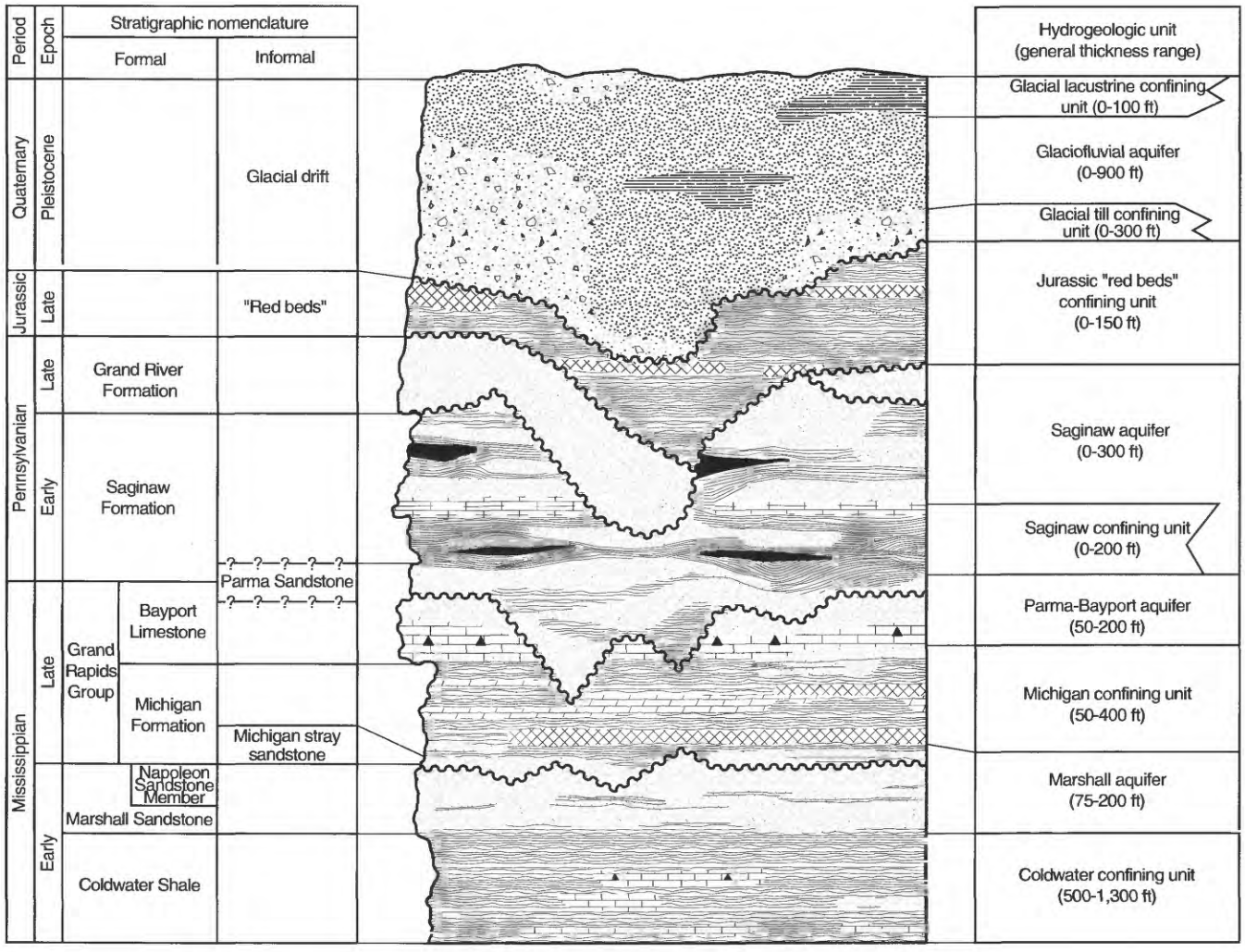


FIGURE 4.—Bedrock geology of the Lower Peninsula of Michigan and trace of hydrogeologic sections A-A′ and B-B′. (Modified from Western Michigan University, 1981, pl. 12; Westjohn and Weaver, 1996a.)



EXPLANATION

- GLACIAL LACUSTRINE SEDIMENTS
- GLACIOFLUVIAL SAND AND GRAVEL
- GLACIAL TILL
- SHALE
- SANDY OR SILTY SHALE
- SANDSTONE
- ARGILLACEOUS OR SHALY SANDSTONE
- LIMESTONE
- ARGILLACEOUS OR SHALY LIMESTONE
- CHERTY LIMESTONE
- DOLOMITE (Same variations as limestone)
- COAL BEDS
- ANHYDRITE OR GYPSUM
- EROSIONAL SURFACE

FIGURE 5.—Mississippian through Pleistocene stratigraphic nomenclature, hydrogeologic units, and rock units in the central Lower Peninsula of Michigan. (Modified from Michigan Geological Survey, 1964.)

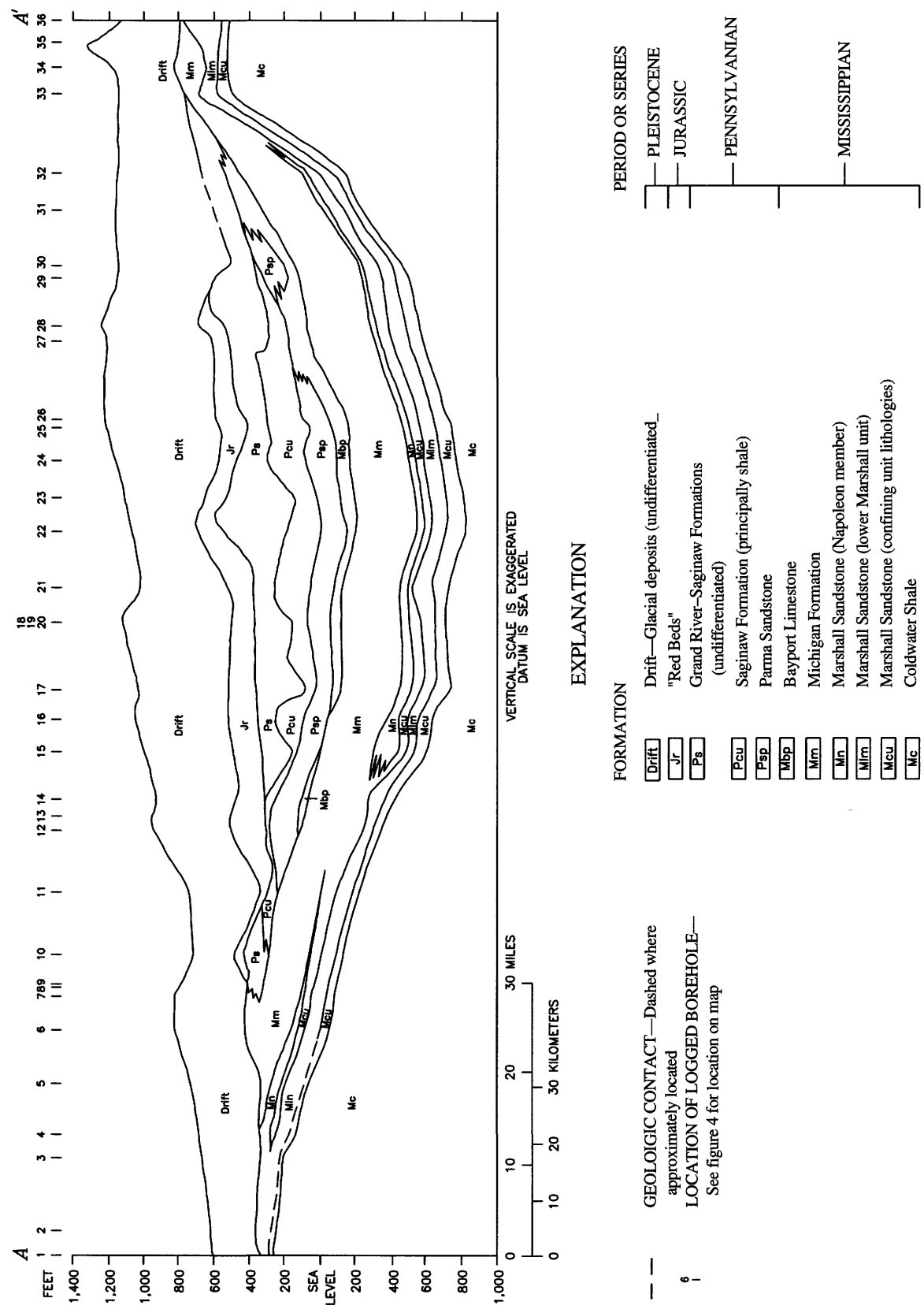


FIGURE 6.—Generalized hydrogeologic section A–A' showing stratigraphic relations of Mississippian and younger geologic units, Muskegon County to Crawford County, Michigan. (Line of section shown in fig. 4.)

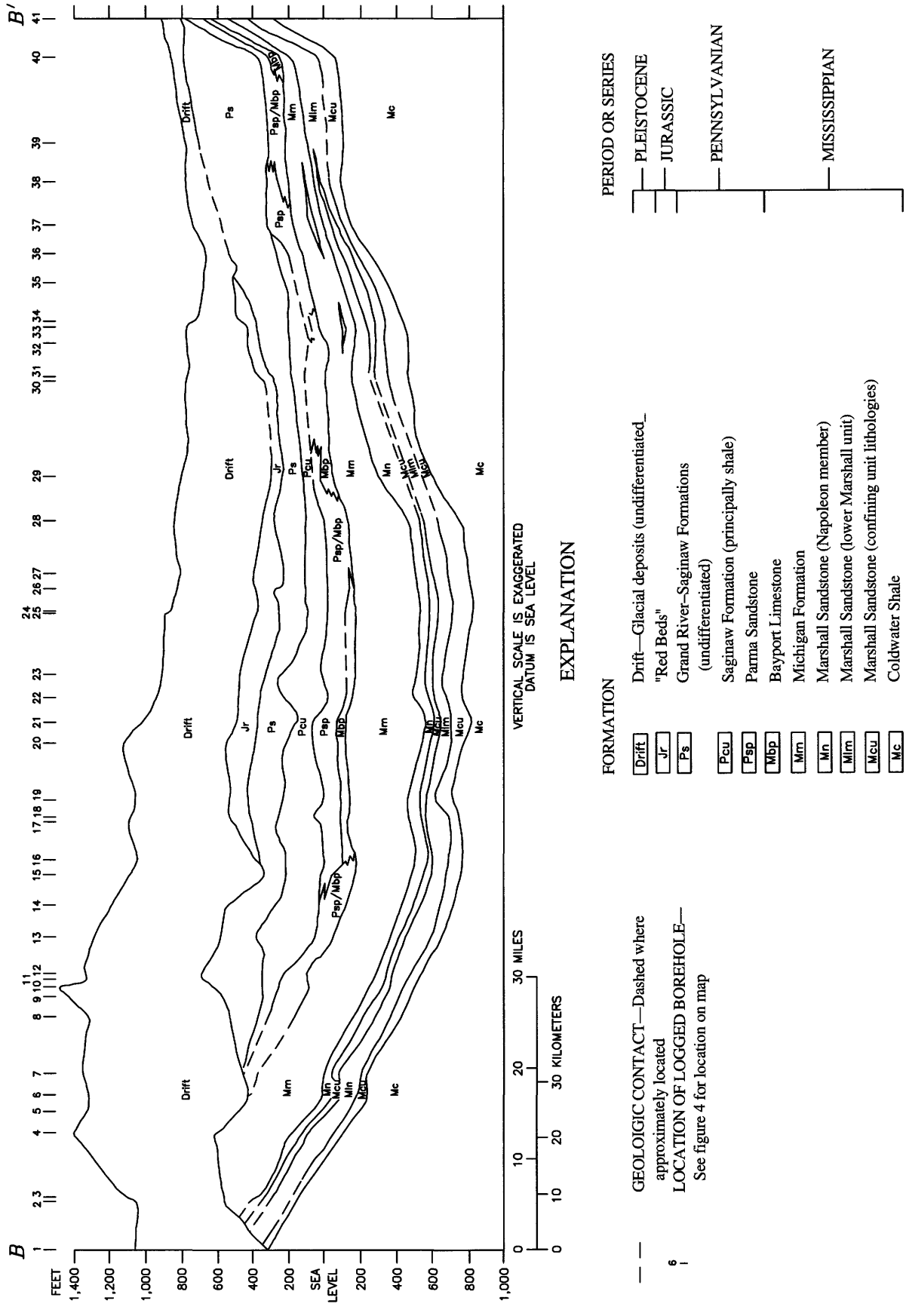


FIGURE 7.—Generalized hydrogeologic section B–B′ showing stratigraphic relations of Mississippian and younger geologic units, Wexford County to Shiawassee County, Michigan. (Line of section shown in fig. 4.)

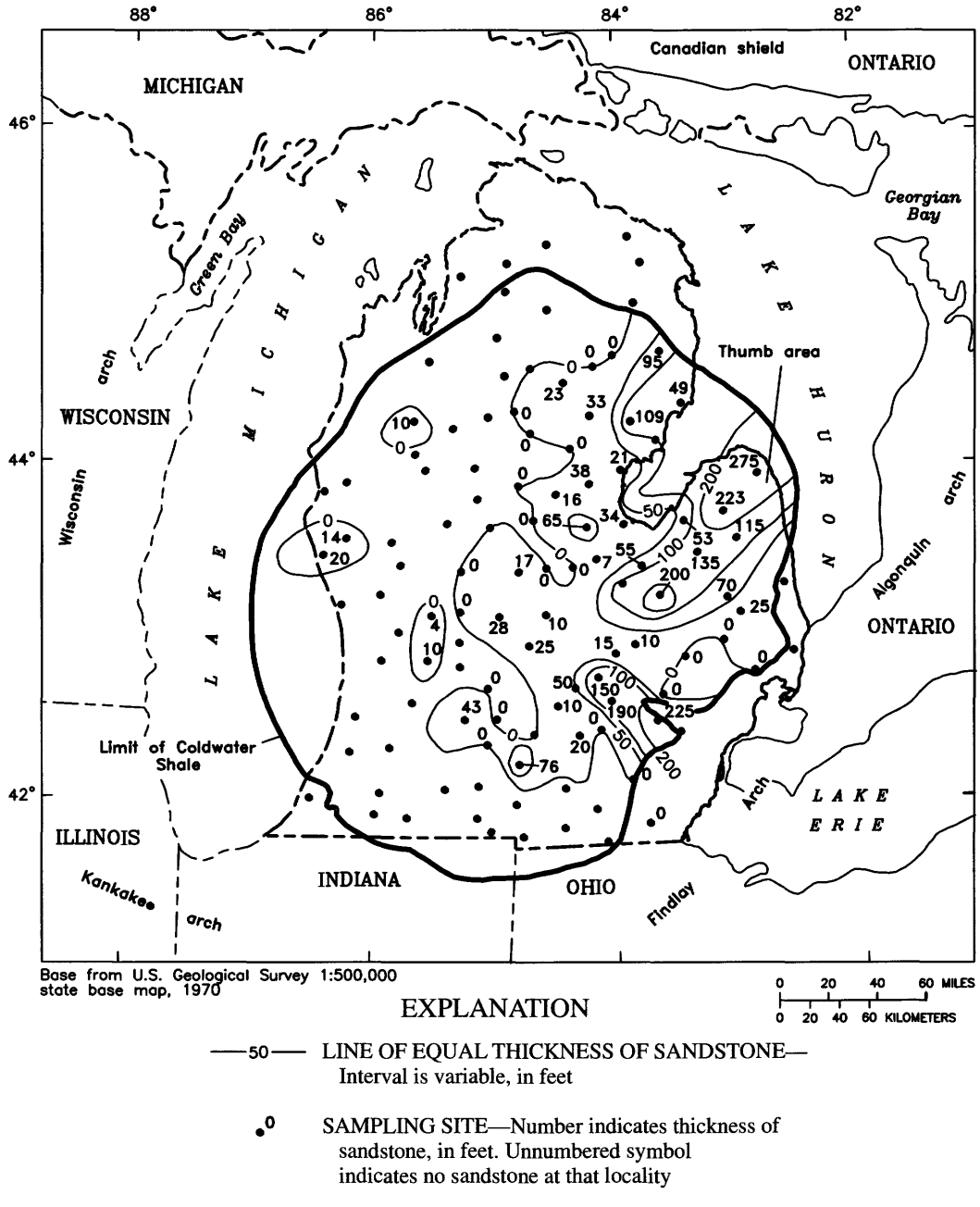


FIGURE 8.—Cumulative thickness of sandstone in the Coldwater Shale in the Lower Peninsula of Michigan. (Modified from Cohee, 1979.)

of a classification scheme for terrigenous sandstones (Pettijohn and others, 1987, p. 145).

Everywhere in the Michigan Basin where the Marshall Sandstone is present, the basal part of the formation consists of 30 to 125 ft of fine- to medium-grained litharenite (figs. 6, 7). This basal unit of the Marshall sequence has a distinctive shaly-sand trace on gamma-ray and spontaneous potential geophysical logs (see Asquith and Gibson, 1982, p. 31 and p. 102). This distinctive geophysical-log trace is the result of abundant detrital micas, which are the most common lithic component of the basal unit. The basal litharenite is overlain by fine- to medium-grained quartzarenite to sublitharenite, which is typically 50 to 125 ft thick. These two units form the lower Marshall sandstone. In some areas of the basin, these two units constitute the entire formation.

In most areas of the basin, a second quartzarenite/sublitharenite is present (Napoleon Sandstone Member). This clastic unit is typically separated from the lower Marshall sandstone by shale, siltstone, and (or) carbonate

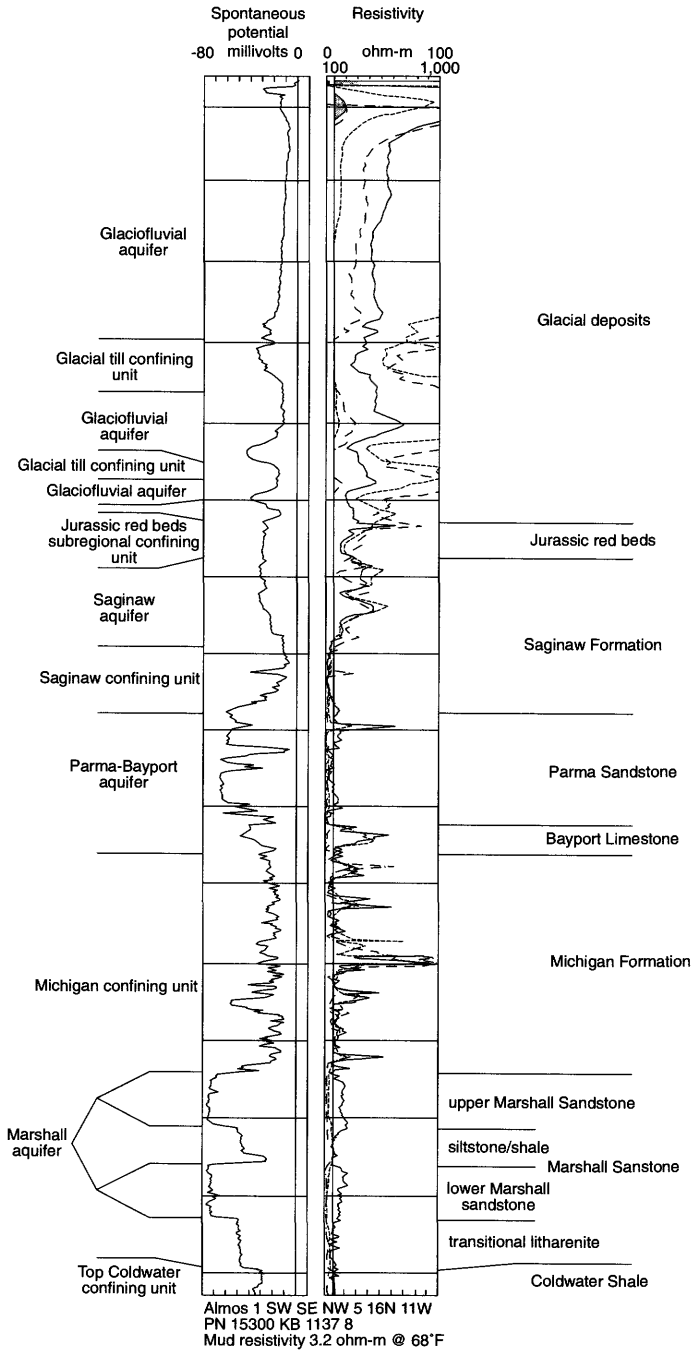


FIGURE 9.—Electric log showing typical resistivity and spontaneous potential characteristics of geologic units, and boundaries of stratigraphic and hydrogeologic units of the regional aquifer system.

rocks. Because the mineralogy and ranges of thickness of the Napoleon Sandstone and the lower Marshall sandstone are the same, arenites/sublitharenites of the upper and lower parts of the Marshall sedimentary sequence cannot be differentiated on the basis of lithologic characteristics. Generally, where the lower Marshall sandstone is thick, the Napoleon Sandstone is thin, and conversely.

The lower Marshall sandstone and the Napoleon Sandstone are separated by strata whose facies relations are complex. In some areas, particularly along a 15-mi-wide corridor that extends southeast from Newaygo County to Livingston County (figs. 2, 3), the lower Marshall sandstone is overlain by 15 ft or more of shale, and this shale is overlain by 30 ft or more of siltstone (fig. 2). On either side of this corridor, an intercalated sequence of carbonate, siltstone, and shale, and (or) evaporite separates the lower Marshall sandstone and the Napoleon Sandstone. Strata between these units interfinger, and they seem to be facies assemblages of time-stratigraphic equivalents, which were deposited in subbasins that developed during late Marshall sedimentation. The division of the Marshall sedimentary sequence into subbasins seems to be related to uplift of the Howell Anticline during Mississippian time. In fact, the trend and general width of the 15-mi-wide corridor, which extends northwest from the nose of the Howell Anticline, are the same as those of the Howell Anticline (fig. 2).

Topics of previous investigations of Mississippian sandstones in the Michigan Basin have included economic geology (Ball and others, 1941; Cohee and others, 1951; Hake, 1938; Hale, 1941; Hard, 1938; Harrell and others, 1991; Newcombe, 1933), general geology (Dorr and Eschman, 1970; Ells, 1979), geophysical properties (Westjohn, 1989, 1994b), hydraulic properties (Westjohn and others, 1990), hydrogeology (Mandle and Westjohn, 1989; Westjohn, 1989; Westjohn and Weaver, 1994, 1996b), mineralogy and petrology (Stearns, 1933; Stearns and Cook, 1931; Zacharias, 1992; Zacharias and others, 1993; Zacharias and others, 1994), paleotectonic setting (Cohee, 1979), paleontology (Driscoll, 1965, 1969), palynology (See, 1980), stratigraphy (Harrell and others, 1991; Lilienthal, 1978; Monnett, 1948; Pawlowicz, 1969; Shaver, 1985), and sedimentology (Harrell and others, 1991; O'Hara, 1954; Potter and Pryor, 1961; Rorick, 1983).

MICHIGAN FORMATION

The Michigan Formation of Late Mississippian age is an interbedded sequence of shale, limestone, dolomite, gypsum or anhydrite, siltstone, and sandstone (listed in order of decreasing abundance). Evaporite beds in this formation indicate a change from deposition in open sea, in which earlier Mississippian rock units were deposited, to deposition in a partially or fully closed basin. Cumulative thickness of all Michigan Formation lithologies is typically 300 to 400 ft (Harrell and others, 1991).

Geophysical logs show that thickness of individual Michigan Formation strata is typically less than 20 ft. The thin beds and marked contrast in lithology result in highly erratic changes in geophysical-log traces (fig. 9).

Typically, 6 to 10 gypsum beds are intercalated with shale and (or) limestone and (or) dolomite. In most areas of the basin, three gypsum beds are distinguished on electrical-resistivity logs by a distinctive signature commonly referred to as "triple gyp" (Lilienthal, 1978, p. 5). These stratigraphically continuous gypsum beds are separated from the top of the Marshall Sandstone by various thicknesses of other Michigan Formation strata, depending on location in the basin (110 to 140 ft in the west, 220 ft in the east, and more than 300 ft in the north). Gypsum beds that underlie the "triple gyp" typically range from 20 to 30 ft in thickness in the eastern and the northeastern parts of the basin.

Some sandstones at or near the base of the Michigan Formation are currently or were formerly natural-gas reservoirs. These sandstones were deposited during the interval between Early and Late Mississippian time. The origin and stratigraphic affinity of these sandstones have been strongly debated. Some geologists argue that areally extensive natural-gas-bearing sandstones interfinger with the Napoleon Sandstone and are part of the late Marshall sedimentary sequence (Ells, 1979; Harrell and others, 1991; Thomas, 1931). RASA investigators' analysis of geophysical logs supports that interpretation (Westjohn and Weaver, 1996b). One factor that complicates interpretation of stratigraphy is that sandstones of Mississippian age were deposited in two distinct sedimentary environments. One depositional environment produced elongate, laterally discontinuous, natural gas-bearing sandstone bodies, which may have formed as offshore sandbars, as suggested by Ball and others (1941). Typically, these elongate, discontinuous sandstone bodies are thin (typically less than 10 ft, but as thick as 30 ft) and are intercalated with evaporite, dolomite, limestone, and shale. The other environment produced areally extensive blanket sandstones[1], in which natural gas was trapped along the closures of north- to northwest-trending anticlines.

The common practice during the early 1930's through the 1950's, a period of considerable exploration for natural gas in Mississippian sandstones, was to name any gas-bearing sandstone the "Michigan stray sandstone" (Newcombe, 1933, p. 196). The problem with this informal stratigraphic term is that natural gas was discovered in multiple, stacked horizons of discontinuous sandstones, as well as in blanket sandstones. Hard (1938) constructed fence diagrams that show the relations of discontinuous sandstone bodies to blanket sandstones. His diagrams illustrate as many as three separate "stray sandstone" horizons above the Napoleon Sandstone. To describe the hydrogeologic framework of the regional aquifer system and avoid confusion of informal stratigraphic names, RASA investigators defined blanket sandstones to be part of the Marshall sedimentary sequence and elongate discontinuous sandstone bodies to be part of the Michigan Formation.

Subjects of previous investigations of the Michigan Formation included economic geology (Briggs, 1970; Cohee and others, 1951; Hake, 1938; Hard, 1938; Harrell and others, 1991; Newcombe, 1933), general geology (Dorr and Eschman, 1970; Ells, 1979), and sedimentology and stratigraphy (Cohee, 1965, 1979; Harrell and others, 1991; Lilienthal, 1978; McGregor, 1954; Moser, 1963; Olszewski, 1978; Shaver, 1985). Extensive bibliographies of previous investigations of the Michigan Formation are included with publications by Harrell and others (1991), Martin and Straight (1956), and Moser (1963).

BAYPORT LIMESTONE

The Bayport Limestone of Late Mississippian age consists of sparsely fossiliferous to highly fossiliferous limestone, dolostone, sandy limestone, cherty limestone, and sandstone (Bacon, 1971; Ciner, 1988; Lasemi, 1975; Tyler, 1980). The Bayport Limestone and the Michigan Formation collectively form the Grand Rapids Group (Michigan Geological Survey, 1964). Thickness of the Bayport Limestone is typically 50 to 100 ft (Cohee and others, 1951; Harrell and others, 1991). Stratigraphic relations of the Bayport Limestone to other strata in the basin are shown in Lilienthal (1978), and are described by Cohee (1979), Ells (1979), and Newcombe (1933). The name "Bayport Formation" is often used informally, but Bayport Limestone, as originally named by Lane (1899), is the recognized formal stratigraphic name for this unit (Michigan Geological Survey, 1964). Most previous investigations of the Bayport Limestone are summarized in unpublished theses (Bacon, 1971; Ciner, 1988; Lasemi, 1975; Strutz, 1978; and Tyler, 1980).

PARMA SANDSTONE

The Parma Sandstone, which consists of medium- to coarse-grained sandstone, is typically less than 100 ft thick (Cohee and others, 1951). This geologic unit has not been the subject of any geologic investigation of the Michigan Basin, but it is mentioned in descriptions of

[1] Blanket sand, as defined by Bates and Jackson (1987, p. 74) is a "deposit of sand or sandstone of unusually wide distribution, typically an orthoquartzitic sandstone deposited by a transgressive sea advancing for a considerable distance over a stable shelf area."

Pennsylvanian rock units by several investigators (Cohee, 1965; Cohee and others, 1951; Dorr and Eschman, 1970, p. 349; Kelly, 1936; Potter and Siever, 1956; Siever and Potter, 1956; Vugrinovich, 1984; Wanless and Shideler, 1975; Westjohn and Weaver, 1994, 1996a; Winchell, 1861, p. 112). Several publications on Michigan Basin stratigraphy do not delineate the Parma Sandstone as a separate stratigraphic unit (Ells, 1979; Lane, 1902a, 1905; Milstein, 1987).

Many stratigraphers consider the Parma Sandstone to be the basal part of the Pennsylvanian Saginaw Formation (Cohee and others, 1951; Kelly, 1936, p. 157; Potter and Siever, 1956; Siever and Potter, 1956; Wanless and Shideler, 1975). However, the relation of this unit to recognized and formally named geologic strata is still a subject of debate. Vugrinovich (1984) used geophysical logs to map thickness of the Parma Sandstone in a region that is about one-half the areal extent of this geologic unit (about 5,500 mi^2 in the western half of the RASA study area). As part of a detailed stratigraphic and lithologic investigation of Late Mississippian and Pennsylvanian rocks in the Michigan Basin, Vugrinovich (1984, p. 9) suggested that "the name Parma should be raised again to formational rank to designate the sequence of sandstones immediately overlying the Bayport Limestone." On the basis of stratigraphy, Vugrinovich (1984) also suggested that the lower part of the Parma Sandstone should be assigned a Late Mississippian age. Westjohn and Weaver (1996a) used geophysical logs to delineate boundaries of the Parma Sandstone and the Bayport Limestone, and they support Vugrinovich's interpretation regarding age of the Parma Sandstone. Because the Parma Sandstone seems to interfinger with the Bayport Limestone in many areas of the central part of the basin, these units may be time-stratigraphic equivalents (Westjohn and Weaver, 1996a).

SAGINAW AND GRAND RIVER FORMATIONS

Pennsylvanian rocks in the Michigan Basin have been formally subdivided into the Saginaw Formation (Early Pennsylvanian) and the Grand River Formation (Late Pennsylvanian) (fig. 5). These Pennsylvanian units consist mostly of alluvial and deltaic deposits (Shideler, 1969; Wanless and Shideler, 1975), although thin beds of fossiliferous limestone are indicative of brief periods of deposition in brackish water to marginal marine environments.

The Saginaw Formation, which constitutes the bulk of the Pennsylvanian rock sequence, consists of interbedded sandstone, siltstone, shale, coal, and limestone. The depositional sequence of these rock units is rhythmic in many areas of the basin; these deposits are typical of cyclothem-type strata, which are characteristic of Pennsylvanian-age sediments in other areas of the United States (Weller, 1930).

The Grand River Formation (originally Grand River Group) is the stratigraphic name given by Kelly (1936, p. 206) to Pennsylvanian rocks exposed along the Grand River in north-central Eaton County (fig. 3). The Grand River Formation is reported to consist predominantly of sandstone, although Kelly (1936, p. 209) indicates that a conglomerate bed at the type locality separates the Grand River Formation from the underlying Saginaw Formation. After examination of more than 12,000 geologic logs of boreholes drilled through the entire Pennsylvanian rock sequence, RASA investigators found that conglomerate is rare and highly localized. The assignment of sandstones or other Pennsylvanian rocks to either the Saginaw Formation or the Grand River Formation is difficult, if not impossible, because there are no lithologic differences or stratigraphic horizons that mark a change from one formation to the next.

The most recent bedrock geologic map of Michigan (Milstein, 1987) shows the areal extent of the Grand River Formation to be small (less than 350 mi^2) in comparison to that of the Saginaw Formation (about 10,600 mi^2). The Grand River Formation is not considered to be an important rock unit from a hydrogeologic standpoint because of its small extent. Further discussion of Pennsylvanian rocks above the Parma Sandstone is limited to the Saginaw Formation.

Previous investigations of Pennsylvanian rocks in Michigan were primarily on geological aspects including stratigraphy (Kelly, 1936; Shideler, 1969; Vugrinovich, 1984; Wanless and Shideler, 1975), coal resources (Cohee and others, 1950; Lane, 1900, 1902b), depositional setting (Martin, 1982; Strutz, 1978; Tyler, 1980), and sedimentology (Cohee and others, 1951; Ells, 1979; Velbel and Brandt, 1989). Studies related to the hydrogeology of Pennsylvanian rocks include a compilation of ground-water-resource information (Western Michigan University, 1981), a water-resources investigation of Clinton, Eaton, and Ingham Counties (fig. 3) (Vanlier and others, 1973), a regional hydrogeologic investigation and simulation of ground-water flow (Mandle and Westjohn, 1989), a summary of solid-phase mineralogy, chemistry, and isotopic compositions (Westjohn, 1994c), a tabulation of matrix-controlled hydraulic properties (Westjohn and others, 1990), and characterization of the hydrogeologic framework (Westjohn and Weaver, 1994; 1996a).

JURASSIC "RED BEDS"

"Red beds" in the Michigan Basin were considered to be Permo-Carboniferous deposits (Newcombe, 1933, p. 62) until the early 1960's, when A.T. Cross (oral commun.,

1964, presented at meeting of the Geology-Mineralogy Section of the Michigan Academy of Sciences, Arts, and Letters) indicated that these deposits are Jurassic in age. Shaffer (1969) studied morphologies of plant microfossils extracted from "red beds" sampled from hydrocarbon-exploration boreholes, and confirmed that these deposits are Jurassic in age. "Red beds" in Michigan have not been assigned a formal stratigraphic name, although a stratigraphic column published by the Michigan Geological Survey (1964) shows "red beds" of Jurassic age overlying the Grand River Formation (Late Pennsylvanian).

Shaffer (1969) indicates that predominant lithologies of the "red beds" sequence are red clay, mudstone, siltstone, and sandstone; as well as gray-green shale, mudstone, and gypsum. The assemblage of plant microfossils in Jurassic "red beds" indicates that these sediments were probably deposited in ephemeral lakes that periodically occupied shallow, arid to semiarid desert-lake basins (Shaffer, 1969).

PLEISTOCENE GLACIAL DEPOSITS

Pleistocene glacial deposits cover bedrock units in the RASA study area, except for scanty exposures of Mississippian and younger rocks that crop out in the Thumb Area and in the southern areas of the aquifer system. Glacial deposits are probably products primarily of the Wisconsin stage of the Pleistocene Epoch, although deposits from older stages (Illinoian or Pre-Illinoian) may underlie them (Eschman, 1985). The distinct lobate character of late Wisconsin glacial ice resulted in a landscape distinguished by multiple recessional moraines and outwash aprons in front of these moraines. These glacial landforms mark still-stand positions of different ice lobes (fig. 10). At least four pulses of ice advance seem to have covered all or part of Michigan during the Late Wisconsin stage (from 21,000 to 10,000 years before present); in the last pulse, ice covered only the northern fringe of the Lower Peninsula of Michigan (the Greatlakean substage; Eschman, 1985).

Glacial deposits in the study area can be separated into three general provinces (fig. 10): (1) glacial deposits in the southern part are primarily recessional moraines and outwash deposits that formed at the front of retreating ice lobes; (2) surficial deposits in the Saginaw Lowlands are primarily basal-lodgment tills and fine-grained lacustrine sediments that were deposited in former proglacial lakes; and (3) glacial deposits of the northern half of the study area are primarily glaciofluvial deposits and some coarse-textured till (Farrand and Bell, 1982). Distinct recessional moraines are uncommon in province 3. Although landforms in the northern part of the study area have the morphology of

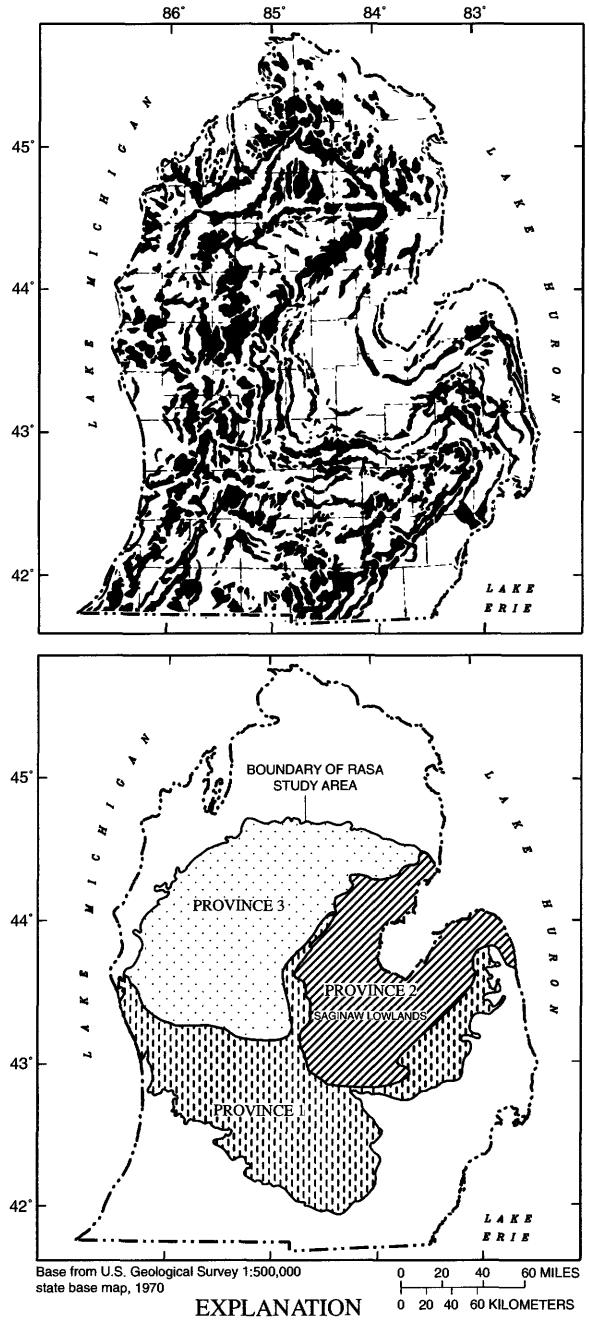


FIGURE 10.—Glacial landforms and generalized glacial-deposit provinces in the central Lower Peninsula of Michigan. (Modified from Kelley, 1967, and Westjohn and others, 1994.)

moraines, by definition they are not moraines because they are not composed of unsorted, unstratified glacial drift. (See Bates and Jackson, 1987, p. 433.) These landforms are composed primarily of glaciofluvial sediments. The moraine-like landforms in the northern part of the Lower Peninsula of Michigan were deposited by meltwater derived from the Michigan and the Saginaw ice lobes (Rieck, 1993). These interlobate glaciofluvial deposits are similar in morphology and composition to deposits mapped and described by Currier (1941) as stagnation-deglaciation deposits, and they are probably the result of stagnation-zone retreat (Bates and Jackson, 1987, p. 639).

The depositional history of Pleistocene glacial deposits is complex. Although multiple sheets of glacial drift have been described by several investigators (Dorr and Eschman, 1970; Eschman, 1985; Rieck and Winters, 1982), little progress has been made in delineation of drift stratigraphy and chronology at the regional scale. Most previous studies of glacial deposits in Michigan have involved surficial deposits. The principal goal was to interpret glacial processes on the basis of morphology and composition of landforms, and on the basis of geography and elevation of proglacial lakes that formed during ice retreat (Flint, 1957, p. 341–49; Hough, 1958, 1966; Leverett and Taylor, 1915).

Early studies of the surficial geology of the Great Lakes area resulted in voluminous literature. For example, a commonly cited report by Leverett and Taylor (1915) lists more than 400 references. A map of the surficial geology of Pleistocene glacial deposits in Michigan was published by the Michigan Department of Conservation (Martin, 1955). This map shows distributions of glacial landforms and is a compilation of work by many individuals. (See Martin, 1955, for a complete list of references.) Farrand and Bell (1982) mapped and classified till, lacustrine, and glaciofluvial deposits on the basis of textures and facies distributions, and they produced a revised map of surficial deposits that shows the same general landforms illustrated by Martin (1955).

HYDROGEOLOGY OF AQUIFERS AND CONFINING UNITS

Most investigations related to hydrogeology of the Michigan Basin are local in scope. A bibliography of publications that are products of many of these investigations was compiled by Corey and Baltusis (1995). Extensive hydrogeologic and water-resource information for the State of Michigan was compiled as a hydrogeologic atlas by Western Michigan University (1981).

RELATIONS OF STRATIGRAPHIC UNITS TO AQUIFERS AND CONFINING UNITS

Relations of commonly used stratigraphic names to hydrogeologic nomenclature established for the Michigan Basin RASA study are shown in figure 5. Also shown are lithologies of formations and approximate thicknesses of aquifers and confining units. 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. 5). Figure 9 is an example geophysical log showing differences between stratigraphic units and hydrogeologic units.

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 and the Marshall Sandstone). Other hydrogeologic units consist of part or all of a single geologic unit. 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 OF INVESTIGATION

Several previous geologic studies of the Michigan Basin include maps of structural surface and (or) thickness of some of the stratigraphic units that form the Michigan Basin RASA study unit. These maps are based mostly on data recorded on geologic logs of hydrocarbon-exploration boreholes. Boundaries of stratigraphic units are different from boundaries of aquifer units and confining beds, so maps that delineate boundaries of aquifer-system units were needed to conduct a quantitative assessment of the basin aquifer system, including regional ground-water flow.

The geologic map used to delineate boundaries of units that form the Michigan Basin regional aquifer system (fig. 4) was modified from the bedrock geologic map in the "Hydrogeologic Atlas of Michigan" (Western Michigan University, 1981, pl. 6). These maps differ in several ways. In figure 4, the contact of Jurassic "red beds" and Pennsylvanian rocks is from Westjohn and others (1994). The geologic map in the "Hydrogeologic Atlas of Michigan" (Western Michigan University, 1981, pl. 6) differentiates the Grand River Formation from the Saginaw

Formations and shows several small outliers and inliers (less than 40 mi^2 in area) of Mississippian rocks; the Grand River Formation and outliers and (or) inliers of Mississippian rocks are not illustrated on figure 4 because of their small areal extent.

Contacts of the Parma Sandstone and the Bayport Limestone and of the Parma Sandstone and overlying Pennsylvanian rocks are not illustrated on the geologic source map (Western Michigan University, 1981, pl. 6), which was modified for use by RASA investigators. Construction of maps that depict the structural surface and thickness of aquifer-unit and confining-unit maps (Parma-Bayport aquifer, Saginaw confining unit, and Saginaw aquifer) required the following assumptions: (1) the contact of Mississippian and Pennsylvanian rocks (Western Michigan University, 1981, pl. 6) approximates the updip extent of permeable rocks that form the Parma-Bayport aquifer; (2) the updip extent of the Saginaw confining unit is about 1 mi inside the contact of the updip extent of the Parma-Bayport aquifer (average subcrop width of Parma-Bayport aquifer, with average thickness of 100 ft and average regional dip of 1 degree); and (3) the updip extent of the Saginaw aquifer is about half a mile inside the updip extent of the Saginaw confining unit (average subcrop width of the Saginaw confining unit, with average thickness of 50 ft and average regional dip of 1 degree).

Geophysical logs are the principal data used to delineate boundaries of aquifer-system units. In some areas of the basin, however, geophysical logs are few and use of information (such as position of geologic contacts and lithologic descriptions) from geologic logs of oil, gas, and water wells in map construction was necessary. The following description of hydrogeology of aquifers and confining units is based primarily on a series of interim reports related to the Michigan Basin RASA investigation (Westjohn and others, 1994; Westjohn and Weaver, 1994, 1996a, 1996b, 1996c).

GLACIOFLUVIAL DEPOSITS

Glaciofluvial deposits are the largest source of fresh ground water in Michigan and in the RASA study area. At least 77 municipalities within the study region rely partially or entirely on ground water from glacial deposits (Baltusis and others, 1992). The term glaciofluvial aquifer is used in this report to refer to any water-bearing deposit of sand and (or) gravel deposited by glacial meltwater.

AREA, DISTRIBUTION, AND THICKNESS

The areal extent and the distribution of glaciofluvial deposits in the RASA study area were delineated on the basis of lithologic descriptions recorded on geologic logs (Westjohn and others, 1994). More than 12,000 logs were examined. In about 500 of these logs, glacial deposits were subdivided by lithology, and thickness of clay, till, and sand and (or) gravel was noted. These logs were used to construct a map that shows the percentage of glaciofluvial deposits relative to total drift thickness (fig. 11). Trends in dominance of glaciofluvial deposits or of till and lacustrine deposits can be recognized. For example, the percentage of glaciofluvial deposits increases in all directions (landward) with distance from the Saginaw Lowlands (fig. 11). Glaciofluvial deposits constitute more than 25 percent of glacial deposits in provinces 1 and 3 but not in the Saginaw Lowlands (fig. 10). Glaciofluvial deposits constitute more than 75 percent of glacial sediments in the northern part of the study area, where they are also thickest. Glaciofluvial deposits also predominate in most of the perimeter area of the aquifer system (fig. 11), where the Marshall Sandstone is a subcrop.

The "Hydrogeologic Atlas of Michigan" (Western Michigan University, 1981) contains a thickness map of glacial deposits. The map showing thickness of glacial deposits is a modification of work by Rieck (Western Michigan University, 1981, pl. 15.), and it was used to establish the boundary of bedrock and glacial deposits for computer simulation of ground-water flow (Mandle and Westjohn, 1989). This thickness map is based on compilation and interpretation of about 80,000 logs of oil, gas, and water wells (Richard Rieck, Western Illinois University, oral commun., 1990). A map illustrating the altitude of the bedrock surface is also included in the "Hydrogeologic Atlas of Michigan" (Western Michigan University, 1981, pl. 13).

Glacial deposits are less than 200 ft thick and are locally absent in an area that extends southwest from the Thumb Area to the southern fringes of the aquifer system. Northwest of this area, glacial deposits progressively thicken; in some places within the study area, they are more than 900 ft thick. The approximate thickness of the glaciofluvial aquifer was mapped using a published thickness map (Western Michigan University, 1981, pl. 15), in conjunction with the percentage of sand and gravel recorded on geologic logs. Thickness of the glaciofluvial aquifer ranges from 0 to a few feet in areas of the Saginaw Lowlands, where basal-lodgment tills and fine-grained lacustrine sediments constitute most or all of glacial deposits (fig. 11). The glaciofluvial aquifer is about 900 ft in the northwestern part of the mapped area (Roscommon, Missaukee, and Wexford Counties, fig. 3), where glacial drift is composed mostly of sand and gravel (Rieck, 1993; Westjohn and others, 1994).

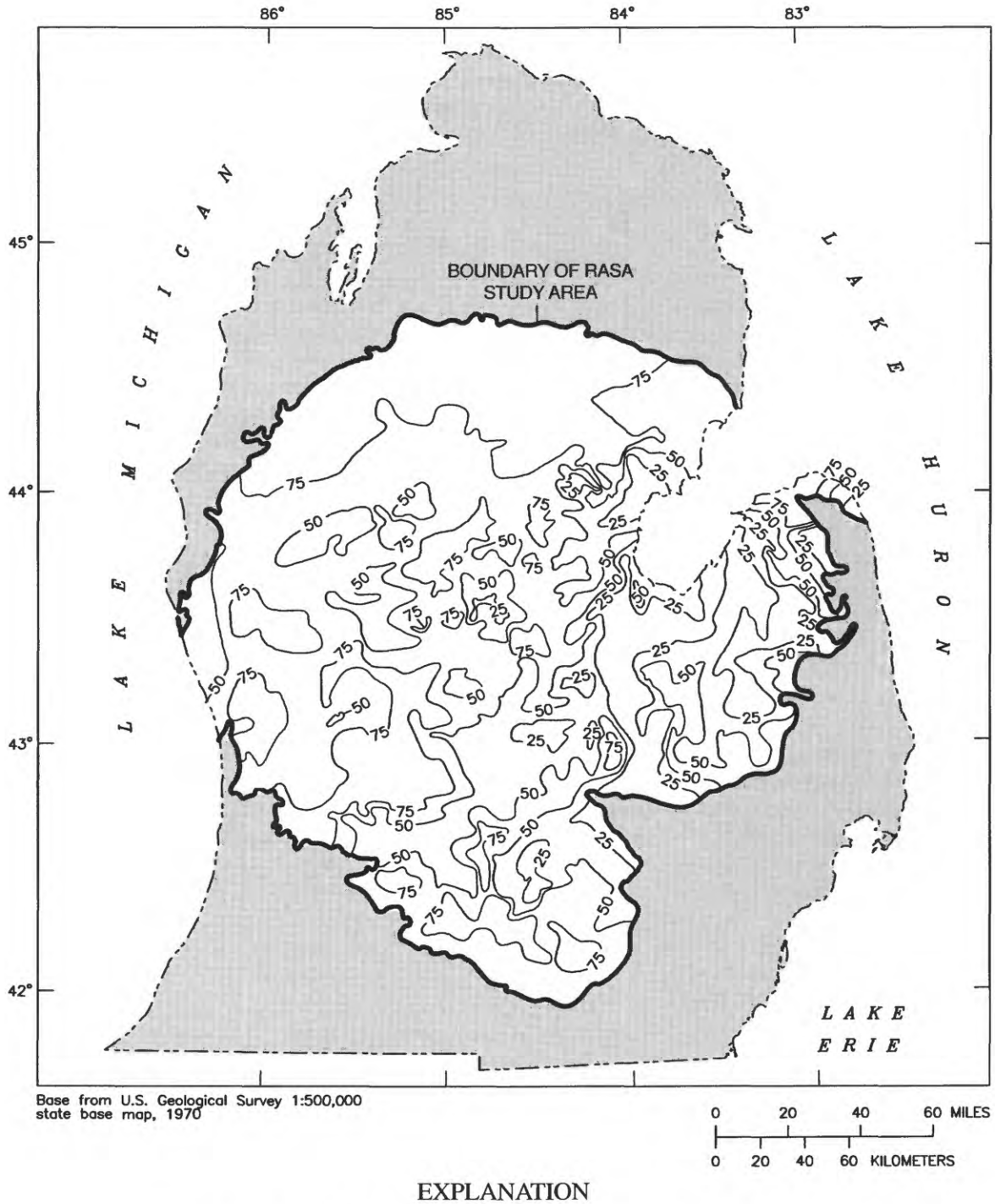


FIGURE 11.—Ratio of sand and gravel to till and lacustrine sediments within Pleistocene glacial deposits in the central Lower Peninsula of Michigan.

HYDRAULIC PROPERTIES

So far as is known, no aquifer-test data for glaciofluvial deposits have been published; however, yields to wells completed in glaciofluvial materials are reported to be larger than those of bedrock aquifers. Grannemann and others (1985) show that yields to wells in glaciofluvial deposits may exceed 2,000 gal/min, where highest yields to sandstone aquifers are about 1,500 gal/min.

GLACIAL LACUSTRINE/GLACIAL TILL CONFINING UNITS

The areal extent and the distribution of fine-grained lacustrine deposits and till, which are assumed to function as confining units, were delineated by use of the same geologic logs described in the section on "Glaciofluvial Aquifers." Glacial lacustrine/glacial till confining beds are vertically and laterally discontinuous in most of the study area. However, in a 1,600-mi^2 area within the Saginaw Lowlands, these confining beds constitute most of glacial drift, which typically ranges from 50 to 200 ft in thickness (Western Michigan University, 1981, pl. 15). Elsewhere in the aquifer system, these confining beds are interspersed with glaciofluvial deposits, and they constitute various percentages of the overall thickness of glacial deposits.

JURASSIC "RED BEDS" CONFINING UNIT

On the basis of data from geophysical logs, permeable sandstone within Jurassic "red beds" is not volumetrically important and most of the sequence is probably of low permeability. Electric logs (spontaneous potential and electrical resistivity) of boreholes open to "red beds" show that electrically resistive gypsum beds are common. Typically one but as many as three gypsum units show on electric logs, and the thickness of individual gypsum strata is usually less than 10 ft. Gypsum beds seem to be stratigraphically continuous and, in some places, at about the same altitude throughout areas larger than 500 mi^2. The presence of stratigraphically continuous gypsum beds at about the same altitude is evidence that basin subsidence was negligible during and after Jurassic time. Gypsum may have been more abundant in "red beds" than reported on drillers' logs. Lost circulation during exploration or production drilling for oil and gas is commonly recorded on drillers' logs. Many lost-circulation zones have been recorded for depth intervals that can be traced by use of geophysical logs to areas where gypsum beds are at about the same altitude. These lost-circulation zones are probably related to areas of dissolution of gypsum or other soluble evaporites, although circulation may have been lost in zones where the "red beds" sequence is poorly consolidated.

AREA, THICKNESS, AND SURFACE CONFIGURATION

Areal extent of the Jurassic "red beds" confining unit is about 4,000 mi^2. Thickness and surface-configuration maps of "red beds" (figs. 12, 13) were prepared entirely from geologic records of hydrocarbon-exploration boreholes (Westjohn and others, 1994). A subset of geologic logs was selected from available collections (Michigan State University subsurface laboratory, Michigan Geological Survey, oil and gas records). About 12,000 geologic logs were examined, but most of these logs were rejected because they did not include the detailed information required for mapping. In many logs, glacial deposits, "red beds," and Pennsylvanian rocks were listed together, but formation contacts or unit thicknesses were not recorded. This type of detailed geologic information was generally not recorded because Pennsylvanian and Jurassic rocks were considered to be of little economic importance in Michigan. The contact between glacial deposits and "red beds" is also difficult to delineate because Jurassic deposits are commonly unconsolidated or poorly consolidated. Delineation of the contact between "red beds" and underlying Pennsylvanian rocks was commonly neglected because many early investigators assumed that "red beds" mark the upper part of the Carboniferous Period (Newcombe, 1933), which negated the need to separate them from underlying Pennsylvanian rocks.

In most of the logs used to construct contour maps of Jurassic rocks, the top and the thickness of "red beds" were clearly identified, or lithologies consistent with strata identified as Jurassic deposits (Shaffer, 1969) were described in detail. In nearly all the logs gypsum (usually selenite), known from geophysical logs to be a common constituent of "red beds," was reported; however, mention of gypsum was not used as a criterion for selecting or rejecting logs for use in map construction. The area of "red beds" was delineated by use of a subset of the logs (425 of 589). Logs from areas outside the mapped boundary of "red beds" did not describe "red beds" or lithologies typical of Jurassic deposits. The logs were judged to be reliable for delineating the areal extent of "red beds" because (1) drift thickness and top of bedrock surface were noted, (2) geologic units of different age were not combined, and (3) detailed descriptions and thicknesses of lithologies were listed, as well as depths to contacts of formations consistent with the stratigraphy established for the basin.

Although thickness of "red beds" is as great as 200 ft, thickness ranges from 50 to 150 ft throughout most of

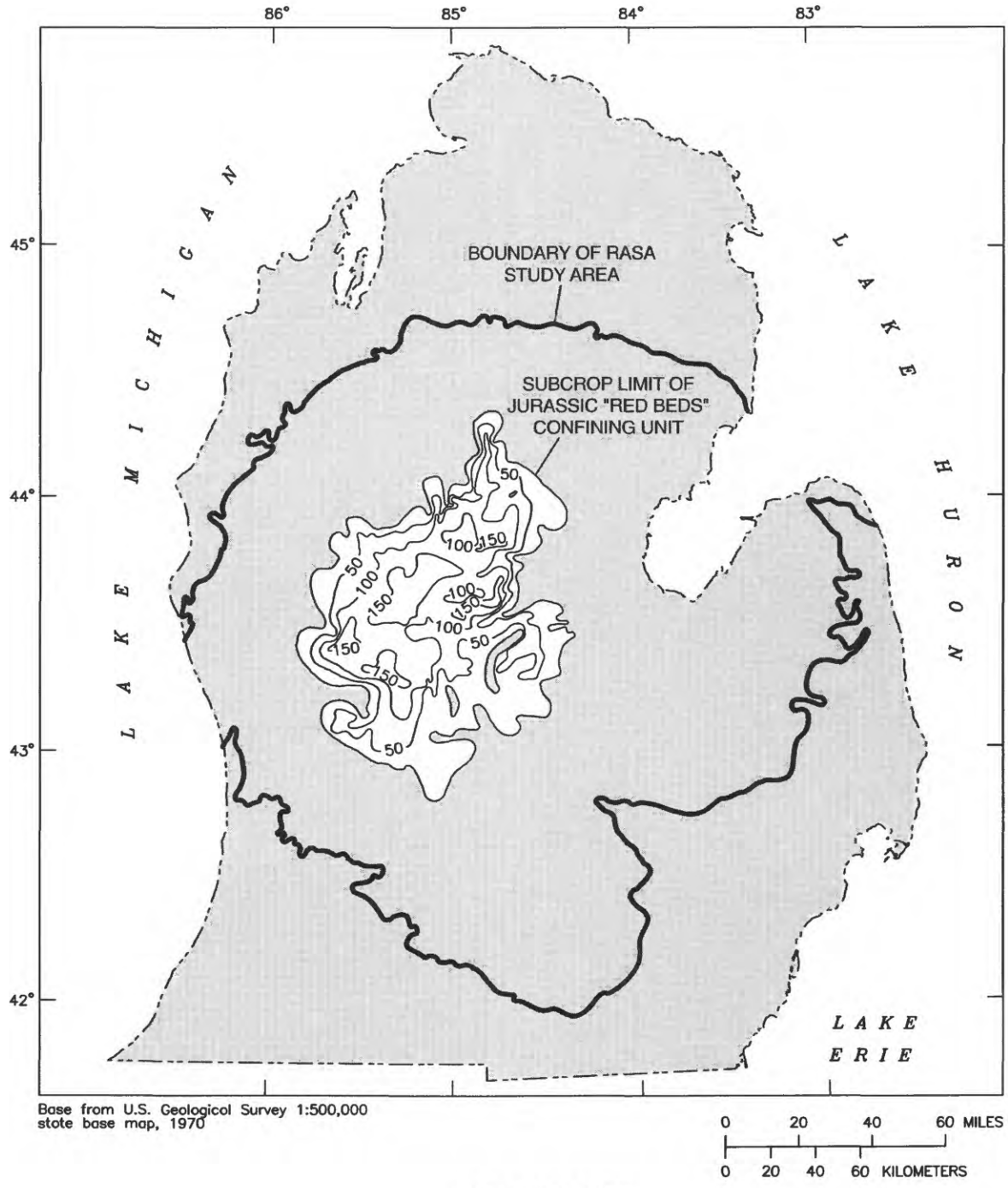


FIGURE 12.—Thickness of Jurassic "red beds" confining unit in the central Lower Peninsula of Michigan.

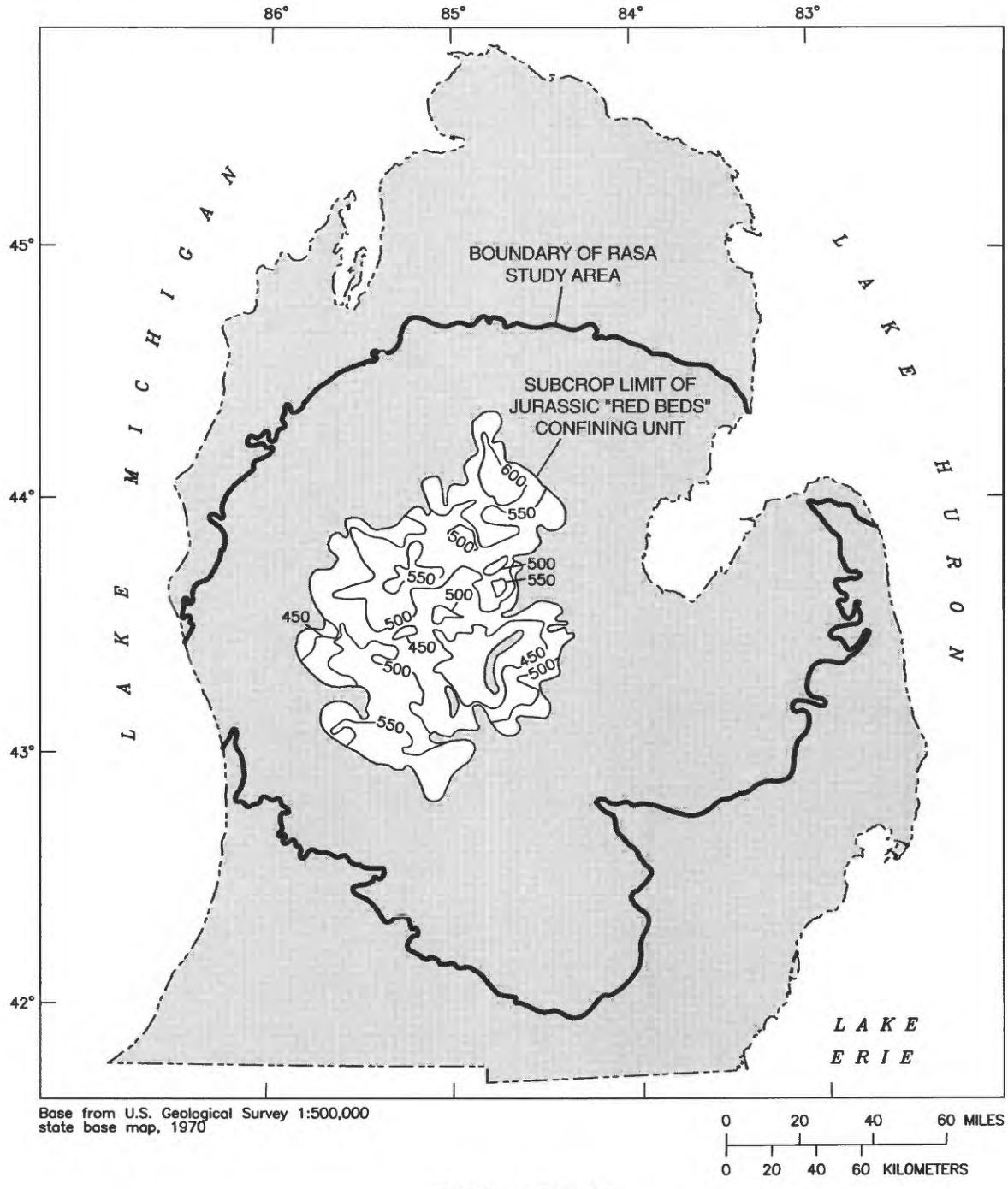


FIGURE 13.—Surface configuration of top of Jurassic "red beds" confining unit in the central Lower Peninsula of Michigan.

the mapped area (fig. 12). Altitude of the top of Jurassic deposits generally ranges from 450 to 600 ft above sea level (fig. 13). Relief on the top of "red beds" is probably related to erosion before or during Pleistocene time (Lilienthal, 1978).

HYDRAULIC PROPERTIES

No hydraulic-property data are available for the Jurassic "red beds" confining unit. Evidence that "red beds" function as a confining unit is inferred on the basis of geophysical data. "Red beds" contain saline water and seem to restrict vertical movement of ground water between glacial deposits and aquifers underlying them. Electrical-resistivity logs have been interpreted to show that the altitude of the base of freshwater coincides approximately with the altitude of the base of glacial deposits overlying "red beds" (Westjohn, 1989). Electrical-resistivity logs indicate that bedrock units underlying "red beds" contain saline water or brine. This boundary between freshwater and saline water supports the interpretation that "red beds" form a confining unit overlying saline-water-bearing Pennsylvanian rocks in the west-central part of the basin.

SAGINAW AQUIFER

The Saginaw aquifer consists of the cumulative thickness of sandstones that overlie the Saginaw confining unit (fig. 5). These sandstones are assumed to be hydraulically connected at the scale of the study area and this unit functions as a regional aquifer.

AREA, THICKNESS, AND SURFACE CONFIGURATION

The area of the Saginaw aquifer is about 10,400 mi^2. The aquifer is less than 100 ft thick near the boundary of the study area (fig. 14). The Saginaw aquifer is thickest along a 30- to 45-mi-wide south-trending corridor near the center of the study area, where thickness ranges from 100 to more than 300 ft (fig. 14). The Saginaw aquifer is the upper part of the Pennsylvanian rock sequence, and the configuration of the top of the Saginaw aquifer (fig. 15) is the same as the top of the Pennsylvanian rock sequence.

HYDRAULIC PROPERTIES

Analyses of aquifer-test data indicate a wide range of transmissivities within the Saginaw aquifer. Transmissivities that range from 130 to 2,700 ft^2/d were reported for Clinton, Eaton, and Ingham Counties (fig. 3), where the Saginaw aquifer is the principal source of water for municipal supply (Vanlier and Wheeler, 1968).

Matrix-controlled hydraulic properties of a suite of core samples from the Saginaw Formation were measured. Porosities and matrix-controlled vertical hydraulic conductivities range from 4 to 34 percent and from 0.0001 to 55 ft/d, respectively. These large ranges of porosities and hydraulic conductivities generally are a function of cement type and degree of cementation. A complete tabulation of the hydraulic-property data can be found in a report by Westjohn and others (1990).

SAGINAW CONFINING UNIT

The Saginaw confining unit separates the Saginaw aquifer from the underlying Parma-Bayport aquifer in most of the study area (fig. 5). This confining unit consists mostly of shale; the rest of the sequence consists of thin beds of sandstone, siltstone, coal, and limestone. Geophysical logs show that sandstone and siltstone beds typically are less than 15 ft thick and generally cannot be traced laterally more than a few miles. Electric logs show that sandstone and siltstone beds within this predominantly shale sequence contain saline water or brine (Westjohn, 1989). These permeable strata probably do not contribute a significant amount of water to the regional flow system. The area of the Saginaw confining unit is about 10,600 mi^2. Thickness of this confining unit ranges from 100 to 240 ft in the northwest, but decreases to approximately 50 ft near the boundary of the study area (fig. 16). In the northwestern part of the aquifer system, where the Saginaw confining unit is thickest, lithology and thickness were delineated by use of electrical-resistivity and spontaneous-potential logs of boreholes open to Pennsylvanian rock units. The thickness of the Saginaw confining unit is less certain in the central and southeastern parts of the study area because geophysical logs for this area are few in number and uneven in distribution.

PARMA-BAYPORT AQUIFER

The Parma Sandstone and Bayport Limestone are considered by most geologists to be separate and distinct time-stratigraphic units. Geophysical logs show that these units consist mostly of permeable sandstones and carbonates and that the formations are hydraulically connected throughout the area of the regional aquifer system. For characterization of hydrogeologic setting and computer simulation of ground-water flow, these units are combined as the Parma-Bayport aquifer.

AREA, THICKNESS, AND SURFACE CONFIGURATION

The area of the Parma-Bayport aquifer is about 11,000 mi^2. Thickness of this aquifer exceeds 200 ft in some parts of the area mapped (fig. 17). In most areas,

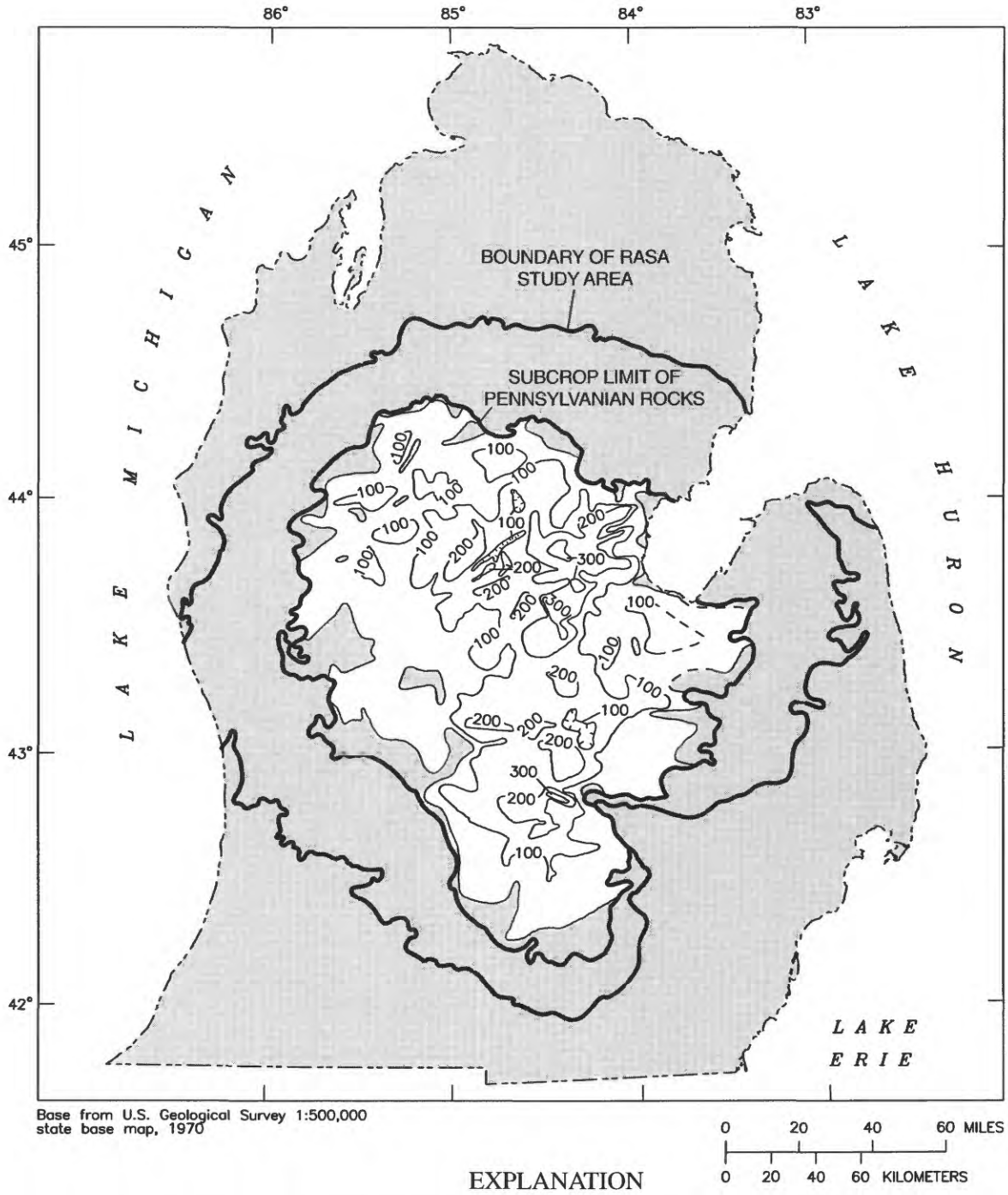


FIGURE 14.— Thickness of Saginaw aquifer in the central Lower Peninsula of Michigan.

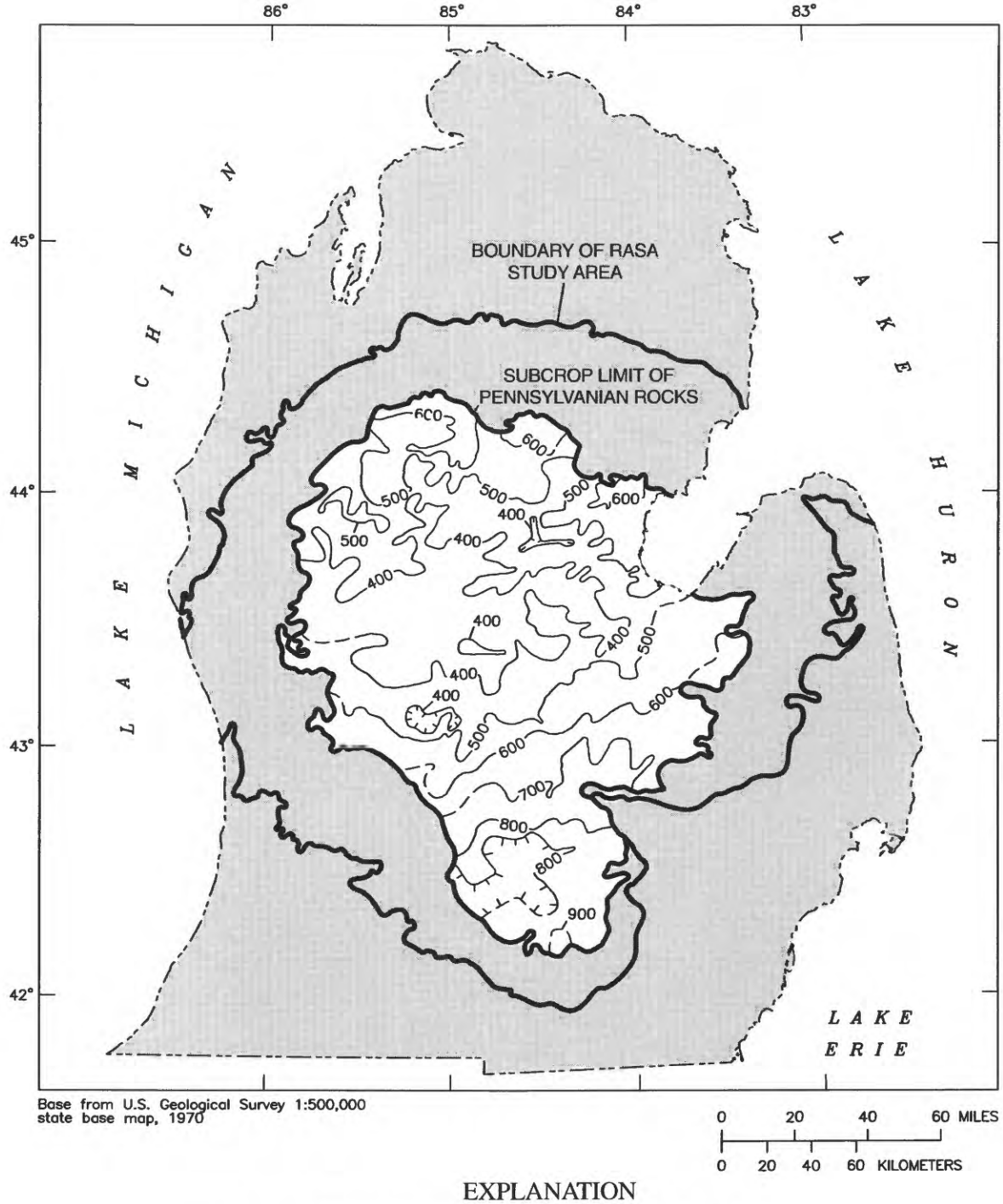


FIGURE 15.—Surface configuration of Pennsylvanian rocks in the central Lower Peninsula of Michigan.

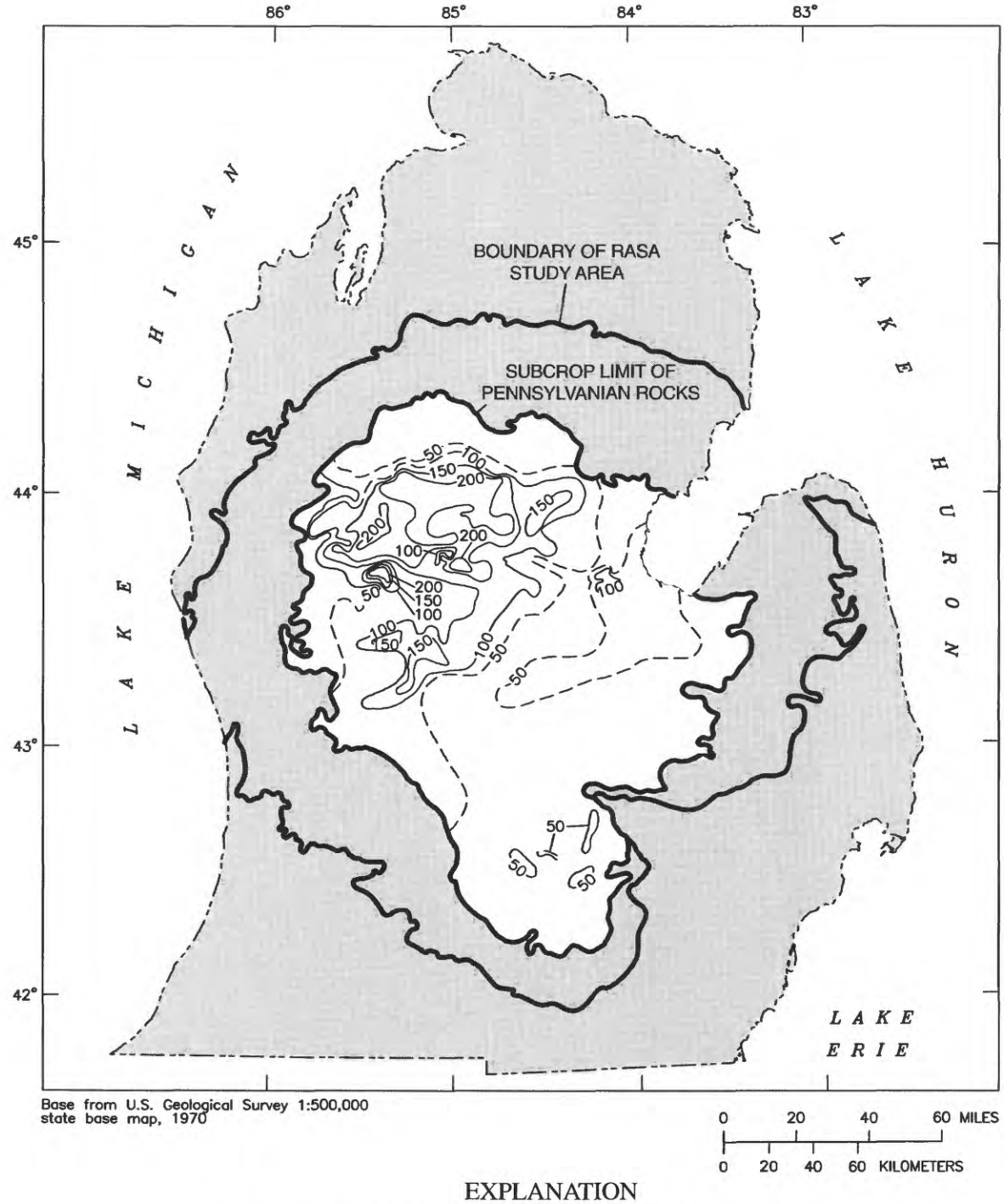


FIGURE 16.—Thickness of Saginaw confining unit in the central Lower Peninsula of Michigan.

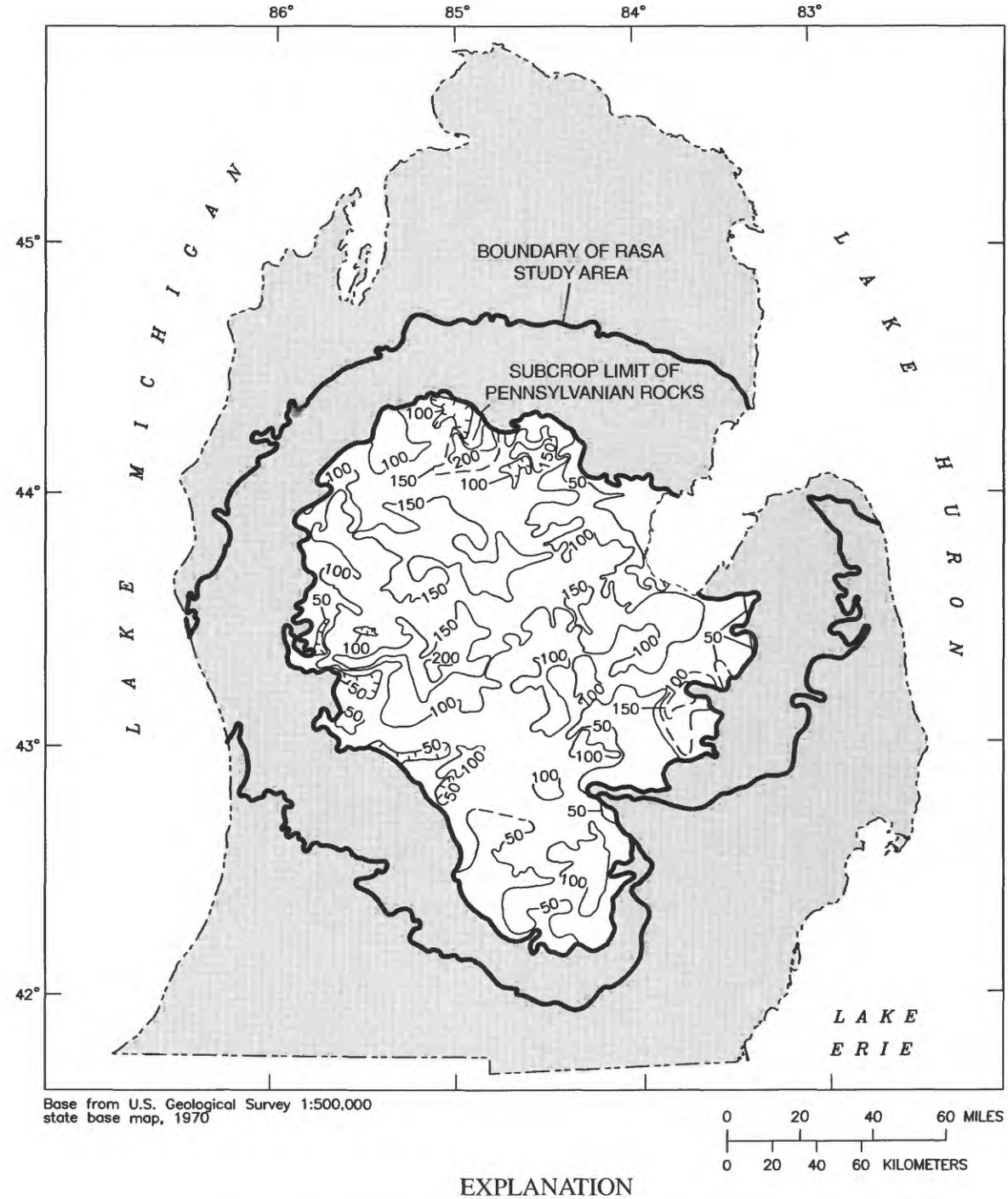


FIGURE 17.—Thickness of Parma-Bayport aquifer in the central Lower Peninsula of Michigan.

thickness generally ranges from 100 to 150 ft. Relief on the top of the Parma-Bayport aquifer is about 1,000 ft (fig. 18). Altitudes are lowest (about 100 ft below sea level) in the north-central part of the study area and highest in the south and north (about 900 and 500 ft, respectively).

In the northeastern part of the aquifer system, the Parma-Bayport aquifer was delineated primarily on the basis of characteristic electric-log traces (Westjohn and Weaver, 1996a). Electric logs typically display mud-invasion profiles, an indication that this aquifer is permeable (fig. 9). Gamma-ray logs were used to delineate boundaries of the aquifer in the southeast. Data recorded in geologic logs were necessary to complete the thickness and surface-configuration maps in several areas where no geophysical logs are available.

HYDRAULIC PROPERTIES

Geophysical logs of boreholes open to the Parma-Bayport aquifer are the basis for the description of general hydraulic characteristics. In the central part of the basin, highly permeable sandstone (about 100 ft thick) is the predominant lithology. Evidence of the high permeability of this sandstone is indicated by caliper and porosity logs. Caliper logs show that borehole diameter is larger than bit diameter by several inches in the upper part of the sandstone sequence. This difference in diameter indicates that fluid circulation during drilling eroded poorly consolidated, permeable sandstone. Geophysical logs show that porosities in the upper part of the sandstone sequence typically range from 25 to 35 percent; these are the highest porosities of any bedrock unit in the aquifer system (Westjohn and others, 1990). Porosity decreases and sandstones become more consolidated with depth.

Hydraulic-property data for the Parma-Bayport aquifer are scanty, primarily because this aquifer is rarely used for water supply. No records of aquifer tests are known, but measurements of hydraulic properties were made of a suite of Parma Sandstone cores by use of helium gas as a test media, to evaluate gas-storage-reservoir properties (Robert Bomar, Michigan Consolidated Gas Company, written commun., 1993). Data reported from these tests are in millidarcies, the standard units used by the oil and gas industry. These units, rather than units for hydraulic conductivity, are retained to indicate that permeability to gas was measured. Vertical and horizontal permeability components and porosity of 106 core specimens were measured. The ranges of vertical and horizontal permeability components are about the same (0.1 to 2,500 millidarcies), and range of porosity is from 2 to 25 percent. These ranges are similar to those reported for Pennsylvanian sandstones that overlie the Parma-Bayport aquifer (Westjohn and others, 1990; Westjohn, 1994c).

Examination of core specimens indicates that permeability and porosity are a function of degree of cementation. Cements in the Parma-Bayport aquifer are the same as those determined for the Saginaw aquifer (Westjohn and others, 1991; Westjohn, 1994c).

MICHIGAN CONFINING UNIT

The Michigan confining unit is composed of all low permeability lithologies of the Michigan Formation, and does not include stratigraphically continuous sandstones at or near the base of the formation. This confining unit separates the Parma-Bayport aquifer from the Marshall aquifer (fig. 5). The Michigan confining unit consists of shale, carbonate, evaporite, and thin, laterally discontinuous siltstone and sandstone lenses. Sandstone/siltstone beds that are intercalated with rocks of very low permeability probably do not contribute a significant quantity of ground water to the regional flow system.

AREA, THICKNESS, AND SURFACE CONFIGURATION

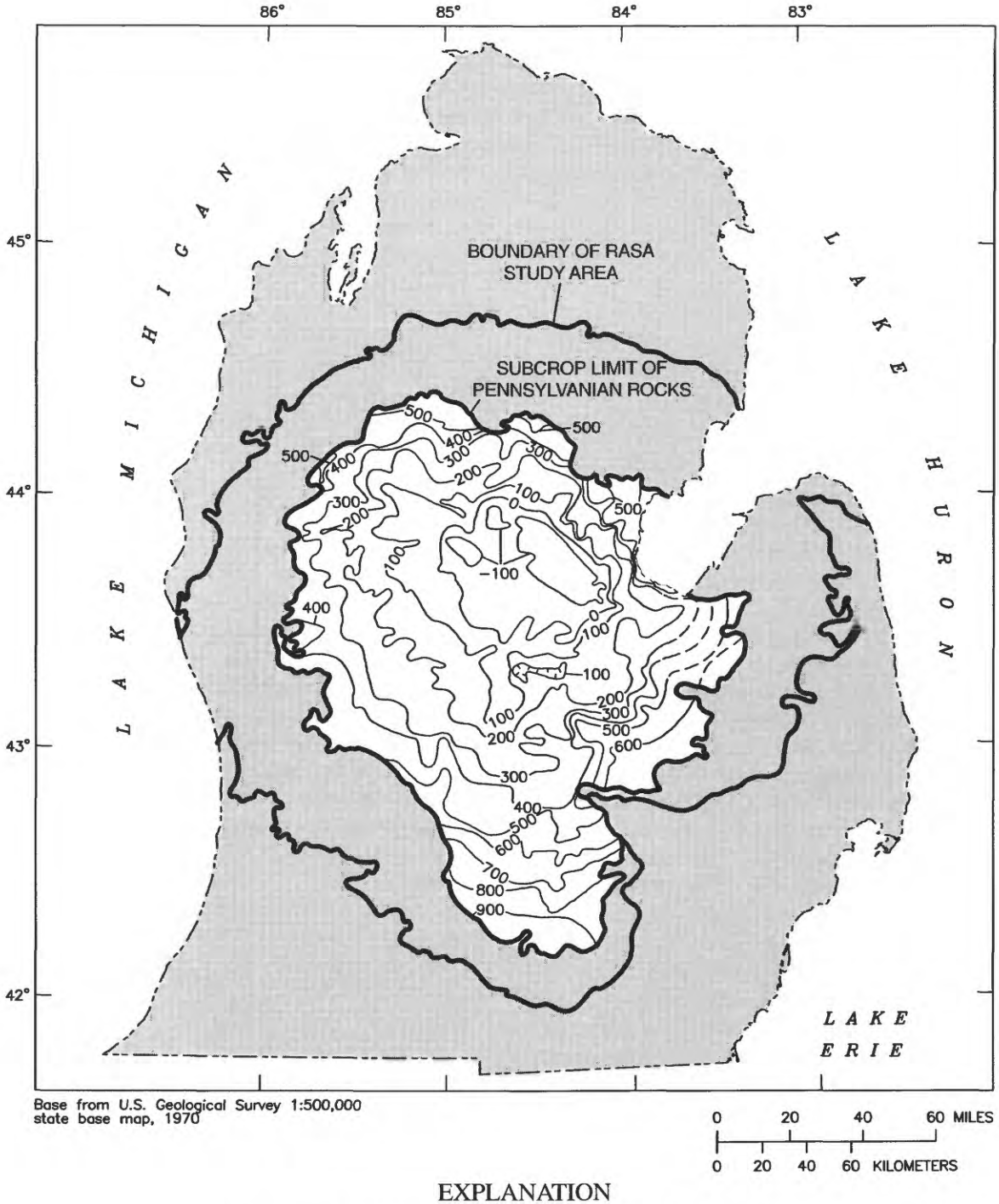
The Michigan confining unit (17,000 mi^2 in area) underlies most of the RASA study area. Thickness of the unit generally increases from south to north (fig. 19). In the northwestern part of the study area, thickness of the confining unit typically ranges from 300 to 400 ft. The unit thins to 100 ft to the south and east. In the northeastern part of the study area, the unit is less than 50 ft thick in places. The configuration of the top of the Michigan confining unit is shown in figure 20. Top of the confining unit is lowest in the north-central part of the study area, where altitude is more than 200 ft below sea level. The top of the Michigan confining unit is highest in the south and east, where altitudes are about 900 and 600 ft, respectively. In the west and north, altitude of the top of the confining unit generally ranges from 300 to 400 ft.

HYDRAULIC PROPERTIES

No hydraulic-property data are available for the Michigan confining unit. The widespread reservoirs of natural gas trapped in sandstones below gypsum, anhydrite, limestone, or dolomite beds of the Michigan confining unit (Rawlins and Schellhardt, 1936) are evidence that the unit functions as a confining unit.

MARSHALL AQUIFER

The Marshall aquifer consists of one or more blanket-type sandstones of Mississippian age that RASA investigators assume are hydraulically connected at the scale of the regional aquifer system. Delineation of permeable



EXPLANATION

— 900 – – BEDROCK CONTOUR—Shows altitude of top of Parma–Bayport aquifer. Dashed where approximately located. Hachures indicate depression. Contour interval 100 feet. Datum is sea level

FIGURE 18.—Surface configuration of Parma-Bayport aquifer in the central Lower Peninsula of Michigan.

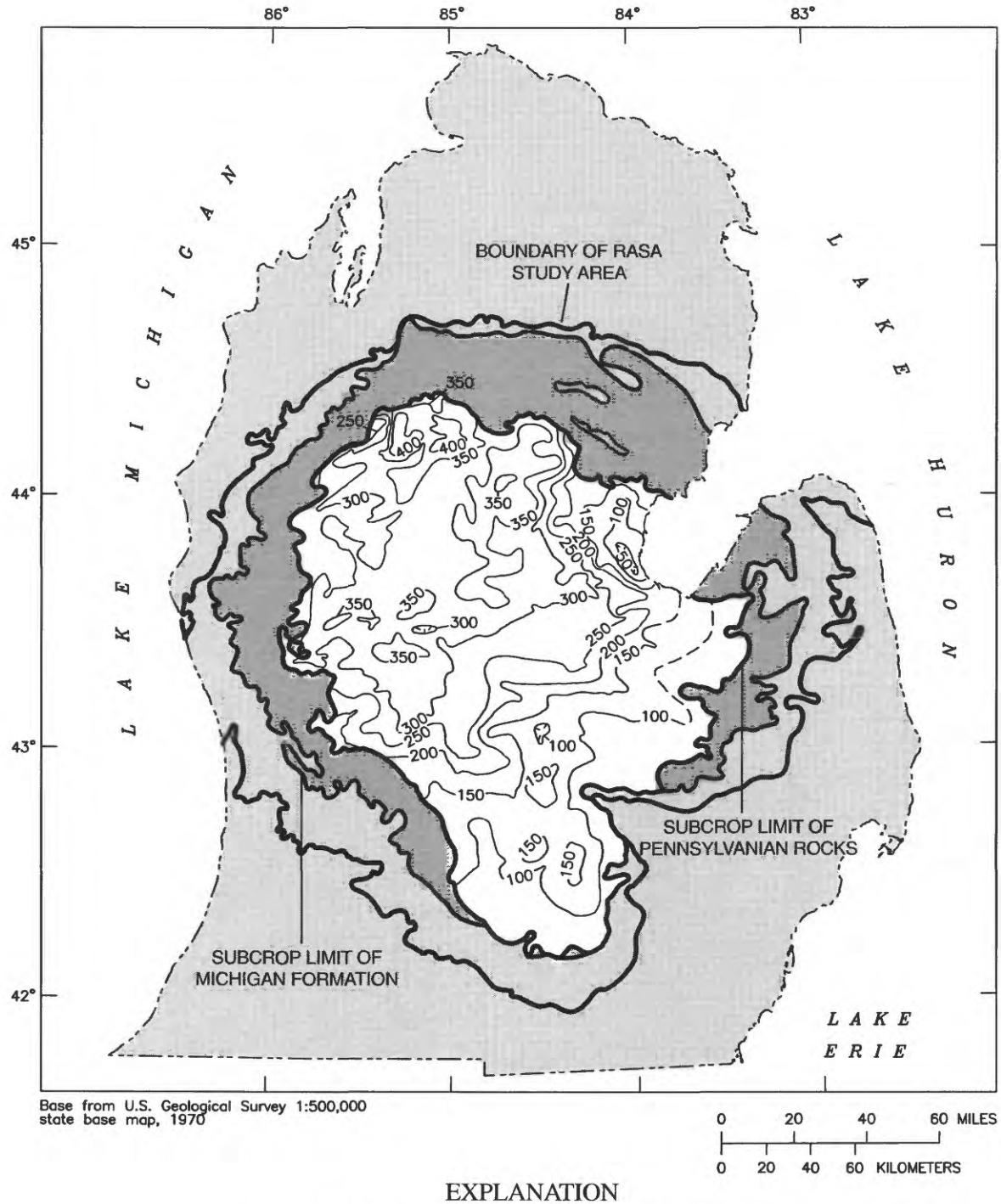
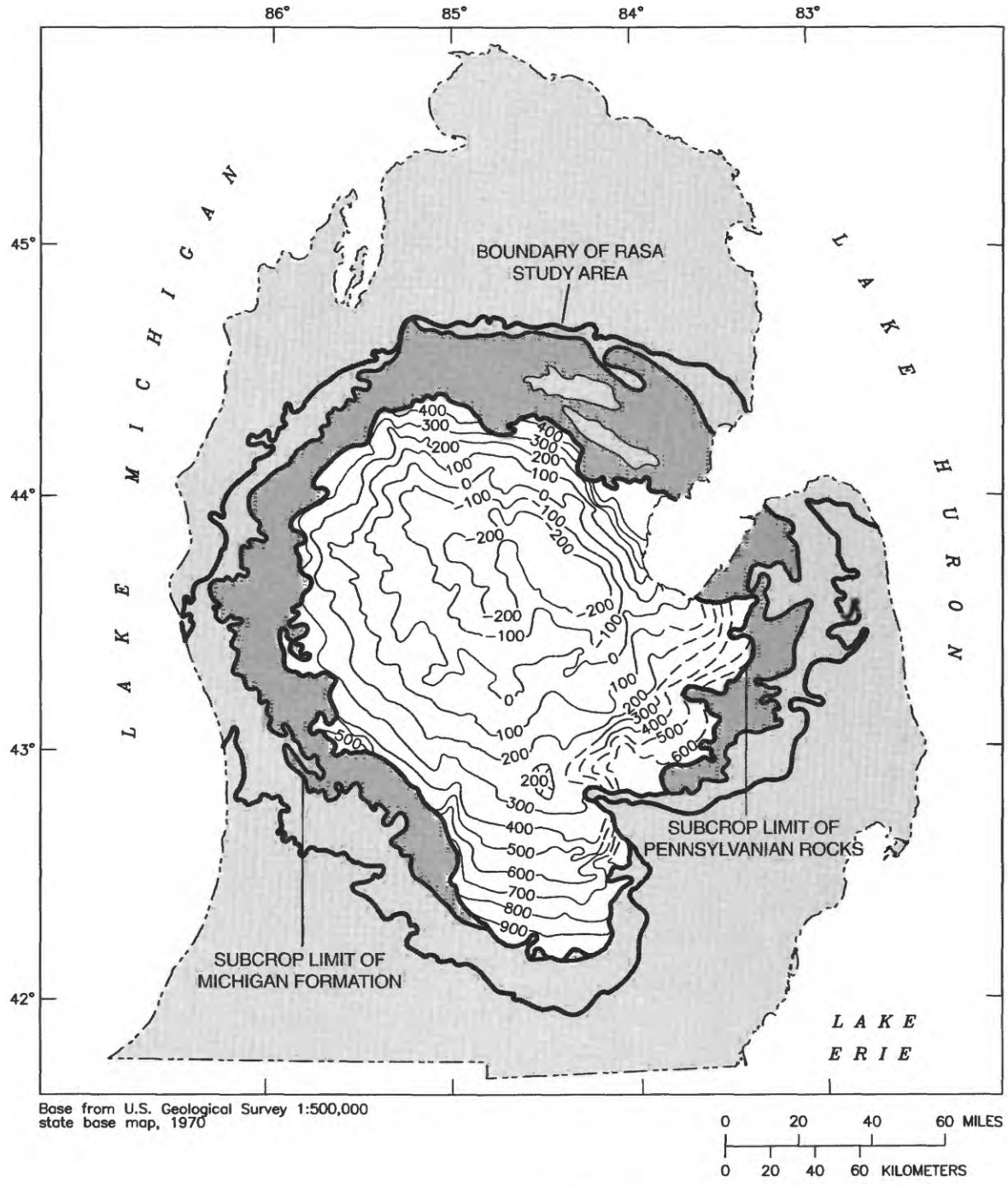


FIGURE 19.—Thickness of Michigan confining unit in the central Lower Peninsula of Michigan.



EXPLANATION

— 900 — — BEDROCK CONTOUR—Shows altitude of top of Michigan confining unit. Dashed where approximately located. Hachures indicate depression. Contour interval 100 feet. Datum is sea level

FIGURE 20.—Surface configuration of Michigan confining unit in the central Lower Peninsula of Michigan.

sandstones by use of geophysical logs is described in several interim reports (Westjohn, 1989, 1991a, 1994b; Westjohn and Weaver, 1996b).

AREA, THICKNESS, AND SURFACE CONFIGURATION

The Marshall aquifer is laterally continuous throughout most of the RASA study area, and the area of this aquifer is about 22,000 mi^2. Only permeable sandstones are considered to constitute the aquifer; all other lithologies were excluded in preparing the Marshall aquifer thickness map (fig. 21). Thickness of the Marshall aquifer is 75 to 125 ft in most of the eastern and southern parts of the RASA study area. Thickness of the aquifer decreases to approximately 75 ft along a northwest-trending corridor from Livingston County to Newaygo County (figs. 3, 21). The aquifer is more than 200 ft thick in the northwestern part of the study area (Wexford and Lake Counties, figs. 3, 21). Surface configuration of the Marshall aquifer is shown in figure 22. Altitudes of the top of the aquifer are lowest in the central part of the basin, where the top of the unit is more than 600 ft below sea level, and highest near the boundary of the study area. In the south, altitude of the top of the aquifer is more than 800 ft. Altitudes range from 300 to 400 ft in the west and from 500 to 700 ft in the north. Altitudes in the east generally range from 500 to 600 ft.

HYDRAULIC PROPERTIES

Hydraulic properties of the Marshall aquifer have been interpreted from aquifer tests at Battle Creek and Jackson (fig. 3), two large municipalities in the southern part of the study area, where the aquifer is highly productive. Each municipality withdraws more than 10 Mgal/d of ground water (Grannemann and others, 1985). Large ground-water withdrawals are possible at these sites because the Marshall aquifer is highly fractured. Transmissivities determined from aquifer tests at the Verona well field in Battle Creek range from 3,000 to 27,000 ft^2/d (Grannemann and Twenter, 1985, p. 25). Transmissivities of the Marshall aquifer determined from aquifer tests at the Jackson well field range from 7,500 to 29,000 ft^2/d (George Econ, Jackson Community College, written commun., 1993).

In other areas of the basin, the Marshall aquifer is substantially less productive. Transmissivities determined from aquifer tests in Huron County (fig. 3) range from 7 to 50 ft^2/d, and hydraulic conductivities range from 0.2 to 1.5 ft/d (Sweat, 1992). Similar ranges of hydraulic properties were derived from double-packer aquifer tests done as part of the Michigan Basin RASA study (Westjohn, 1993a). Analysis of aquifer tests of the Marshall aquifer in three counties (Muskegon, Genesee, and Eaton Counties; fig. 3) indicate a small range of transmissivities (10 to 37 ft^2/d) and hydraulic conductivities (0.2 to 0.5 ft/d).

Hydraulic properties of sandstone core samples from the Marshall aquifer were determined (Westjohn and others, 1990; unpublished data, U.S. Geological Survey, Lansing, Mich.). Data include porosity of 63 sandstone cores, vertical hydraulic conductivity of 43 cores, and horizontal hydraulic conductivity of 20 cores. The suite of sandstone specimens selected for laboratory determinations of hydraulic properties are well-cemented, unfractured sandstones, so the values reflect matrix-controlled hydraulic properties. The upper range of matrix-controlled hydraulic conductivities (1.3 to 1.8 ft/d) determined of cores is similar to higher hydraulic conductivities determined from aquifer tests in several counties (Eaton, Genesee, Huron, and Muskegon Counties; fig. 3). These similarities indicate that fractures are absent in the Marshall aquifer at these localities and that ground-water flow in the aquifer is dominated by hydraulic properties of the sandstone matrix.

COLDWATER CONFINING UNIT

The Coldwater confining unit is the base of the regional aquifer system. This basal confining unit consists mostly of shale. Siltstone, sandstone, limestone, and dolomite are part of this hydrogeologic unit in some areas of the basin. The Coldwater confining unit is about 1,300 ft thick in the eastern part of the study area (John Esch, Michigan Department of Natural Resources, written commun., 1994), but it is about 500 ft thick in the western part (Cohee, 1979).

Although the cumulative thickness of sandstone and siltstone lenses is larger than 200 ft in parts of the Thumb Area (fig. 8), these lenses are laterally discontinuous and are separated from the overlying Marshall aquifer by shale. These sandstone and siltstone lenses probably do not contribute a significant amount of ground water to the regional-flow system.

AREA AND SURFACE CONFIGURATION

The area of the Coldwater confining unit is more than 32,000 mi^2. This unit extends south into northern Indiana and Ohio. The subcrop of this confining unit also extends west under Lake Michigan and east under Lake Huron (fig. 4). The surface configuration of the Coldwater confining unit (fig. 23) is similar to surface configurations of the Michigan confining unit (fig. 20) and Marshall aquifer (fig. 22). Altitudes of the top of the Coldwater confining unit are more than 800 ft below sea level in the central part of the Michigan Basin. Altitudes are highest in the northern and southern parts of the aquifer system (700 to

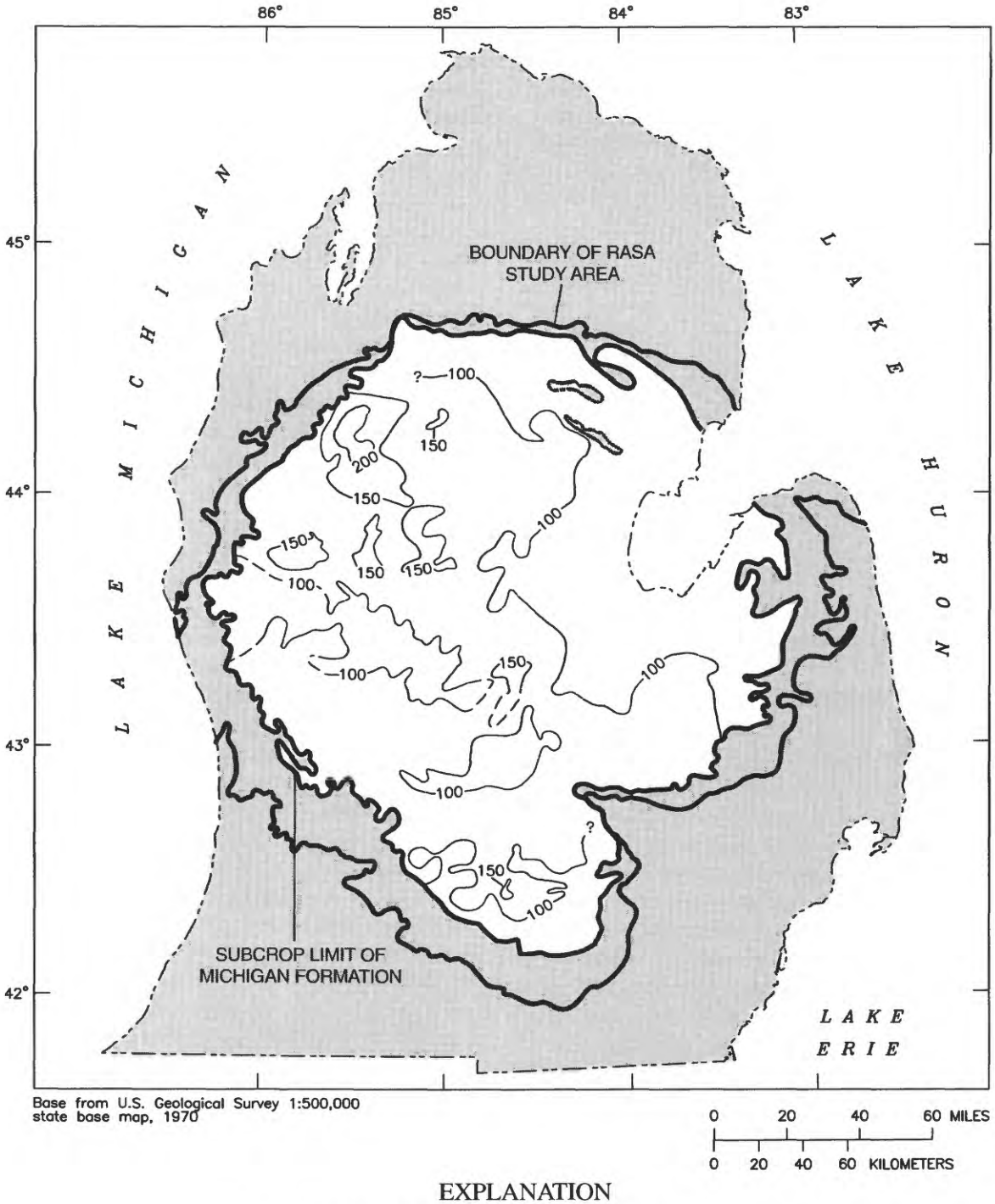


FIGURE 21.—Thickness of Marshall aquifer in the central Lower Peninsula of Michigan.

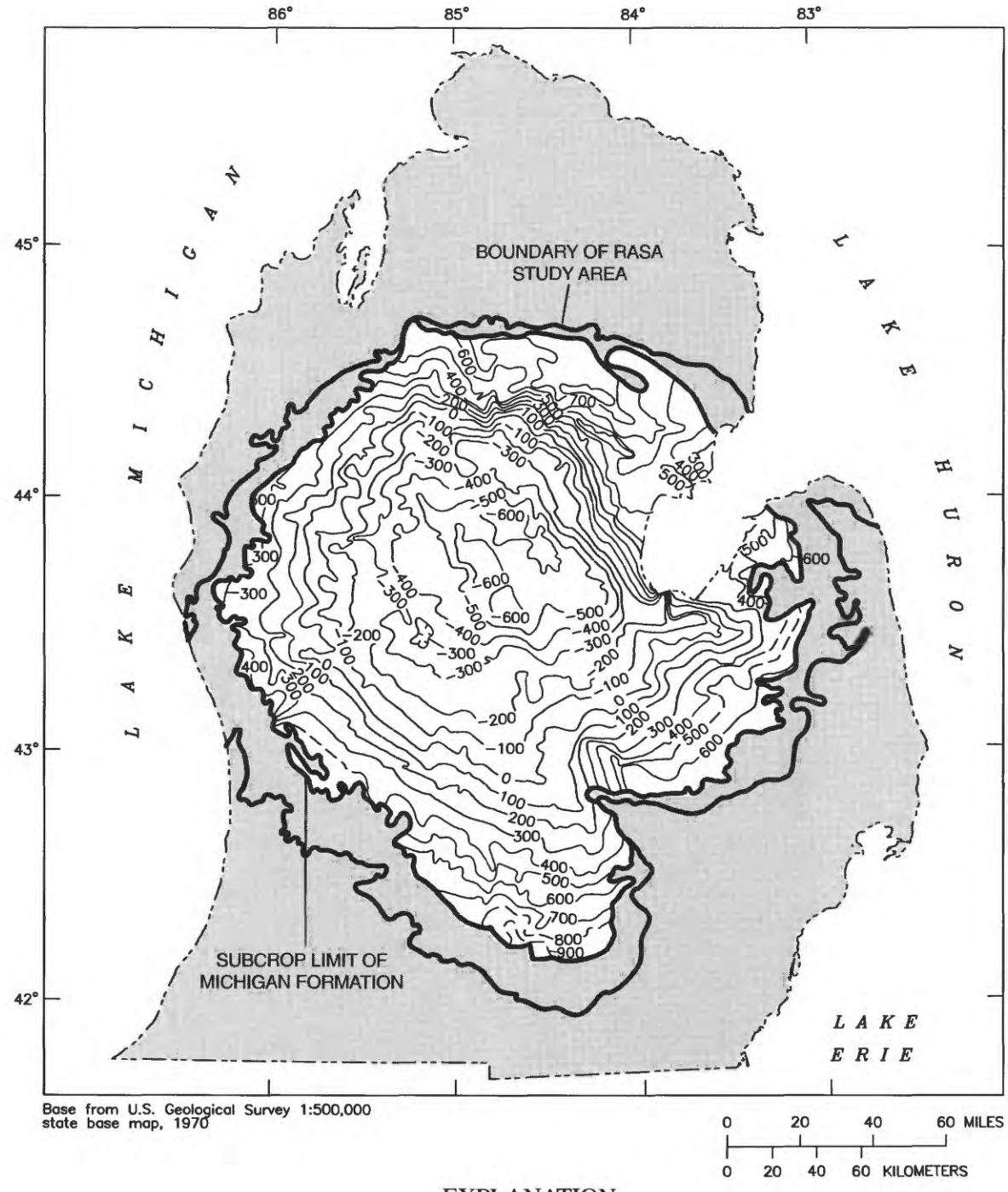


FIGURE 22.—Surface configuration of Marshall aquifer in the central Lower Peninsula of Michigan.

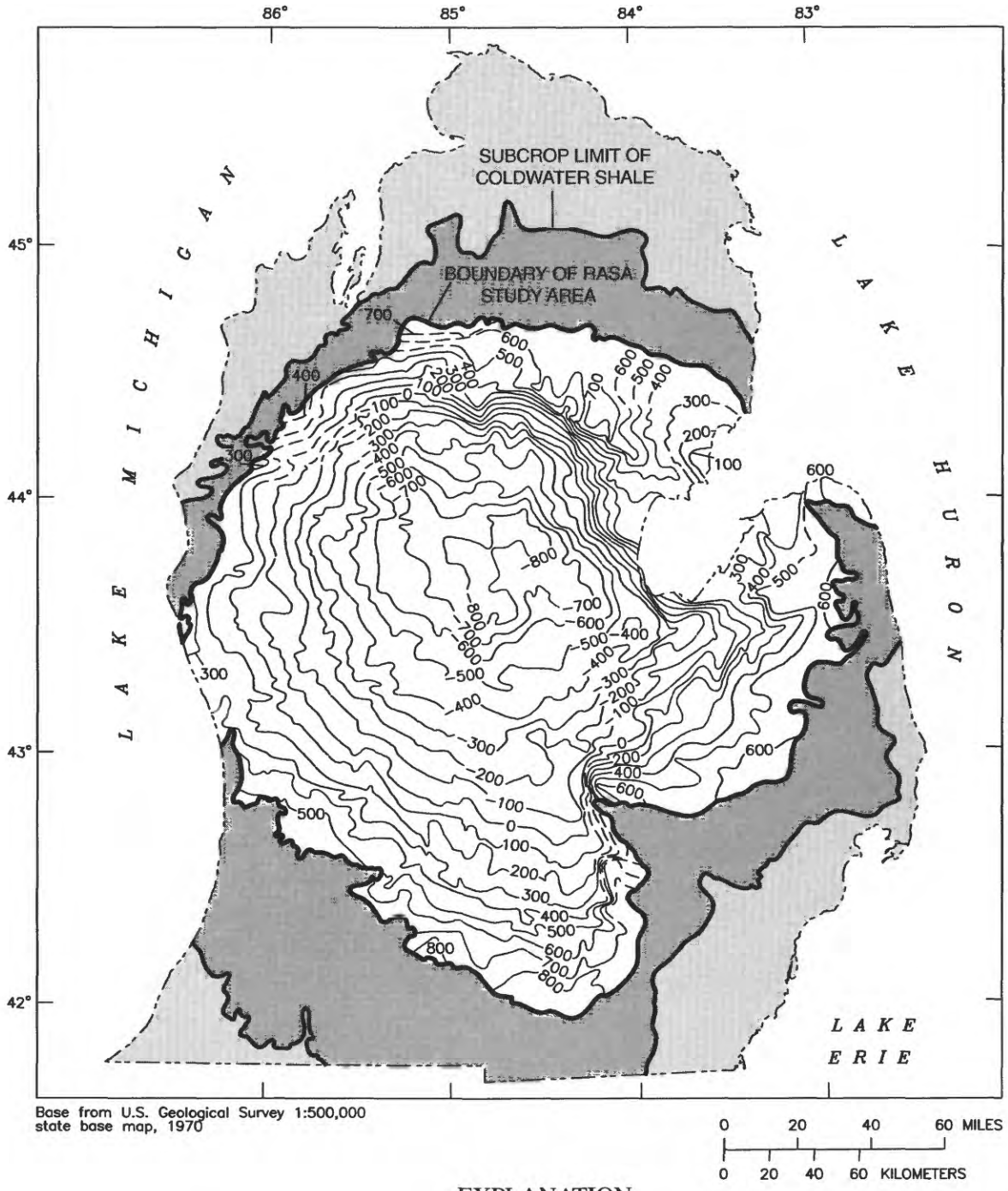


FIGURE 23.—Surface configuration of Coldwater confining unit in the central Lower Peninsula of Michigan.

800 ft), lowest in the west (300 ft), and intermediate in the east (600 ft).

HYDRAULIC PROPERTIES

No hydraulic-property data are available for the Coldwater confining unit. Laboratory determinations of porosity and hydraulic conductivity have been made of cores of the basal part of the Marshall sedimentary sequence. Vertical and horizontal hydraulic conductivities of these rocks are generally two to three orders of magnitude less than those of overlying permeable sandstones (either lower Marshall sandstone or upper Marshall sandstone). Shales that form the bulk of the Coldwater confining unit probably have lower hydraulic conductivities than the micaceous sandstones/siltstones at the base of the Marshall aquifer; typically hydraulic conductivities of these are less than 10^{-7} cm/s (unpublished data, USGS, Lansing, Mich.).

BASE OF FRESHWATER

Freshwater, as defined in this report, is water containing less than 1,000 mg/L dissolved solids. Ground water is considered to be saline if its dissolved solids concentration is in the range of 1,000 mg/L to 100,000 mg/L. Saline-ground water underlies 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. In the northwestern part, few wells penetrate bedrock because glacial deposits are a shallow source of freshwater. Consequently, water-quality data are scanty for bedrock aquifers in the northwestern part of the study area, and depth to the base of freshwater was uncertain before the USGS investigation that is described in this report. For the northwestern area, approximately 200 electrical-resistivity logs are available for hydrocarbon-exploration boreholes that were open to glacial deposits and bedrock units that form the aquifer system. These logs were used to map the base of freshwater. Figure 24 is a suite of example geophysical-log traces typical of freshwater- and saline-water-bearing units. Use of water-quality data and applications of geophysical logs are briefly described in the section that follows; details of log interpretation can be found in Westjohn (1989, 1994b).

COMPILATION AND ANALYSIS OF WATER-QUALITY DATA

Water-quality data were compiled from several sources (Michigan Department of Public Health; USGS files, Western Michigan University, 1981; Michigan Geological Survey) to delineate the approximate altitude of the base of freshwater in the southern and eastern parts of the aquifer system (Westjohn and Weaver, 1996c). The altitude of the base of freshwater was estimated on the basis of a 1,000 mg/L maximum dissolved-solids concentration of freshwater.

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

1. Water wells completed in Pennsylvanian rocks are commonly open to multiple sandstone beds, which are intercalated with confining beds (mostly shale). Water sampled from these wells is a composite mixture of water contributed by different producing zones. Typically, sandstone beds at or near the bedrock/glacial-deposits contact contain freshwater, but sandstone beds successively deeper in the Pennsylvanian rock sequence contain progressively higher concentrations of dissolved solids. Consequently, a well completed below the base of freshwater that is open to both freshwater- and saline-water-bearing sandstones may produce ground water with dissolved-solids concentrations less than 1,000 mg/L.
2. The concentration of dissolved solids 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). The water-quality data used to interpret the altitude of the base of freshwater are for 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. Aquifers that underlie saline-water-bearing units can contain freshwater. 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). Freshwater lenses below saline-water-bearing aquifers are uncommon and highly local. Nevertheless, the base of freshwater may be different than interpreted by RASA investigators in areas where freshwater lenses underlie saline-water-bearing aquifers (water-quality data or geophysical logs are not available to delineate freshwater lenses below saline water in such areas).

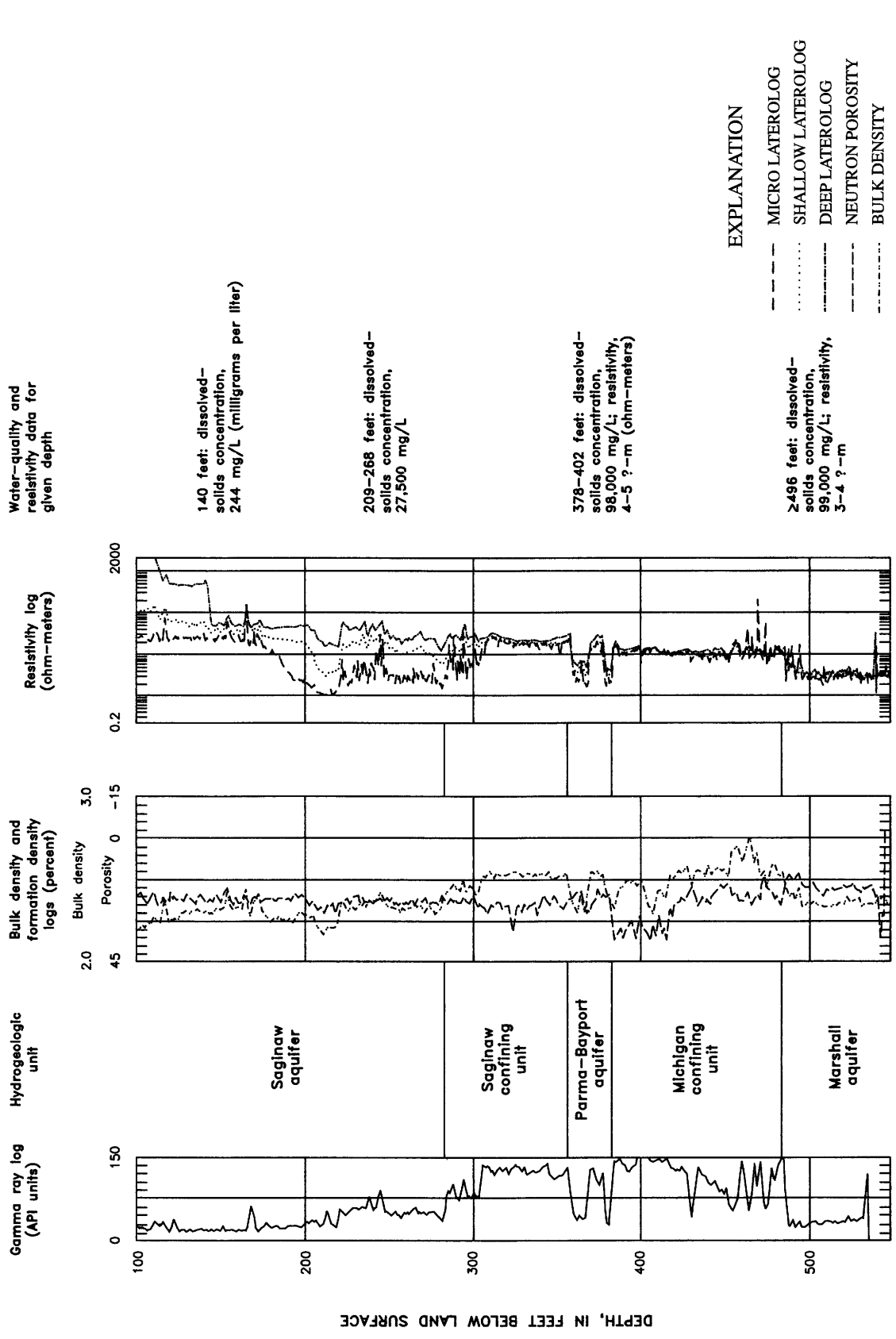


FIGURE 24.—Suite of geophysical logs and water-quality data showing typical traces of selected units of Pennsylvanian and Mississippian age, central Lower Peninsula of Michigan.

COLLECTION AND ANALYSIS OF GEOPHYSICAL LOGS

Electrical-resistivity logs were used to delineate the altitude of the base of freshwater in some parts of the Michigan Basin (Westjohn, 1989, 1994b). 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 in the aquifer system were established by examination of more than 600 electric logs (combination of spontaneous potential/electrical resistivity). Electric logs record spontaneous-potential data for lithologic determinations, as well as short-normal, long-normal, and commonly lateral log resistivities for estimating formation-fluid salinity. Resistivity properties of freshwater-bearing strata were interpreted from resistivity-log traces of glacial sand and gravel. Such glaciofluvial deposits are assumed to contain freshwater, and their electrical resistivity consistently exceeded 100 ohm-m. Sandstones having electrical-resistivity characteristics similar to those of glaciofluvial deposits are likewise assumed 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 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). Figure 24 is a suite of logs that illustrate the range of resistivities and other geophysical properties of aquifers that contain freshwater, saline water, or brine.

The principal source of error in the use of electrical-resistivity logs to delineate altitude of the base of freshwater is their age: the logs are of boreholes drilled during 1942–56. Electrical resistivity data used to interpret altitude of base of freshwater are for conditions at the time the borehole was logged. The current depth of the base of freshwater could be different at any of the logged sites.

GEOLOGIC CONTROLS OF DISTRIBUTION OF FRESHWATER

Configuration of the base of freshwater is shown in figure 25. The map is based primarily on water-quality data (612 data points), supplemented with electric-log data (198 data points). (See Westjohn and Weaver, 1996c, appendices C and E, for locations of sampling points and borehole geophysical logs.) The configuration of the base of freshwater as shown is an approximation. Overall, the map depicts only a very generalized trend of the base of freshwater.

Relief on the base of freshwater is about 600 ft (fig. 25). Altitudes of the base of freshwater are low (200 to 400 ft) along a 30 to 45 mi-wide north-south-trending corridor that extends about 100 mi from Gladwin County to Ingham County (figs. 3, 25). In several isolated areas in the northern, central, and western parts of the aquifer system, the altitude of the base of freshwater is less than 400 ft, but the 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, respectively (fig. 25).

The configuration of the contours showing the base of freshwater is primarily a function of geologic controls. These geologic controls of the distribution of freshwater are described by hydrogeologic unit in the section that follows.

GLACIAL DEPOSITS

Glacial deposits contain freshwater in most areas of the aquifer system. However, glacial deposits within a 1,600-mi^2 area of the Saginaw Lowlands (fig. 3) 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 that the Saginaw Lowlands is a subregional discharge area for Pennsylvanian-Mississippian rocks (Mandle and Westjohn, 1989). The Michigan Lowlands (fig. 3) also seems 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) compiled maps of surficial deposits of the Saginaw Lowlands, which show most surficial materials to be glacial lacustrine sediments. These deposits are thought to have been deposited in Glacial Lake Saginaw; this lake occupied the lowland area during a period from about 12,000 to 13,000 years ago (Flint, 1957, p. 347).

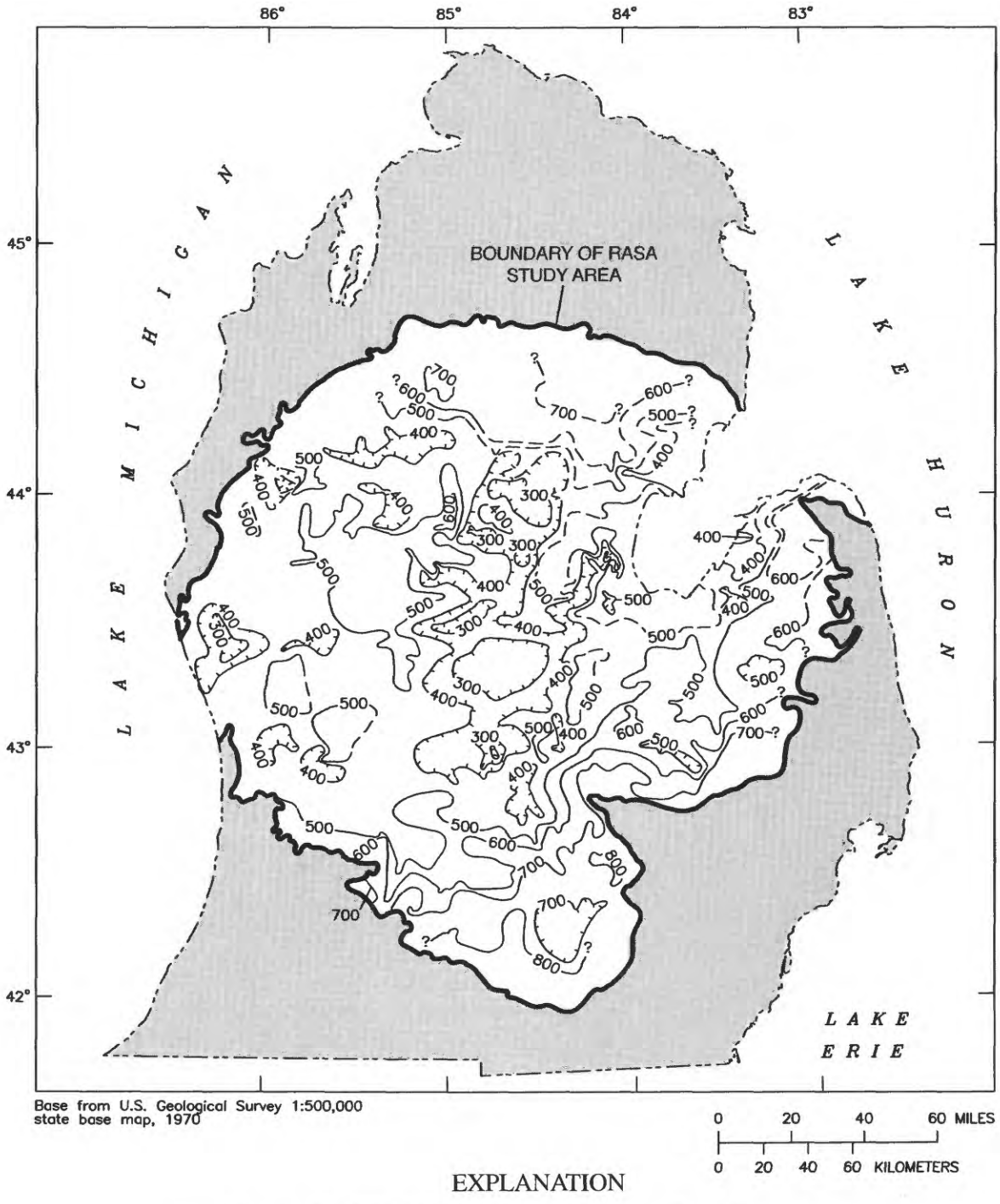


FIGURE 25.—Altitude of base of freshwater in the central Lower Peninsula of Michigan.

Analysis of data collected as part of the Michigan Basin RASA project supports an alternative interpretation regarding age and origin of these glacial deposits. Nine boreholes were drilled to or near bedrock along a 36-mi-long transect from eastern Gratiot County to central Bay County (fig. 3) and in other areas of the Saginaw Lowlands. Split-spoon core samples of clay-dominant material were collected at 5- to 10-ft intervals (Westjohn and Weaver, 1996c). By examining samples collected from these boreholes, RASA investigators concluded 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 probably lodgment 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 could be substantially older than previously interpreted.

That glacial deposits of the Saginaw Lowlands contain saline water at altitudes as much as 70 ft above bedrock (unpublished data, USGS, Lansing, Mich.) is also 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, USGS, unpub. data, 1993). If this clay-dominant lodgment till were older than formerly thought, then the hypothesis of upward migration of saline water into these low-permeability deposits, at distances as much as 70 ft above bedrock, would be more plausible given more time for fluid migration. In addition, the differential in hydraulic head between glacial deposits and the underlying Saginaw aquifer might have been much larger before development of ground-water resources, than it is currently (1995). Under that condition, substantial vertical migration of saline water into lodgment tills, which have very low vertical hydraulic conductivities, would be possible.

SAGINAW AQUIFER

The Saginaw aquifer contains freshwater in the northern (about 2,000 mi^2) and the southern parts (about 3,000 mi^2) of the aquifer system (fig. 26). 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 poorly permeable lodgment 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. In this area, "red beds" may impede discharge of saline water from underlying bedrock. Alternatively, the "red beds" may impede recharge of freshwater to Pennsylvanian rocks from overlying glacial deposits.

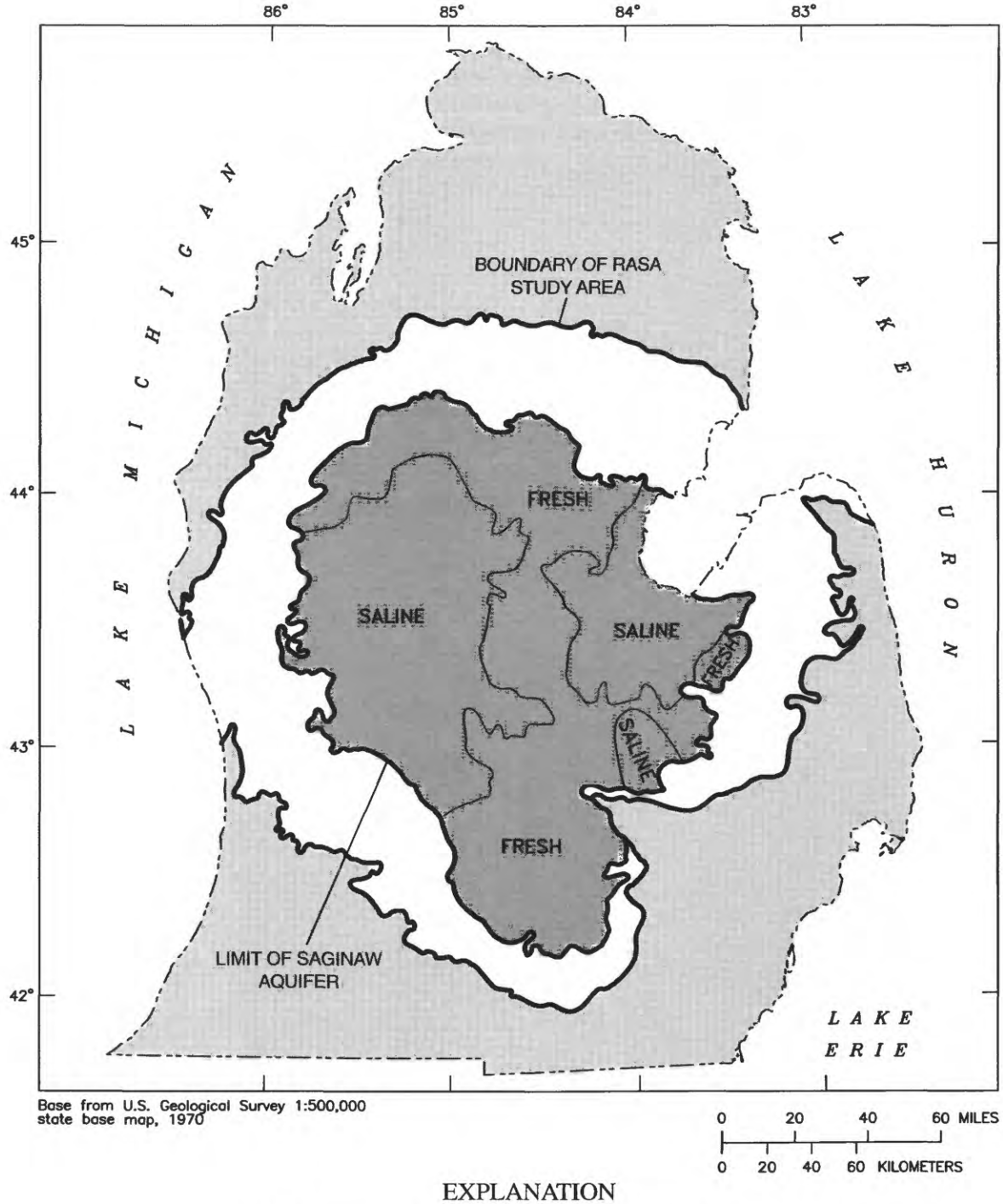
Distribution of freshwater and saline water in the Saginaw aquifer may also be controlled by the relative proportion of aquifer and confining-unit material. The proportion of aquifer material is large in most of the northern and southern areas, as well as along the north-south-trending corridor between them (fig. 14), where thickness of the Saginaw aquifer ranges from 100 ft to more than 300 ft. In most of the eastern and western parts of the mapped area, composite thickness of sandstones in the Saginaw aquifer is less than 100 ft. The aquifer is typically saline-water bearing and is isolated from freshwater-bearing glacial deposits by lodgment till in the east and by "red beds" in the west.

PARMA-BAYPORT AQUIFER

The distribution of freshwater, saline water, and brine in the Parma-Bayport aquifer was 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, table 7h, pl. 24). Few water-quality data and geophysical logs are available in the southern part of the aquifer, and no attempt was made to interpret geologic controls on the base of freshwater in this area.

The Parma-Bayport aquifer contains freshwater in the northern part of the study area, where the aquifer is a subcrop beneath Pleistocene glacial deposits (fig. 27). 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 in the 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 as wide as 30 mi in the northeast. 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 boundary separating saline water and brine range from 200 to 400 ft (fig. 27). 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. The interpretation that brine is present in the aquifer is supported by water-quality data, which show that the Parma-Bayport aquifer contains ground water with dissolved-solids concentration that

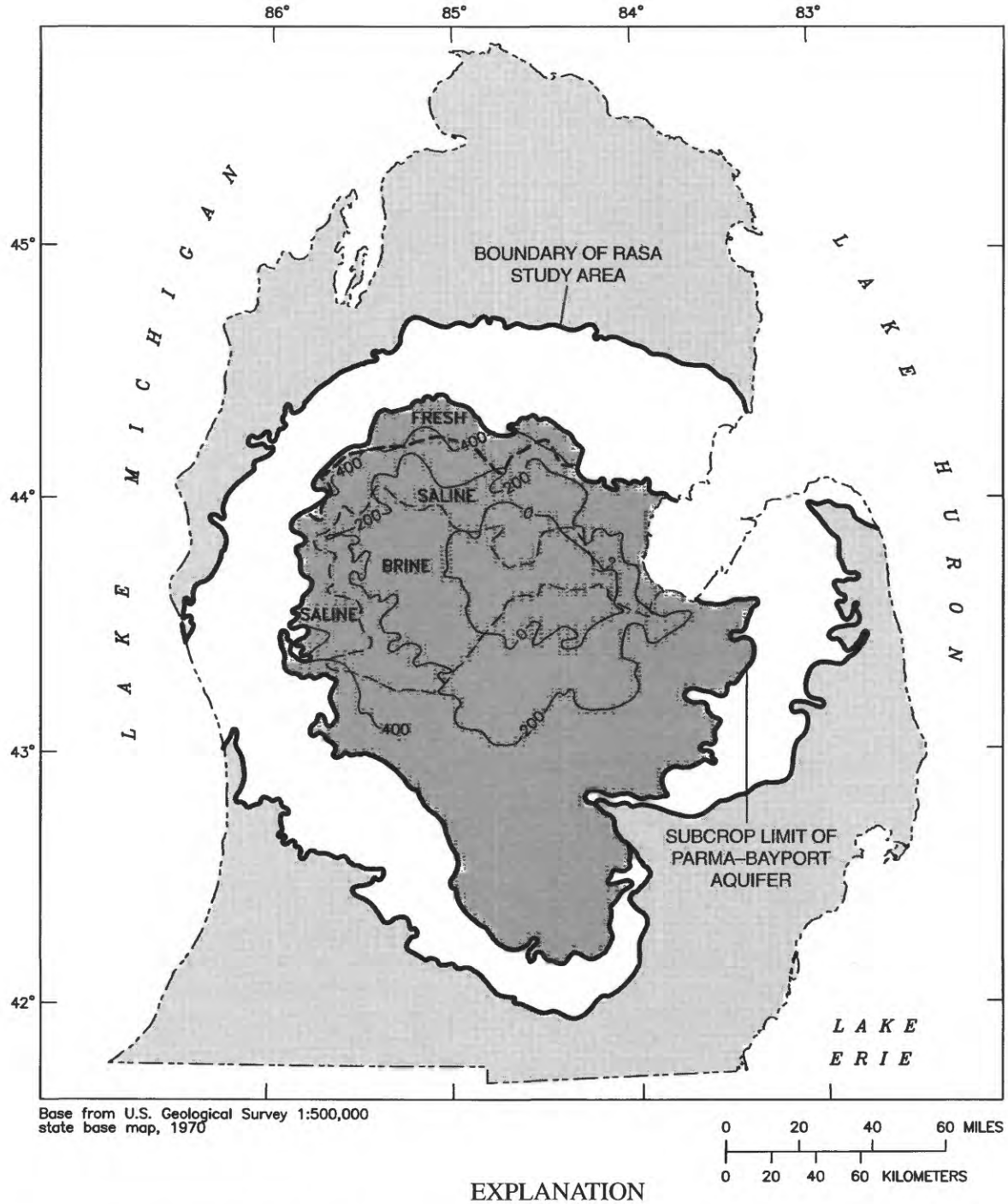


EXPLANATION

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

SALINE SALINE WATER—Greater than 1,000 and less than 10,000 mg/L dissolved solids

FIGURE 26.—Distribution of freshwater and saline water in the Saginaw aquifer, central Lower Peninsula of Michigan.



EXPLANATION

—200— BEDROCK CONTOUR—Shows altitude of top of Parma–Bayport aquifer in selected areas. Contour interval 200 feet. Datum is sea level

— — — FRESH WATER/SALINE WATER INTERFACE—Absent where data are insufficient

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

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

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

BRINE 100,000 mg/L or more dissolved solids

FIGURE 27.—Distribution of freshwater, saline water, and brine in the Parma-Bayport aquifer, central Lower Peninsula of Michigan.

exceeds 225,000 mg/L (Western Michigan University, 1981, table 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. 27). This feature is, at present, geologically inexplicable.

MARSHALL AQUIFER

Regional geologic control of the distribution of freshwater, saline water, and brine in the Marshall aquifer is 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 confining unit. The transition zone from freshwater to brine is as narrow as 2 mi in the northwest; elsewhere, width of the transition zone typically ranges from 15 to 50 mi (fig. 28).

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. 28). In the northern subcrop area of the Marshall aquifer, the altitude of the transition zone between freshwater and saline water ranges from 200 to more than 600 ft 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, although altitudes of the transition zone range from about -100 ft to sea level in the north-central and south-central parts of the study area (fig. 28).

As can be seen in geophysical logs, dissolved-solids concentration of ground water increases with depth in the Marshall aquifer. Lithologic differences within the aquifer contribute to this condition. For example, vertical hydraulic conductivity is especially low in certain sandstone layers in the aquifer; low hydraulic conductivity of these layers seems to be related to the presence of abundant detrital micas or the presence of clay, silica, or carbonate cement that nearly or entirely occludes pore space (Westjohn, 1991a, 1991b; Westjohn and others, 1991; Westjohn and Weaver, 1996b; Zacharias and others, 1994). 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 impede vertical flow of ground water (Westjohn, 1991a). Authigenic carbonate, quartz, or clay minerals in sandstone aquifers 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.

Additional controls on the distribution of freshwater and saline water could be the presence of layers of shale, siltstone, and carbonate rocks that separate permeable sandstones of the Marshall aquifer. In the subcrop areas of the Marshall aquifer, electrical resistivities of sandstones at or near the glacial-deposits/bedrock interface are typically greater than 100 ohm-m, an indication of freshwater. In locations where shale or other low permeability rock underlies freshwater-bearing sandstone, electrical resistivities of sandstones underlying this confining-unit material are typically 10 to 50 ohm-m, an indication of the presence of saline water.

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

SUMMARY

Mississippian and younger geologic units form a regional system of aquifers and confining units in the central Lower Peninsula of Michigan. Boundaries of aquifer-system units were delineated on maps by use of geophysical and geologic logs, as part of characterization of the hydrogeologic framework. Maps showing thickness and surface configuration of aquifers and confining units were prepared to aid in the assessment of hydrogeologic and geochemical characteristics of the regional aquifer system, and to delineate boundaries of these units for use in computer simulation of groundwater flow. Water-quality data and electrical-resistivity logs were used to delineate the position of the base of freshwater, and to determine geologic controls on distribution of freshwater.

The uppermost aquifer of the system is composed of Pleistocene glaciofluvial deposits, the largest reservoir of freshwater in the mapped area. These deposits are as much as 900 ft thick in the northern part of the aquifer system, where they constitute the bulk of the glacial material. In most areas, glaciofluvial deposits are complexly intercalated with glacial till and fine-grained lacustrine confining beds. Glacial-lodgment till constitutes the bulk of glacial deposits within a 1,600-mi^2 area of the Saginaw Lowlands, where it typically contains saline water.

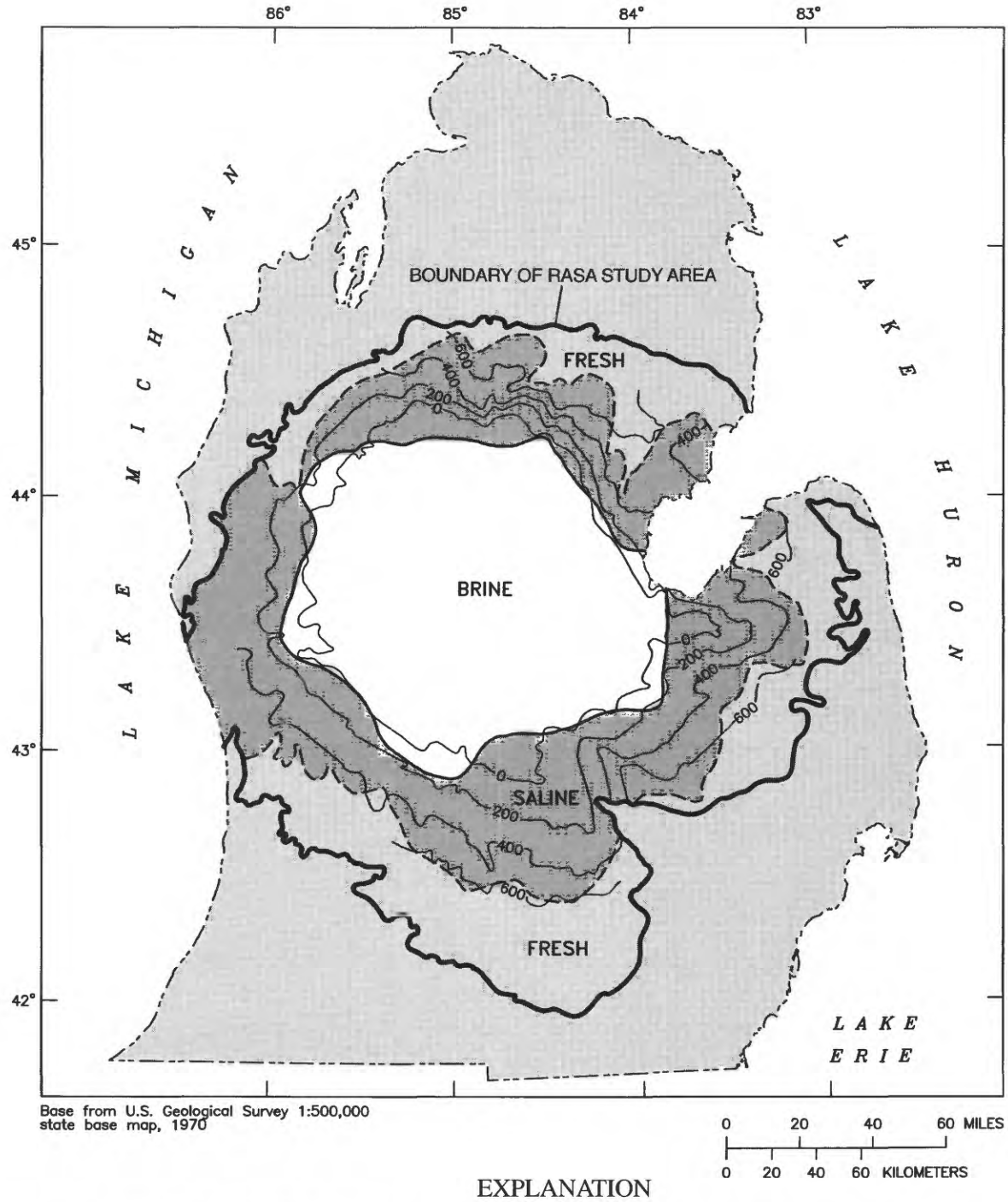


FIGURE 28.—Distribution of freshwater, saline water, and brine in the Marshall aquifer, central Lower Peninsula of Michigan.

The youngest bedrock unit of the aquifer system is the Jurassic "red beds" confining unit, which overlies Pennsylvanian rocks in a 4,000-mi^2 area in the west-central part of the Lower Peninsula of Michigan. Thickness of this confining unit typically ranges from 100 to 150 ft. "Red beds" contain saline water and probably impede recharge of freshwater from glacial deposits to underlying sandstone aquifers.

The Saginaw aquifer, the composite of Pennsylvanian sandstones, ranges in thickness from 100 to more than 300 ft along a 30- to 45-mi-wide south-trending corridor near the center of the aquifer system. This trend of thick sandstone approximately delineates the area where the Saginaw aquifer is freshwater bearing; all municipalities that use the aquifer for water supply are along this corridor. On either side of the south-trending corridor, the Saginaw aquifer is typically less than 100 ft thick, and it contains saline water.

The Saginaw confining unit, which consists mostly of shale, separates sandstones of the Saginaw aquifer from the underlying Parma-Bayport aquifer. The Saginaw confining unit is about 100 to 240 ft thick in the northwestern part of the aquifer system, but thickness is typically 50 ft or less in the eastern and southern parts of the mapped area.

The Parma-Bayport aquifer (Early Pennsylvanian/Late Mississippian) consists of permeable sandstones and carbonate rocks that are hydraulically connected and laterally continuous throughout the mapped area. Composite thickness of these permeable units typically ranges from 100 to 150 ft. The Parma-Bayport aquifer contains freshwater only in subcrop areas, where it is in direct hydraulic connection with glacial deposits. Down regional dip, dissolved-solids concentration of ground water in the aquifer increases. Width of the transition zone from freshwater to brine is typically 5 to 30 mi.

The Michigan confining unit consists mostly of interbedded shale, carbonate rocks, and evaporites; it separates the Parma-Bayport aquifer from the Marshall aquifer. Thickness of this confining unit is 300 to 400 ft in most areas.

The Marshall aquifer consists of one or more stratigraphically continuous and hydraulically connected sandstones of Mississippian age. The composite thickness of permeable sandstones that form the aquifer ranges from about 75 to 200 ft. The Marshall aquifer contains freshwater in subcrop areas where sandstones are in direct hydraulic connection with glacial deposits. Dissolved-solids concentration increases in the Marshall aquifer down regional dip, where it is confined by beds of the overlying Michigan confining unit. Width of the transition zone from freshwater to brine is typically 15 to 50 mi, but is only about 2 mi in width in some areas. The basal unit of the aquifer system is the Coldwater confining unit, which consists mostly of shale.

Relief on the base of freshwater is about 600 ft. Altitudes of the base are low (200 to 400 ft) along the 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 in most of the study area, altitude is greater than 400 ft. In the southern and northern parts of the aquifer, 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, respectively. Geologic controls on 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 lodgment tills, which have very low permeability; (3) impedance of recharge of freshwater to bedrock (or discharge of saline water from bedrock) by Jurassic "red beds" of very low permeability; and (4) the presence of units characterized by low vertical-hydraulic-conductivity, which are within and between sandstone units.

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