

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

By B.D. MEISSNER, D.T. LONG, and R.W. LEE

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CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

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

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

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8.$$

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 ¹⁸O and ²H isotopic standard). The unit δ¹⁸O is the standard expression of the ratio of the ¹⁸O ion with respect to the ¹⁶O ion. The unit δD is the standard expression of the ratio of the ²H ion (deuterium) with respect to the ¹H 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 of water from wells completed in the Saginaw aquifer in the central Lower Peninsula of Michigan were used to prepare maps that show areal variation of $\delta^{18}\text{O}$; distribution of dissolved solids, dissolved chloride, dissolved iron, dissolved sulfate; and distribution of hydrochemical facies. Delta oxygen-18 values indicate the presence of modern meteoric water ($\delta^{18}\text{O}$ approximately -10 parts per thousand) and glacial-age meteoric water, which is isotopically light ($\delta^{18}\text{O}$ 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 concentration ranges from 41 to 92,300 milligrams per liter, and dissolved-chloride concentrations range from less than 1 to 55,000 milligrams per liter. Dissolved-solids and dissolved-chloride concentrations increase toward Saginaw Bay. Dissolved-iron and dissolved-sulfate concentration ranges from 0.01 to 7.80 and 0.2 to 3,500 milligrams per liter, respectively. Most ground water from the Saginaw aquifer is classified as calcium bicarbonate, calcium sulfate, or sodium chloride.

INTRODUCTION

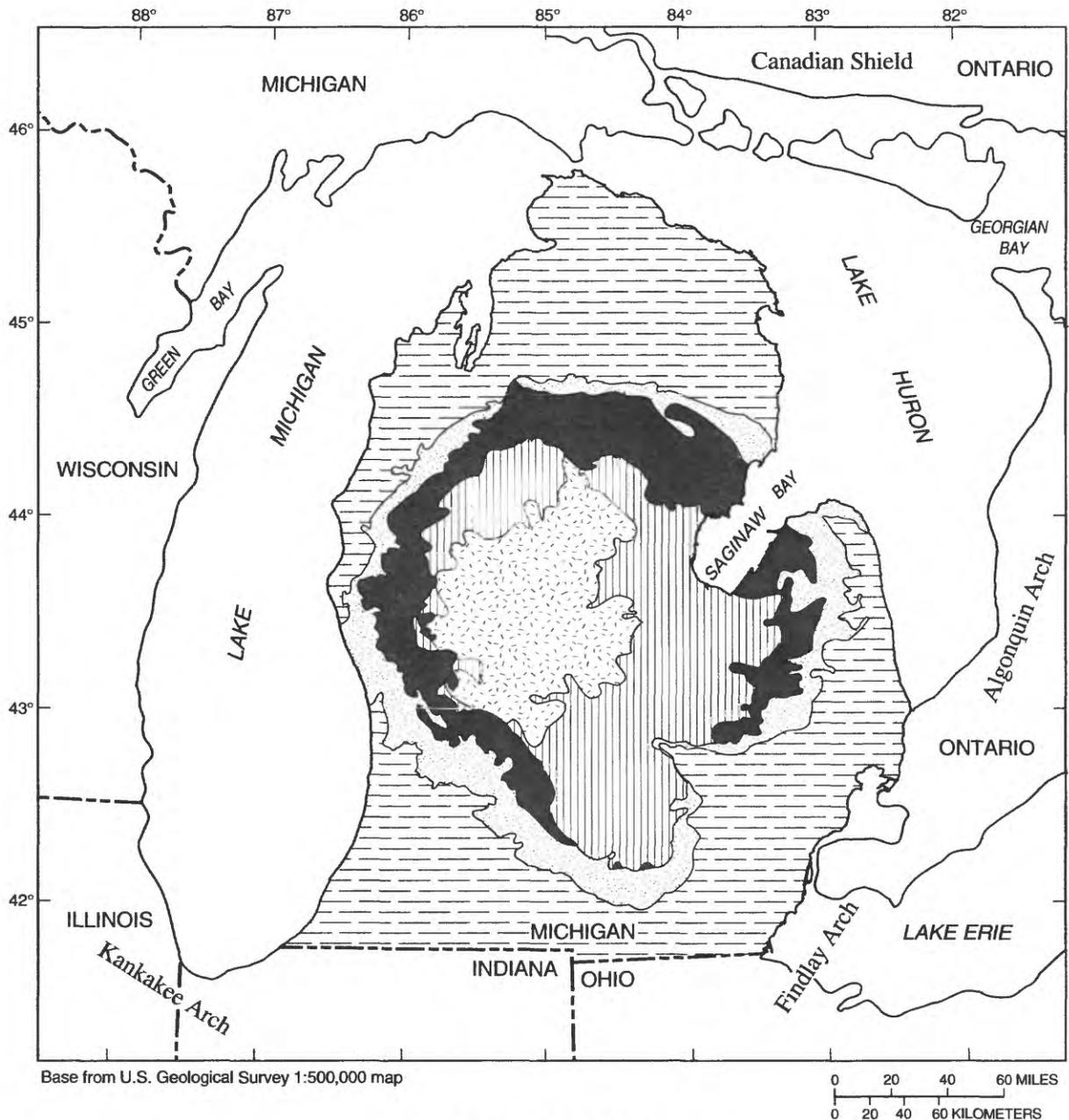
This report describes the areal variation of selected geochemical characteristics of ground water from the Saginaw aquifer of the Michigan Basin. It is one of several reports whose purpose is to describe the geology, hydrology, and geochemistry of aquifers in the central part of Michigan's Lower Peninsula (Mandle, 1986; Mandle and

Westjohn, 1989; Westjohn, 1989; Dannemiller and Baltusis, 1990). These aquifers are being studied as a part of the U.S. Geological Survey's Regional Aquifer-System Analysis (RASA) program in Michigan. The Michigan Basin RASA study area is a 22,000 mi² area of central lower Michigan and is bounded by the contact between the Coldwater Shale and the Marshall Sandstone (fig. 1).

Chemical analyses of water from wells completed in the Saginaw aquifer (fig. 2) were compiled and plotted to construct maps that illustrate selected geochemical characteristics of water in the study area. 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). Additional sources of chemical data include the U.S. Geological Survey's Water Data Storage and Retrieval system (WATSTORE) data base, Wood (1969), the Michigan Department of Natural Resources (written commun., 1987), and the Michigan Department of Public Health (Mark Breithart, written commun., 1992).

Chemical data used to construct maps are of water sampled from wells completed at different depths in the Saginaw aquifer. Therefore, the maps represent areal distributions of dissolved constituents, stable isotopes, and hydrochemical facies. No chemical or isotope data are available for the northwestern part of the Saginaw aquifer because wells in that area are completed in overlying glacial deposits.

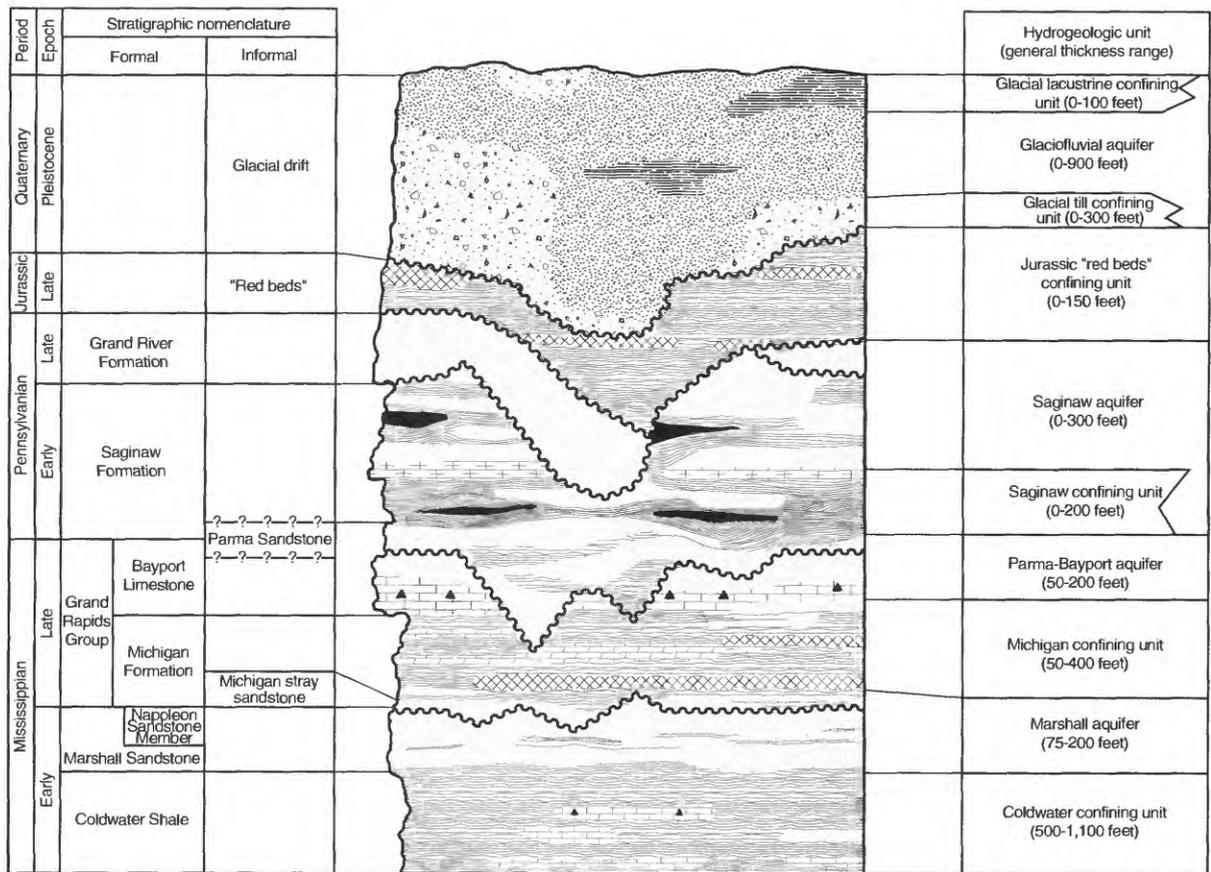
The authors thank the Michigan Department of Public Health, especially Mark Breithart, for providing chemical data. The Michigan Department of Natural Resources provided access to well logs and chemical data of Michigan Basin brines.



EXPLANATION
DESCRIPTION OF MAP UNITS

- | | | | |
|---|---|---|---|
|  | Jurassic "red beds" |  | Mississippian Marshall Sandstone |
|  | Pennsylvanian Grand River and Saginaw Formations (includes Upper Mississippian Parma Sandstone and Bayport Limestone) |  | Mississippian Coldwater Shale and older rocks |
|  | Mississippian Michigan Formation | | |

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



EXPLANATION

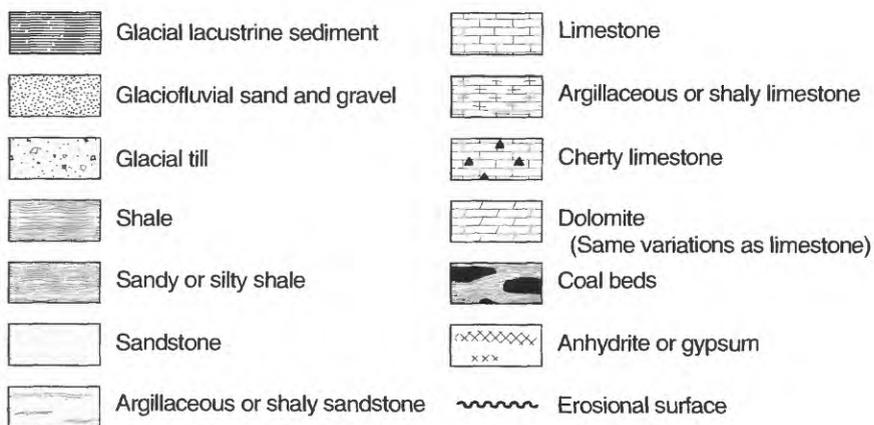


Figure 2. Relation between stratigraphic and hydrogeologic units in the study area (from Westjohn and others, 1994).

GEOHYDROLOGIC FRAMEWORK

The Michigan Basin is an ovate basin in which an extensive accumulation of sedimentary rocks is present in the Lower Peninsula of Michigan and parts of Michigan's Upper Peninsula, Illinois, Ohio, Indiana, Wisconsin, and Ontario, Canada. Sedimentary rocks of Precambrian through Jurassic age are more than 17,500 ft thick near the center of the basin (Lillienthal, 1978). Sedimentary rocks are mantled by glacial deposits of Pleistocene age.

There are four aquifers in the Michigan Basin RASA study area [Glaciofluvial, Saginaw, Parma-Bayport, and Marshall aquifers (fig. 2)]. Glaciofluvial aquifers dominantly consist of thick sequences of sand and gravel, but, in parts of the study area, they also consist of sand and gravel beds within till or other fine-grained glacial deposits. In this report, the uppermost aquifer is referred to as a single unit even though it is composed of multiple sand and gravel layers. "Red beds" of Jurassic age overlie the Saginaw aquifer in the west-central part of the study area. These "red beds" are dominantly composed of red mud, poorly consolidated red shale, gypsum, and minor amounts of sandstone. More than 400 ft of freshwater-bearing glacial deposits overlie the Jurassic "red beds." Consequently, wells are rarely completed in the "red beds" or underlying bedrock aquifers, and quality of water data for the underlying units are sparse. Together with the fine-grained glacial deposits, "red beds" form subregional confining units (Westjohn and others, 1994).

Pennsylvanian rocks have been subdivided into the Saginaw Formation (Early Pennsylvanian) and the Grand River Formation (Late Pennsylvanian) (Michigan Geological Survey, 1964). Sandstone and shale of these formations are intercalated and constitute the dominant lithology in some parts of the study area. Siltstone, limestone, and coal are minor contributors to the total thickness of the Pennsylvanian rock sequence. For characterization of the hydrogeological framework of the Michigan Basin aquifer system, the composite thickness of the Pennsylvanian sandstone is grouped to form the Saginaw aquifer (Westjohn and Weaver, 1996). Sandstone, which is the most productive aquifer material in the unit,

generally comprises less than 100 ft in thickness except in the east-central part of the basin, where the composite thickness of sandstone ranges from 200 to 370 ft (Westjohn and Weaver, 1996).

In most areas of the basin, shale underlies the Saginaw aquifer. This shale constitutes the Saginaw confining unit, separates the Saginaw aquifer from the Parma-Bayport aquifer, and ranges in thickness from 0 to 200 ft (fig. 2).

The Parma-Bayport aquifer ranges from 50 to 200 ft in thickness and consists of the Parma Sandstone and Bayport Limestone (fig. 2). The Parma Sandstone contains sandstone, shale, siltstone, and thin lenses of limestone (Cohee, 1965). The Bayport Limestone is predominantly limestone, sandstone, and sandy limestone (Cohee, 1965). The Marshall aquifer, which is the lowermost aquifer in the Michigan Basin RASA study area, predominantly consists of sandstone of Mississippian age.

Ground-water flow in the Saginaw aquifer is not well understood. However, a generalized simulated potentiometric surface indicates that a major component of ground-water flow is toward the Saginaw Bay Area (fig. 3) (Mandle and Westjohn, 1989). For purposes of this report, the Saginaw Bay Area is defined as the east-central part of the Michigan Basin bounded by the outermost moraine of the Port Huron Morainal system within the Saginaw Lowlands. Some ground water also flows to the west away from the Saginaw Bay Area.

SELECTED GEOCHEMICAL CHARACTERISTICS

Maps that illustrate the general distribution of selected dissolved constituents, stable-isotope values, and hydrochemical facies were prepared for the Saginaw aquifer. The maps include areal variation of $\delta^{18}\text{O}$ and distributions 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

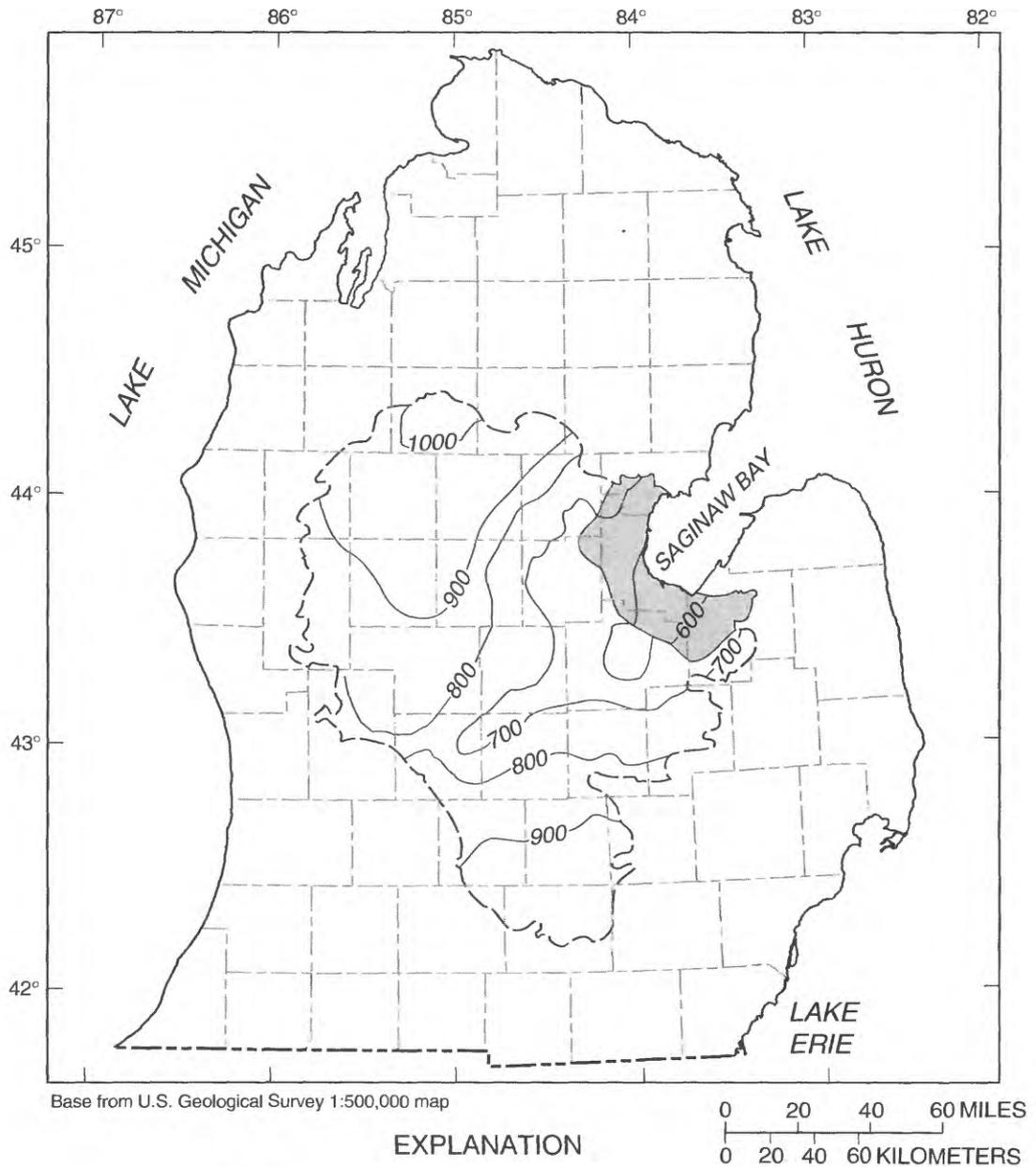


Figure 3. Simulated predevelopment equivalent freshwater head in the Saginaw aquifer, Lower Peninsula of Michigan, and location of the Saginaw Bay Area (modified from Mandle and Westjohn, 1989).

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

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

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

The relation of δD and $\delta^{18}\text{O}$ for 151 ground-water samples collected from the Saginaw aquifer is shown in figure 4. Values of $\delta^{18}\text{O}$ range from -18.19 to -7.85 permil, and values of δD range from -131.5 to -53.5 permil. These data are compared to the global meteoric water line of Craig (1961) and a local meteoric water line (Simcoe line) developed for Simcoe, Ontario, Canada (Desaulniers and others, 1981) (fig. 4). The Simcoe data were collected from precipitation approximately 120 mi east of the study area. The plot indicates that water in the Saginaw aquifer is of meteoric origin because the trend of the data is similar to trends of the Simcoe and global meteoric water lines. The $\delta^{18}\text{O}$ values that range from -12.00 to -7.85 permil are consistent with isotope values of modern precipitation in the Lower Peninsula of Michigan (Sheppard and others, 1969; Grahame Larson, Michigan State University, written commun., 1992) and, therefore, are interpreted to represent modern meteoric ground water in the Saginaw aquifer. Isotopically light values (less than -12.0 permil), however, are lighter than expected for modern recharge. These light isotopic values indicate that water recharged when climate was cooler, such as 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 (Desaulniers and others, 1981; Siegel and Mandle, 1984). The isotopic values of the glacial-age meteoric water are not known; however, for the purposes of this report, an isotopic value of less than -15.0 permil is considered to be glacial-age water.

The areal variation of $\delta^{18}\text{O}$ determined from 151 samples is shown in figure 5. Trends in δD are generally the same as trends in $\delta^{18}\text{O}$ and are not included in this report. In the southern, west-central, and east-central parts of the aquifer, $\delta^{18}\text{O}$ values range from -10.0 to -8.0 permil (fig. 5). These values are the same as those of modern meteoric water in Michigan. The $\delta^{18}\text{O}$ values of water from parts of the Saginaw Bay Area are less than -16.0 permil. Variation of $\delta^{18}\text{O}$ values between -16.0 and -10.0 permil in the central and northeastern parts of the aquifer indicates mixing of water with different $\delta^{18}\text{O}$ values. Variation of $\delta^{18}\text{O}$ values is similar in water from overlying glacial deposits (Wahrer and others, 1996).

The distributions of data in figures 4 and 5 indicate that mixing of modern meteoric and glacial-age meteoric water has resulted in a continuum of isotopic values. An alternative hypothesis is that the variation in $\delta^{18}\text{O}$ is a result of a change in the isotopic value of recharge water due to the gradual change in climate from a cooler period. Ground water in the Saginaw Bay Area retains its isotopically light signature because of slow flushing of the system by present-day recharge water. The slow flushing is due to the presence of low permeability sediment (Long and others, 1988; Mandle and Westjohn, 1989), which is mapped as glaciolacustrine clay (Farrand and Bell, 1984).

Dissolved Constituents

Dissolved Solids

Dissolved-solids concentrations in 399 ground-water samples from the Saginaw aquifer were determined by summing major cation and anion species (fig. 6). Concentrations range from 41 to 92,300 mg/L. In general, the least-concentrated water is in the southern half of

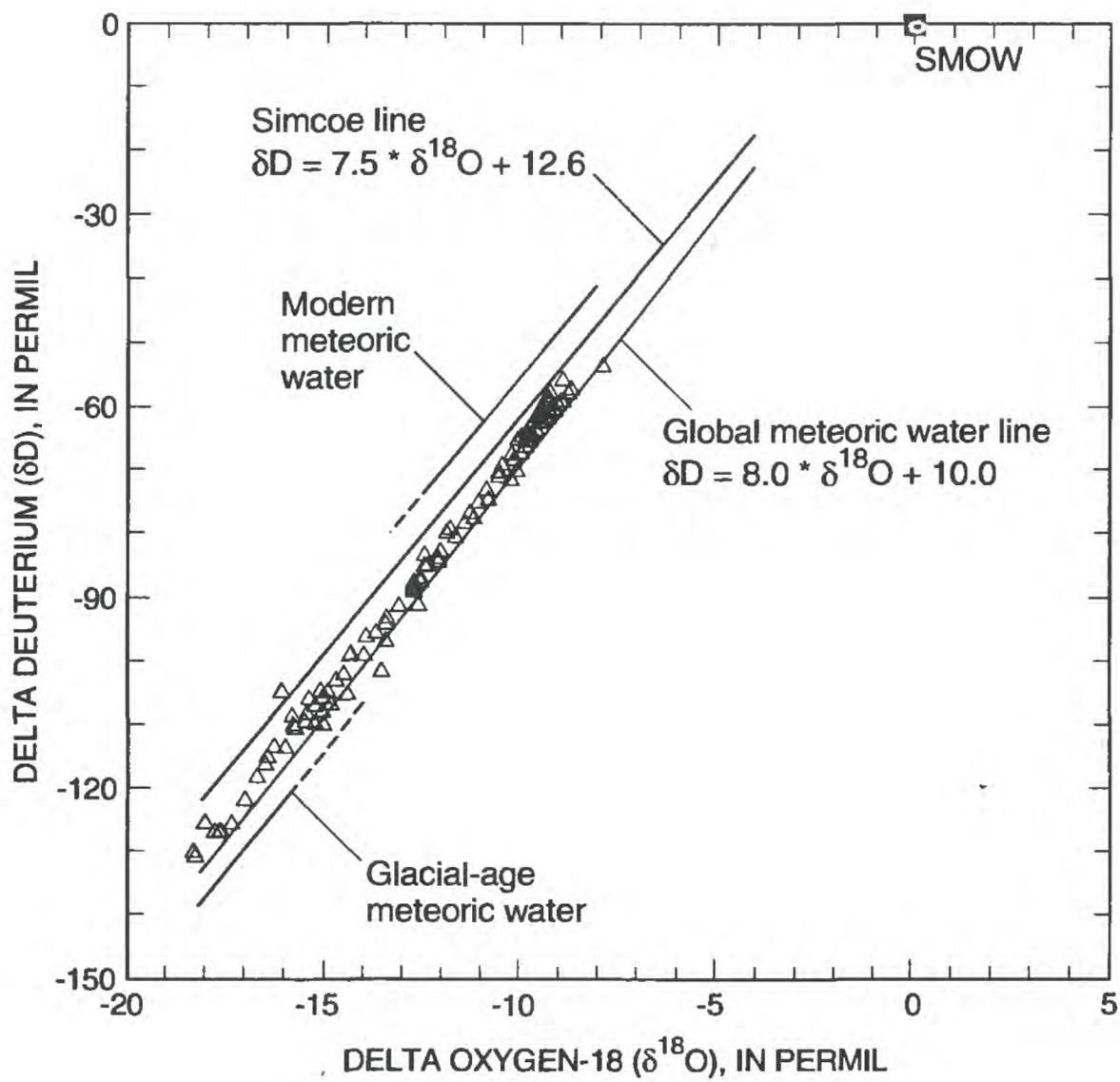
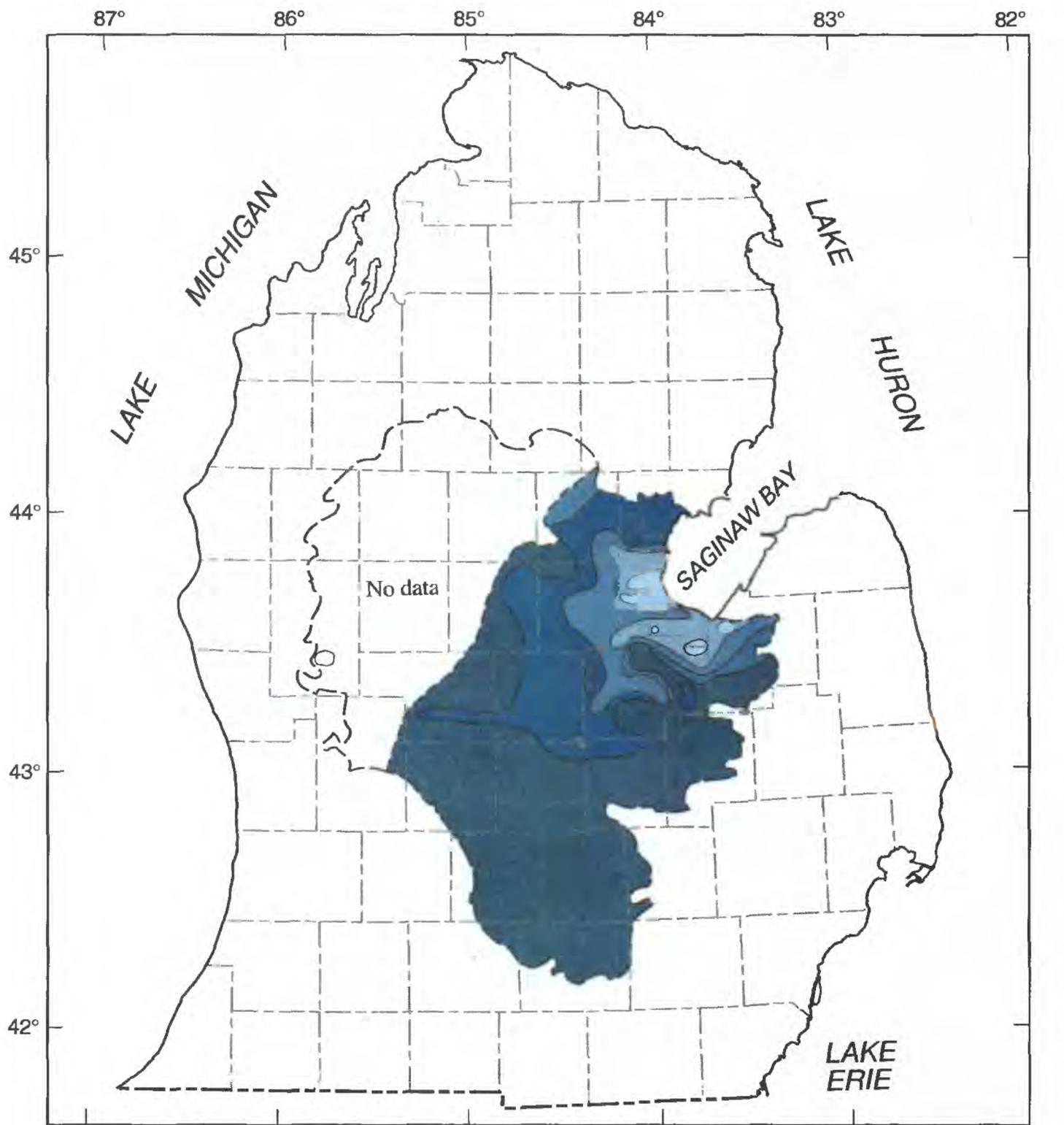
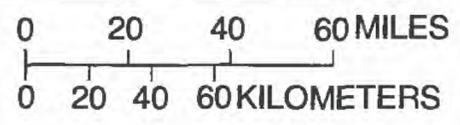


Figure 4. Relation between delta deuterium and delta oxygen-18 for ground water from the Saginaw aquifer, Lower Peninsula of Michigan.



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



EXPLANATION

DELTA OXYGEN-18 VALUE, IN PERMIL

- Less than -16
- 16 to -14
- Greater than -14 to -12
- Greater than -12 to -10
- Greater than -10

--- BOUNDARY OF PENNSYLVANIAN SUBCROP

Figure 5. Variation of delta oxygen-18 in ground water from the Saginaw aquifer, Lower Peninsula of Michigan.

the aquifer. Water from the east-central part of the aquifer and most of the Saginaw Bay Area contains dissolved-solids concentrations that commonly exceed 1,000 mg/L and locally exceed 10,000 mg/L. Sources of dissolved solids may be solutes added through water-rock interaction or through mixing of meteoric water and brine from within the Saginaw or the underlying aquifers. For example, dissolved-solids concentrations of water from the Parma-Bayport aquifer exceed 200,000 mg/L in the Saginaw Bay Area and the west-central part of the aquifer. Within the Michigan Basin, dissolved-solids concentrations increase with depth, and the highest dissolved-solids concentrations in the Saginaw aquifer (greater than 10,000 mg/L) are associated with samples derived from deeper parts of the aquifer.

Dissolved Chloride

Dissolved-chloride concentrations in 427 ground-water samples from the Saginaw aquifer range from 0.7 to 55,000 mg/L (fig. 7). Water from the southern one-third of the aquifer and in a few small areas in the north has a chloride concentration of less than 10 mg/L. Ground water from part of the Saginaw Bay Area and in a narrow (approximately 10 mi wide) corridor that extends from the Saginaw Bay Area to the north-central part of the aquifer has concentrations of chloride greater than 1,000 mg/L. Chloride concentrations in water from about one-half of the areal extent of the aquifer range from 10 to 1,000 mg/L. The source of chloride in ground water in the Saginaw aquifer may be from mixing with brine from within the aquifer or from underlying aquifers. Similar to high concentrations of dissolved solids, high chloride concentrations are associated with deep wells in the Saginaw aquifer. Dissolved-chloride concentrations of water from the Parma-Bayport aquifer exceed 100,000 mg/L in the Saginaw Bay Area and the west-central part of the aquifer.

Dissolved Iron

Dissolved-iron concentrations in 337 ground-water samples from the Saginaw aquifer range from 0.01 to 7.80 mg/L. The dissolved-iron concentrations mapped in figure 8 represent the combined concentrations of ferrous and ferric iron. Dissolved-iron concentrations in water from the

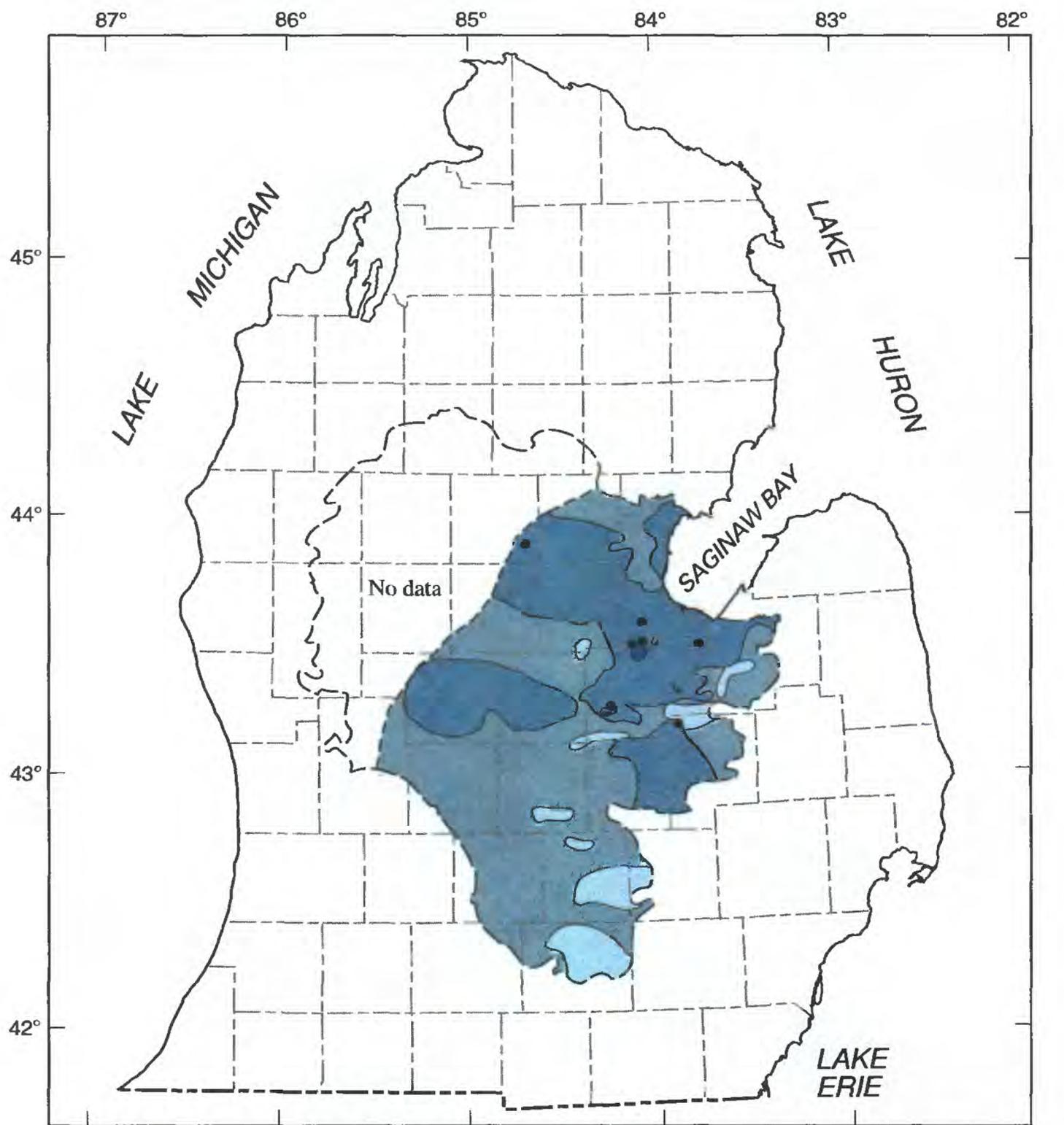
central and eastern parts of the aquifer typically range from 0.1 to 1.0 mg/L. Concentrations greater than 1.0 mg/L are found in water from the west-central, southwest, and east-central parts of the aquifer. Trends of the data are not readily apparent throughout the aquifer.

Dissolved Sulfate

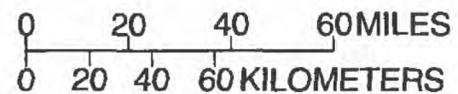
Concentrations of dissolved sulfate in 427 water samples from the Saginaw aquifer range from 0.2 to 3,500 mg/L. Water from the southern part of the aquifer has a dissolved-sulfate concentration generally less than 100 mg/L and locally less than 10 mg/L (fig. 9). Concentrations of less than 100 mg/L are also found in water from part of the Saginaw Bay Area, from the eastern edge of the aquifer as well as from the center of the basin. The zone of low sulfate concentration in the Saginaw Bay Area may be due to sulfate reduction. This process is taking place in the Saginaw Bay Area according to an interpretation of stable-isotope ratios of carbon and sulfur from ground water (Long and others, 1988). Sulfate concentrations exceed 100 mg/L in water from much of the north-central and northeastern parts of the aquifer. Sulfate concentrations are greater than 1,000 mg/L in water from three areas that adjoin the dashed line that delineates the area of no data on the west (fig. 9). The southernmost of these areas coincides with the presence of Jurassic deposits that contain gypsum (Cohee, 1965; Westjohn and others, 1994), which may be the source of sulfate to ground water. The other areas may also be affected by Jurassic deposits directly to the west. In addition, the dissolution of gypsum and anhydrite, believed to be unevenly distributed in overlying glacial deposits, or oxidation of pyrite may provide an additional source of sulfate to the Saginaw aquifer (Wood, 1969).

Hydrochemical Facies

The concept of hydrochemical facies is a means of describing the diagnostic chemical character of 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



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



EXPLANATION

DISSOLVED-SOLIDS CONCENTRATION,
IN MILLIGRAMS PER LITER

- Less than 500
- 500 to 1,000
- Greater than 1,000 to 5,000
- Greater than 5,000

----- BOUNDARY OF PENNSYLVANIAN
SUBCROP

- WELL--Water sample with greater than 10,000
milligrams per liter dissolved-solids concentration

Figure 6. Distribution of dissolved solids in ground water from the Saginaw aquifer, Lower Peninsula of Michigan.

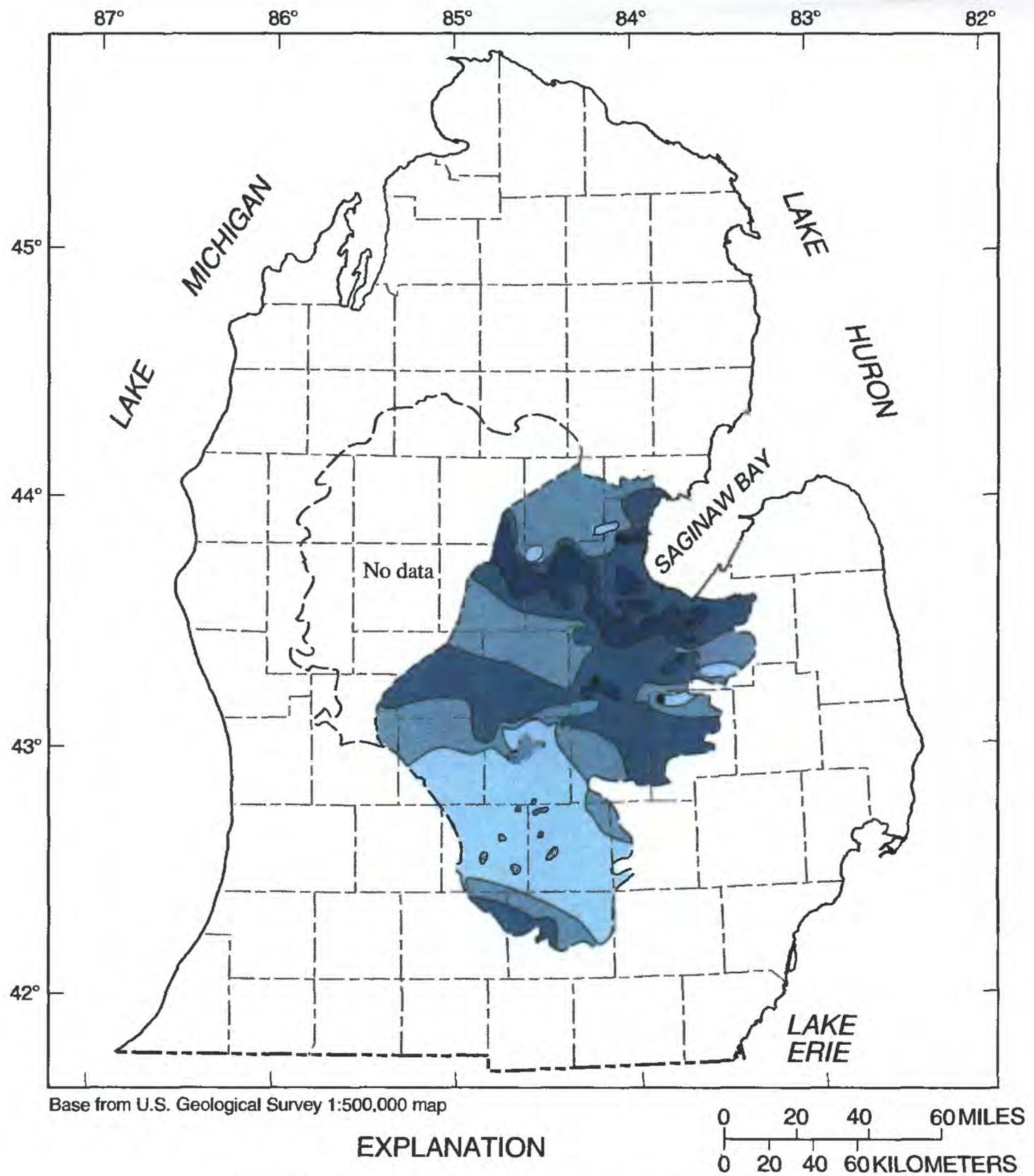


Figure 7. Distribution of dissolved chloride in ground water from the Saginaw aquifer, Lower Peninsula of Michigan.

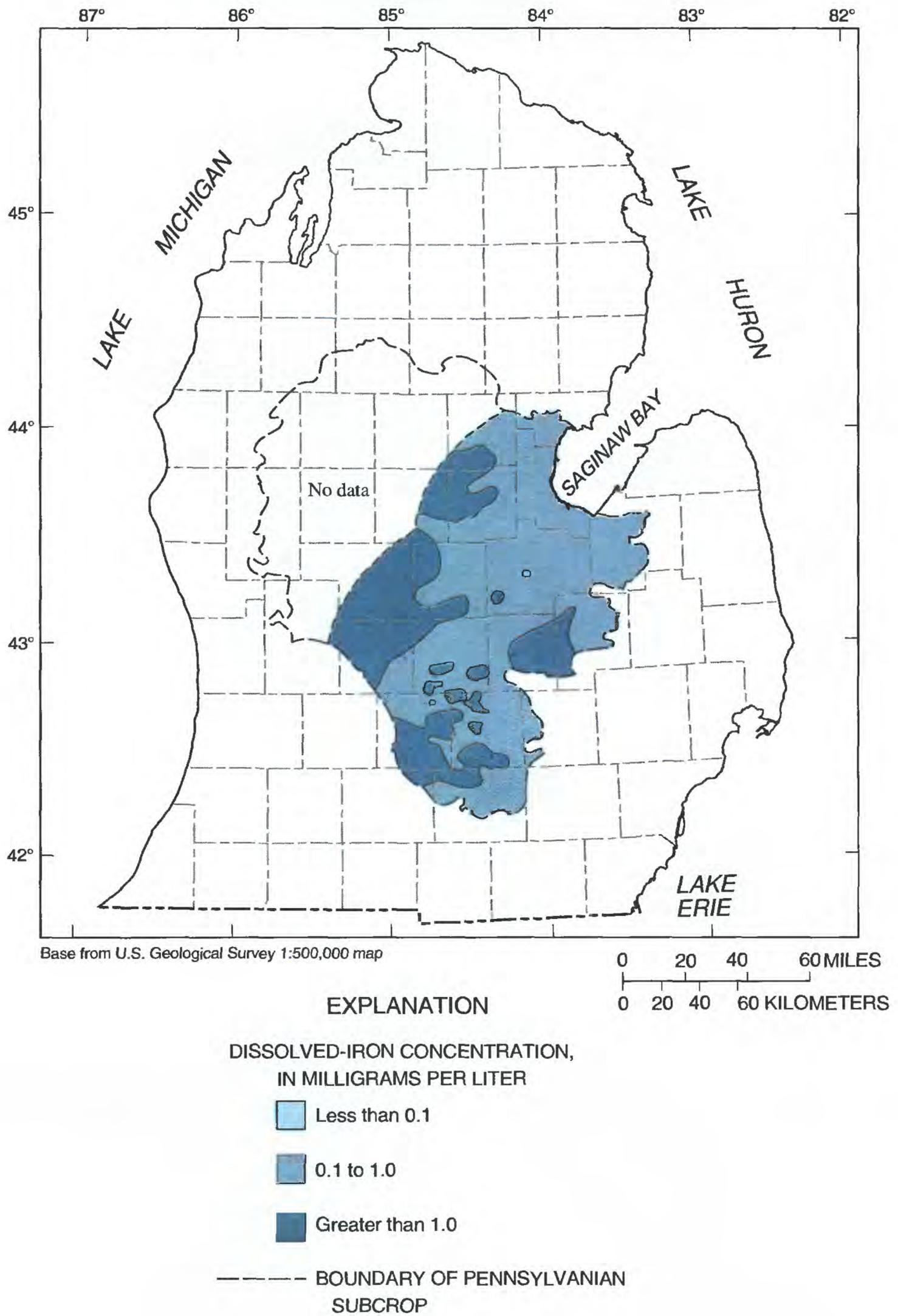
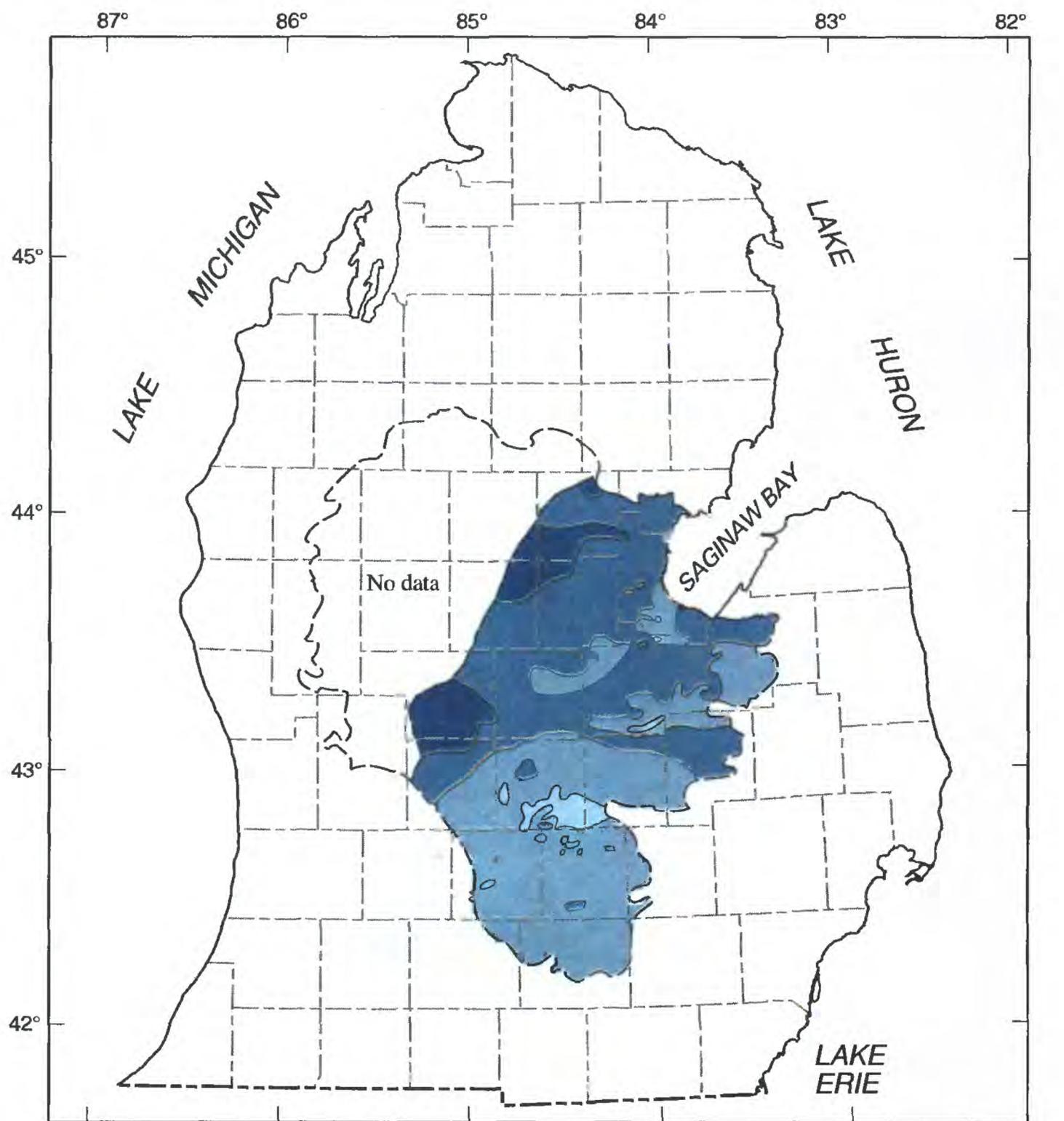
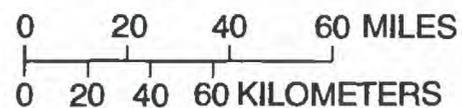


Figure 8. Distribution of dissolved iron in ground water from the Saginaw aquifer, Lower Peninsula of Michigan.



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



EXPLANATION

DISSOLVED-SULFATE CONCENTRATION,
IN MILLIGRAMS PER LITER

- Less than 10
- 10 to 100
- Greater than 100 to 1,000
- Greater than 1,000

--- BOUNDARY OF PENNSYLVANIAN
SUBCROP

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

of the chemistry of water samples, identification of water with similar chemical characteristics, evaluation of mixing among water having 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 plotted on a diagram by converting cation and anion concentrations to milliequivalents per liter and then calculating relative percentages of cation and anion species or groups of species. For diagrammatic purposes, cations and anions each sum to 100 percent. Values of each sample are plotted on respective cation and anion ternary diagrams and also on a central diamond-shaped diagram (fig. 10a). Locations of the samples on ternary diagrams are the basis for identifying hydrochemical facies of a ground-water sample (fig. 10a). 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 to construct the Piper plot of ground water from the Saginaw 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 is addressed by constructing three Piper plots (fig. 10b to 10d) 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 750 mg/L, 751 to 2,000 mg/L, and greater than 2,000 mg/L.

At all ranges of dissolved-solids concentrations, the trend of data on the cation ternary diagram is from the calcium-dominant area to the sodium-dominant area with little scatter. However, most samples are calcium dominant at low dissolved-solids concentrations (fig. 10b) and sodium dominant at high dissolved-solids concentrations (fig. 10d). Most analyses of water samples plot on the anion ternary diagram as bicarbonate sulfate dominant at low dissolved-solids concentrations (fig. 10b) and as chloride dominant at high dissolved-solids concentrations (fig. 10d). Water with the highest dissolved solids in all diagrams plots toward the chloride-dominant facies. 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 10b. At high dissolved-solids concentrations, ground water is commonly sodium chloride and calcium sulfate dominant (fig. 10d) because of dissolution of halite, gypsum, and anhydrite and (or) because of mixing with brine. Mixing among such water could explain observed trends (fig. 10d). Trends at intermediate dissolved-solids concentrations (fig. 10c) are probably a result of mixing of water of low and high dissolved-solids concentrations.

A hydrochemical facies map for the Saginaw aquifer (fig. 11) was prepared to show the areal distribution of chemical aspects of facies as classified on Piper plots (figs. 10b to 10d). Most water from the Saginaw aquifer is classified as calcium bicarbonate, sodium chloride, or calcium

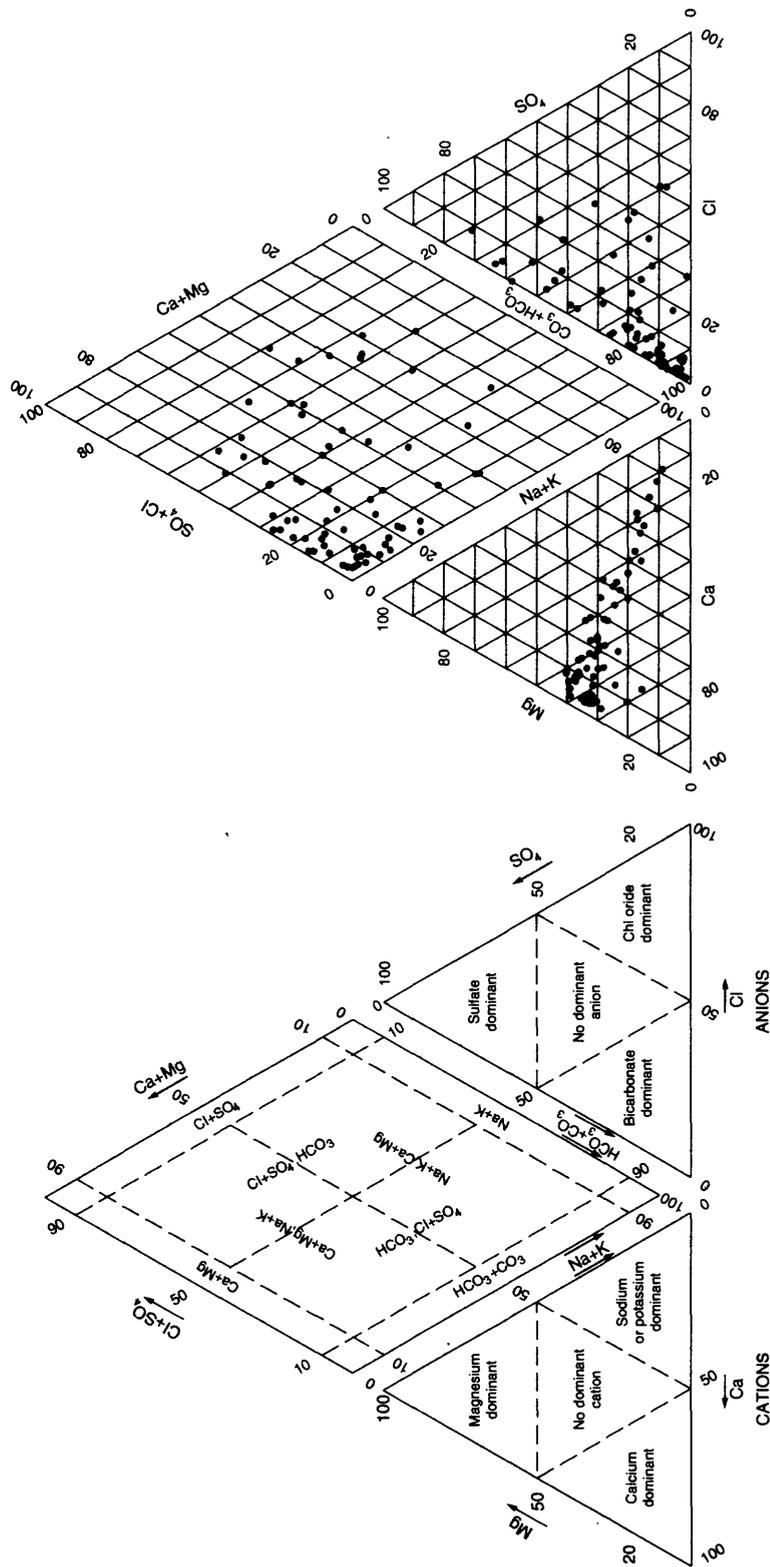
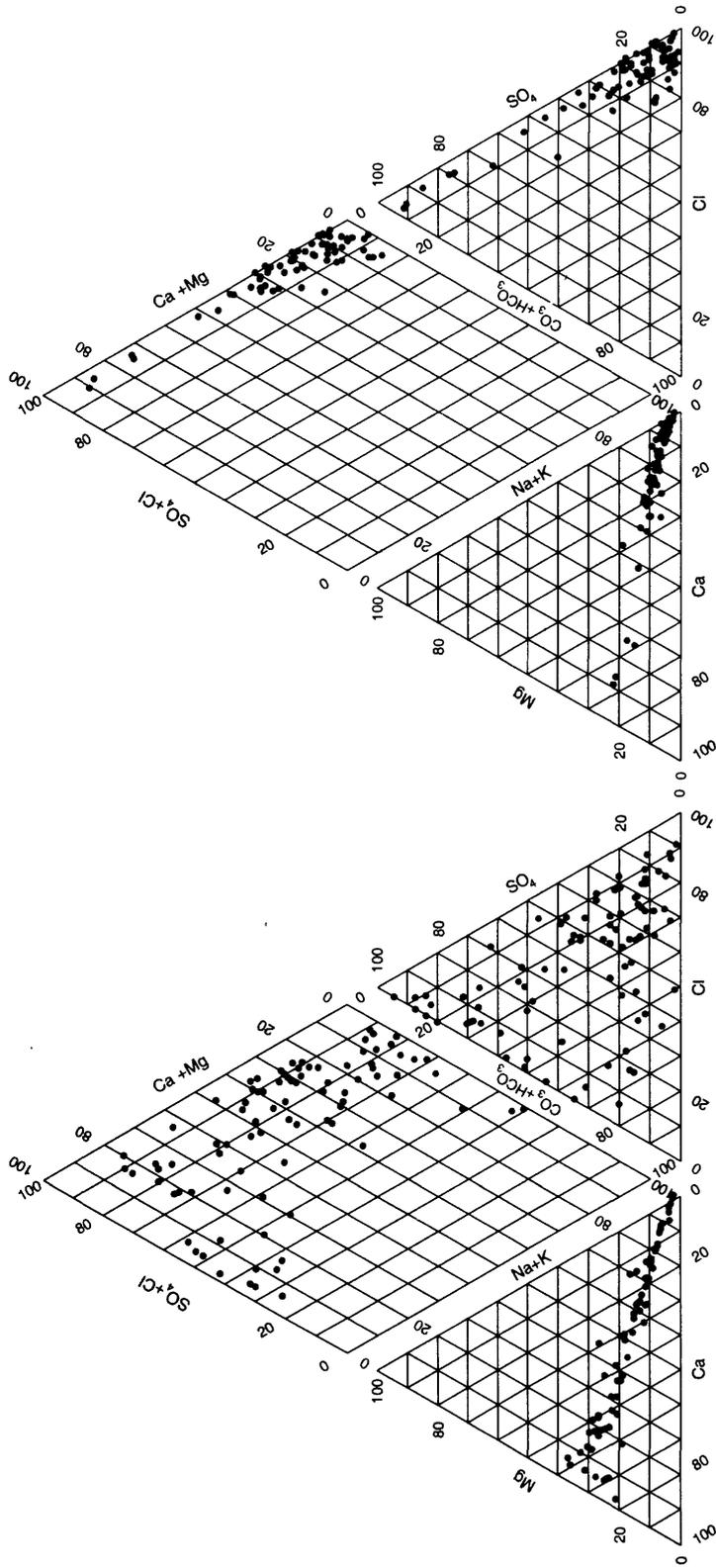


Figure 10. Modified Piper plot of the classification scheme for hydrochemical facies and Piper plots for ground water from the Saginaw aquifer, Lower Peninsula of Michigan, at different ranges of dissolved-solids concentrations.



c. Dissolved-solids concentrations 750 to 2,000 milligrams per liter

d. Dissolved-solids concentrations greater than 2,000 milligrams per liter

Figure 10. Modified Piper plot of the classification scheme for hydrochemical facies and Piper plots for ground water from the Saginaw aquifer, Lower Peninsula of Michigan, at different ranges of dissolved-solids concentrations--Continued

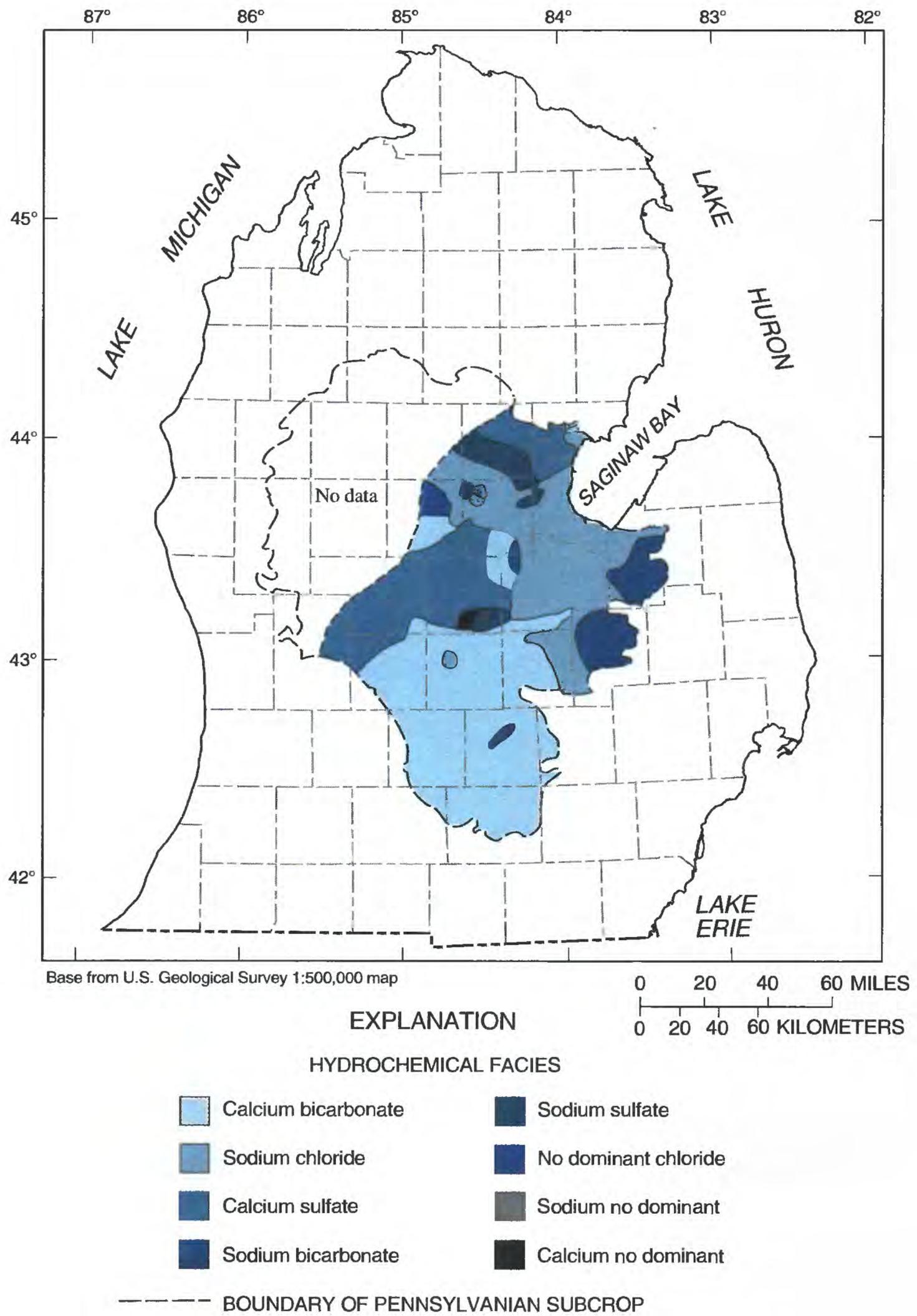


Figure 11. Distribution of hydrochemical facies for ground water from the Saginaw aquifer, Lower Peninsula of Michigan.

sulfate facies. Sodium bicarbonate and sodium sulfate facies are present in some isolated areas.

Ground water from the southern part of the Saginaw aquifer is dominantly calcium bicarbonate facies. Calcium and bicarbonate dominance is typical of water that recently entered an aquifer from precipitation (Back, 1961; Berner and Berner, 1987). A calcium sulfate facies is dominant in the west-central and northeastern parts of the aquifer. In the Saginaw Bay Area and extending out to the basin center, a sodium chloride facies is dominant. Calcium sulfate facies in the west and southwest are most likely influenced by gypsum dissolution in overlying Jurassic deposits (D.B. Westjohn, U.S. Geological Survey, written commun., 1992; Westjohn and others, 1994). Calcium sulfate facies in the north may be the result of gypsum and anhydrite dissolution or pyrite oxidation (Wood, 1969). The sodium chloride facies present in and around the Saginaw Bay Area are most likely the result of mixing with saline water or brine. Separating calcium sulfate and sodium chloride facies in the north-central part of the aquifer is an area of sodium sulfate facies. The sodium sulfate facies are believed to be the result of mixing water that has sodium and chloride as dominant ions with water that has calcium and sulfate as dominant ions. Sodium bicarbonate facies, which are present along the eastern edge of the aquifer, are believed to be derived from mixing water with sodium and chloride as dominant ions with calcium and bicarbonate as dominant ions.

SUMMARY

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

Interpretation of δD and $\delta^{18}\text{O}$ relations indicates that modern meteoric (post glacial) and glacial-age meteoric water are present in the Saginaw aquifer. The $\delta^{18}\text{O}$ 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. The slow flushing seems to be due to the presence of low-permeability sediments.

Analyses of dissolved solids and dissolved chloride in water from the Saginaw aquifer indicate that the most concentrated water is in and around the Saginaw Bay Area, and the most dilute water is mainly in the south. The source of some solutes for dissolved solids may be from mixing with brine from underlying geologic units.

Dissolved-iron concentrations throughout the basin show no apparent spatial trend. Low concentrations of sulfate in the Saginaw Bay Area may be due to sulfate reduction, which is taking place according to an interpretation of stable-isotope ratios of carbon and sulfur from ground water in that region. High concentrations of sulfate may be due to dissolution of either gypsum in Jurassic deposits, dissolution of gypsum and anhydrite that are unevenly distributed in the overlying glacial deposits, and (or) oxidation of pyrite.

Distribution of data on Piper plots show a cation trend from calcium dominant at low dissolved-solids concentrations to sodium dominant at high dissolved-solids concentrations, and an anion trend from bicarbonate sulfate dominant at low dissolved-solids concentrations to chloride sulfate dominant at high dissolved-solids concentrations. At intermediate concentrations, cation and anion dominance indicates mixing of water with different chemical and isotopic compositions. Most ground water from the Saginaw aquifer is classified as calcium bicarbonate, calcium sulfate, or sodium chloride facies. Calcium bicarbonate facies, located mainly in the southern part of the aquifer, are consistent with water recently recharged to an aquifer. Calcium sulfate facies are located mainly in the west-central and northeastern areas, and sodium chloride facies are in the Saginaw Bay Area extending out into the central part of the aquifer.

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