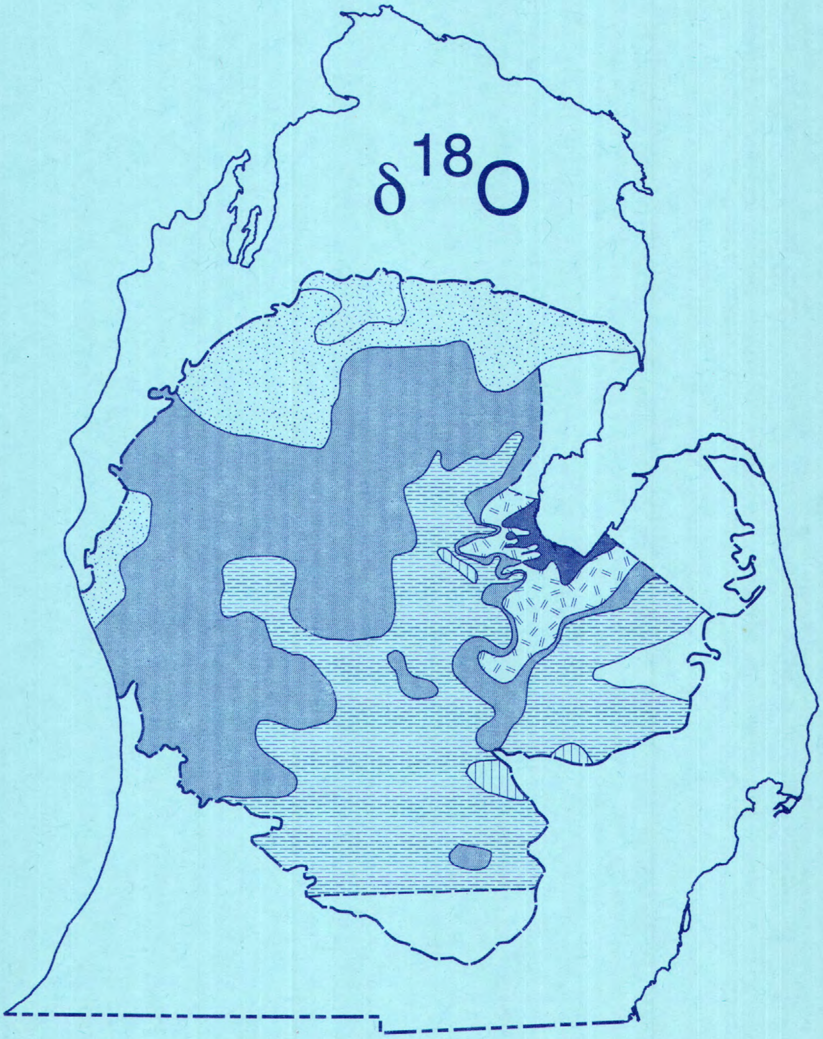
Selected Geochemical Characteristics of Ground Water from the Glaciofluvial Aquifer in the Central Lower Peninsula of Michigan



United States
Geological
Survey

Water-Resources
Investigations
Report 94-4017

Michigan Basin Regional
Aquifer-System Analysis

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By M.A. WAHRER, D.T. LONG, and R.W. LEE

U.S. GEOLOGICAL SURVEY
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Michigan Basin Regional Aquifer-System Analysis

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FIGURES

CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To obtain
foot (ft)	0.3048	meter
gallon (gal)	3.785	liter
mile (mi)	1.609	kilometer
pound (lb)	453.6	gram
square mile (mi^2)	2.590	square kilometer

Degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) by using the following equation:

$$^{o}C = (^{o}F - 32)/1.8.$$

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

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

Isotopic composition of water is expressed as permil (parts per thousand) differences in the measured isotopic ratios of the sample and SMOW (Standard Mean Ocean Water, the ^{18}O and ^{2}H isotopic standard). The unit $\delta^{18}0$ is the standard expression of the ratio of the ^{18}O ion with respect to the ^{16}O ion. The unit δD is the standard expression of the ratio of the ^{2}H ion (deuterium) with respect to the ^{1}H ion.

Other abbreviations:

RASA: Regional Aquifer-System Analysis.
WATSTORE: U.S. Geological Survey National WATer Data STOrage and REtrieval System.

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ABSTRACT

Chemical and stable-isotope data for water from wells completed in the Glaciofluvial aquifer in the central Lower Peninsula of Michigan were used to prepare maps that show the areal variation of $\delta^{18}O$; distribution of dissolved solids, dissolved chloride, dissolved iron, and dissolved sulfate; and distribution of hydrochemical facies. Delta oxygen-18 values indicate the presence of modern meteoric water ($\delta^{18}O$ approximately -10 parts per thousand) and glacial-age meteoric water, which is isotopically light ($\delta^{18}O$ less than -15 parts per thousand). Isotopically light ground water is present in the Saginaw Bay Area in the eastern part of the study area. Dissolved-solids concentrations are generally less than 1,000 milligrams per liter, and dissolved-chloride concentrations are generally less than 100 milligrams per liter. These concentrations are greatest in ground water from the Saginaw Bay Area where measured concentrations are as large as 12,000 milligrams per liter for dissolved solids and 6,700 milligrams per liter for dissolved chloride. Dissolved-iron concentrations range from 0.001 to 6.0 milligrams per liter. Dissolved-sulfate concentrations range from 1 to 1,800 milligrams per liter. Most ground water from the Glaciofluvial aquifer is classified as a calcium bicarbonate type. In the Saginaw Bay Area, ground water is a sodium chloride type.

INTRODUCTION

The geochemistry, geology, and hydrology of aquifers in the central part of Michigan's Lower Peninsula are being studied as a part of the U.S. Geological Survey's Regional Aquifer-System Analysis (RASA) program in Michigan (Mandle, 1986). The Michigan Basin RASA study area covers 22,000 mi^2 area of central lower Michigan and is bounded by the contact between the Coldwater Shale and the Marshall Sandstone (fig. 1).

This report contains descriptions of areal variations of selected geochemical characteristics of ground water from aquifers in deposits of Pleistocene age in the central Lower Peninsula. The report includes maps showing the areal variation of $\delta^{18}O$; distribution of dissolved solids, dissolved chloride, dissolved iron, and dissolved sulfate; and distribution of hydrochemical facies of ground water from the Glaciofluvial aquifer (fig. 2). In addition to chemical and isotopic data collected for the Michigan Basin RASA study (Dannemiller and Baltusis, 1990), chemical and isotopic data were obtained from Long and others (1986), the U.S. Geological Survey Water Data Storage and Retrieval System (WATSTORE) data base, Wood (1969), the Michigan Department of Natural Resources (written commmun., 1987), and the Michigan Department of Public Health (Mark Breithart, written commun., 1992).

Chemical data used for maps in this report were derived from water samples obtained from wells completed at different depths in the

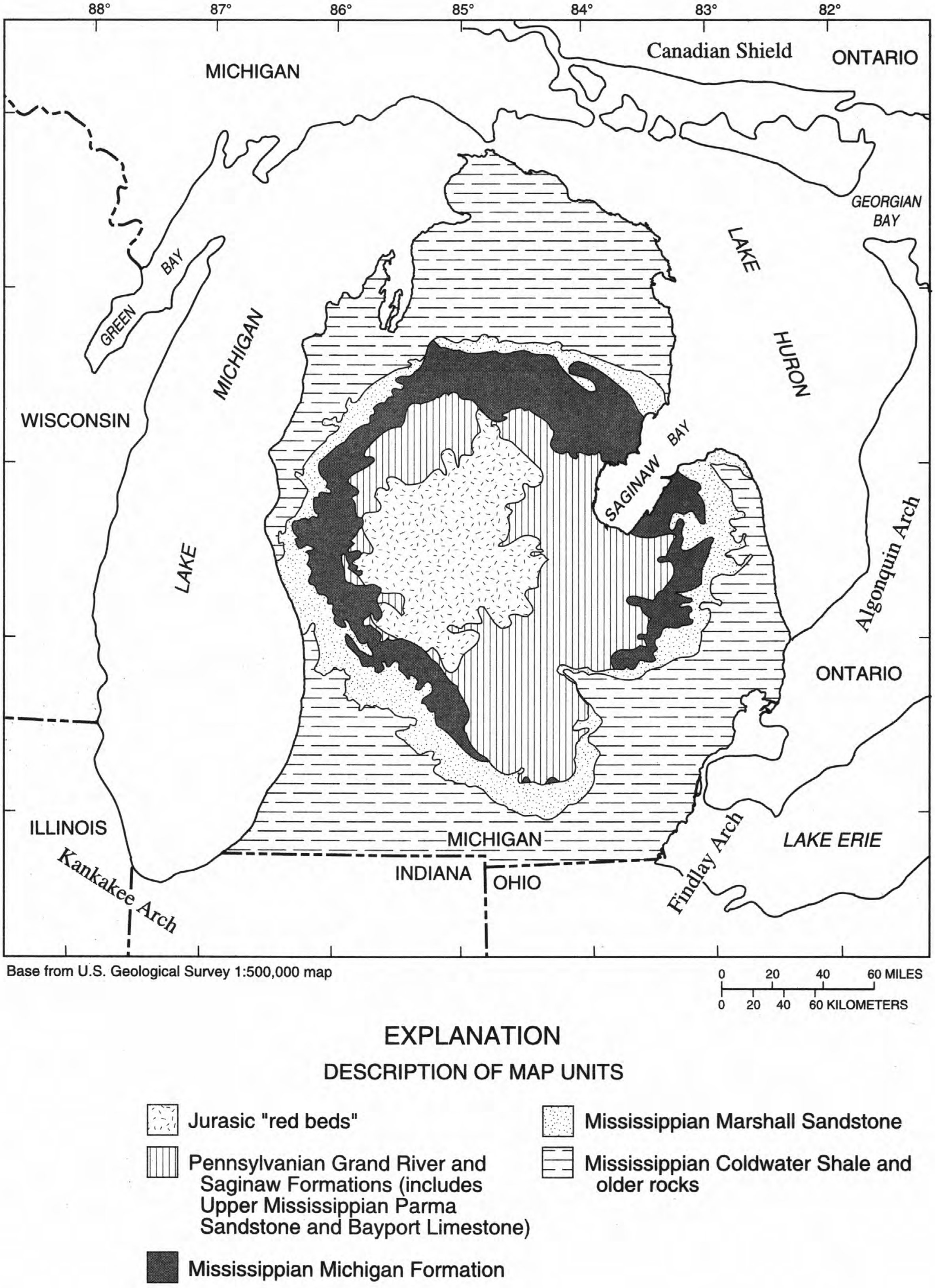


Figure 1. Bedrock geology of the Lower Peninsula of Michigan (modified from Martin, 1955, fig. 11).

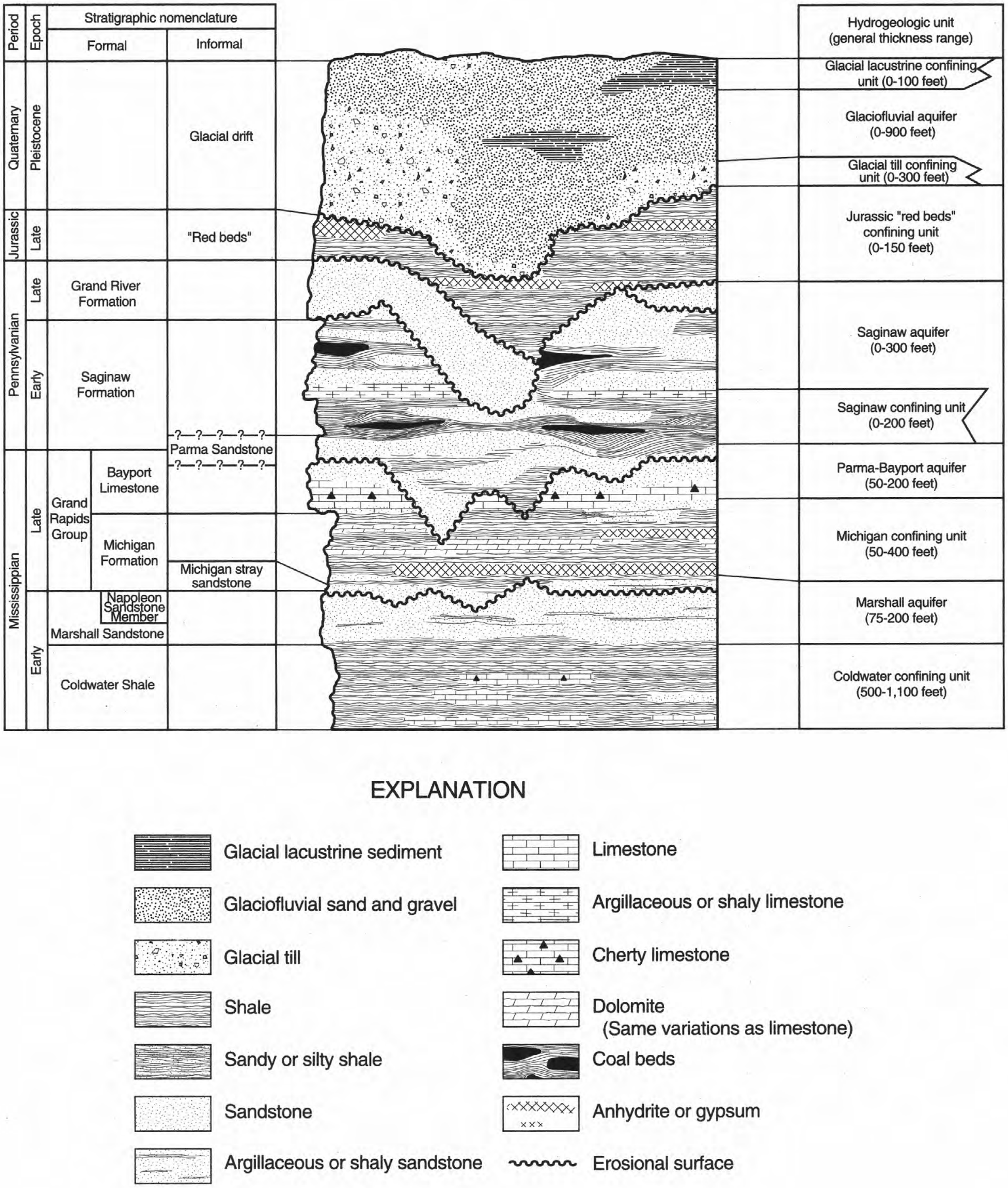


Figure 2. Relation between stratigraphic and hydrogeologic units in the study area (modified from Westjohn and others, 1994).

Glaciofluvial aquifer; therefore, the maps represent only general areal trends of dissolved constituents, stable isotopes, and hydrochemical facies.

The authors thank the Michigan Department of Public Health, especially Mark Breithart, for providing chemical data. The Michigan Department of Natural Resources provided access to well logs and chemical data on Michigan Basin brines.

GEOHYDROLOGIC FRAMEWORK

The ovate Michigan Basin consists of an extensive accumulation of sedimentary rocks in the Lower Peninsula of Michigan and parts of Michigan's Upper Peninsula, Wisconsin, Illinois, Indiana, Ohio, and Ontario, Canada (fig. 1). It is bounded by the Canadian Shield on the north, the Wisconsin Dome and Wisconsin Arch on the northwest and west, the Kankakee arch on the southwest, and the Algonquin and Findlay Arches on the east and southeast (Mandle, 1986; Cohee, 1965).

The maximum thickness of Precambrian through Jurassic deposits exceeds 17,500 ft, and these sedimentary rocks overlie Precambrian crystalline rocks throughout the study area (Lillienthal, 1978). Paleozoic through Jurassic rocks are mantled by glacial deposits that are the result of the recent Wisconsinan and possibly earlier glaciations. According to Broecker and Farrand (1963), ice from the last glaciation receded from Michigan approximately 10,000 years ago. Stratigraphic and hydrogeologic relations of aquifers and confining units in the basin are shown in figure 2. The Glaciofluvial aquifer overlies the Saginaw, Parma-Bayport, and the Marshall bedrock aquifers in the study area (fig. 2).

Glacial deposits cover bedrock in most of the study area (fig. 3). Thickness ranges from 10 to 200 ft in the southern part of the study area and from 600 to 1,000 ft in the northern part (Western Michigan University, 1981, pl. 15). In the central part of the study area, glacial deposits generally range from 200 to 400 ft in thickness. The glacial deposits include lacustrine silt and clay, till, and glaciofluvial deposits (Westjohn and others, 1994). In the northern and northwestern parts of the study area, coarse-grained glacial deposits predominate, forming productive aquifers. Where fine-grained deposits predominate, such as the Saginaw Bay Area, glacial deposits form confining units. In this report, the Saginaw Bay Area refers to the area east of the outermost moraine of the Port Huron Morainal System (Farrand and Bell, 1984), within the Saginaw Lowland Area (fig. 3).

A surficial map of the Pleistocene glacial deposits of Michigan was published by Martin (1955). Farrand and Bell (1984) mapped and differentiated surficial glacial deposits. Currently, a large-scale map that differentiates the subsurface drift lithologies has not been produced. However, from available data, regional stratigraphic trends of glacial deposits cannot be recognized. The absence of trends probably reflects the heterogeneity and complex depositional history of the glacial deposits. Although the glacial deposits form a heterogeneous aquifer, they are considered a single aquifer unit called the Glaciofluvial aquifer for the purpose of this study (Westjohn and others, 1994).

On a regional scale, the water table generally follows the topography of the Lower Peninsula (Mandle and Westjohn, 1989). A water-table map of the Lower Peninsula shows two areas of relatively high water-table altitude in which separate subregional flow systems are assumed; these are the Northern and Southern Upland Areas (Mandle and Westjohn, 1989). General ground-water flow directions (fig. 4) in the Glaciofluvial aquifer are from upland areas downgradient toward lowland areas (Mandle and Westjohn, 1989). Most ground water in the aquifer discharges to streams along local flow paths. In the rest of the upland area, recharge infiltrates into the Glaciofluvial aquifer, and ground water moves along intermediate and regional flow paths toward discharge areas such as the Saginaw Bay Area or Michigan Lowlands Area (fig. 3). A small amount of ground water discharges from the Glaciofluvial aquifer directly to the lakes.

SELECTED GEOCHEMICAL CHARACTERISTICS

Maps that illustrate the general distribution of selected dissolved-chemical constituents, stable-isotope values, and hydrochemical facies were

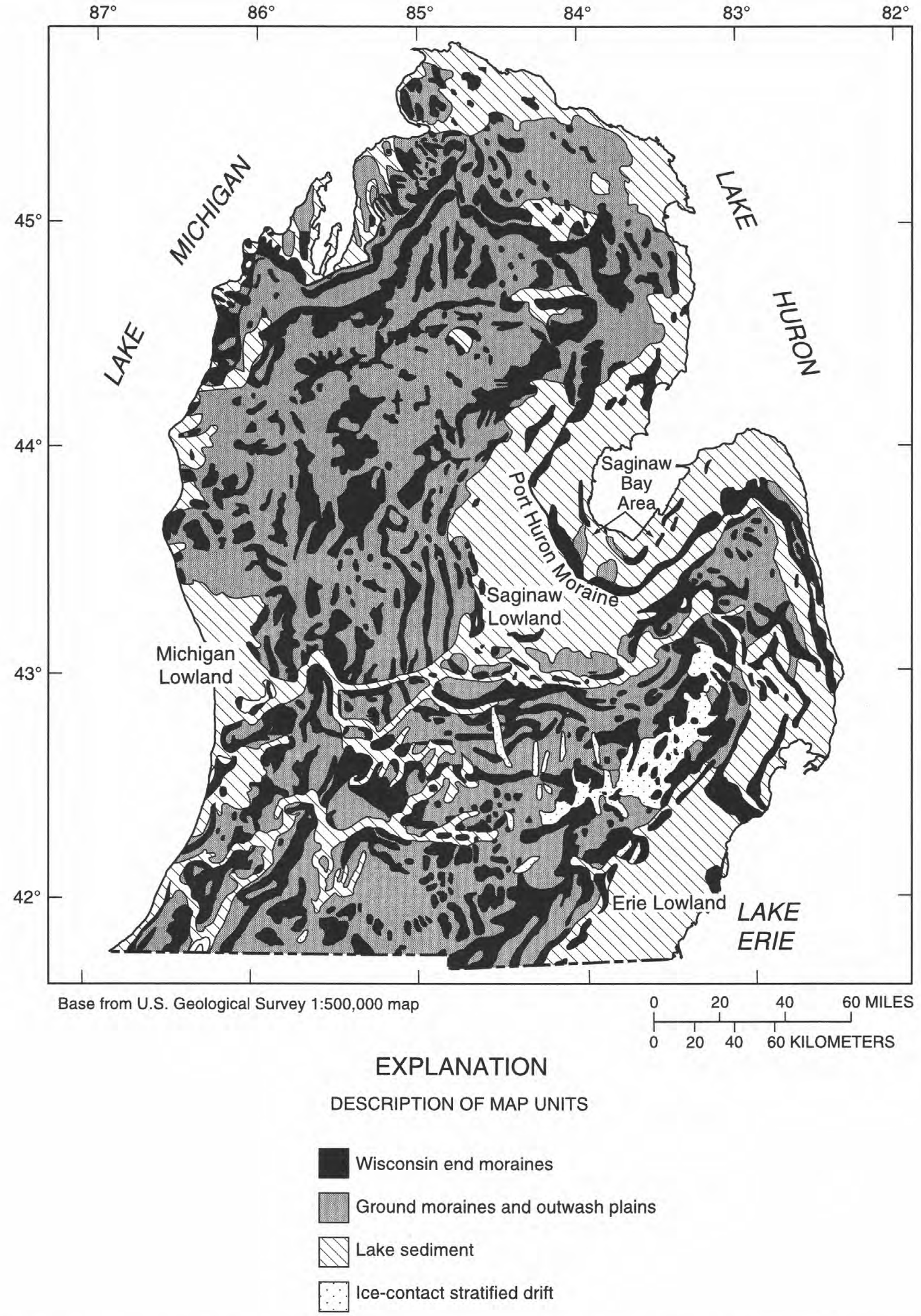
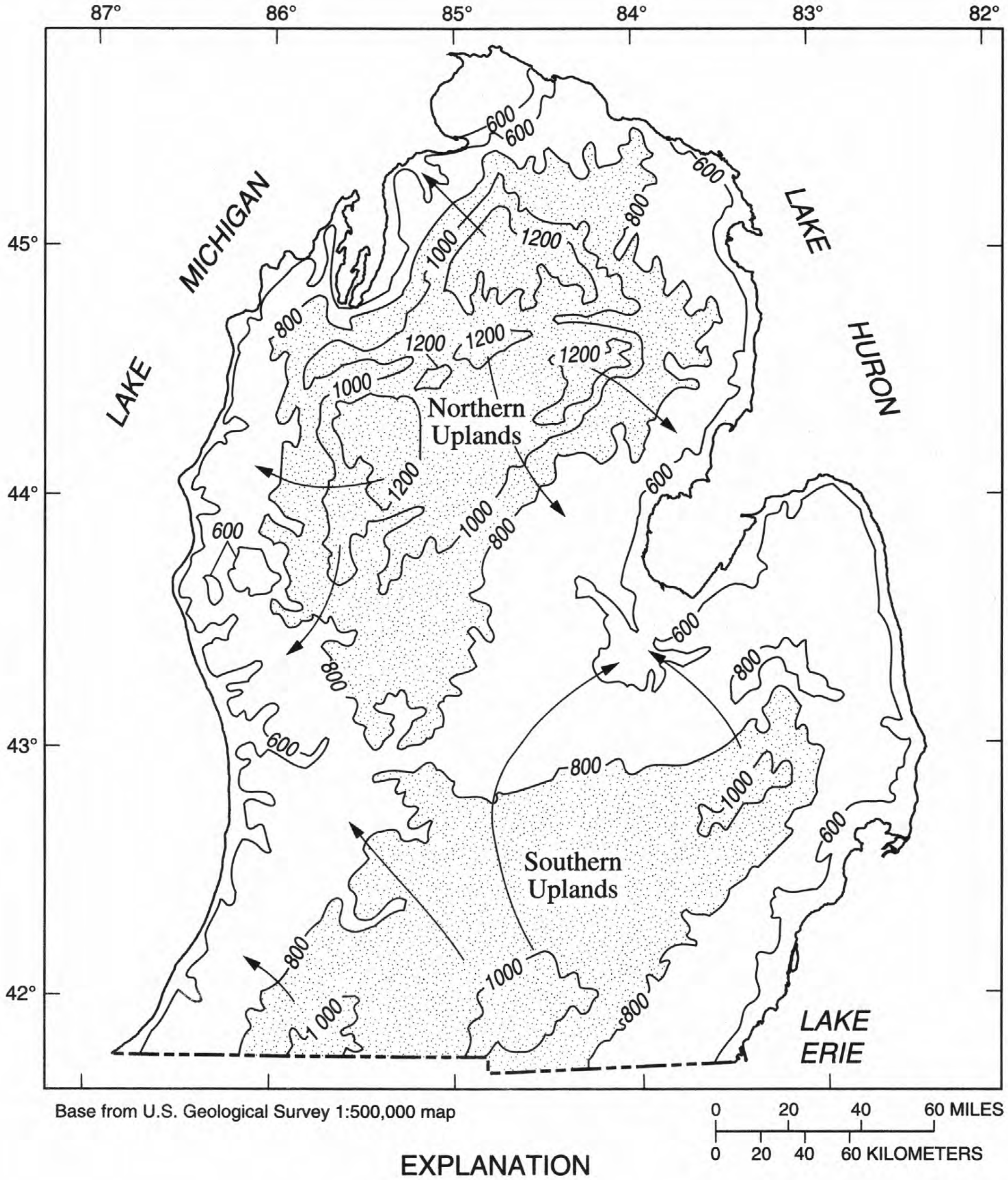


Figure 3. Surficial geology of the Lower Peninsula of Michigan and locations of the Michigan and Saginaw Lowlands and the Saginaw Bay Area (modified from Geological Society of America, 1959).



Base from U.S. Geological Survey 1:500,000 map

EXPLANATION

▨ AREA WHERE WATER-TABLE ALTITUDE IS GREATER THAN 800 FEET ABOVE SEA LEVEL

—600— WATER-TABLE CONTOUR--Shows generalized altitude of water table. Contour interval 200 feet. Datum is sea level

◄—— GROUND-WATER FLOW--Arrow indicates general direction of flow

Figure 4. General ground-water flow directions in the Glaciofluvial aquifer, Lower Peninsula of Michigan (modified from Mandle and Westjohn, 1989).

prepared for the Glaciofluvial aquifer. The maps include areal variation of $\delta^{18}O$ and distribution of dissolved solids, dissolved chloride, dissolved iron, dissolved sulfate, and hydrochemical facies.

Stable Isotopes of Oxygen and Hydrogen

The isotope composition of oxygen and hydrogen in water is reported in terms of the difference of the $^{18}O/^{16}O$ and $D/^{1}H$ ratios relative to Standard Mean Ocean Water (SMOW). The isotope ratios are reported as $\delta^{18}O$ and δD, where δ is expressed as a permil (parts per thousand) deviation from that of the standard SMOW by use of the formula

$$\delta = \frac{[R_x - R_{std}]}{R_{std}} \times 1000 , \qquad (1)$$

where R_x is the isotopic ratio in the sample, and R_{std} is the isotopic ratio in the standard (Faure, 1986). Because the differences between the standard and the sample are commonly small, the ratio is multiplied by 1,000 as indicated. Water with a negative δ value is enriched in the lighter isotope (^{16}O or ^{1}H) compared to SMOW, and water with a positive δ value is enriched in the heavier isotope (^{18}O or D) compared to SMOW. Different $\delta^{18}O$ compositions can be used to identify ground-water masses, to indicate mixing of ground-water masses, and to determine indirectly relative ages of water masses (Long and others, 1986).

The relation of δD and $\delta^{18}O$ in 194 ground-water samples collected from the Glaciofluvial aquifer is shown in figure 5. These data are compared to the global meteoric water line of Craig (1961) and the Simcoe line, a local meteoric water line developed for Simcoe, Ontario, Canada (Desauliniers and others, 1981). Data for the Simcoe line were collected from precipitation sampled approximately 120 mi east of the study area. The $\delta^{18}O$ and δD values for most ground-water samples from the Glaciofluvial aquifer range from -12.4 to -8.3 permil and from -83.5 to -56.0 permil, respectively. The plot indicates that water in the Glaciofluvial aquifer is of meteoric origin because the trends in the data coincide with trends of the Simcoe and global meteoric water lines. The $\delta^{18}O$ values ranging from -12 to -8 permil in water from the Glaciofluvial aquifer are consistent with modern precipitation for the Lower Peninsula of Michigan (Sheppard and others, 1969; Grahame Larson, Michigan State University, oral commun., 1992). Therefore, these values are interpreted to indicate modern meteoric water.

Isotopically light values (less than -12.0 permil), however, are lighter than expected for modern recharge. The most isotopically light values (less than -15.0 permil) are anomalous and indicate that ground water recharged the aquifer when the climate was cooler than present, such as for example, during glaciation. This would indicate that ground-water recharge by glacial meltwater depleted in the ^{18}O isotope occurred during periods of glacial ice advances in Michigan as has been proposed for isotopically light water in other ground-water systems (Fritz and others, 1974; Desauliniers and others, 1981; Perry and others, 1982; Siegel and Mandle, 1984). The isotopic values of the glacial-age meteoric water are not known; however, for the purposes of this report, isotopic values of less than -15.0 permil are considered to be glacial-age water.

Two regional trends are present in the areal variation of $\delta^{18}O$ (fig. 6). The same general trends are observed for δD as for $\delta^{18}O$, and therefore, a map of δD is not included in this report. The first is a north-south gradient in which $\delta^{18}O$ values become lighter from the southern part of the study area northward. Values of $\delta^{18}O$ are heavier (less negative) in the south, ranging from -8.7 to -10.6 permil, and become lighter (more negative) in the north, ranging from -10.0 to -12.4 permil. Such a gradient in the isotopic signature of near-surface ground water might be expected because latitudinal climatic differences affect the isotopic signature of recharge water (Gat and Gonfiantini, 1981). For example, Sheppard and others (1969) contoured δD and $\delta^{18}O$ values in recent precipitation for North America and showed a south-to-north gradient for $\delta^{18}O$ values from -7.5 to -10 permil in the Lower Peninsula of Michigan.

The $\delta^{18}O$ values presented by Sheppard and others (1969) are slightly heavier than those of the north-south gradient found in water from the Glaciofluvial aquifer. This variation in $\delta^{18}O$ values can be explained by the fact that, in Michigan, precipitation and subsequent ground-water recharge is greater in the cool months of late fall and early spring (Vanlier, 1963). Precipitation

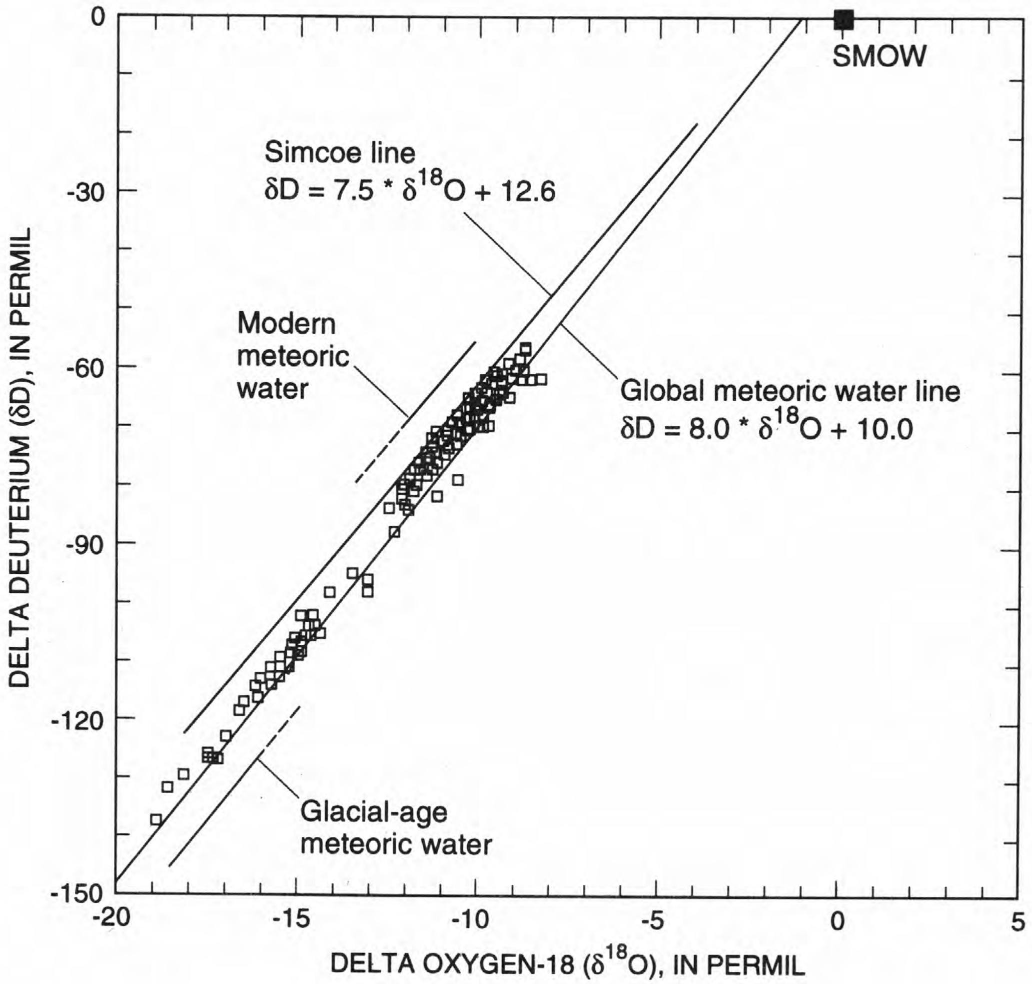


Figure 5. Relation between delta deuterium and delta oxygen-18 for ground water from the Glaciofluvial aquifer, Lower Peninsula of Michigan. The intersection of the zero points on the two axes represents Standard Mean Ocean Water (SMOW). See text for definition of modern meteoric and glacial-age meteoric water.

during cold temperatures has less ^{18}O and D than precipitation during warm temperatures (Gat, 1980) because isotopic fractionation increases with decreasing temperature (Faure, 1991). Thus, the regional isotopic variations of ground water in the Glaciofluvial aquifer are caused by latitudinal variations in recharge water and not by seasonal isotopic variability in recharge water. This supports the observations of others that the $\delta^{18}O$ values of ground water are typically an integration of the seasonally isotopic variability of the recharge water (Lloyd and Heathcote, 1985).

The second regional trend is the decrease of $\delta^{18}O$ from approximately -11.0 permil around the perimeter of the Saginaw Bay Area to -18.8 permil near Saginaw Bay. The latter value is among the lightest in the Michigan Basin. As discussed above, this isotopically light ground water indicates the presence of glacially derived recharge. A similar variation of $\delta^{18}O$ values, in part of the Saginaw Bay Area, is in water from Pennsylvanian bedrock aquifers beneath the drift (Meissner and others, 1996).

Distributions of data in figures 5 and 6 indicate that mixing of modern meteoric and glacial-age

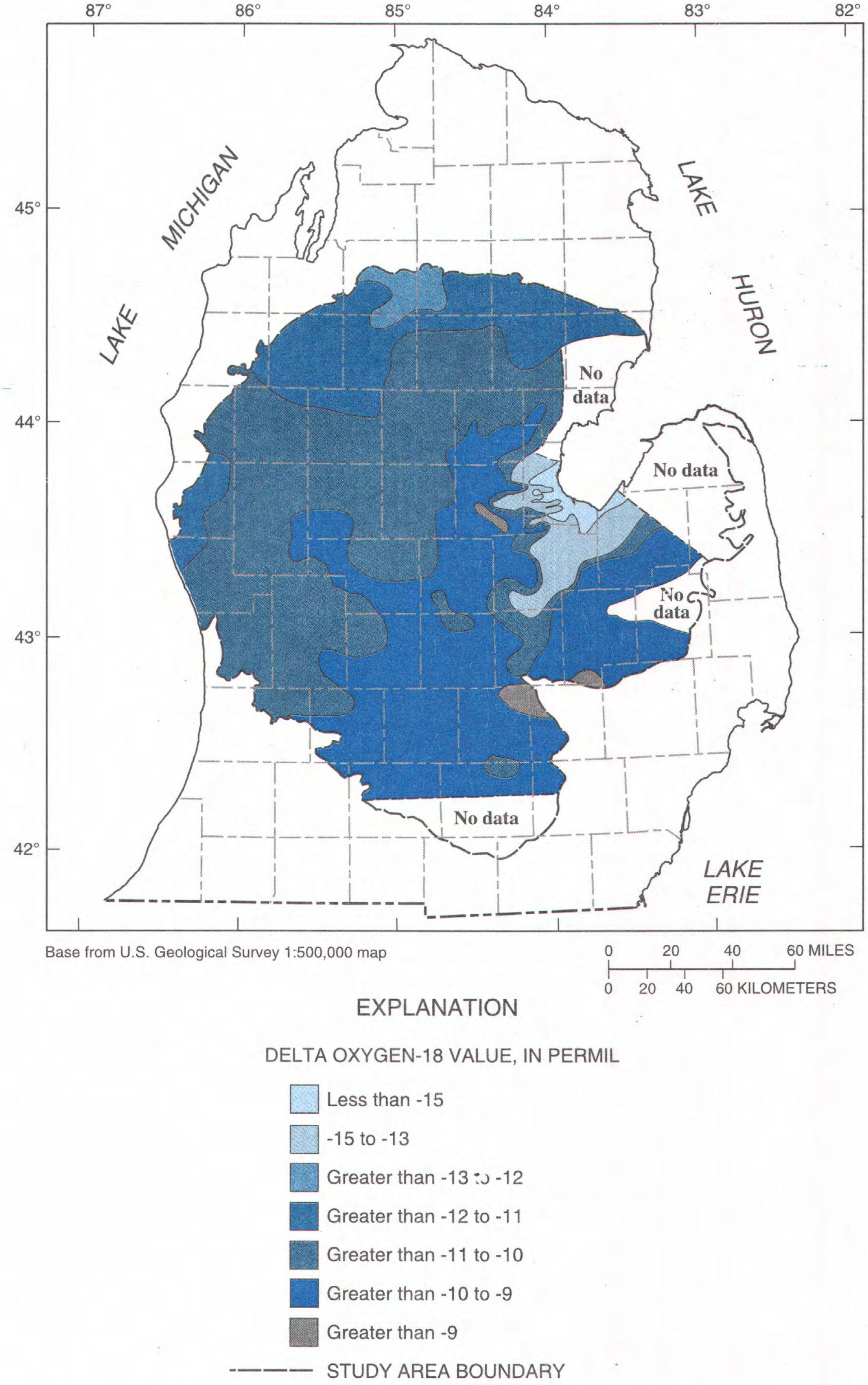


Figure 6. Variation of delta oxygen-18 ground water from the Glaciofluvial aquifer, Lower Peninsula of Michigan.

meteoric water has resulted in a continuum of isotopic values. An alternative hypothesis is that the variation in $\delta^{18}O$ is a result of a change in the isotopic value of recharge water due to the gradual change in climate from a cooler period. Isotopically light water in the Saginaw Bay Area retains its isotopic signature because of slow flushing of the system by present-day recharge water. Slow flushing could be due to low permeability sediment (Long and others, 1988; Mandle and Westjohn, 1989), which are mapped as glaciolacustrine clay (Farrand and Bell, 1984).

Dissolved Constituents

Dissolved Solids

Dissolved-solids concentrations of ground water from the Glaciofluvial aquifer were determined by summing the major cation and anion species from the analysis of each sample. Concentrations in 290 samples range from 99 to 12,000 mg/L. In general, dissolved-solids concentrations increase from the outer parts of the study area toward the Saginaw Bay Area (fig. 7). Dissolved-solids concentrations in water from parts of the Saginaw Bay Area range from 500 to 12,000 mg/L. In addition, there is a narrow (5 to 20 mi wide) corridor that extends from the central part of the study area toward the Michigan Lowlands, where ground water has relatively high dissolved-solids concentrations. Most dissolved-solids concentrations along this trend range from 500 to 1,000 mg/L. Sources of dissolved solids may be solutes added through water-rock interaction or through mixing of meteoric water and brine from underlying bedrock aquifers.

Dissolved Chloride

Dissolved-chloride concentrations in 279 ground-water samples from the Glaciofluvial aquifer range from 1 to 6,700 mg/L (fig. 8). Water in the aquifer from most of the study area has a chloride concentration less than 100 mg/L. Chloride concentrations generally increase from the outer parts of the aquifer to the Saginaw Bay Area, where concentrations are highest. Chloride concentrations between 100 and 1,000 mg/L also are found to the south and west of the Saginaw Bay Area. Water with a chloride concentration less than 10 mg/L is probably of recent meteoric origin. The source of chloride in ground water in the Saginaw Bay Area could be the upward advection or diffusion of ions in water from the underlying bedrock formations that is mixing with modern meteoric water (Long and others, 1988).

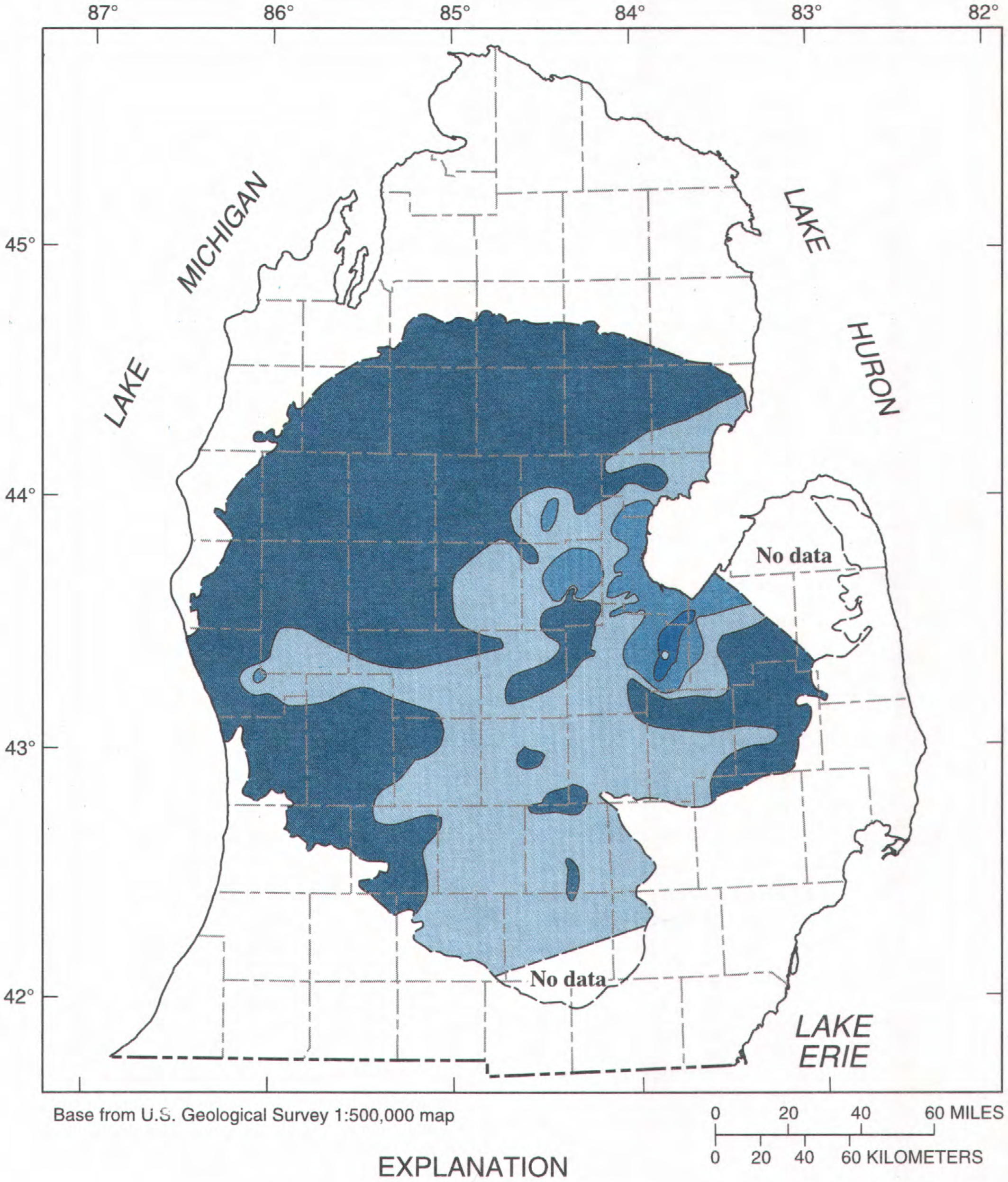
Dissolved Iron

Dissolved-iron concentrations in 244 ground-water samples from the Glaciofluvial aquifer range from 0.001 to 6.0 mg/L (fig. 9). Dissolved-iron concentrations represent the combined concentrations of ferrous and ferric ions. Dissolved-iron concentrations of less than 0.1 mg/L are in ground water from the northern fringe of the study area and, to a greater extent, from the northwestern part. There are also several small, isolated areas where dissolved-iron concentrations in ground water are less than 0.1 mg/L.

Dissolved-iron concentrations greater than 1 mg/L are in ground water from a large band that generally parallels the southern part of the study area from the Saginaw Bay Area to the Michigan Lowland Area. Concentrations of dissolved iron greater than 1 mg/L were also measured in ground water in two isolated areas west of the Saginaw Bay Area. Dissolved-iron concentrations between 0.1 and 1 mg/L are present in ground water from the eastern and southern fringes, in the central and north-central parts of the study area, and in about half of the Saginaw Bay Area.

Dissolved Sulfate

Dissolved-sulfate concentrations in 200 ground-water samples from the Glaciofluvial aquifer range from 1 to 1,800 mg/L (fig. 10). Throughout most of the study area, sulfate concentrations range from 10 to 100 mg/L. In the northern and eastern fringes and the northwestern part of the study area, sulfate concentrations are less than 10 mg/L. A small part of the Saginaw Bay Area where sulfate concentrations are less than 10 mg/L is surrounded by an area that extends out toward the center of the aquifer where sulfate concentrations range from 10 to 100 mg/L. In the northern and southern parts of the Saginaw Bay Area



EXPLANATION

DISSOLVED-SOLIDS CONCENTRATION,
IN MILLIGRAMS PER LITER

▨ ~~Less than 500~~ >10,000 mgl
▨ 500 to 1,000
▨ Greater than 1,000 to 5,000
▨ Greater than 5,000 to 10,000
▨ ~~Greater than 10,000~~ < 500 mgl
------ STUDY AREA BOUNDARY

Figure 7. Distribution of dissolved solids in ground water from the Glaciofluvial aquifer, Lower Peninsula of Michigan.

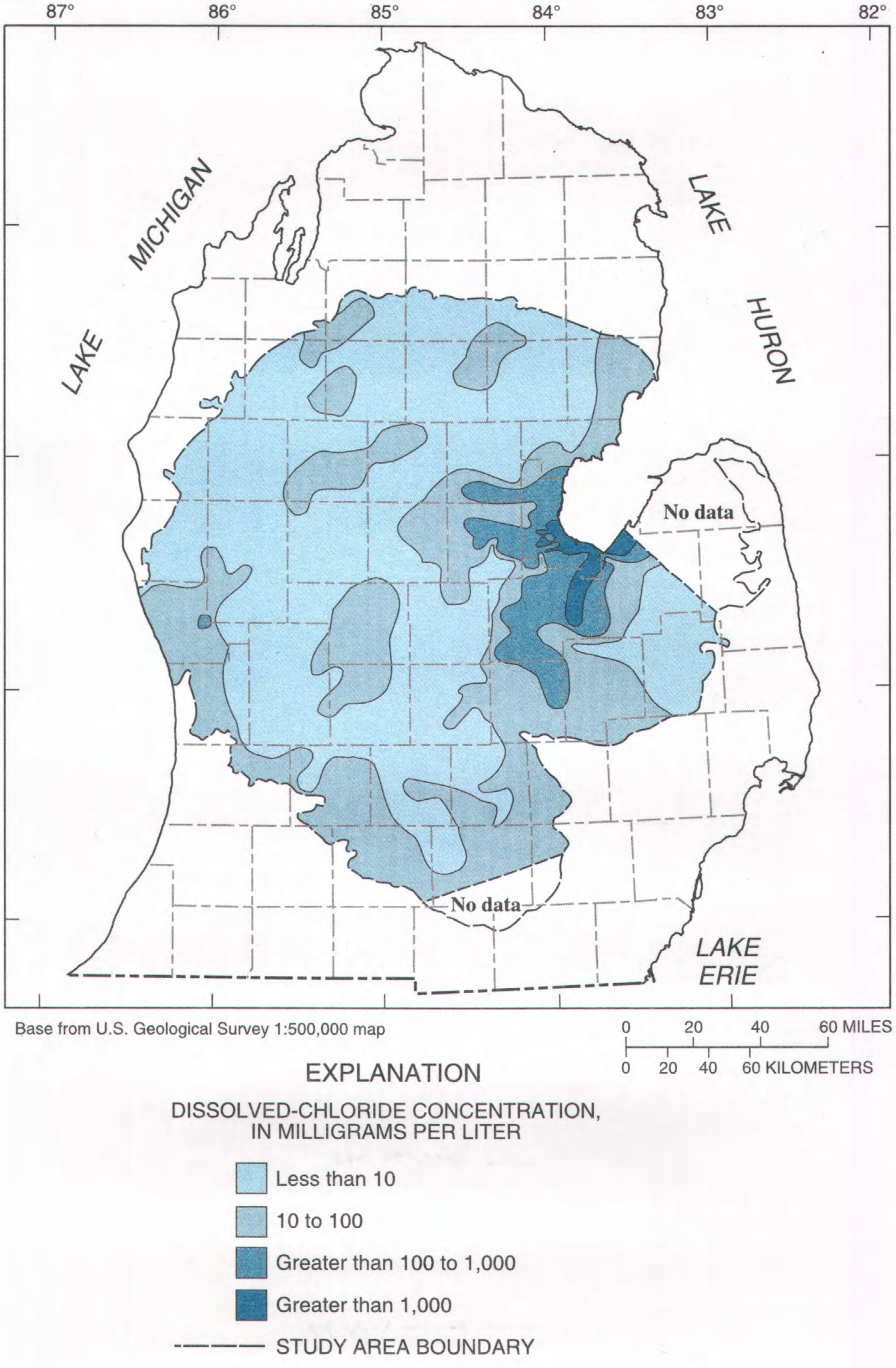


Figure 8. Distribution of dissolved chloride in ground water from the Glaciofluvial aquifer, Lower Peninsula of Michigan.

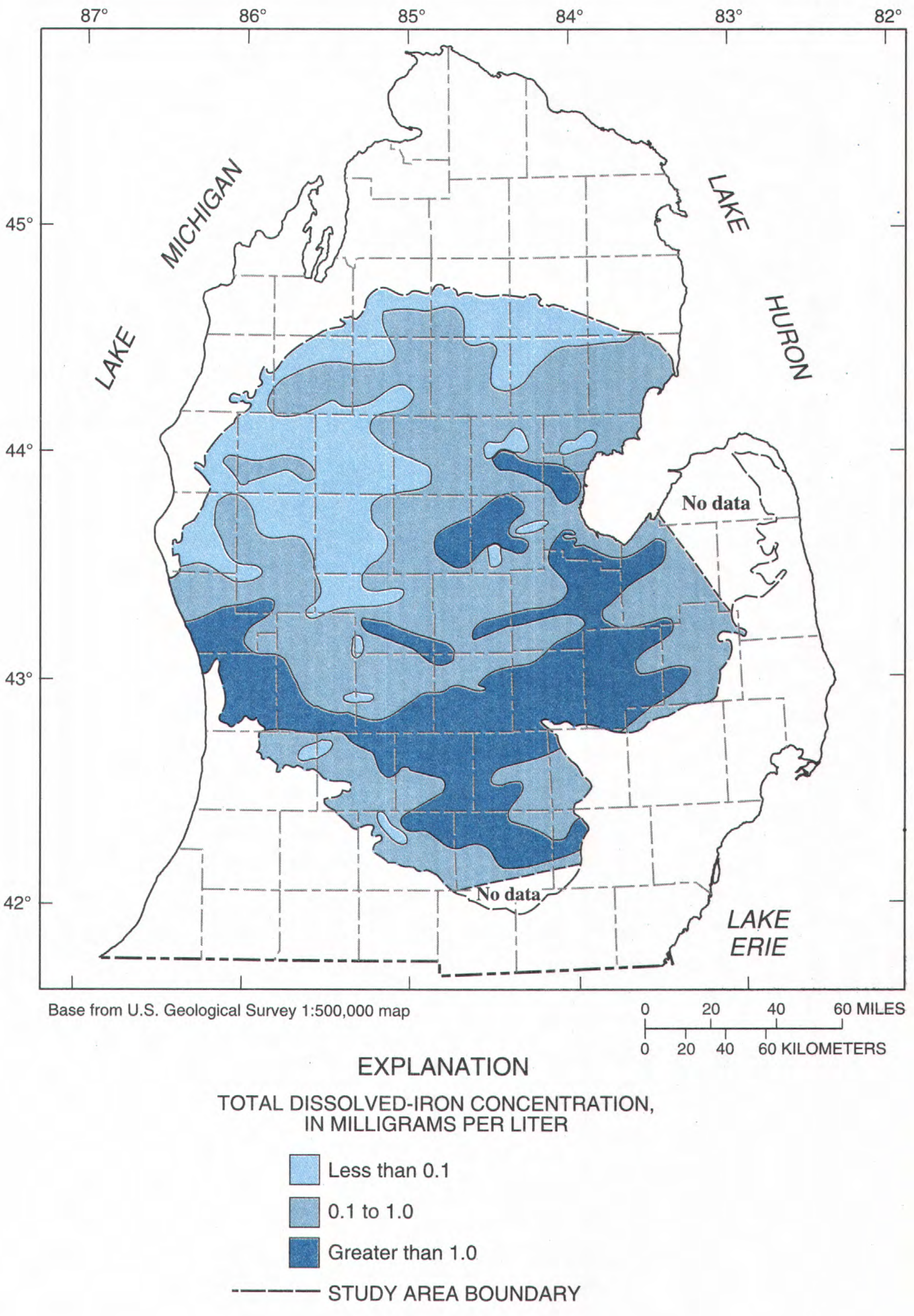


Figure 9. Distribution of dissolved iron in ground water from the Glaciofluvial aquifer, Lower Peninsula of Michigan.

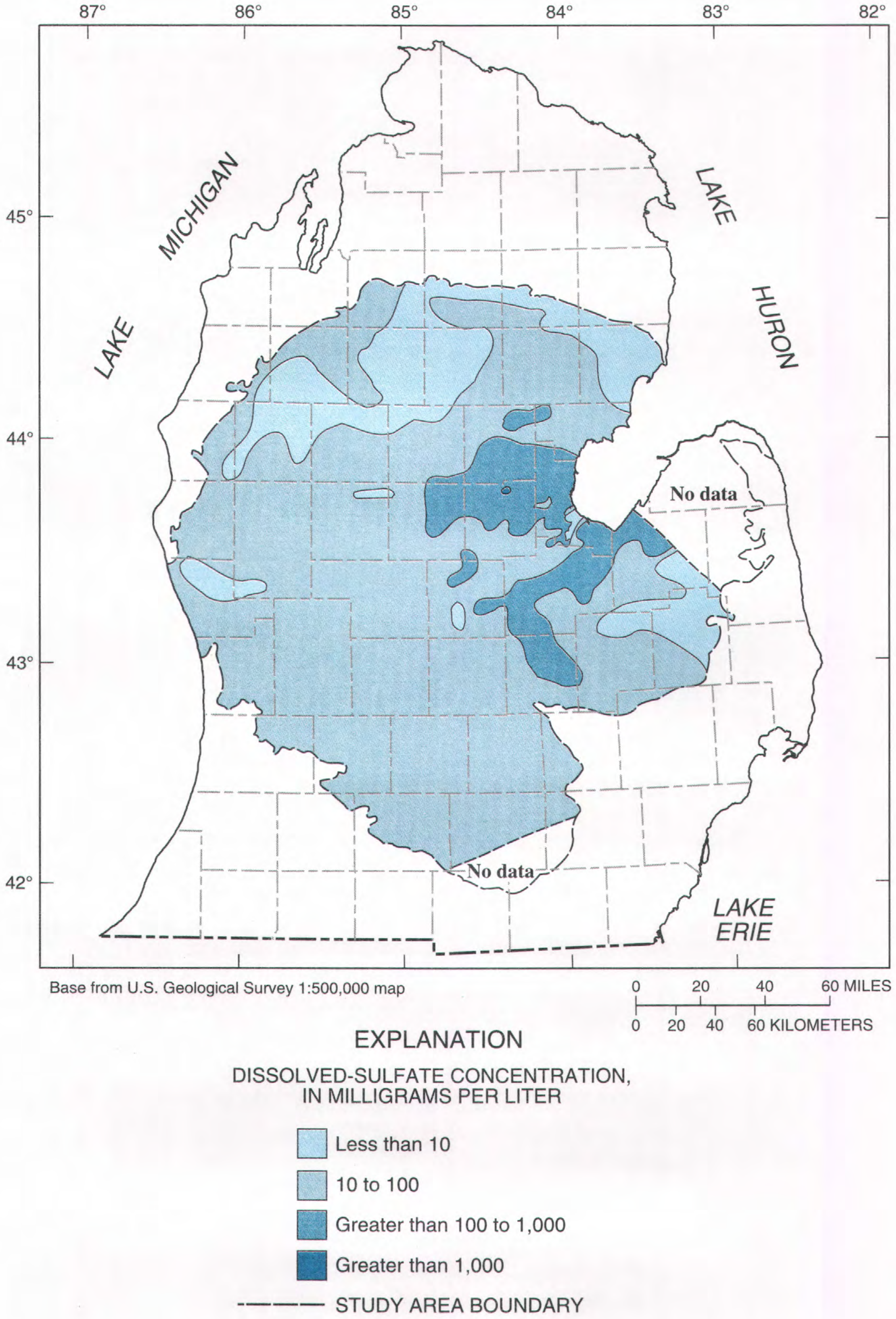


Figure 10. Distribution of dissolved sulfate in ground water from the Glaciofluvial aquifer, Lower Peninsula of Michigan.

there are two large areas where sulfate concentrations are between 100 and 1,000 mg/L. These areas extend to the west and southwest of the Saginaw Bay Area.

The high sulfate concentrations in the Saginaw Bay Area may be the result of upward advection and (or) diffusion of ions from water with higher sulfate concentrations from underlying aquifers (fig. 4). High sulfate concentrations could be the result of dissolution of gypsum and anhydrite, which are thought to be unevenly distributed in the glacial-drift deposits (Wood, 1969). Low sulfate concentrations could be the result of sulfate reduction. Long and others (1988) have interpreted from stable-isotopic values of sulfur and carbon that microbial reduction of sulfate in the aquifer occurs within the Saginaw Bay Area. Microbial reduction decreases the concentrations of sulfate and increases the concentrations of bicarbonate in water.

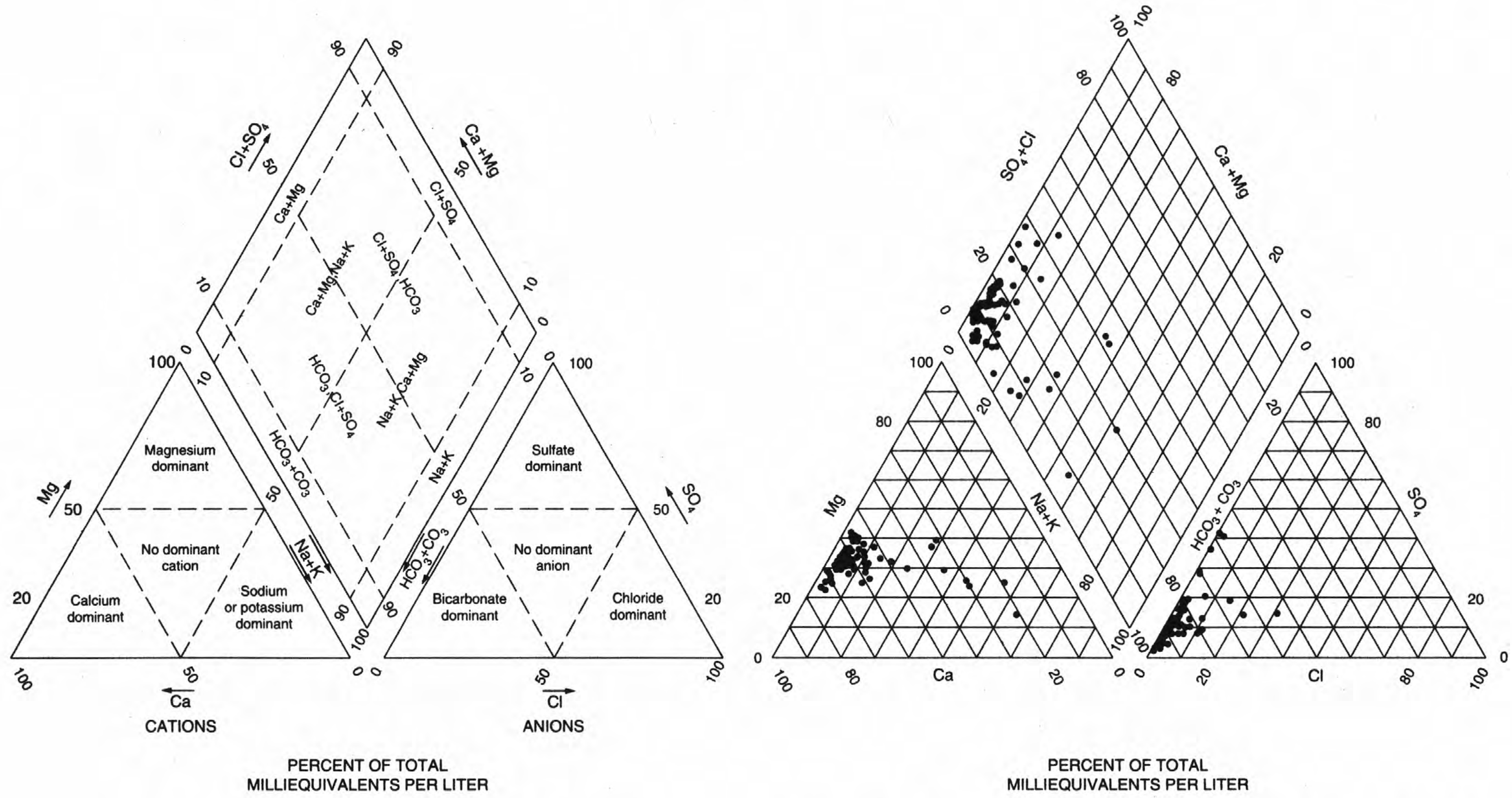
Hydrochemical Facies

The concept of hydrochemical facies is a means of describing the diagnostic chemical character of ground water (Back, 1961). Piper (1944) developed a diagram, commonly referred to as a "Piper plot," that enables the classification of water on the basis of six chemical components. The Piper plot allows easy visual chemical comparisons of the chemistry of water samples, identification of water with similar chemical characteristics, evaluation of mixing among water with different characteristics, and possible determination of the chemical evolution of ground water. Chemical components used consist of three cation (calcium, magnesium, and sodium plus potassium) and three anion (chloride, sulfate, and carbonate plus bicarbonate) species or groups of species. These ions account for the electrical balance in most natural water (Hem, 1985). Values are determined by converting cation and anion concentrations to milliequivalents per liter and then calculating relative percentages of cation and anion species or groups of species and are plotted on a diagram. For diagrammatic purposes, cations and anions each sum to 100 percent. Values of each ground-water sample from the Glaciofluvial aquifer in the Lower Peninsula of Michigan are plotted on respective cation and anion ternary diagrams and also on a central diamond-shaped diagram (fig. 11*a*). Locations of the samples on ternary diagrams are the basis for identifying hydrochemical facies of a ground-water sample (fig. 11a). Hydrochemical facies are used to classify the chemical composition of ground water in terms of the dominant cation and anion. For simplification of terminology, potassium is not mentioned in the cation facies in the rest of this report because of the minor importance for determining facies. Likewise, carbonate is not mentioned in the anion facies.

The dominance criteria is based on percentage of milliequivalents of major cations (calcium, magnesium, and sodium) and major anions (chloride, sulfate, and bicarbonate). For example, in water dominated by sodium and chloride, sodium and chloride ions would be greater than 50 percent of total cations and anions, respectively. A water sample in which no cation or anion exceeds 50 percent of the total cations or anions is termed a "no dominant cation" or "no dominant anion facies."

The data used for the Piper plot of ground water from the Glaciofluvial aquifer consists of water analyses with less than a 10-percent charge imbalance. A major limitation in making interpretations from Piper plots is that water samples with very different dissolved-solids concentrations, but with the same relative proportions of cation and anion species, will plot at the same position on the diagram. This limitation can be handled in many ways (Hem, 1985). In this study, this limitation was addressed by developing three Piper plots (fig. 11*b* to 11*d*) in which the samples are grouped as a function of dissolved-solids concentration. The ranges of dissolved-solids concentration are less than or equal to 450 mg/L, 451 to 750 mg/L, and greater than 750 mg/L.

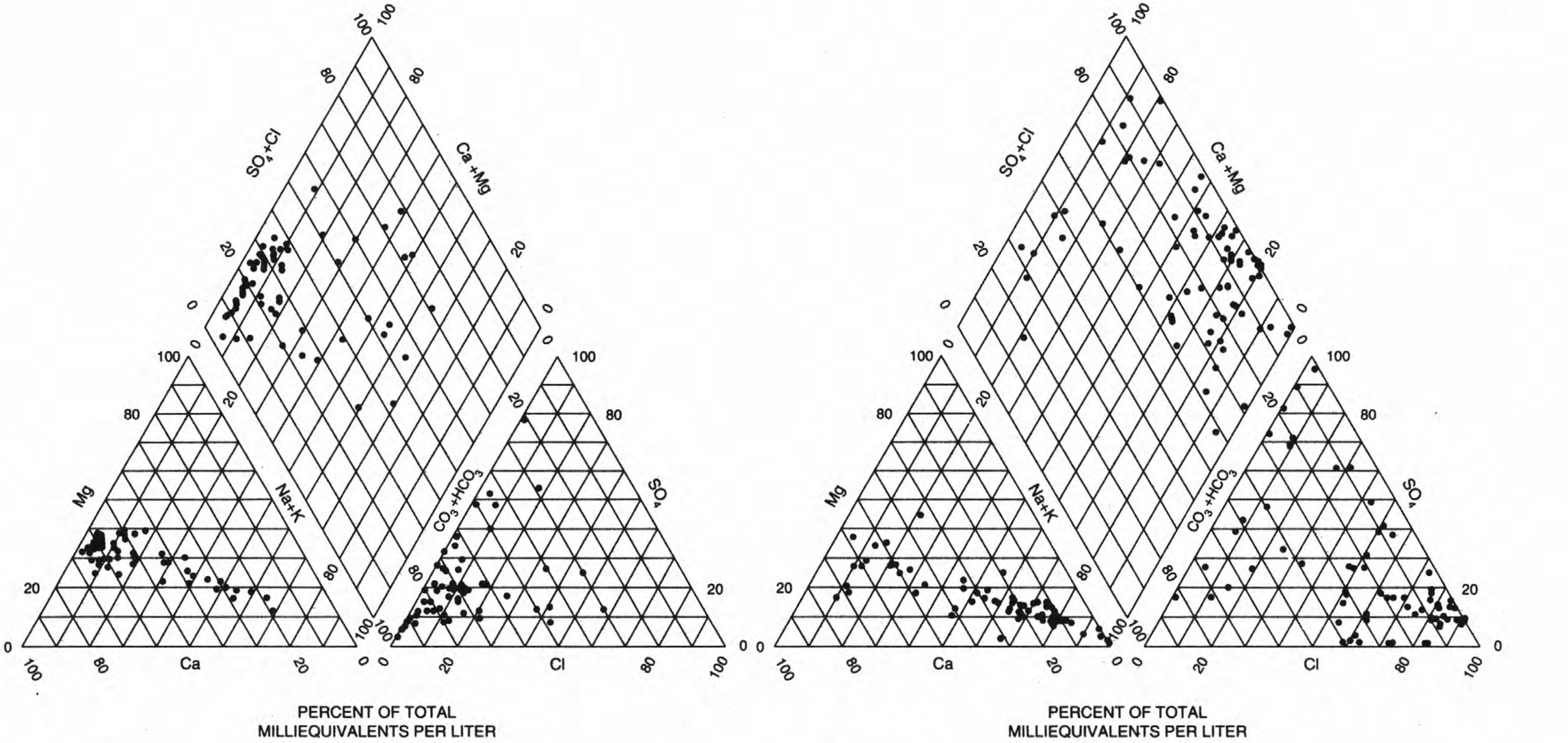
At all concentrations of dissolved solids, water samples in the cation ternary diagrams plot along a line with very little scatter from the calcium-dominant area to the sodium-dominant area. Samples with low concentrations of dissolved solids are more calcium dominant, and samples with high concentrations of dissolved solids are more sodium dominant. In the anion ternary diagrams, samples with low dissolved-solids concentrations plot along the bicarbonate sulfate



a. Classification scheme for hydrochemical facies

b. Dissolved-solids concentrations less than or equal to 450 milligrams per liter

Figure 11. Modified Piper plot (Piper, 1944) of the classification scheme for hydrochemical facies and Piper plots for ground water from the Glaciofluvial aquifer, Lower Peninsula of Michigan, at different ranges of dissolved-solids concentrations.



c. Dissolved-solids concentrations from 451 to 750 milligrams per liter

d. Dissolved-solids concentrations greater than 750 milligrams per liter

Figure 11. Modified Piper plot (Piper, 1944) of the classification scheme for hydrochemical facies and Piper plots for ground water from the Glaciofluvial aquifer, Lower Peninsula of Michigan, at different ranges of dissolved-solids concentrations--Continued.

boundary (fig. 11*b*), samples with intermediate dissolved-solids concentrations plot among the bicarbonate chloride sulfate boundary (fig. 11*c*), and samples with high dissolved-solids concentrations plot along the chloride sulfate boundary (fig. 11*d*). The change in the distribution pattern of data in the diamond area as a function of increasing dissolved-solids concentrations reflects those changes in cation and anion ternary diagrams.

The plotted values in the ternary and diamond diagrams are consistent with a hypothesis that water with different compositions have mixed. At low dissolved-solids concentrations, meteoric water commonly evolves from sodium or calcium sulfate dominant precipitation to calcium bicarbonate dominant ground water soon after infiltration (Berner and Berner, 1987). Such an evolutionary pathway could explain the trends in figure 11*b*. At high dissolved-solids concentrations, ground water is commonly sodium chloride and calcium sulfate dominant (fig. 11*d*) because of dissolution of halite, gypsum, and anhydrite and (or) because of mixing with brine. Mixing among such water could explain observed trends (fig. 11*d*). Trends at intermediate dissolved-solids concentrations (fig. 11*c*) are probably a result of mixing of water of low and high dissolved-solids concentrations.

A hydrochemical facies map (fig. 12) was prepared for the Glaciofluvial aquifer to show the areal distribution of ground-water facies as classified on the Piper plots (figs. 11*b* to 11*d*). A few samples had either no dominant cation or no dominant anion. These were primarily individual samples scattered throughout the study area and were not included in figure 12. The hydrochemical facies observed in the Glaciofluvial aquifer are calcium bicarbonate, calcium sulfate, sodium chloride, and sodium bicarbonate (fig. 12). The predominant hydrochemical facies, calcium bicarbonate (fig. 12), are consistent with water having recently recharged the aquifer. Ground water from the Saginaw Bay Area is dominated by sodium chloride facies and has higher dissolved-solids concentrations than water from other areas. The sodium chloride facies also extend to the south of the Saginaw Bay Area. The sodium chloride facies could be the result of upward advection or diffusion of ions from water from the underlying bedrock aquifers. Calcium sulfate facies are present in the northwest part of the Saginaw Bay Area and extend toward the west. Ground water dominated by calcium sulfate facies is found in an area to the southwest of the Saginaw Bay Area. Calcium sulfate facies may be the result of the dissolution of gypsum or anhydrite. Sodium bicarbonate facies are just west of the Saginaw Bay Area and are possibly the result of mixing between sodium chloride facies and calcium bicarbonate facies.

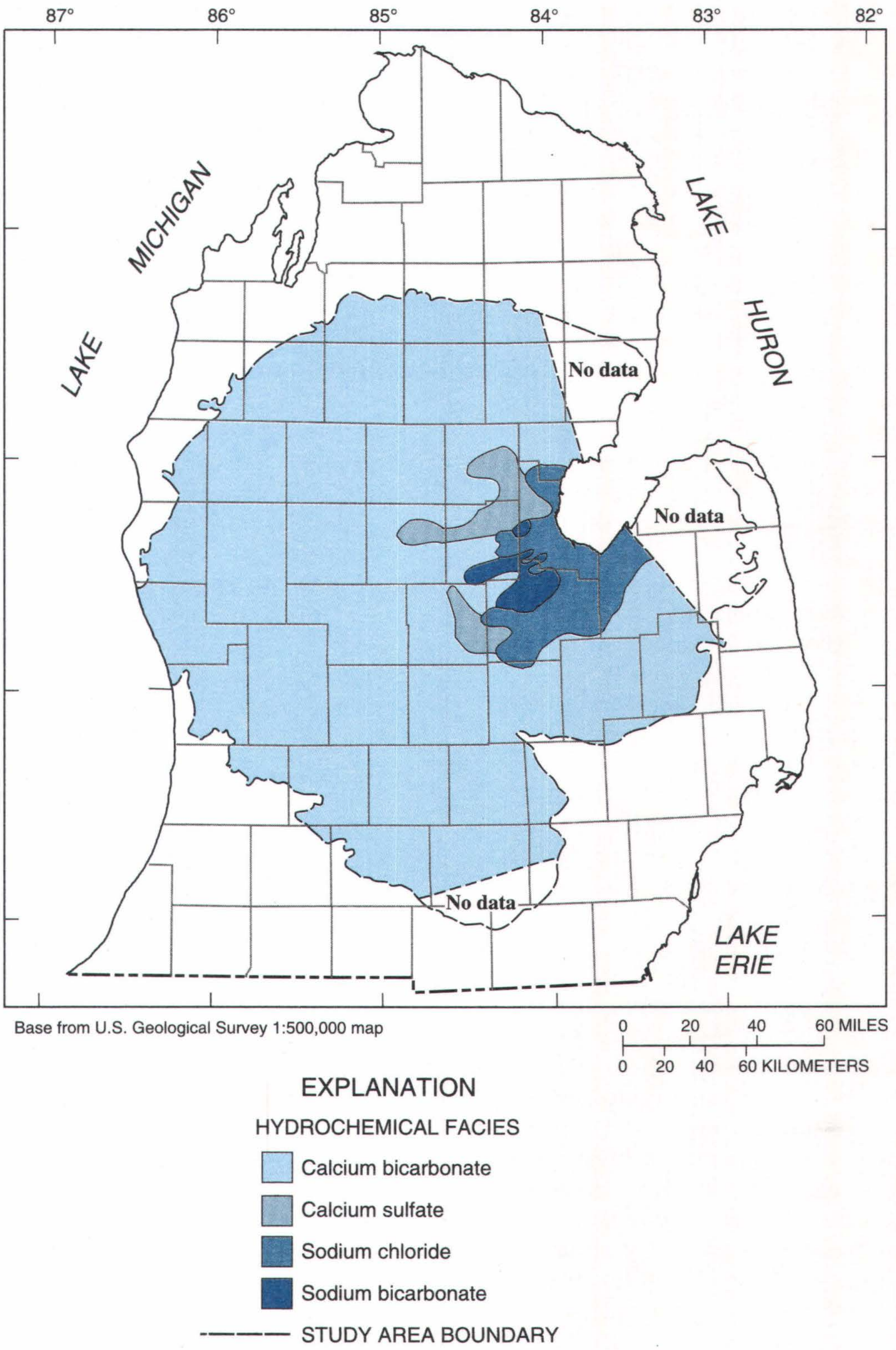
SUMMARY

Maps based on chemical analyses of ground water from the Glaciofluvial aquifer in the Lower Peninsula of Michigan were prepared to show the areal variation of $\delta^{18}O$, and distribution of dissolved solids, dissolved chloride, dissolved iron, dissolved sulfate, and hydrochemical facies.

Interpretation of δD and $\delta^{18}O$ relations indicate that modern meteoric and glacial-age meteoric water are present in the Glaciofluvial aquifer. A continuum of values of δD and $\delta^{18}O$ indicates mixing of modern meteoric and glacial-age meteoric water. The $\delta^{18}O$ values are significantly lighter than modern meteoric water in the Saginaw Bay Area. The likely origin of this isotopically light ground water is recharge with glacial meltwater. Isotopically light water in the Saginaw Bay Area retains this isotopic signature because of slow flushing of the system by present-day recharge water. The slow flushing seems to be due to the presence of low-permeability sediment mapped as glaciolacustrine clay.

Dissolved-solids and dissolved-chloride concentrations in water from the Glaciofluvial aquifer indicate that the most samples with higher concentrations are in and around the Saginaw Bay Area. A source of some solutes for dissolved solids in this area may be from mixing with brine from underlying bedrock aquifers. Dissolved solids in the rest of the Lower Peninsula are relatively low.

Dissolved-iron concentrations are lowest in water from the northern fringe and, to a greater extent, in the northwestern part of the Lower Peninsula. Highest dissolved-iron concentrations form a large band that extends from the southern



Base from U.S. Geological Survey 1:500,000 map

Figure 12. Distribution of hydrochemical facies in ground water from the Glaciofluvial aquifer, Lower Peninsula of Michigan.

part of the aquifer system to the southern part of the Saginaw Bay Area and west to the Michigan Lowland Area. Dissolved-iron concentrations in the remainder of the ground water in the study area are intermediate to concentrations in the above areas.

Dissolved-sulfate concentrations are lowest in water from the northern and eastern fringe areas, the northwestern part of the study area, and in a small part of the Saginaw Bay Area. In the northern and southern parts of the Saginaw Bay Area, there are two large areas where ground water from the Glaciofluvial aquifer has the highest dissolved-sulfate concentrations. In the remainder of the study area ground water has dissolved-iron concentrations intermediate to the concentrations in the above areas. A small part of the aquifer in the Saginaw Bay Area contains water with low sulfate concentrations that are the result of sulfate reduction.

Distribution of data on Piper plots shows a cation trend where samples with low concentrations of dissolved solids are calcium dominant, and samples with high concentrations of dissolved solids are sodium dominant. In the anion ternary diagrams, samples with low dissolved-solids concentrations plot along the bicarbonate sulfate boundary, samples with intermediate dissolved-solids concentrations plot among the bicarbonate chloride sulfate boundary, and samples with high dissolved-solids concentrations plot along the chloride sulfate boundary. These trends are indicative of mixing of water masses of different chemical compositions.

The four major hydrochemical facies observed in the Glaciofluvial aquifer are calcium bicarbonate, calcium sulfate, sodium chloride, and sodium bicarbonate. The predominant hydrochemical facies, calcium bicarbonate, is consistent with recent recharge of the aquifer. Water from the Saginaw Bay Area is dominated by sodium chloride facies, which could be the result of upward advection or diffusion of ions from water from the underlying bedrock aquifers. In addition, ground water in this area has higher dissolved-solids concentrations than water from other areas in the Lower Peninsula of Michigan. Calcium sulfate facies found in ground water from the northwest and in an area southwest of the Saginaw Bay Area are possibly the result of the dissolution of gypsum or anhydrite. Water dominated by sodium bicarbonate facies is found just west of the Saginaw Bay Area and may be the result of mixing between sodium chloride facies and calcium bicarbonate facies.

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