GEOCHEMISTRY OF THE CAMBRIAN-ORDOVICIAN AQUIFER SYSTEM IN THE NORTHERN MIDWEST, UNITED STATES

REGIONAL AQUIFER-SYSTEM ANALYSIS

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Geochemistry of the Cambrian–Ordovician Aquifer System in the Northern Midwest, United States

By D.I. SIEGEL

REGIONAL AQUIFER–SYSTEM ANALYSIS—
NORTHERN MIDWEST AQUIFER SYSTEM

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. 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, both 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, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Dallas L. Peck

Dallas L. Peck
Director

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For readers who prefer to use metric (International System) units rather than the inch-pound units used in this report, conversion factors are listed below.

Multiply inch-pound unit	*By*	*To obtain metric unit*
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow	
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per square mile per year [(ft^3/mi^2)/yr]	0.01093	cubic meter per square kilometer per year [(m^3/km^2)/yr]
	Temperature	
degree Fahrenheit (°F)	0.5556 (°F−32)	degree Celsius (°C)

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."

SYMBOLS AND DEFINITIONS

δ	Isotopic composition expressed as permil differences in the measured isotopic ratios of sample and standard.
$\delta^{13}C$	Standard expression of the ratio of the ^{13}C ion with respect to the ^{12}C ion.
δD	Standard expression of the ratio of the ^{2}H ion (deuterium) with respect to the ^{1}H ion.
$\delta^{18}O$	Standard expression of the ratio of the ^{18}O ion with respect to the ^{16}O ion.
$\delta^{34}S$	Standard expression of the ratio of the ^{34}S ion with respect to the ^{32}S ion.
μg/L	Micrograms per liter.
Eh	Oxidation potential, log activity of e^1.
e^1	Electron.
(g)	Gaseous.
meq/L	Milliequivalents per liter.
mg/L	Milligrams per liter.
P_{CO_2}	Partial pressure of carbon dioxide.
PDB	PeeDee belemnite ^{13}C isotopic standard.
pCi/L	Picocuries per liter.
pH	Negative log activity of H^+.
ppm	Parts per million.
SI	Saturation index.
SMOW	Standard Mean Ocean Water ^{18}O and ^{2}H isotopic standard.
(s)	Solid.

REGIONAL AQUIFER-SYSTEM ANALYSIS—NORTHERN MIDWEST AQUIFER SYSTEM

GEOCHEMISTRY OF THE CAMBRIAN-ORDOVICIAN AQUIFER SYSTEM IN THE NORTHERN MIDWEST, UNITED STATES

By D.I. SIEGEL

ABSTRACT

Distributions of solutes in aquifers of Cambrian and Ordovician age were studied in Minnesota, Wisconsin, Iowa, Illinois, northwestern Indiana, and northern Missouri to determine the sources of solutes and the probable chemical mechanisms that control regional variations in water quality. This work is part of the Northern Midwest Regional Aquifer-System Analysis project, whose objective is to describe and model the regional hydrogeology of the Cambrian-Ordovician aquifer system in the study region. The data base used included more than 3,000 ground-water-quality analyses from all major aquifers, but especially from the St. Peter, Jordan, and Mount Simon Sandstones and their equivalents. Regional variations in the water chemistry of glacial drift and other sedimentary units that overlie the Cambrian-Ordovician aquifer system in recharge areas in Minnesota, Iowa, Wisconsin, and Illinois were also studied, but to a lesser degree.

The most important chemical variation in the aquifer is the change in water type from calcium-sodium-sulfate-bicarbonate water to sodium-calcium-sulfate-bicarbonate and sodium-chloride waters along the longest regional flow path from northwestern Iowa to the Illinois basin. Sodium predominance downgradient from the recharge area is probably related to mechanisms of ion exchange and shale-membrane filtration near the Illinois and Forest City basins.

The most striking aspect of the distribution of dissolved solids and carbon isotopic content of bicarbonate is the increase in concentration and isotopic enrichment from southwestern Wisconsin, southern Minnesota, and northwestern Illinois south toward Missouri. This trend is perpendicular to the present hydraulic gradient that trends from northwestern Iowa southeastward to the Illinois basin. The distribution of dissolved solids defines a "plume" of dilute water having a dissolved-solids concentration of about 500 milligrams per liter, compared with surrounding concentrations more than twice as large. Distribution of the isotopic content of oxygen ($\delta^{18}O$) and hydrogen (δD) in water closely parallels that of dissolved solids and shows covariance similar to modern meteoric water. The isotopic contents are more depleted (lighter) toward the south, perpendicular to the direction of current hydraulic gradients. The degree of depletion, compared with the isotopic content of modern recharge water, indicates that the plume and a significant fraction of the ground water in Iowa, northern Missouri, and possibly central Illinois may have originated as recharge during Pleistocene time.

Distributions of dissolved trace constituents in the aquifers probably are related to the proximity to mineralogic sources as well as chemical and hydraulic mechanisms. For example, concentrations of some constituents, such as cadmium and arsenic, are largest in the vicinity of the Dakota Formation in northwestern Iowa. Other constituents, such as beryllium and vanadium, have larger concentrations near the edge of the Forest City basin in southwestern Iowa and northwestern Missouri. Strontium and fluoride concentrations generally increase from north to south, which suggests the input of these trace constituents during the recharge events. However, concentrations of bromide, radium-226, and lithium show distribution patterns similar to the "plume" defined by dissolved solids and isotopes of water, suggesting dilution of concentrations of trace constituents by Pleistocene recharge. Concentrations of other constituents are partly controlled by aquifer temperature, such as silica in south-central Iowa, and solubility controls, such as barium in northeastern Illinois. Additional information on the chemical and mineralogical composition of the aquifer matrix and the isotopically lightest ground water is needed to evaluate the hypothesis of Pleistocene mixing before more quantitative studies can be done to evaluate the different proposed mechanisms that have controlled and modified the water chemistry over time. This study, however, indicates that the ground water in the region is thousands of years old. The study also indicates that the major chemical trends in the aquifers probably are related as much to paleohydrogeologic flow systems during Pleistocene time as to the present flow system, which may postdate the retreat of the last ice sheet about 12,000 years ago.

INTRODUCTION

Sandstone and dolomite strata of Cambrian and Ordovician age make up much of the sedimentary rocks overlying the Precambrian basement in the northern Midwest and form the major aquifer system of that area. In October 1978, the U.S. Geological Survey began a regional assessment of the Cambrian-Ordovician aquifer system in that area (Steinhilber and Young, 1979) as part of its national Regional Aquifer-System Analysis (RASA) program (Bennett, 1979). The major goals of the RASA program are to (1) gain an understanding of the hydrogeologic system in each region, including the nature of the hydrogeologic units, ground-water flow system, and chemical quality of the water, and (2) describe the regional interaction of components of the system, especially as affected by large-scale withdrawal of ground water. The latter goal is accomplished by constructing digital-computer models that simulate the ground-water flow system.

Manuscript approved for publication November 15, 1985.

PURPOSE AND SCOPE

This report describes the hydrologic and geochemical mechanisms that cause regional differences in groundwater quality in the northern Midwest. Other regional reports on the aquifer system are being published as chapters of U.S. Geological Survey Professional Paper 1405. They include chapter A, a summary of the Northern Midwest RASA (H.L. Young, U.S. Geological Survey, written commun., 1988), chapter B, which describes the regional hydrogeology and water quality (Young, in press), chapter C, which describes a regional three-dimensional ground-water model of the study area (Mandle and Kontis, in press), and chapter E, which describes a detailed three-dimensional ground-water flow model of the Chicago-Milwaukee area (H.L. Young and A.J. MacKenzie, U.S. Geological Survey, written commun., 1988).

The study covers about 161,000 mi^2 in northern Illinois, northwestern Indiana, Iowa, southeastern Minnesota, northern Missouri, and Wisconsin (fig. 1). The border of the study area delimits either the natural physical or hydrologic boundaries of the aquifer system or places where the aquifers are not used because of poor water quality. The northern boundary, from northwestern Iowa to northeastern Wisconsin, delineates the erosional edge of Cambrian rocks overlying crystalline basement rocks of Precambrian age. The Missouri River is a discharge line and forms the western and southwestern boundary. Beyond the eastern and southeastern boundary in Michigan, Illinois, and Indiana, water in the aquifer is too highly mineralized to be used. As a first approximation, the brine-saltwater interface at about 30,000 mg/L is assumed to be a minimal-flow boundary.

The primary subject of the study is the Cambrian- and Ordovician-age rocks that form the dominant aquifer system in the study area. However, because some wells developed in the Cambrian-Ordovician aquifer system are also open to the overlying carbonate rocks of the Silurian-Devonian aquifer, the latter, although only a minor aquifer regionally, is included in the study.

ACKNOWLEDGMENTS

I express my appreciation to many U.S. Geological Survey colleagues for their assistance in this study. Special thanks go to E.C. Alexander, Jr., and H.E. Wright, Jr., University of Minnesota, and to E.G. Perry, Jr., Northern Illinois University, for discussions on Pleistocene geology and environmental isotope geochemistry in the study area, and to the many geologists in State agencies with whom I had helpful conversations.

HYDROGEOLOGIC SETTING

The regional hydrogeology of the Cambrian-Ordovician aquifer system in the northern Midwest is summarized in Professional Paper 1405–B. The following is a brief regional synopsis of the structural, lithologic, and hydrologic features of the geologic formations in the study area and a description of the vertical discretization of geologic units into layers used in the regional flow model. Detailed accounts of the geology and hydrology of each of the States in the study area can be found in publications of State agencies and the U.S. Geological Survey referenced in Professional Paper 1405–B. The nomenclature used in this report was established for the Northern Midwest RASA (see Professional Paper 1405–B) and does not necessarily coincide with that previously accepted by the U.S. Geological Survey. It follows usage prevalent in the majority of the study area, or usage of a particular State, where appropriate.

The consolidated sedimentary rocks in the northern Midwest consist of sandstone, carbonate, and shale sequences that range in age from Precambrian to Cretaceous (fig. 2). They overlie the eroded surface of the Precambrian basement complex, which consists of crystalline igneous and metamorphic rocks. This basement complex forms the North American craton, the more permanent nucleus of the continent. The widespread sedimentary rocks were deposited in the midcontinental interior by a series of transgressions and regressions of the epeiric Sauk and Tippicanoe seas (King, 1959) as the craton subsided. Irregular subsidence resulted in the formation of the Illinois, Michigan, and Forest City basins, beginning in Early Cambrian time. The major structurally high areas, the Kankakee, Transcontinental, and Wisconsin arches, also began developing during Cambrian time (fig. 2). Cambrian and Ordovician rocks presently crop out or subcrop beneath Pleistocene drift and Holocene sediments in southeastern Minnesota, northeastern Iowa, northern Illinois, and southern Wisconsin. A band of Silurian and Devonian rocks subcrop beneath glacial drift along the trend of the Kankakee arch between Michigan and Illinois, along the eastern part of Wisconsin, and in northeastern Iowa (fig. 2). Mississippian and younger rocks border the major sedimentary basins and are present southwest and east of the Silurian rocks.

The Cambrian and Ordovician rocks in the northern Midwest have long been divided into rock-stratigraphic units on the basis of lithology and lateral continuity. For this study, the units were grouped into five aquifer layers and four confining layers on the basis of their hydrologic properties. Figure 3 is a generalized geologic

Base enlarged from
U.S.Geological Survey
1:7,500,000, 1970

FIGURE 1.—Location and general features of the Northern Midwest Regional Aquifer-System Analysis area.

section from Missouri to Wisconsin, which shows this hydrogeologic grouping. The first and deepest hydrogeologic unit, the Mount Simon aquifer (aquifer layer 1), is composed mainly of the Mount Simon Sandstone and its equivalents. This basal sandstone rests on the Precambrian basement complex in much of the study area, but on older Precambrian red clastic rocks in Minnesota and western Wisconsin. The latter are included in aquifer layer 1. The Mount Simon Sandstone is a marine, fine- to coarse-grained conglomeratic sandstone and ranges in thickness from less than 100 ft in Minnesota and Wisconsin to more than 2,500 ft in the northern part of the Illinois basin. In the northern part of the area it is overlain by shale, dolomitic sandstone, siltstone, and dolomite of the Eau Claire Formation, which constitutes a regional confining unit. The Eau Claire is predominantly a fine-grained sandstone in Wisconsin but has varying amounts of shale. The Eau

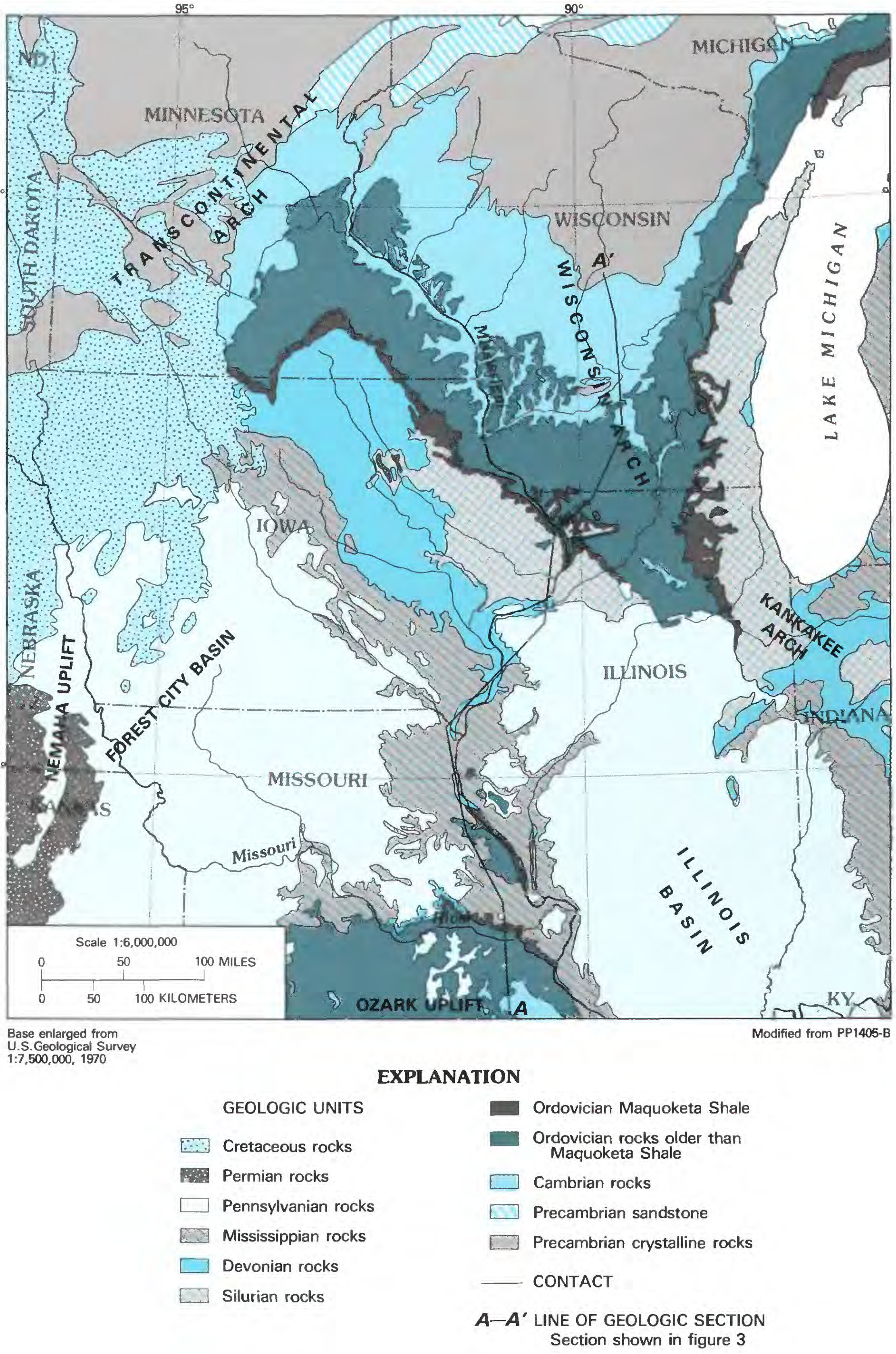
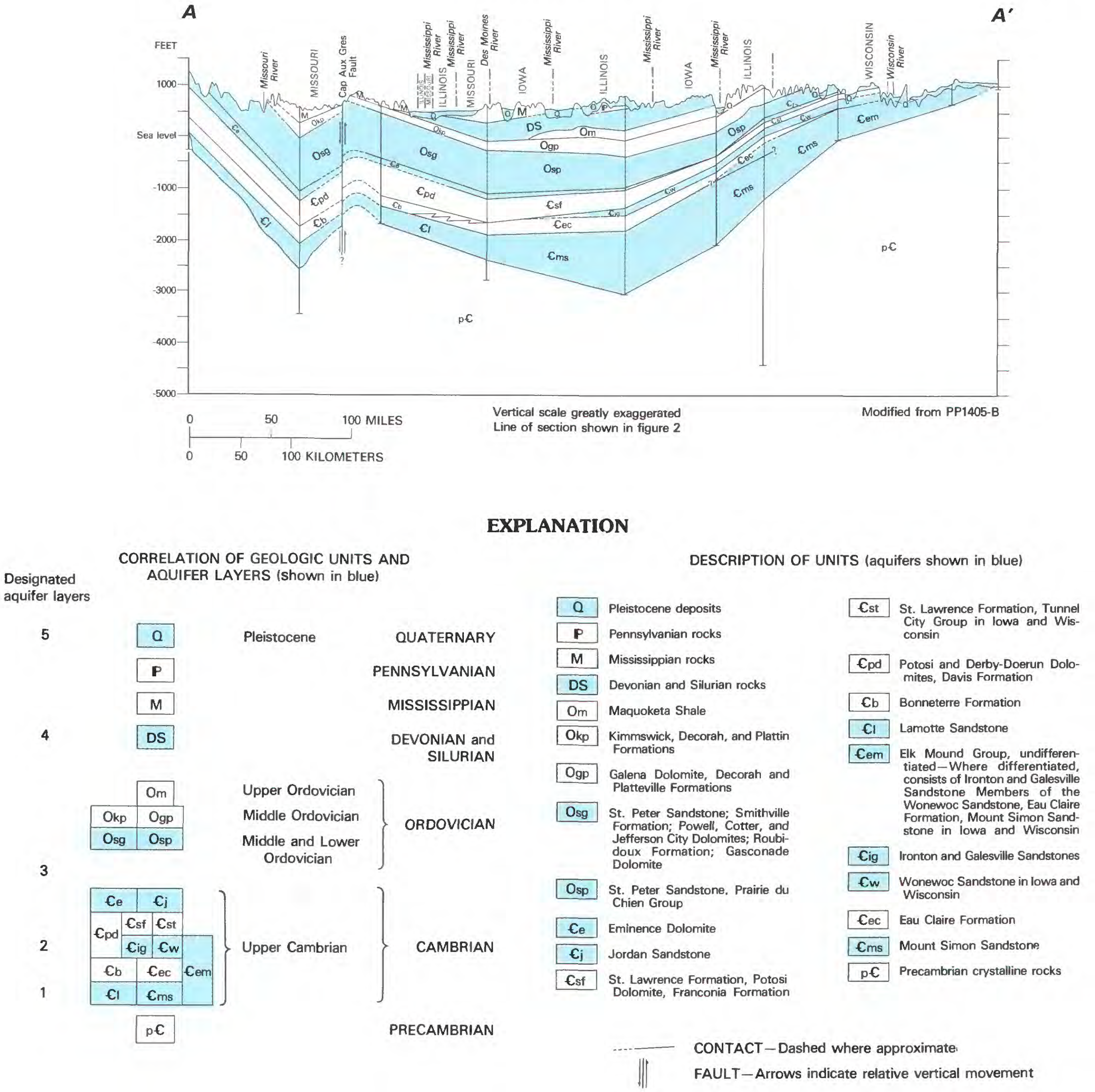


FIGURE 2.—General bedrock geology of the northern Midwest. (Modified from Young, in press.)



EXPLANATION

CORRELATION OF GEOLOGIC UNITS AND AQUIFER LAYERS (shown in blue)

DESCRIPTION OF UNITS (aquifers shown in blue)

Q	Pleistocene deposits
P	Pennsylvanian rocks
M	Mississippian rocks
DS	Devonian and Silurian rocks
Om	Maquoketa Shale
Okp	Kimmswick, Decorah, and Plattin Formations
Ogp	Galena Dolomite, Decorah and Platteville Formations
Osg	St. Peter Sandstone; Smithville Formation; Powell, Cotter, and Jefferson City Dolomites; Roubidoux Formation; Gasconade Dolomite
Osp	St. Peter Sandstone, Prairie du Chien Group
Ꞓe	Eminence Dolomite
Ꞓj	Jordan Sandstone
Ꞓsf	St. Lawrence Formation, Potosi Dolomite, Franconia Formation
Ꞓst	St. Lawrence Formation, Tunnel City Group in Iowa and Wisconsin
Ꞓpd	Potosi and Derby-Doerun Dolomites, Davis Formation
Ꞓb	Bonneterre Formation
Ꞓl	Lamotte Sandstone
Ꞓem	Elk Mound Group, undifferentiated—Where differentiated, consists of Ironton and Galesville Sandstone Members of the Wonewoc Sandstone, Eau Claire Formation, Mount Simon Sandstone in Iowa and Wisconsin
Ꞓig	Ironton and Galesville Sandstones
Ꞓw	Wonewoc Sandstone in Iowa and Wisconsin
Ꞓec	Eau Claire Formation
Ꞓms	Mount Simon Sandstone
pꞒ	Precambrian crystalline rocks

CONTACT—Dashed where approximate

FAULT—Arrows indicate relative vertical movement

FIGURE 3.—Geologic section from Missouri to Wisconsin. (Modified from Young, in press.)

Claire is not strongly confining in much of Wisconsin and is hydrologically connected with the underlying Mount Simon Sandstone and the overlying Ironton and Galesville Sandstones, except toward the south where the upper part becomes more shaly. To the south in Missouri, the Eau Claire grades into dolomite of the Bonneterre Formation. In northern Illinois, the lower part of the Eau Claire, the Elmhurst Sandstone Member, is included in aquifer layer 1, which is locally termed the "basal sandstone aquifer." In south-central Minnesota, the Eau Claire Formation consists, in part, of glauconitic "greensands."

Aquifer layer 2, the Ironton-Galesville aquifer, is the combined Ironton and Galesville Sandstones and, in Iowa and Wisconsin, the equivalent Wonewoc Formation. It is generally less than 100 ft thick but exceeds 200 ft in the Illinois basin. It consists of calcareous to dolomitic sandstone in Minnesota, Wisconsin, and northern Illinois. The aquifer layer is absent in southern Illinois and is thin or absent and grades into carbonate rocks of the lower part of the Davis Formation in southwestern Iowa and Missouri. Shaly sandstones of the Franconia Formation and limestone and dolomite of the St. Lawrence Formation overlie and confine the Ironton-Galesville aquifer in the north. The southern equivalent of the St. Lawrence-Franconia confining unit is the upper Davis Formation through Potosi Dolomite interval.

The composition of the third aquifer layer varies with its geographic location. In most of the study area it consists of, from oldest to youngest, the Jordan Sandstone, the overlying Prairie du Chien Group, and the St. Peter Sandstone. In Missouri, the Gasconade Dolomite-Smithville Formation sequence is a general equivalent and replaces the Prairie du Chien Group. Also, the Jordan Sandstone is replaced by the Eminence Dolomite in Missouri and all but the extreme northwestern part of Illinois. These formations are generally in hydrologic connection. They are treated as a single unit because fractures commonly penetrate through the Prairie du Chien Group.

The Jordan Sandstone is a coarse- to medium-grained orthoquartzite to dolomitic sandstone in Minnesota, Wisconsin, and Iowa, grading into sandy dolomite and dolomite in southern Iowa, northern Missouri, and all but the extreme northwestern part of Illinois. The Prairie du Chien Group consists of fossiliferous dolomite and limestone interbedded with thin, discontinuous beds of sandstone, siltstone, and shale. Aquifer layers 1 and 3 generally range from 200 to 600 ft in thickness in the northern half of the study area but thicken to more than 1,500 ft in the Illinois basin. The St. Peter Sandstone is a laterally persistent clean and friable orthoquartzite, generally 100 to 200 ft thick except locally in northern Illinois, where thickness exceeds 700 ft upon pre-St. Peter karstic topography.

The Maquoketa Shale forms a very effective confining unit above aquifer layer 3 over much of the study area. The Maquoketa consists of thick pyritic shales except in western Iowa and Minnesota, where the shales grade into interbedded dolomitic limestones and shaly dolomites that provide a hydraulic connection with overlying and underlying carbonates. The shaly dolomites, which make up the Galena Dolomite and Decorah and Platteville Formations or equivalents, are generally of low permeability where overlain by the Maquoketa and are included as part of the confining unit. The base of the confining unit is the Glenwood Formation, which consists generally of shale and silty, shaly sandstone. Extensive phosphatic beds are present within the Maquoketa in Iowa. The Cambrian-Ordovician aquifer system is further confined by thick sequences of younger Paleozoic rocks south of the outcrop of the Maquoketa Shale.

Aquifer layer 4 consists of the carbonate rocks of the Silurian through Middle Devonian and is termed the Silurian-Devonian aquifer for this study. The rocks are dominantly thick- to thinly bedded dolomites, limestones, and shales that are hydraulically connected by fractures. Where not eroded, they generally range in thickness from 200 to 500 ft, but they are more than 1,000 ft thick in the Illinois basin. The excellent confinement of the Maquoketa Shale, which separates aquifer layer 4 from aquifer layer 3, limits the potential of water in aquifer layer 4 to affect the chemistry of water in the Cambrian-Ordovician aquifer system. However, the opposite may be true where the Maquoketa is mainly a fractured carbonate. The very thick sequence of younger consolidated rocks from the Upper Devonian through the Pennsylvanian contains little aquifer material and, for the purposes of this study, is considered to be a confining unit between aquifer layers 4 and 5. In Iowa, the Mississippian is classified as a separate aquifer (Horick and Steinhilber, 1973).

Aquifer layer 5 consists of the combined Holocene surficial deposits, Pleistocene glacial drift, or Cretaceous rocks that form the land surface over most of the study area. This layer directly overlies the units of the Cambrian-Ordovician aquifer system in much of the Cambrian-Ordovician outcrop areas in Minnesota, Iowa, Wisconsin, and Illinois. Most drift is calcareous because of carbonate minerals derived from the glacial erosion of Paleozoic limestones and dolomites in Manitoba and Michigan and within the study area. Except for the Driftless Area of southwestern Wisconsin and adjacent small areas in Illinois and Iowa, the entire study area was glaciated during the Pleistocene. Cretaceous rocks that overlie the Cambrian and Ordovician rocks in western Minnesota and Iowa consist of varicolored marine shales, siltstones, and lignitic sandstones of the Dakota Formation, which commonly contains disseminated pyrite in its basal part.

The ground-water reservoir is recharged by infiltration of precipitation through the soil into the underlying rock. Because glacial deposits are the surficial rocks in most of the northern Midwest, they receive most of the initial recharge. Aquifer layers 1 through 4 also are recharged by infiltration of precipitation where they crop out at the land surface, such as in the Driftless

Area. These aquifers also receive recharge by vertical seepage across confining beds, where they subcrop beneath aquifer layer 5 and where they are penetrated by buried bedrock valleys eroded by glacial meltwater streams during Pleistocene time. Both field observation and steady-state simulation of the ground-water flow system (Mandle and Kontis, in press) indicate that vertical head gradients in the Cambrian-Ordovician aquifers (aquifer layers 1 through 3) are generally upward where overlain by the Maquoketa Shale in Iowa, Illinois, and Wisconsin (fig. 4). Vertical head gradients are downward in the Cambrian-Ordovician outcrop areas in much of south-central Minnesota, south-central Wisconsin, and northern Iowa.

Ground water flows from topographically high recharge areas to low discharge areas. Most of the ground water in aquifer layer 5 moves within local flow systems of a few miles in length and discharges to small first- and second-order tributaries of the major rivers. Ground-water movement in the unconfined parts of the Cambrian-Ordovician aquifer system is similar, but the flow systems are larger and discharge is toward the major river valleys. Figure 5 is a representation of the original predevelopment potentiometric surface of aquifer layer 3, for which the most data are available, and is generally representative of the predevelopment potentiometric heads in the lower aquifer layers. The more localized flow systems in the unconfined areas are shown by the topographic control and steeper gradient of the contours there. In the confined areas, ground water moves toward the Illinois and Michigan basins but can discharge only as upward leakage across confining units. Thus the rate of lateral flow into the basins is greatly decreased. The longest flow paths in the aquifer system (more than 300 mi) extend from recharge areas in northwestern Iowa to the center of the Illinois basin (fig. 5). Shorter flow paths (less than 50 mi) in the northern part of the area extend from recharge areas: in central Minnesota to the Minnesota River; in central Wisconsin, central Minnesota, northeastern Iowa, and northwestern Illinois to the Mississippi River; and in eastern Wisconsin and northeastern Illinois toward Lake Michigan. Penetration of aquifer layers by the Mississippi River valley during the Pleistocene causes the flow system in the northern part of the study area to have shorter flow paths. This effect of the Mississippi River is most pronounced in aquifer layers 3 and 4 and is less pronounced in layers 1 and 2. For example, flow in layer 3 discharges to the Mississippi River as far south as about 50 mi south of the Wisconsin-Illinois State line, but the direct influence of the river on aquifer layer 1 extends only as far as the Minnesota-Iowa State line. Aquifer layer 4 discharges toward the Mississippi River downstream from northeastern Iowa.

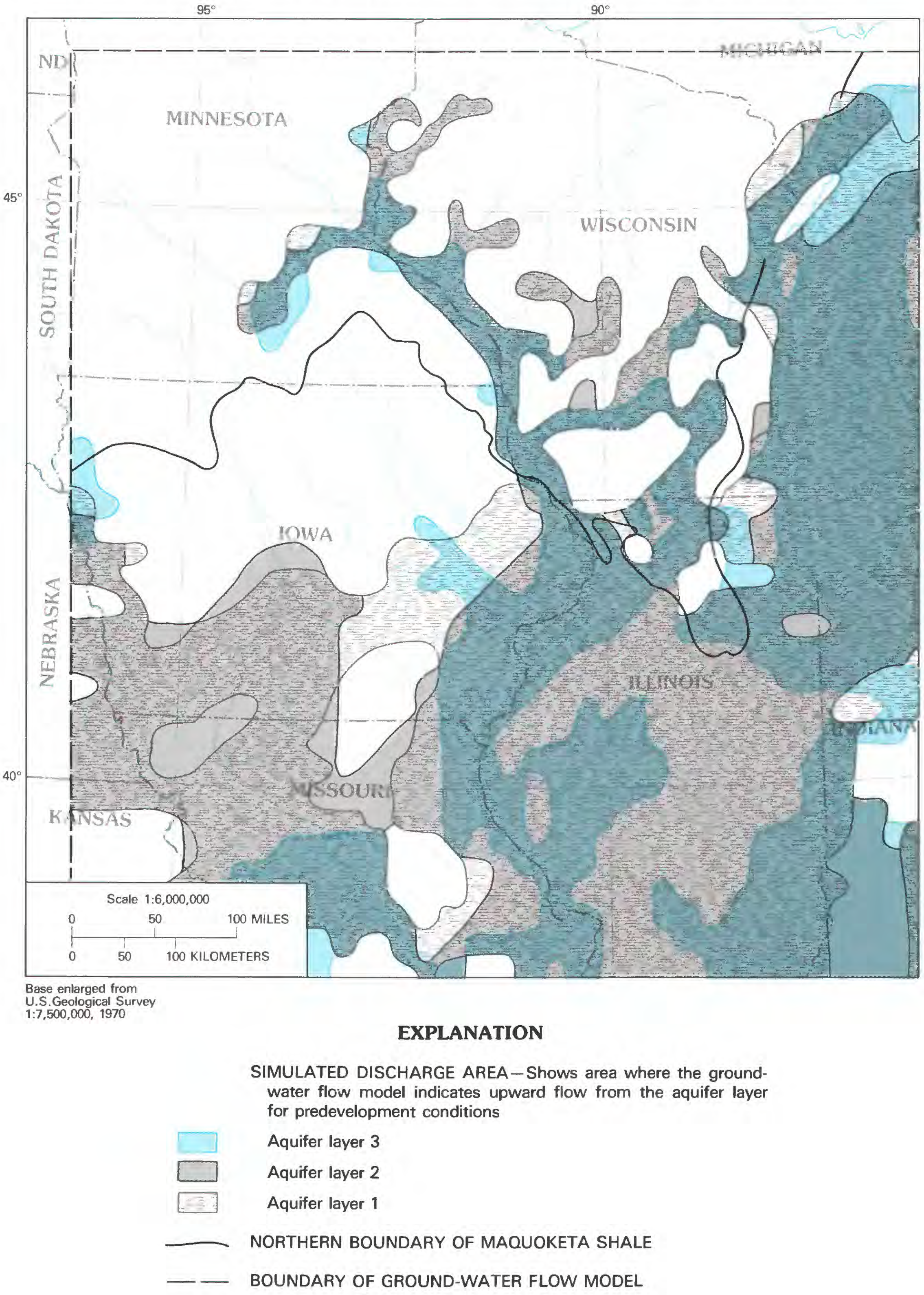
GEOCHEMISTRY

METHODS OF INVESTIGATION

The interpretation of regional ground-water quality is based on a synthesis of more than 3,000 chemical analyses of ground water available from the U.S. Geological Survey WATSTORE (Water Data Storage and Retrieval System) data base, publications of State and Federal agencies, and scientific journals. Published descriptions of the water chemistry of parts of the Cambrian-Ordovician aquifer system were reviewed, particularly in the following references (grouped by State): Minnesota—Winter (1974), Norvitch and others (1973), and Maderak (1965); Wisconsin—Kammerer (1981), Holt and Skinner (1973), and Ryling (1961); Iowa—Horick and Steinhilber (1978); Missouri—Feder (1979) and Gann and others (1971, 1973); and Illinois—Larson (1963), Gibb and O'Hearn (1980), and Schicht and others (1976). Description and analyses of brines in Cambrian-Ordovician aquifer units were obtained from Meents and others (1952), Graf and others (1965, 1966), Bond (1972), and the files of the Indiana and Michigan Geological Surveys and the Illinois State Water Survey.

Mean concentrations are used where multiple analyses are available. In general, analyses that did not balance electrochemically within 5 percent were deleted from the data base. Some partial analyses of brines include data for only dissolved solids and chloride, but these analyses were used to complete the areal distribution of dissolved solids along the southeastern boundary of the study area. Thus, the lines of equal concentration there should be considered approximate.

One hundred and sixty-four ground-water samples were collected for the study during the period 1980–82 to determine the concentrations of trace constituents and radiochemical species as well as stable isotope ratios. Seventy-five samples were collected to determine the isotopic composition of oxygen and hydrogen in the ground water and of carbon in bicarbonate. The isotopic composition of sulfur in sulfate was determined for selected samples. Field pH, alkalinity, and temperature of the water were measured at critical sample locations along ground-water flow paths to enable calculation of chemical species at equilibrium. Analyses were made using methods described in American Public Health Association (1980) and Skougstad and others (1979). Isotopic composition of water, carbon in inorganic carbon, and sulfur in sulfate was determined by standard methods. By convention, the isotopic variations are expressed as $\pm \delta$ values in parts per thousand (permil) differences in the measured isotopic ratios in a sample and in appropriate standards: Standard Mean Ocean Water (SMOW) for oxygen ($\delta^{18}O$) and



Base enlarged from
U.S.Geological Survey
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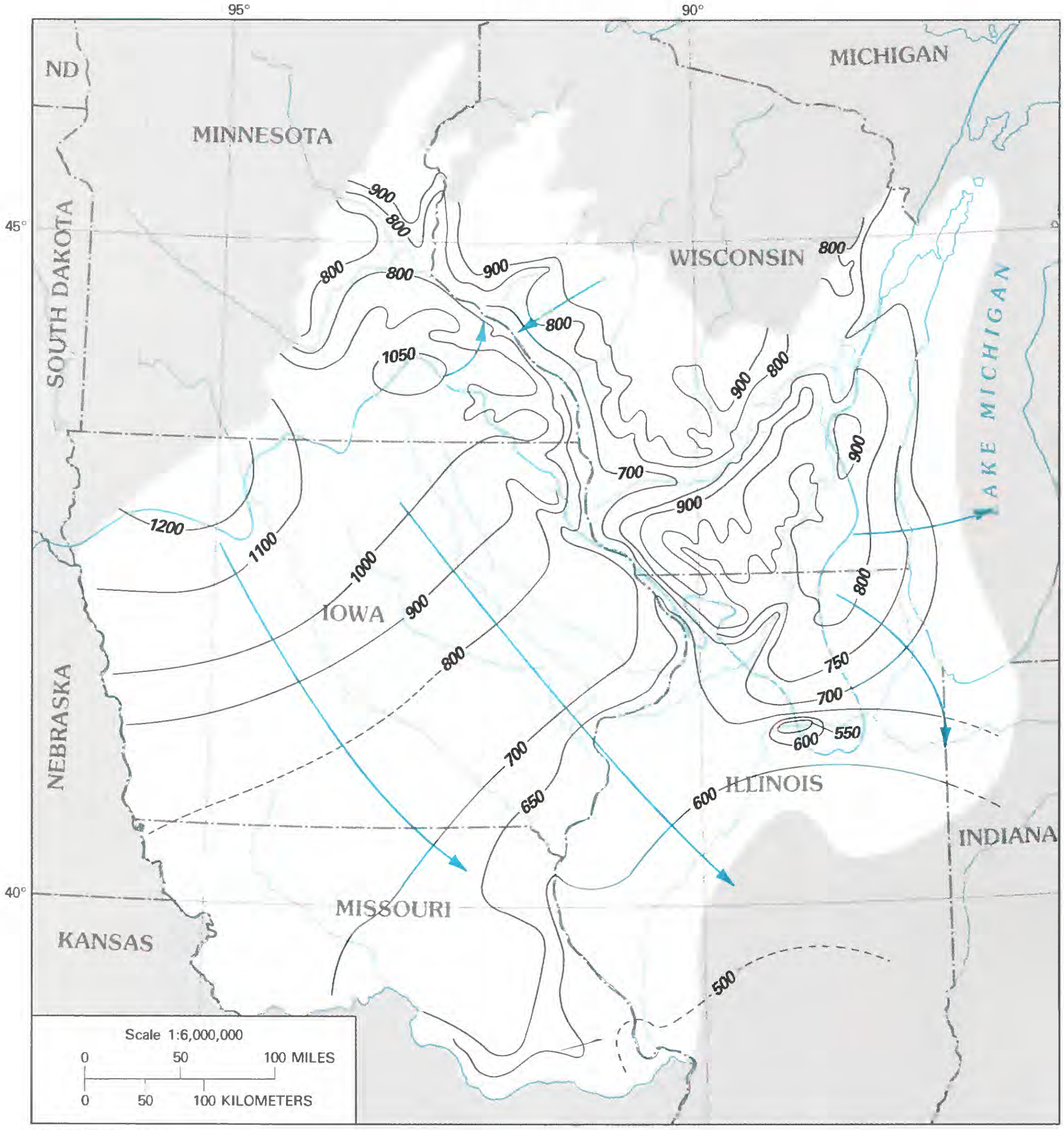
FIGURE 4.—Simulated predevelopment discharge areas for aquifer layers 1, 2, and 3. (Modified from Mandle and Kontis, in press.)



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EXPLANATION

—600— POTENTIOMETRIC CONTOUR—Shows altitude of predevelopment potentiometric surface for aquifer layer 3. Dashed where approximate. Interval, in feet, is variable. Datum is sea level

DIRECTION OF GROUND-WATER MOVEMENT

NORTHERN BOUNDARY OF MAQUOKETA SHALE

FIGURE 5.—Approximate predevelopment potentiometric surface for aquifer layer 3. (Modified from Young, in press.)

hydrogen (δD) in water, Canyon Diablo troilite for sulfur (δ^{34}S), and PeeDee belemnite (PDB standard) for carbon (δ^{13}C). Results of the analyses for the study are given in tables 1, 2, and 3 (at the end of the report). Figure 6 shows the locations of the wells in aquifer layers 1, 3, and 5 sampled for this study and the locations of selected wells in aquifer layers 1 and 3 with WATSTORE and published analyses. Data distribution for aquifer layer 5 was dense throughout the recharge areas of Wisconsin, Minnesota, Iowa, and Illinois; consequently, the locations of only new data for this aquifer layer are shown in figure 6. In subsequent figures that show areal distribution of solutes, only locations of data collected during this study are plotted.

Maps showing the areal distribution of solutes were derived from a composite of data from aquifer layers 1 and 3, for which there is significant regional coverage. It is recognized that because the lithologies of these layers are different, the chemistry may be different. However, the composited data are used as a first approximation in describing the regional chemical patterns for the following reasons:

1. The chemical quality of ground water in aquifer layers 1 and 3 is essentially the same in outcrop areas in Minnesota, Wisconsin, Illinois, and Iowa.
2. In the major confined areas in Iowa, Missouri, Illinois, and eastern Wisconsin, all but a few data points are from aquifer layer 3 (fig. 6).

The maps of areal solute distribution in this report, therefore, represent mainly aquifer layer 3 in the confined part of the aquifer and aquifer layers 1, 2, and 3 in outcrop areas. Where data distribution was dense, maps of concentrations of dissolved solids and particular ions were prepared, in part, by data-management techniques described by Kontis and Mandle (1980).

The detailed evaluation of the water quality of the Cambrian-Ordovician aquifer system was restricted to aquifer layers 3 and 5, for which the areal distribution of data was considered sufficient to evaluate regional trends and variations in concentrations of major dissolved constituents. In most of Wisconsin and north-central Illinois, aquifer layers 1, 2, and 3 are unconfined and are hydraulically connected; thus water quality in those aquifer layers is probably similar. All statistical calculations were made using computer methods of the Statistical Analysis System (SAS Institute, Inc., 1979).

DISSOLVED SOLIDS

The chemical quality of the water in the Cambrian-Ordovician aquifer system varies widely from recharge areas to discharge areas. Dissolved-solids concentrations range from less than 200 mg/L in the outcrop areas in Wisconsin and southeastern Minnesota to more than 200,000 mg/L in the Illinois basin. The 500-mg/L line of equal dissolved solids (isopleth) in figure 7 roughly outlines the extent of the predominantly unconfined flow systems in the northern half of the study area. The 500-mg/L line also is approximately parallel to the outcrop pattern of the Maquoketa Shale in Illinois and Wisconsin, the major confining unit between the Cambrian-Ordovician aquifer system and the overlying units. Dissolved solids generally increase in the direction of the hydraulic gradient.

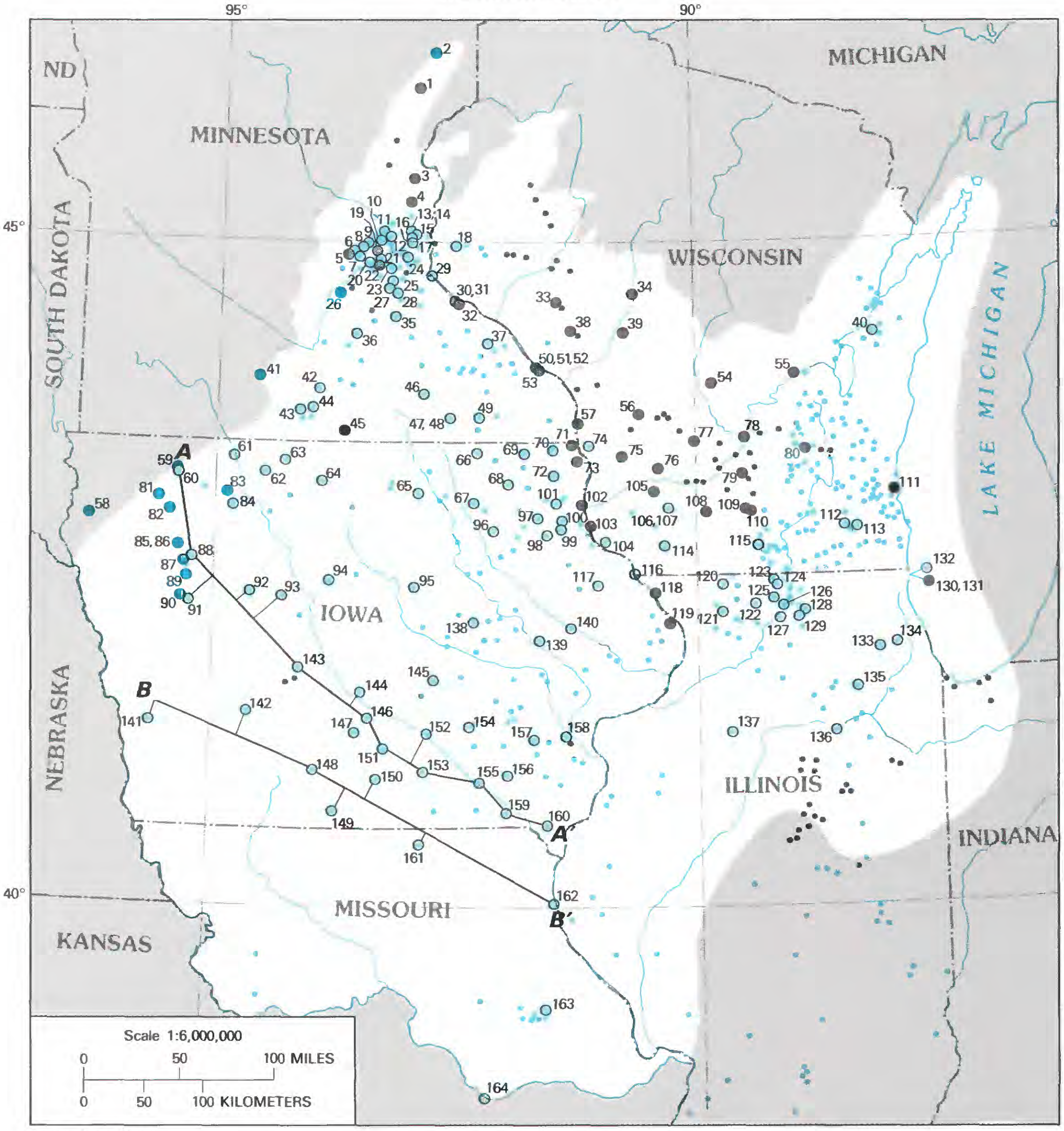
In Iowa, the 500-mg/L line shows a plume-shaped zone of fresher water trending from the northeast to the south-southwest across the Maquoketa Shale outcrop (figs. 2, 7). In both Iowa and Missouri, the gradient toward increasing dissolved solids (fig. 7) varies but is generally perpendicular to the direction of the hydraulic gradient shown in figure 5. For example, along the flow path that is approximately coincident with geochemical section *A–A′* (fig. 6), dissolved solids decrease from 2,400 mg/L at well 59 (Hibbing, Iowa) to 440 mg/L at well 144 (Altoona, Iowa) in the south-central part of the State. Dissolved solids increase southeast of Altoona to more than 100,000 mg/L in the Illinois basin (fig. 7). Dissolved solids normally increase along the hydraulic gradient because as the residence time of water in the aquifer increases, the water has a longer period of interaction with the rock minerals (Chebotarev, 1955; Back and Hanshaw, 1965). The discordance of increasing dissolved-solids distribution with the hydraulic gradient in the central part of the study area is an abnormal occurrence and poses a major geochemical anomaly that is examined and discussed in a later section, "Hypothetical Geochemical Models."

CHEMICAL CLASSIFICATION

Water chemistry in the aquifer system was classified by calculating percentages of equivalents per liter for major cations and anions. Maps were prepared showing the areal distribution of water types according to the method described by Back (1966). These maps were used to relate water chemistry to lithologic changes in aquifers and to evaluate possible geochemical and hydrologic processes that control the evolution of water chemistry along and across the hydraulic gradients.

A wide range of water types is present in the Cambrian-Ordovician aquifer system. Water recharged to the system through aquifer layer 5 ranges from a Ca-Mg-HCO_3 type in the northern part of the area to a Ca-Na-SO_4-HCO_3 type in northwestern Iowa and southwestern Minnesota (fig. 8). Dissolved solids in aquifer layer 5 range from less than 300 to more than 2,000 mg/L in Minnesota, Wisconsin, and northwestern Iowa.

Water chemistry in the Cambrian-Ordovician aquifer system in recharge areas in Minnesota, Wisconsin, Illinois, and Iowa is very similar to that in the overlying



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EXPLANATION

WELL WITH CHEMICAL ANALYSIS—Sample collected during this study. Numbers refer to tables 1, 2 and 3

- ● 39 Mount Simon aquifer
- ○ 65 St. Peter-Prairie du Chien-Jordan aquifer
- ● 45 Silurian-Devonian aquifer
- ● 89 Drift or Cretaceous aquifer

WATSTORE and published data

- • Mount Simon aquifer
- • St. Peter-Prairie du Chien-Jordan aquifer

B——B′ LINE OF GEOCHEMICAL SECTION—Sections shown in figures 17 and 18

FIGURE 6.—Location of wells with water-quality analyses and location of geochemical sections *A-A′* and *B-B′*.

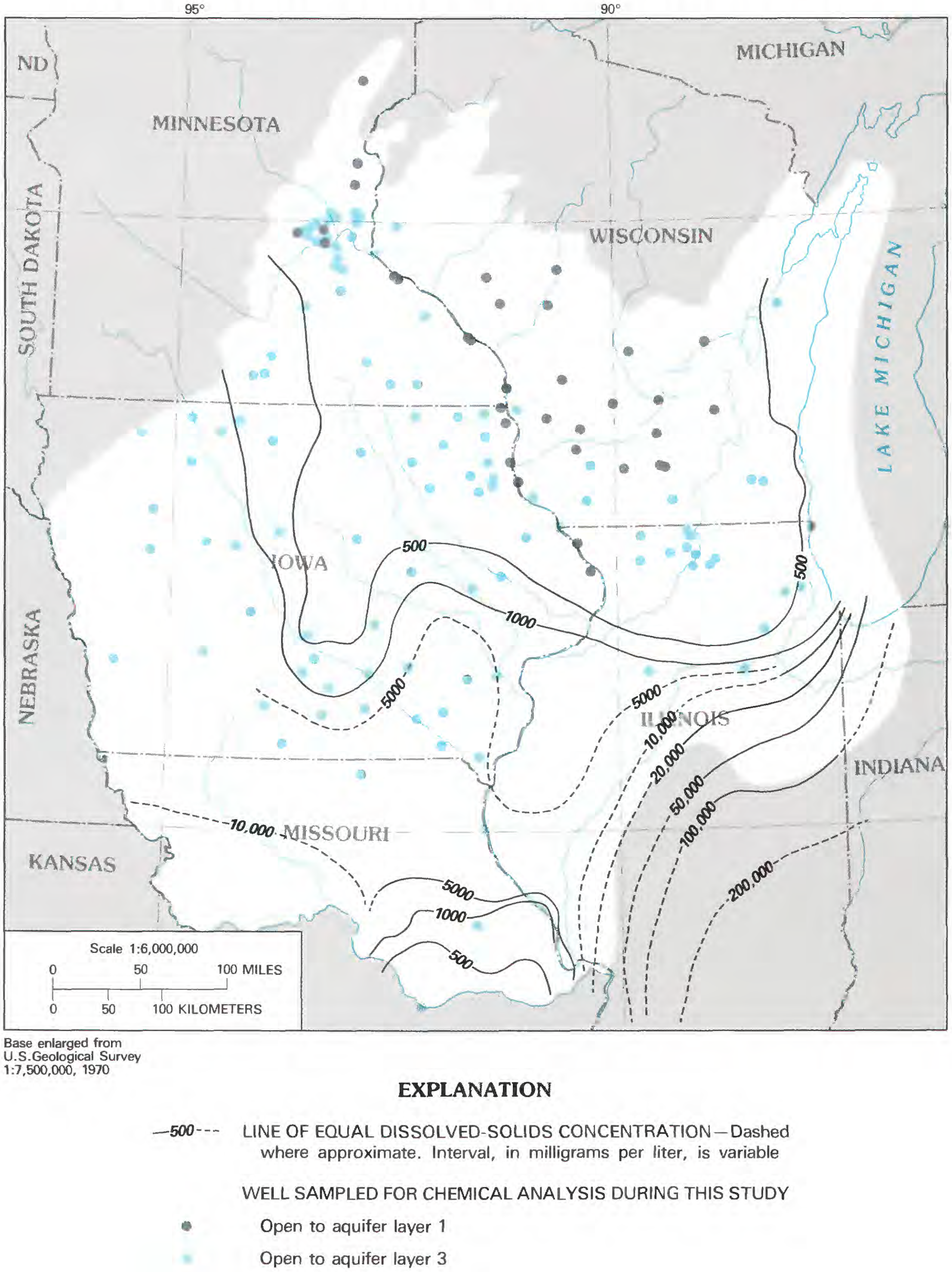
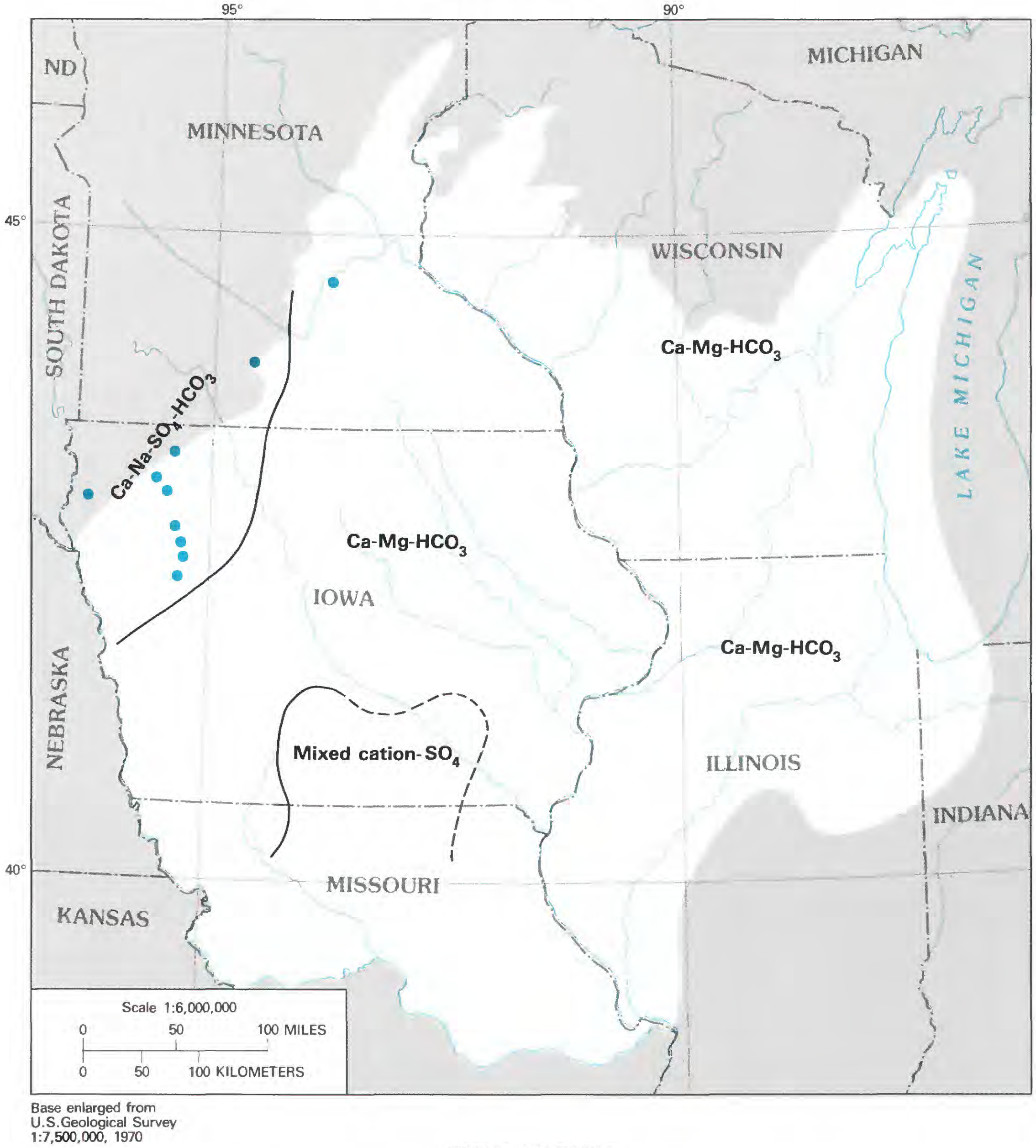


FIGURE 7.—Dissolved-solids distribution in aquifer layers 1 and 3. (Modified from Young, in press.)

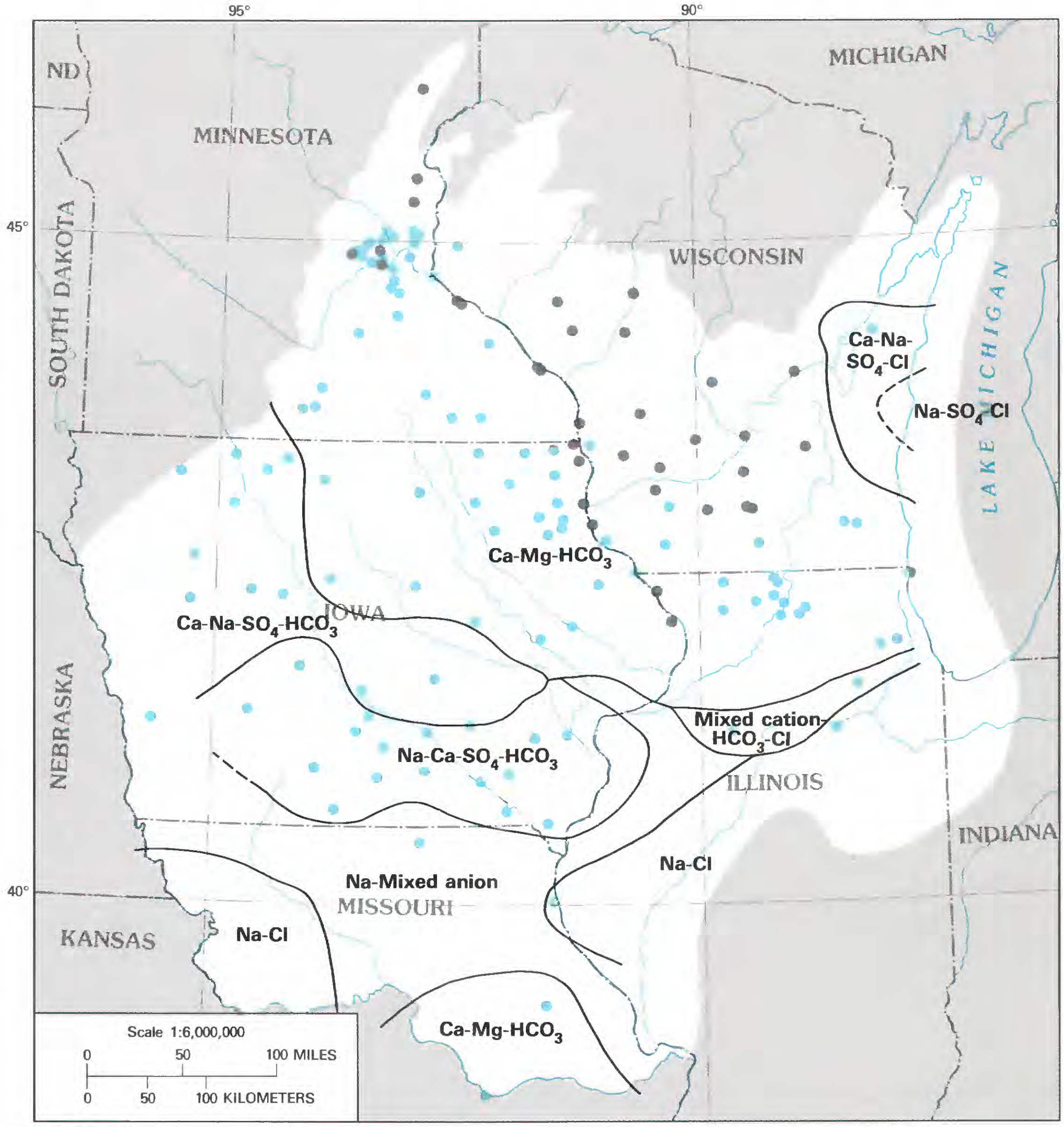


EXPLANATION

--- — HYDROCHEMICAL FACIES ZONE BOUNDARY—Dashed where approximate

● WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY
Open to aquifer layer 5

FIGURE 8.—Hydrochemical facies of ground water in aquifer layer 5.



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EXPLANATION

—·— HYDROCHEMICAL FACIES ZONE BOUNDARY—Dashed where approximate

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

● Open to aquifer layer 1

● Open to aquifer layer 3

FIGURE 9.—Hydrochemical facies of ground water in aquifer layers 1 and 3.

aquifer layer 5. Water in both aquifer layers 1 and 3 in the northern part of the study area is a Ca-Mg-HCO_3 type, but water in northwestern Iowa and southwestern Minnesota is a Ca-Na-SO_4-HCO_3 type (fig. 9).

The most pronounced geochemical changes occur in the confined parts of the aquifer system. Along flow paths confined by the Maquoketa Shale from eastern Wisconsin east toward the Michigan basin, water chemistry changes from Ca-Mg-HCO_3 to Ca-Na-SO_4 and Na-Cl-SO_4 waters, a transition to the Ca-SO_4 and Ca-Cl_2 types of brines in the Michigan basin (fig. 9). From northern Illinois to central Illinois also, the water changes from a Ca-Mg-HCO_3 type to a Na-Cl type similar to the brines in the Illinois basin.

The largest variability in water chemistry occurs along confined flow paths in the aquifer system from northwestern Iowa to central Illinois. Water type evolves along the hydraulic gradient to the Illinois basin from the Ca-Na-SO_4-HCO_3 water that typically is present in the Dakota Formation and overlying drift of aquifer layer 5 to Na-Ca-SO_4-HCO_3, Na-anion (no dominant anion), and Na-Cl water. This change occurs in aquifer layer 3 even though the dissolved-solids concentration decreases along the central part of the flow path. South of the Na-Ca-SO_4-HCO_3 facies in south-central Iowa, the water is of either the Na-Cl or the Na-anion type.

Few generalizations can be made about variations in water types in aquifer layers 1 and 2 or with depth in individual aquifer layers because of the scant data on the areal distribution of the major solutes in aquifer layers 1, 2, and 4. Saline water is present in aquifer layer 1 at several locations along the Mississippi River valley. Chemical data from municipal wells in aquifer layer 1 at Red Wing, Minn. (fig. 1), indicate that the water type changes from Ca-Mg-HCO_3 to Na-Cl at depth (table 4). This change in water quality with depth can occur with increases of dissolved solids from less than 500 to several thousand milligrams per liter (Hall and others, 1911; Thiel, 1944). A similar increase in dissolved solids and change in water type in aquifer layer 1 occurs near Lake Michigan, where high salinity makes aquifer layer 1 nonpotable in some places. Samples collected from aquifer layer 1 in a deep test well drilled for this study at Zion, Ill. (fig. 1), illustrate the increase in salinity with depth (table 4). This increase in salinity is also found in aquifer layer 1 within the Illinois basin in central Illinois and eastern Indiana (Meents and others, 1952; R.J. Shedlock, U.S. Geological Survey, written commun., 1983). These data plus scant data from wells in south-central Iowa (fig. 6) suggest that the Na-Cl water type in Iowa in aquifer layer 1 may be present much farther up the hydraulic gradient than in aquifer layer 3.

TABLE 4.—*Selected chemical data that show variation of water quality with depth in aquifer layer 1*

[Results in milligrams per liter, except as indicated. Map number is location in figure 6]

	Well name			
	USGS test well Zion, Illinois		Red Wing no. 1 west, Minnesota	Red Wing no. 3, Minnesota
Map number	130	131	30	32
Date of collection	12–10–80	1–14–81	2–12–80	2–13–80
Field pH (standard units)	7.2	—	7.4	7.4
Dissolved solids, residue on evaporation	2,800	58,300	410	1,110
Calcium, Ca	311	1,000	64	80
Magnesium, Mg	39	930	27	44
Sodium, Na	440	15,000	53	250
Potassium, K	16	270	6.8	7.9
Sulfate, SO_4	1,300	1,400	34	36
Chloride, Cl	370	37,000	80	550
Interval sampled (feet below land surface)	1,775–1,935	3,120–3,475	350–630	385–770

GEOCHEMICAL PROCESSES

CALCIUM-MAGNESIUM-BICARBONATE WATER TYPE

The major geochemical and hydrologic processes that cause the changes in dissolved-solids concentrations and water types in the Cambrian-Ordovician aquifer system can be evaluated at different levels of complexity. Qualitatively, the Ca-Mg-HCO_3 water in all layers probably reflects the dissolution of calcite ($CaCO_3$) and dolomite [$CaMg(CO_3)_2$] in the aquifer matrix and overlying drift. The chemical reactions involved in the dissolution of carbonate minerals are a combination of hydrolysis and dissociation. The major source of acidity in the northern part of the study area is probably carbon dioxide in the atmosphere and soil. The pertinent reactions for the dissolution of calcite by carbonic acid may be expressed by

$$CO_{2(g)}+H_2O=H_2CO_3, \qquad (1)$$

$$H_2CO_3=H^++HCO_3^-, \qquad (2)$$

$$HCO_3^{-1}=H^++CO_3^{2-}, \qquad (3)$$

and

$$(Ca_{1-x}Mg_x)CO_{3(s)}+2H^+=(1-x)Ca^{2+}+xMg^{2+}+2HCO_3^-. \qquad (4)$$

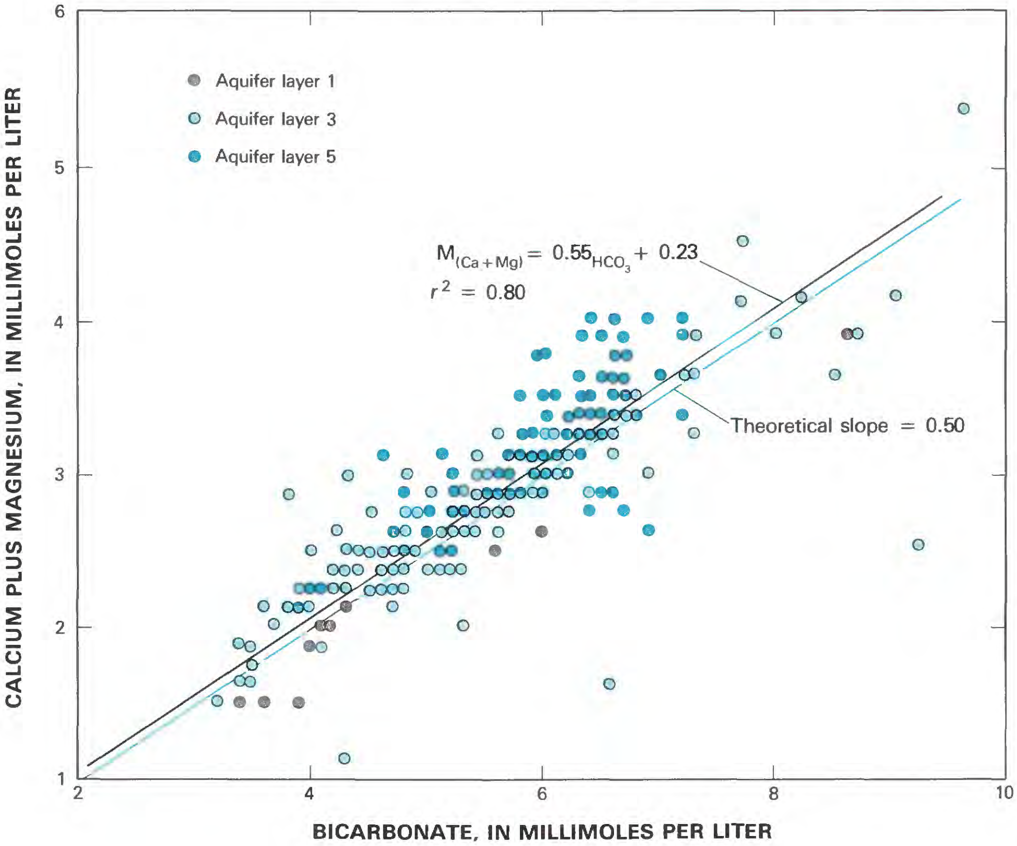


FIGURE 10.—Correlation of calcium plus magnesium and bicarbonate in ground water from the Ca-Mg-HCO_3 facies in aquifer layers 1, 3, and 5 in the northern outcrop area of the Cambrian-Ordovician aquifer system.

Combining equations 1 through 4 and neglecting CO_3^{2-} because of the near-neutral pH conditions in the aquifer,

$$(Ca_{1-x}Mg_x)CO_{3(s)}+H_2O+CO_{2(g)} = (1-x)Ca^{2+}+xMg^{2+}+2HCO_3^-. \quad (5)$$

Little information exists on the mole fractions of calcium and magnesium in the major carbonate minerals in either the Cambrian-Ordovician aquifer system or the overlying units in aquifer layer 5. A large number of rock analyses of carbonate units from Minnesota obtained from the Cambrian-Ordovician aquifer system are available—for example, Prokopovich and Schwartz (1956), Thiel and Stauffer (1947), and Stauffer (1950)—and show that there is both wide vertical and wide areal variability in the CaO and MgO content of the aquifer carbonate rocks and confining units. It is likely that there is a similar variability in calcium and magnesium content of the carbonate rocks elsewhere in the study area.

However, if dissolved calcium, magnesium, and bicarbonate in the ground water result mainly from the dissolution of carbonate minerals according to equation 5, then the molar proportions of $(Ca^{2+}+Mg^{2+})$ to HCO_3^- should be linear with a slope of 0.5. Calcium and magnesium are summed because of variability of the mole fractions within the carbonate minerals. The line of regression (fig. 10) of $(Ca^{2+}+Mg^{2+})$ versus HCO_3^- for ground-water samples in aquifer layers 1, 3, and 5 in the northern outcrop area of the Cambrian-Ordovician aquifer system in Minnesota, Wisconsin, and northeastern Iowa has a slope of 0.55. The coefficient of correlation (r^2) is 0.80, which indicates a good fit between the carbonate-dissolution model and field data.

The state of equilibrium between ground water and carbonate minerals can be tested by use of saturation indices (*SI*), expressed as

$$SI_{\text{mineral}}=\log \frac{IAP}{K_{sp}}, \quad (6)$$

where *IAP* is the ion-activity product calculated from analytical data and K_{sp} is the solubility product, an equilibrium constant for ions in a saturated solution in contact with excess solid phases.

A saturation index of 0.0 indicates that *IAP* and K_{sp} are equal and that thermodynamic equilibrium of the solution exists with the solid phase in question; a negative or positive index indicates undersaturation and oversaturation, respectively. Saturation indices for calcite and dolomite in selected water samples from aquifer layer 3 in Iowa and northeastern Missouri were determined by use of WATEQF, a U.S. Geological Survey water chemical-equilibrium calculation program (Truesdell and Jones, 1974; Plummer and others, 1976). Saturation indices calculated for calcite and dolomite range generally from about 0.0 to +0.6 and from −0.2 to +1.0, respectively (fig. 11), for wells in Iowa and northeastern Missouri.

The accuracy of the saturation index for determining equilibrium between solution and carbonate minerals depends largely on the accuracy of field measurements of pH and alkalinity. The most accurate method of measuring pH is by using a flow-through cell or bath until pH is constant for at least 15 minutes (Thorstenson and others, 1979). Precision by this method can be within 0.05 pH unit. Unfortunately, during this study the general accuracy of field pH measurements may have been within only ±0.1 pH unit. Accurate field measurements of alkalinity should be done by potentiometric titration to inflection points rather than to specified end points (Barnes, 1964), which was the method used during this study. The combined errors in pH measurements and alkalinity determinations could result in errors in saturation indices for carbonate dissolution reactions within a range of 20 percent. Within these error limits, ground water in the Cambrian-Ordovician aquifer system seems to be nearly saturated or oversaturated with respect to calcite and dolomite (fig. 11).

CALCIUM-SODIUM-SULFATE-BICARBONATE WATER TYPE

Ca-Na-SO_4-HCO_3 water is common in the drift and the Dakota Formation (table 5) and is present in all aquifer layers that subcrop beneath the Dakota Formation. For instance, samples of water collected at "nests" of vertically spaced observation wells (piezometers) in aquifer layers 1, 2, and 3 in southwestern Minnesota are all of the Ca-Na-SO_4-HCO_3 type (table 6). The relative chemical uniformity of water in aquifer layers 1, 2, and 3 observed in the piezometers in southwestern Minnesota is an important factor in evaluating chemical and hydrologic mechanisms that affect changes in chemistry southeastward along the major direction of groundwater flow in Iowa. Water-quality data are scant for aquifer layers 1, 2, and 4. If the chemistry of water recharging these aquifer layers is similar to the chemistry of the ground water in aquifer layer 3, one can probably assume that the major geochemical mechanisms that control the water chemistry in all aquifer layers in the recharge areas are generally similar.

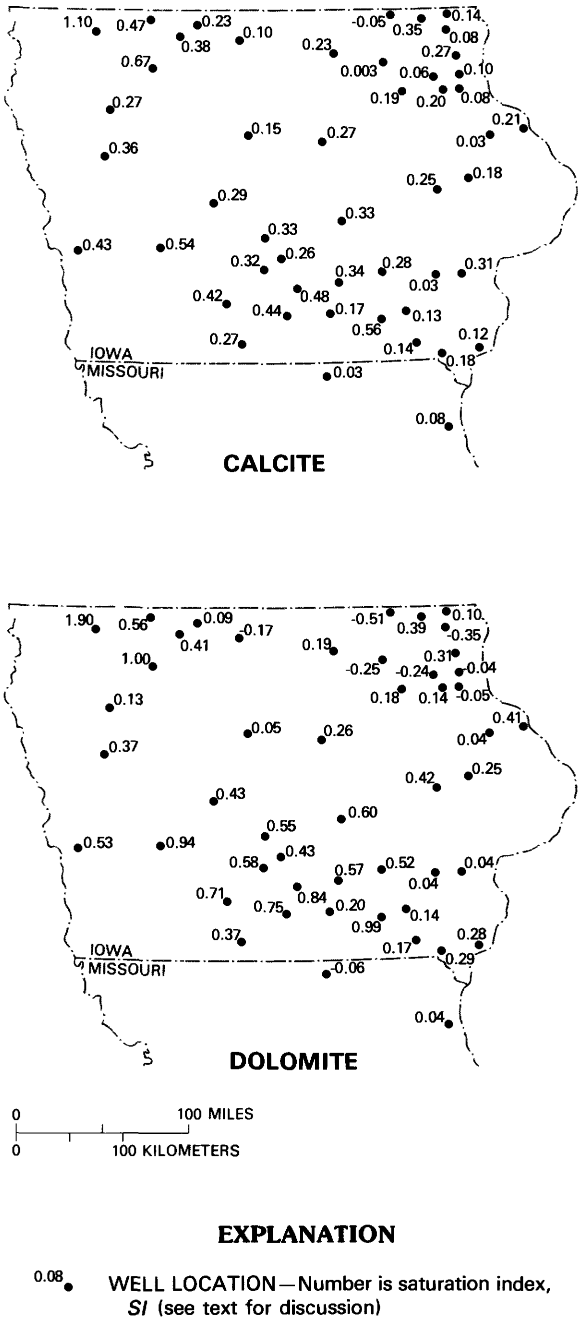


FIGURE 11.—Saturation indices for calcite and dolomite in water from selected wells in aquifer layer 3 in Iowa and northeastern Missouri.

The origin of Ca-Na-SO_4-HCO_3 water in the Dakota Formation, the Quaternary drift, and the Cambrian-

TABLE 5.—*Selected chemical analyses of water from the Dakota Formation in northwestern Iowa*

[Map number is location in figure 6]

	Well name				
	Sutherland no. 3	Primghar	Arthur no. 4	Schaller no. 3	Ruthven no. 5
Map number	82	81	90	89	83
Date of collection	2-23-82	2-23-82	2-22-82	2-22-82	2-23-82
Temperature (°C)	9.9	11.1	11.9	7.1	12.3
Field pH (standard units)	7.3	7.4	7.4	7.5	7.5
Calcium, Ca (mg/L)	320	—	260	310	220
Magnesium, Mg (mg/L)	80	—	63	100	58
Sodium, Na (mg/L)	96	—	140	190	100
Lab alkalinity, as HCO_3 (mg/L)	341	412	285	415	404
Sulfate, SO_4 (mg/L)	930	1,000	850	1,200	520
Chloride, Cl (mg/L)	6.7	20	8.5	16	5.0
Dissolved solids, residue on evaporation (mg/L)	1,790	—	1,560	2,340	1,160
Arsenic, As (μg/L)	<50	<50	<50	<50	<50
Barium, Ba (μg/L)	9	9	10	8	13
Cadmium, Cd (μg/L)	<2	<2	<2	<2	<2
Chromium, Cr (μg/L)	<5	<5	<5	<5	<5
Silica, SiO_2 (mg/L)	11	10	5	12	11
Sulfide, S (μg/L)	<3	<3	<3	<3	<3
Selenium, Se (μg/L)	<5	<5	<5	<5	<5
Copper, Cu (μg/L)	6	2	4	3	4
Iron, Fe (μg/L)	2,900	1,400	2,900	71	4,200
Manganese, Mn (μg/L)	640	—	460	2,600	270
Nickel, Ni (μg/L)	<10	—	<10	<10	<10
Lead, Pb (μg/L)	<50	—	<50	<50	<50

Ordovician aquifer system in northwestern Iowa and southwestern Minnesota is related to both the oxidation of pyrite and the dissolution of carbonate minerals. Oxidation of pyrite produces sulfuric acid that dissociates to sulfate and hydrogen ions as follows:

$$FeS_{2(s)}+\tfrac{7}{2}O_{2(g)}+H_2O=Fe^{2+}+2SO_4^{2-}+2H^+. \quad (7)$$

Depending on the Eh (redox potential) and pH of the water, the resultant ferrous iron may then be oxidized to ferric iron,

$$Fe^{2+}+\tfrac{1}{4}O_2+H^+=Fe^{3+}+\tfrac{1}{2}H_2O, \quad (8)$$

which hydrolyzes to form insoluble iron oxides or hydroxide, for example,

$$Fe^{3+}+3H_2O=Fe(OH)_{3(s)}+3H^+. \quad (9)$$

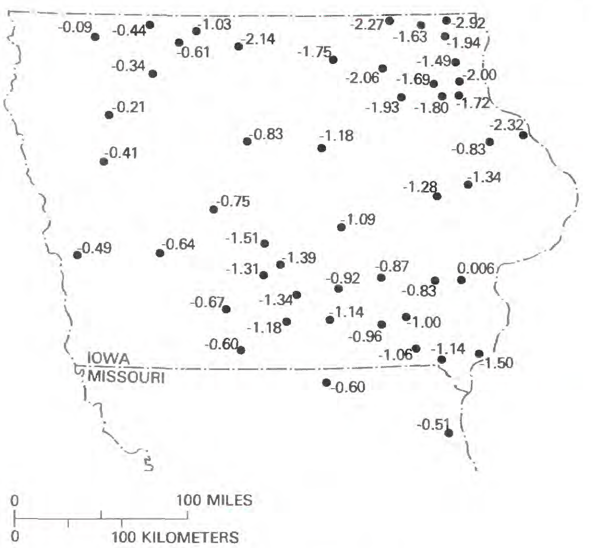
TABLE 6.—*Water-quality data for water samples obtained from piezometers at Schroeder and Kingstrom sites, Goodhue County, Minn., January 1980*

[Results in milligrams per liter, except as indicated Analyses by Minnesota Department of Health]

	Well name					
	Schroeder no. 5	Schroeder no. 2	Schroeder no. 4	Kingstrom no. 1	Kingstrom no. 3	Kingstrom no. 4
Aquifer layer	1	2	3	1	2	3
Field pH (standard units)	7.1	7.3	7.2	7.2	7.3	7.1
Calcium, Ca	148	136	116	140	140	136
Magnesium, Mg	41	51	56	63	51	39
Sodium, Na	52	62	111	149	74	51
Potassium, K	10	19	24	20	26	9.7
Silica, SiO_2	6.6	6.3	6.7	6.4	5.7	6.6
Manganese, Mn (μg/L)	69	89	48	240	97	59
Iron, Fe (μg/L)	1,900	4,500	2,600	4,600	3,500	50
Alkalinity, as $CACO_3$	306	320	317	328	315	317
Sulfate, SO_4	300	370	317	490	400	290
Chloride, Cl	5.5	9.3	33	49	13	8.6
Dissolved solids, sum of constituents	860	960	1,000	1,300	1,000	800

Acidity produced in the oxidation process may be neutralized by carbonate minerals (eq. 5) that are found as part of the matrix in the Dakota Formation and the underlying aquifer units.

Sulfate in the Dakota Formation and other aquifers in northwestern Iowa and southwestern Minnesota has also been attributed to possible dissolution of either gypsum ($CaSO_4 \cdot 2H_2O$) or anhydrite ($CaSO_4$) (Winter, 1974; Munter and others, 1983). No petrographic evidence of primary evaporite minerals has been noted in the literature, however. Dissolution of gypsum proceeds rapidy compared with dissolution of carbonates and other common minerals in the aquifer matrix. The hydraulic conductivity of the Dakota Formation is generally low owing to bedded shale and siltstone. Therefore, the residence time of ground water in the Dakota probably is long. This is supported by the carbon-14 dates for water in the Dakota ranging from 22,000 to more than 35,000 years B.P. (before present) (D.L. Iles, South Dakota Geological Survey, written commun., 1982). Because of this long residence time, ground water in the Dakota Formation should be in equilibrium with gypsum, if gypsum is present, as should the ground water in aquifer layer 3, where the ground water is recharged from the Dakota. However, negative saturation indices for gypsum in ground water in aquifer layer 3 in northwestern Iowa (fig. 12) show the water to be undersaturated with respect to gypsum, and this indi-



EXPLANATION

-0.75 ● WELL LOCATION—Number is saturation index, *SI* (see text for discussion)

FIGURE 12.—Saturation indices for gypsum in water from selected wells in aquifer layer 3 in Iowa and northeastern Missouri.

rectly indicates that there is not enough gypsum in the Dakota Formation to be the source of sulfate, as suggested by other investigators.

Data on the isotopic composition of sulfur in sulfate is another way to test independently whether the sulfur is from the oxidation of pyrite (FeS_2) or the dissolution of gypsum or anhydrite. Negative $\delta^{34}S$ values typically indicate that the source of sulfur is weathered sulfide from shales, whereas positive values generally indicate an evaporitic mineral source (Holser and Kaplan, 1966; Hitchon and Krouse, 1972; Hoefs, 1980).

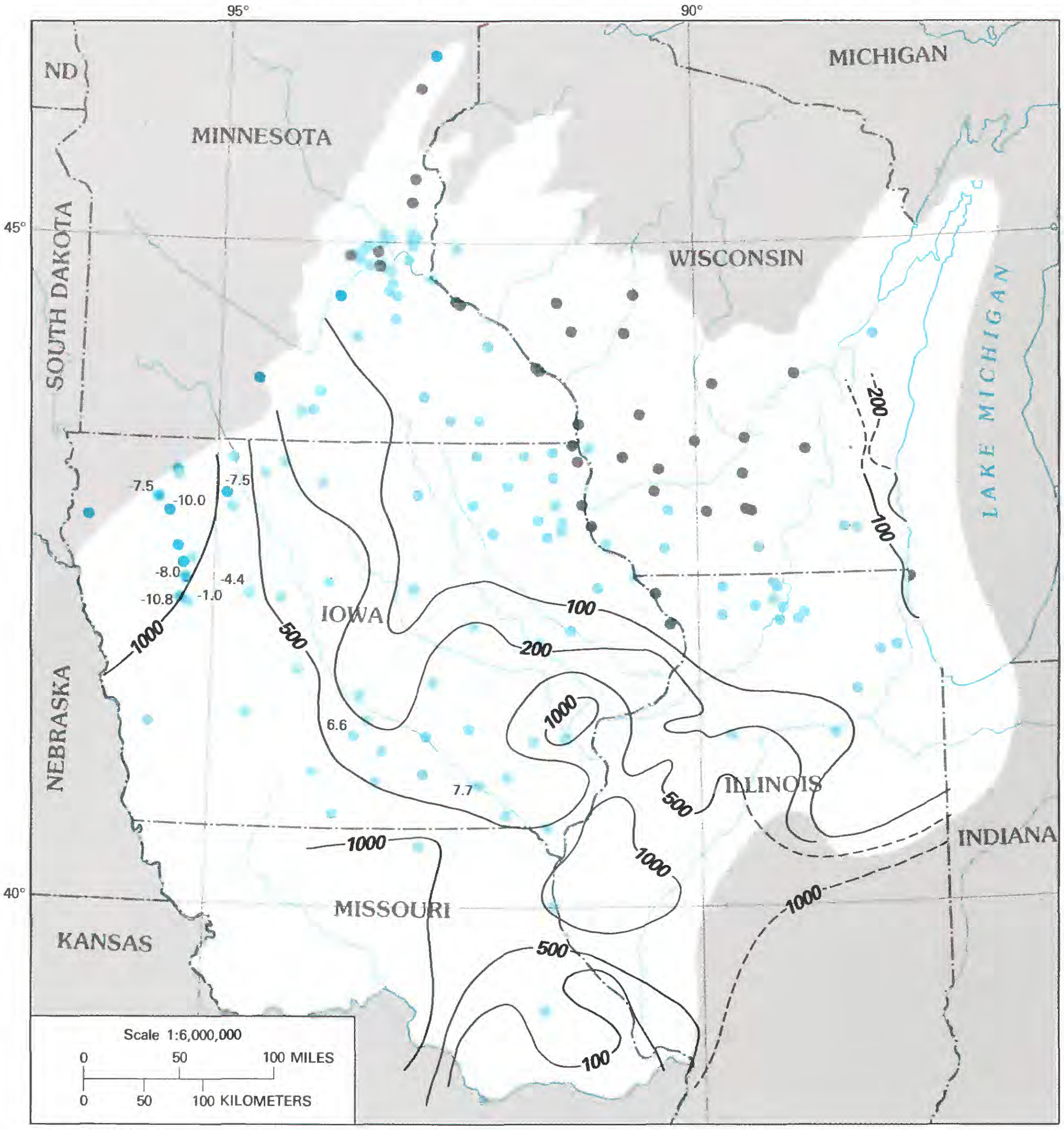
The $\delta^{34}S$ in sulfate from the Cambrian-Ordovician aquifer system and the Dakota Formation in northwestern Iowa (fig. 13) ranges from −10.8 to −1.0 permil (parts per thousand, written o/oo), considerably lighter than $\delta^{34}S$ associated with marine evaporites in the Cretaceous Period (Claypool and others, 1980). $\delta^{34}S$ of pyrite and other disseminated sulfide minerals in shales tends to be less than +10 o/oo, the lower limit for evaporitic sulfate (Holser and Kaplan, 1966). These values are similar to isotopic sulfur ratios in streams that drain basins underlain by marine Cretaceous rock, roughly similar to the Dakota Formation, in the MacKenzie River Basin of Canada (Hitchon and Krouse, 1972). The values of $\delta^{34}S$ indicate that the original source of sulfur was probably pyrite in the Dakota Formation.

The isotopic composition of the sulfur in sulfate reflects the isotopic composition of the sulfur in the original pyrite and depends on many factors. Sulfur isotopes approach equilibrium at earth temperatures and pressures very slowly (Pearson and Rightmire, 1980). Most differences in sulfur isotope content in aqueous sulfur compounds are caused by kinetic fractionation accompanying inorganic or bacterial reduction or by oxidation of sulfur compounds (Kaplan and Rittenburg, 1964; Goldhaber and Kaplan, 1974). Hydrogen sulfide degassing is a common problem in many wells in the Dakota Formation; this indicates that reducing conditions do exist locally in the formation (U.S. Geolgical Survey, unpub. data; Burkart, 1984). In southwestern Minnesota, methane is also common in both drift and the underlying Cambrian-Ordovician aquifer system (Coleman, 1978, 1979).

$\delta^{34}S$ in sulfate in aquifer layer 3 is enriched downgradient from the northwestern recharge area in central Iowa but is still less than +10 o/oo (fig. 13). The $\delta^{34}S$ enrichment may be related to the preferential bacterial reduction and consequent loss of sulfur-32 in H_2S or metal sulfide precipitates. Although sulfide in solution is present in the aquifer system in central Iowa (fig. 14), data are insufficient to document the presence of such possible bacteriological mediation of the reduction process. The low concentrations of sulfide may reflect precipitation of pyrite or other metal sulfides. Calculations from the WATEQF program show that sulfide-bearing solutions are supersaturated with respect to pyrite.

Some input of sulfur to the aquifer system could have been from the oxidation of pyrite in the Maquoketa Shale along the outcrop area in northeastern Iowa. However, the scant data on the isotopic content of sulfur in sulfate in central Iowa (fig. 13) show $\delta^{34}S$ greater than +5 o/oo, which is considerably heavier than that of the sulfur in sulfate derived from either the oxidation of pyrite in northwestern Iowa or from the Maquoketa Shale in northeastern Iowa.

Elsewhere in the aquifer system, $\delta^{34}S$ in sulfate may indicate a sulfur source from evaporite minerals. East of the Maquoketa confining unit in northern Illinois, $\delta^{34}S$ in sulfate in oxidized water is about +20 o/oo and is too enriched to be derived solely from the oxidation of sulfide minerals (Perry and others, 1982). Gilkeson and others (1981) proposed that some of the sulfate may have been placed in the aquifer system during Pleistocene glaciations and may be related to Michigan basin evaporites. Hydraulic gradients in Illinois, at least during the Wisconsin ice advances, could have been from east to west, reversed from current hydraulic gradients, because of the pressure head from the weight of the ice sheets that periodically covered the Lake Michigan



Base enlarged from
U.S.Geological Survey
1:7,500,000, 1970

EXPLANATION

—500— - - LINE OF EQUAL CONCENTRATION OF SULFATE—Dashed where approximate. Interval, in milligrams per liter, is variable

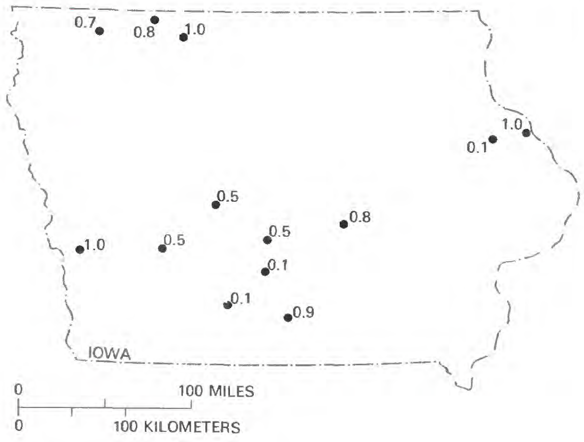
WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY
Number is isotopic composition of sulfur in sulfate, $\delta^{34}S$, permil

● Open to aquifer layer 1

● -4.4 Open to aquifer layer 3

● -7.5 Open to aquifer layer 5

FIGURE 13.—Sulfate distribution in aquifer layers 1 and 3 and sulfur isotopic composition in sulfate in water from selected wells in aquifer layer 3 and aquifer layer 5 (Dakota Formation).



EXPLANATION

1.0 ● WELL LOCATION—Number is sulfide concentration in milligrams per liter

FIGURE 14.—Sulfide distribution in water from selected wells in aquifer layer 3 in Iowa.

basin (Gilkeson and others, 1981; Filley and Parizek, 1983; Siegel and Mandle, 1983). The influence of Pleistocene glaciations on the water chemistry of the Cambrian-Ordovician aquifer system was profound and is discussed in a later section, "Isotopic Composition of Water and Pleistocene Recharge Model."

SODIUM-MIXED ANION WATER TYPE

The evolution of Ca-Na-SO_4-HCO_3 water to Na-Ca-SO_4-HCO_3 and Na-Cl water is well illustrated in figure 15, a plot of analyses in terms of equivalent weights on the trilinear diagram of Piper (1944). Data from wells along geochemical sections *A–A′* and *B–B′* indicate a trend toward sodium predominance on the cation plot, and toward chloride predominance on the anion plot. The increase in sodium and the decrease in calcium and magnesium along the flow path could be the result of several processes.

Sodium could be contributed by dissolution of sodium-bearing silicate or evaporite minerals in the aquifer system. However, no petrographic evidence exists to indicate the presence of halite (NaCl) in the aquifer system, and the dissolution rate of sodic plagioclase ($NaAlSi_3O_8$) is much too slow to account for the concentrations of sodium found in central Iowa.

The inverse relationship between concentrations of sodium and alkaline-earth metals could also be explained by ion exchange, which has been identified in many aquifer systems elsewhere (for example, Foster, 1950; Krothe and Parizek, 1979; Thorstenson and others, 1979; Krothe and Bergeron, 1981; Chapelle and Knobel, 1983). Exchange would follow the generalized reaction

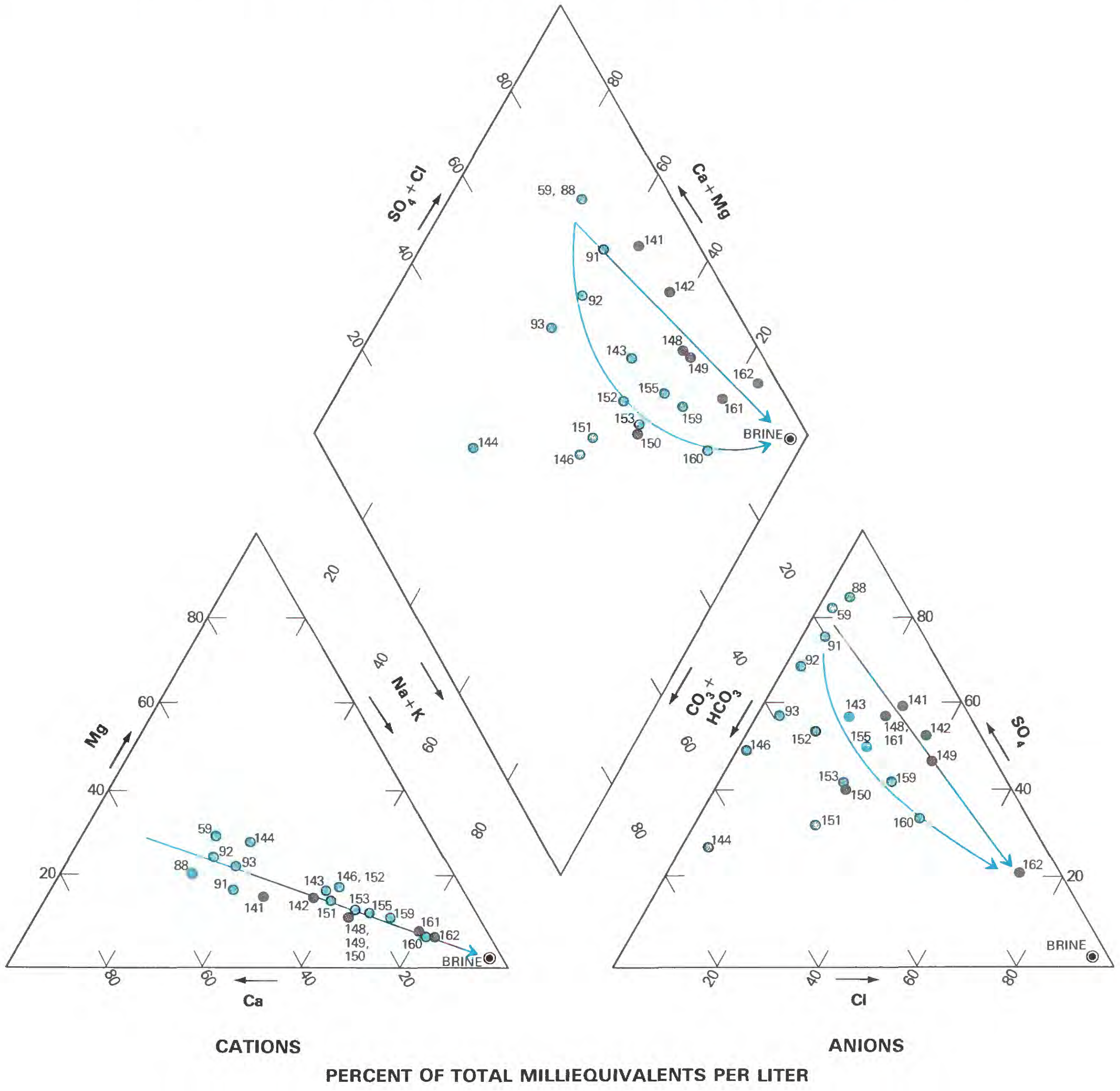
$$M^{2+} + Na_2\text{-Clay} = 2Na^{+} + M\text{-Clay}, \qquad (10)$$

where $M^{2+}$is $Ca^{2+}+Mg^{2+}$or other alkaline-earth metals.

Micaceous clays such as illite and glauconite are more common in the Cambrian-Ordovician aquifer system than are mixed-layered clays such as montmorillonite and smectite, which are usually associated with cation exchange. Major clay minerals in the Ordovician Decorah Formation and Glenwood Formation, which are part of the Maquoketa confining unit that separates aquifer layer 3 from aquifer layer 4, are kaolinite and illite (Parham and Austin, 1967, 1969). However, distinctive beds of potassium montmorillonite have been identified in the Decorah Formation and other Ordovician formations throughout the study area (Mossler and Hayes, 1966). Although the presence of montmorillonite in Ordovician and Cambrian rocks suggests that significant cation-exchange capacity may be present in the aquifers, such exchange probably cannot completely account for the linear plot of the cations (fig. 15). If cation exchange were the dominant mechanism, the plot would trend more parallel to the calcium-sodium axis rather than toward the sodium apex (Piper, 1944), unless exchange of calcium and magnesium for sodium occurred at rates that would maintain similar Ca:Mg molar ratios along the flow path. Covariance of the molality of sodium to molality of (Ca+Mg) has a low coefficient of correlation (r^2) of 0.3 and a slope of +2.1. If ion exchange were a major process, r^2 would be closer to unity and the slope would be close to −2 (Chapelle, 1983). Given the areal variability and probable scarcity of clays having high cation-exchange capacity for calcium and magnesium in the aquifer system, it is unlikely that much ion exchange occurs except in recharge areas underlain by clayey till and the Dakota Formation.

Mixtures of two waters will also plot on straight lines if all solutes remain in solution and do not increase or decrease as a result of chemical reactions. The linearity of the cation plot (fig. 15) may indicate simple mixing of Na-mixed anion water with Ca-Na-mixed anion water, but the curvilinear fit of the anion data indicates sources and sinks along the flow path with respect to bicarbonate and sulfate.

Although cation trends on the trilinear diagrams could indicate mixing of two types of water, sodium and chloride concentrations along the major southeastward direction of ground-water flow across Iowa probably



EXPLANATION

WELL ON GEOCHEMICAL SECTION—Number is location in figure 6

146 ● Section *A—A′*

150 ● Section *B—B′*

BRINE ◉ PLOT OF TYPICAL BRINE IN ILLINOIS BASIN

← DIRECTION OF PRESENT GROUND-WATER FLOW PATH

FIGURE 15.—Trilinear diagram of water chemistry along geochemical sections *A-A′* and *B-B′*.

reflect a gradual mineralization of the waters as they approach the Na-Cl brines of the Illinois basin. The origin of the brines is related to reverse chemical osmosis and membrane filtration (Graf and others, 1965; Clayton and others, 1966; Hanshaw and Coplen, 1973; Graf, 1982). The combined effects of these processes that concentrate sodium and chloride probably extend upgradient in the Cambrian-Ordovician aquifer system outside the Illinois basin proper. For example, chloride concentrations increase to more than 100 mg/L in southern Iowa, halfway down the regional flow paths from northwestern and western Iowa to southeastern Iowa (fig. 16). The overall trend toward more chloride-rich waters occurs even in central Iowa within the plume of low-dissolved-solids water, where concentrations of chloride are several times greater than to the northeast (figs. 7, 16). Figures 17 and 18 show concentrations of major constituents along geochemical sections *A–A′* and *B–B′*. Concentrations of chloride and sodium begin to increase from south-central Iowa down the major flow paths to the southeast toward the Illinois basin.

The trilinear plot of anions (fig. 15) shows that, although chloride is less than 10 percent, sulfate decreases from about 80 percent at the recharge area in western Iowa to about 55 percent near the Mississippi River. Bicarbonate plus carbonate increases from less than 20 percent to more than 40 percent. The apparent inverse relationship between equivalents of these constituents suggests that sulfate is possibly being reduced to sulfide along the hydraulic gradient, probably with an associated loss of oxygen, in the presence of a reducing agent such as organic material.

If the reducing agent is organic material, the following reactions are possible:

$$15CH_2O+2Fe_2O_3+8SO_4^{2-}+H_2CO_3 = 4FeS_2+16HCO_3^{-}+8H_2O \tag{11}$$

or

$$SO_4^{2-}+2CH_2O+2H^{+}= H_2S+2CO_2+2H_2O. \tag{12}$$

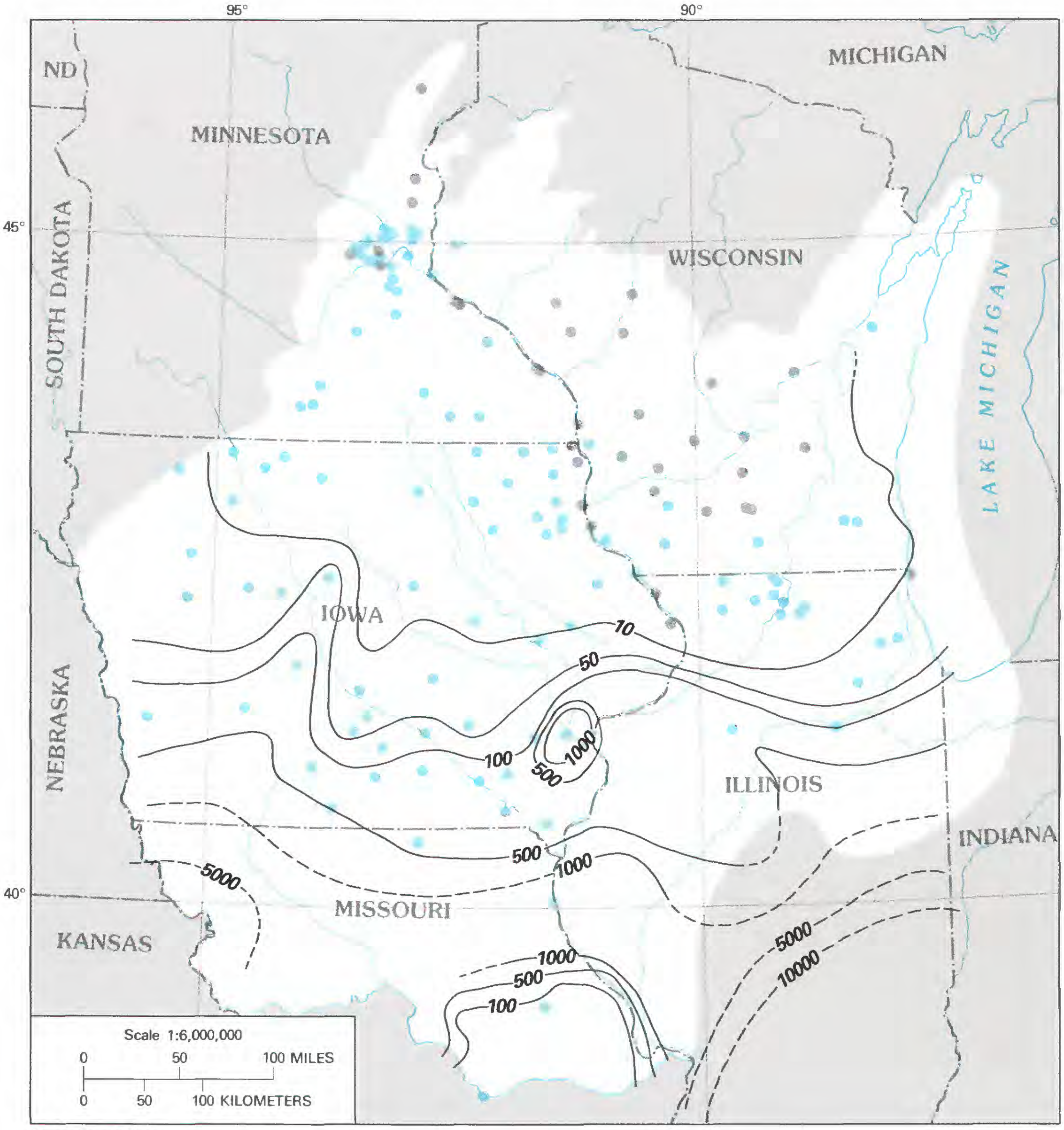
Hematite (Fe_2O_3) and ferric oxyhydroxide [$FeO(OH)$] are common in the Cambrian-Ordovician aquifer system. Organic material is less common, but bacteriogenic decomposition of organic material occurs within the overlying Dakota Formation. Thus, recharge from the Dakota Formation and possible reduction of organic material in shales associated with aquifer layer 3 could produce bacteriogenic methane in water. Methane concentrations of as much as 15 ppm in aquifer layer 3 and 7 ppm in aquifer layers 2 and 1 were identified in southwestern Minnesota (Coleman, 1978; Minnesota Department of Natural Resources, written commun., 1981).

The equivalent weight of sulfate lost should approximately equal that of bicarbonate gained if the reactions are a reasonable explanation for the observed chemical changes (eqs. 11, 12). A plot of equivalents of sulfate against bicarbonate for sections *A–A′* and *B–B′* shows the contrary (fig. 19); as sulfate decreases, bicarbonate remains the same, at about 5 meq/L. Furthermore, saturation indices indicate that the ground water is oversaturated or is nearly in equilibrium with calcite and dolomite (fig. 11). Bicarbonate concentrations remain constant even in the vicinity of the dilute plume in central Iowa. If the dilute plume is caused by dilution of ground water with recharge water of low dissolved-solids content, the uniform bicarbonate concentrations and saturation indices would suggest that ground water has reequilibrated with carbonate minerals in the aquifer since the dilution episode or episodes. The mechanism, timing, and amount of such recharge can be explained hypothetically by glacial advances during the Pleistocene and are discussed later in the section "Isotopic Composition of Water and Pleistocene Recharge Model."

TRACE AND MINOR CONSTITUENTS

The areal distribution of many trace constituents in the aquifer system is related approximately to the availability of the constituents in the source rocks. Although specific data on the trace-element content of the aquifer matrix is lacking, compilation of the average distribution of elements in major rock types (Turekian and Wedepohl, 1961; Drever, 1982) indicates that higher concentrations of many transition metals are found in shales rather than in carbonate rocks or sandstones. Concentrations of the alkaline earth strontium and of halogens, such as bromine and fluorine, are more variable with respect to rock type.

The areal distribution of the transitional metals cadmium and arsenic in the aquifer system may be related to the proximity of the argillaceous Dakota Formation. Concentrations of these metals are generally less than 5 μg/L, except where the aquifer subcrops beneath the Dakota Formation in northwestern Iowa and southwestern Minnesota (fig. 20). Scant data suggest that selenium concentrations are less than 5 μg/L except at one location beneath the Dakota Formation. Cadmium concentrations may also increase to more than 5 μg/L in southeastern Iowa and northeastern Missouri on the edge of the Illinois basin. Concentrations of iron and manganese increase where the aquifer is overlain by the Dakota Formation and by drift derived from the Dakota (fig. 21). For example, concentrations of iron



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EXPLANATION

–50– – – LINE OF EQUAL CHLORIDE CONCENTRATION—Dashed where approximate. Interval, in milligrams per liter, is variable

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

● Open to aquifer layer 1

● Open to aquifer layer 3

FIGURE 16.—Chloride distribution in aquifer layers 1 and 3.

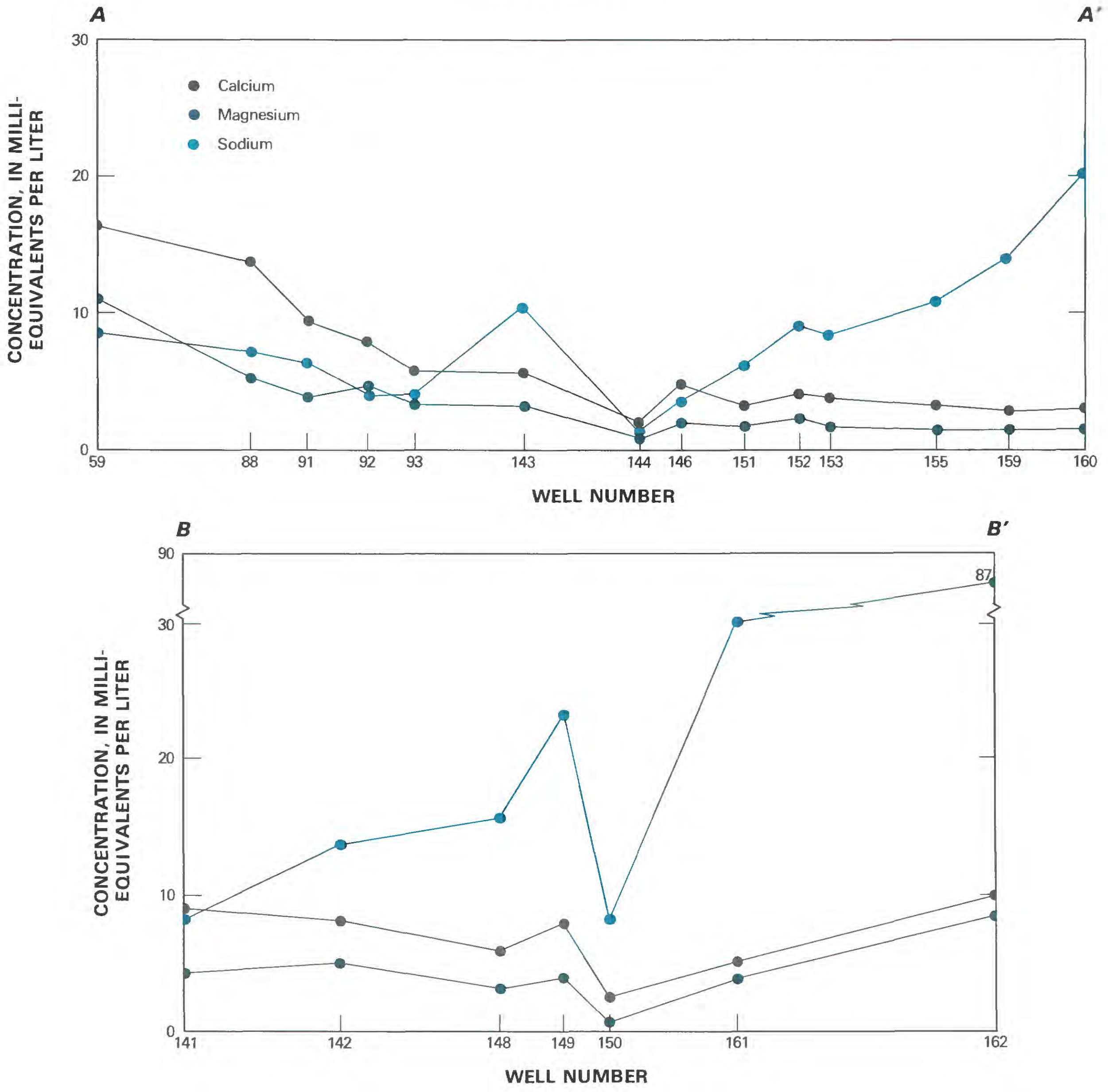

FIGURE 17.—Concentrations of major cations in water from wells in aquifer layers 1 and 3 along geochemical sections *A-A′* and *B-B′*. (Location of wells shown in fig. 6.)

and manganese exceed 1,000 μg/L and 100 μg/L, respectively, in northwestern Iowa. Concentrations of iron, manganese, copper, lead, and cobalt increase in southwestern Iowa near the margin of the Forest City basin (figs. 21, 22). Concentrations of cadmium and copper are more than 5 and 20 μg/L, respectively, in southeastern Iowa near the western flank of the Illinois basin (figs. 20, 22).

The controls on the concentrations of these and other trace metals are complicated and are related as much to complexation of metals by organic and inorganic ligands, sorption of metals onto solids, and oxidation-reduction potential of the water as to the metal content of the source rock (Garrels and Christ, 1965; Stumm and Morgan, 1981; Eichenberger and Chen, 1982; Hem, 1985). The influence of these processes on the trace-metal content of the water cannot be evaluated at the present time because the detection limits of the analyses for the metals were at reconnaissance levels and because information on the composition of dissolved organic carbon in the water and regional mineralogical and trace-metal composition of the aquifer matrix are

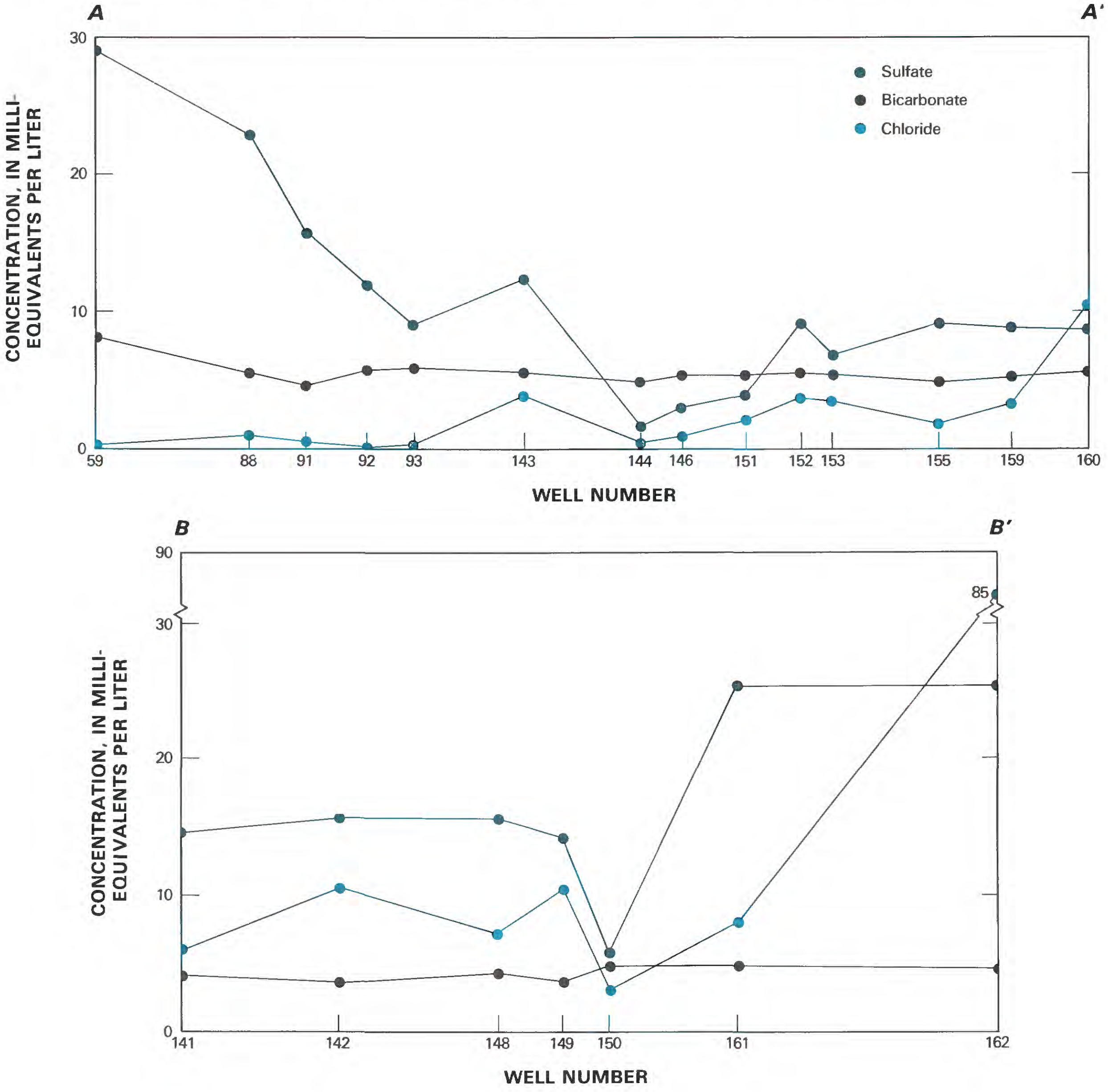

FIGURE 18.—Concentrations of major anions in water from wells in aquifer layers 1 and 3 along geochemical sections *A-A'* and *B-B'*. (Location of wells shown in fig. 6.)

lacking. Some trace metals, such as iron, can be reduced by bacteria at the pH values prevalent in the aquifer. Reducing conditions, identified by measurable dissolved sulfide, are present throughout the aquifer where it is confined by the Maquoketa Shale (fig. 14) and locally in the Dakota Formation (Burkart, 1984), and they probably are a major control on trace-metal concentrations in western Iowa.

The relationship between some trace-metal concentrations in ground water and proximity to the Forest City basin may be indicated by concentrations of beryllium and molybdenum of more than 1 and 10 μg/L, respectively, in southwestern Iowa (fig. 23). Concentrations of these and other metals may increase near the Illinois basin. However, no trace-metal data for water from the Cambrian-Ordovician aquifer system are available for that area. Several wells in northeastern and north-central Iowa inexplicably have molybdenum concentrations of more than 10 μg/L.

Some trace constituents that have relatively similar average concentrations in different sedimentary rock types show increases in concentration in ground water

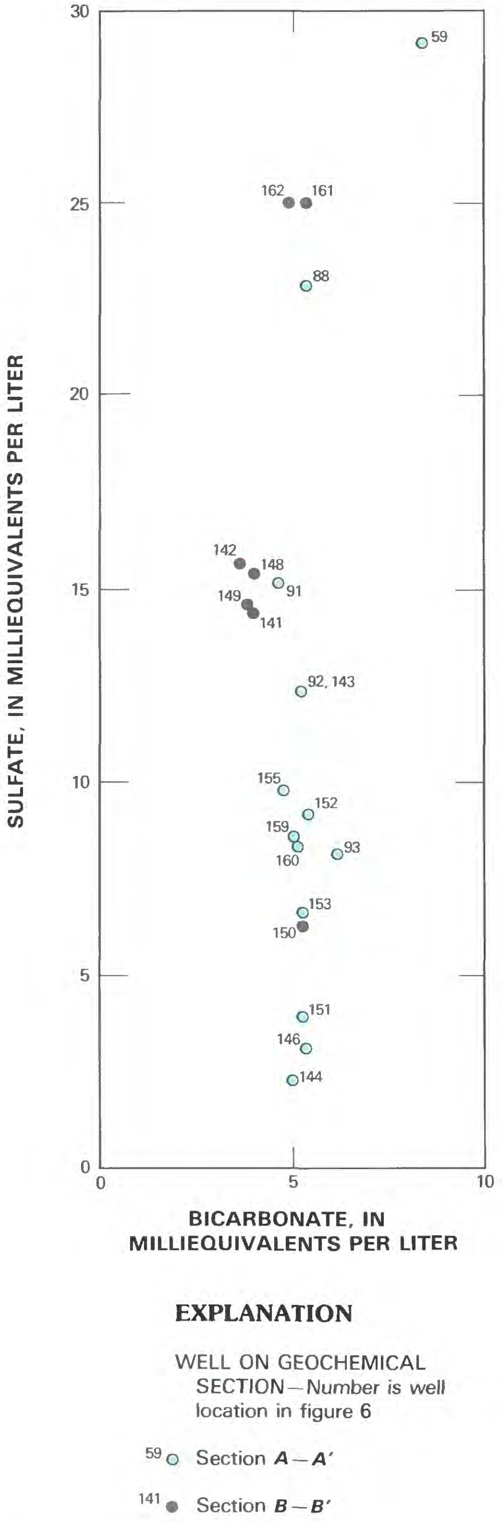

FIGURE 19.—Sulfate-bicarbonate relationship along geochemical sections *A-A′* and *B-B′*.

southwestward across Iowa and eastward across Wisconsin. For example, fluoride concentrations increase from less than 1 to more than 2 mg/L, lithium from less than 10 to more than 400 μg/L, boron from less than 200 to more than 2,000 μg/L, and strontium from less than 1,000 to more than 6,000 μg/L across Iowa (figs. 24–27). Strontium concentrations exceed 1,000 μg/L in eastern Wisconsin where dissolved solids generally exceed 500 mg/L (Nichols and McNall, 1957; Kammerer, 1981). Boron concentrations exceed 5,000 μg/L near the western edge of the Illinois basin (fig. 26).

There is no identifiable plume of dilute concentration of trace constituents in Iowa (as there is for dissolved solids), with the exception of bromide (fig. 28) and possibly lithium (fig. 25). Bromide concentrations in the aquifer are generally less than 0.5 mg/L except near the western edge of the Illinois basin, where concentrations approach 10 mg/L. In central and southern Iowa, a broad zone of bromide concentration of less than 0.5 mg/L is surrounded by areas of bromide concentrations of greater than 1.0 mg/L (fig. 28). This distribution roughly matches the dilution shown by the dissolved-solids distribution (fig. 7). Bromide is a conservative, relatively nonreactive constituent and therefore is a good indicator of hydrological processes that involve mixing of different water types. The lack of similar dilution plumes in the distribution of strontium, fluoride, and boron suggests that chemical processes other than mixing have controlled the distribution of these trace constituents, thus masking the reacharge plume(s).

Concentrations of barium in the ground water are related both to source and to geochemical processes. Gilkeson and others (1981) showed that barium concentrations or more than 1 mg/L in northeastern Illinois are due to a zone of reducing conditions in the confined Cambrian-Ordovician aquifer system. Sulfate ion is reduced to sulfide, thereby allowing concentrations of barium to increase until the solubility limit of barite ($BaSO_4$) is reached. Concentrations exceeding 100 μg/L in the northwestern part of the study area are probably due to barium contained in shales of the Dakota Formation (fig. 29). Concentrations also exceed 100 μg/L in the northeastern corner of Iowa near the Mississippi River. The cause of the higher barium concentrations in Iowa is unknown. Higher barium concentrations also are present in the aquifer in southeastern Wisconsin along the strike of the Maquoketa Shale, apparently an extension of the conditions in northeastern Illinois. Additional work is needed to determine whether the solubility of barite controls the high barium concentrations in these waters.

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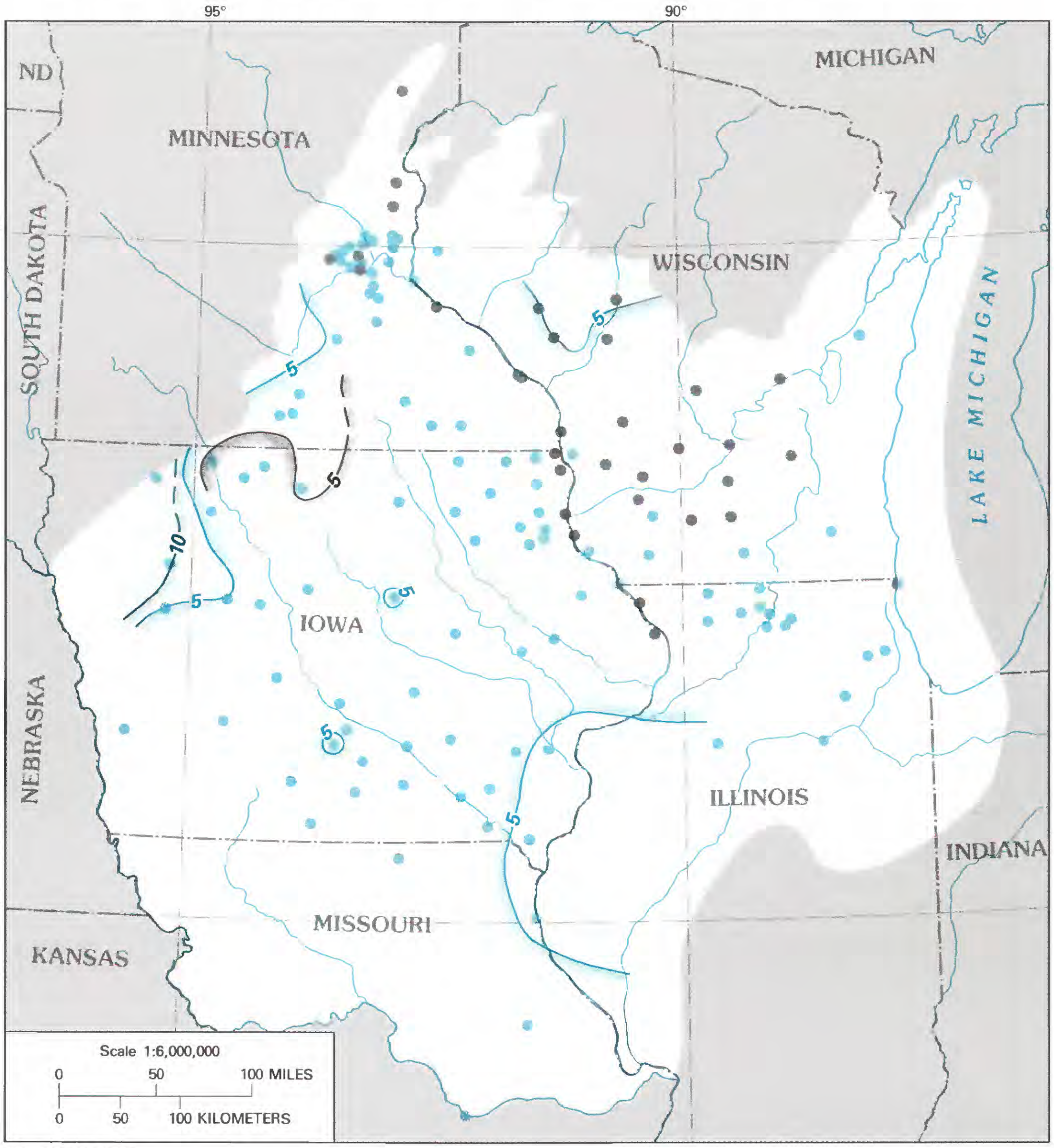


Base enlarged from
U.S.Geological Survey
1:7,500,000, 1970

EXPLANATION

LINES OF EQUAL CONCENTRATION—Stippled in direction of lower concentration. Dashed where approximate. Interval, in micrograms per liter, is variable

—5— Cadmium

– —5— Arsenic

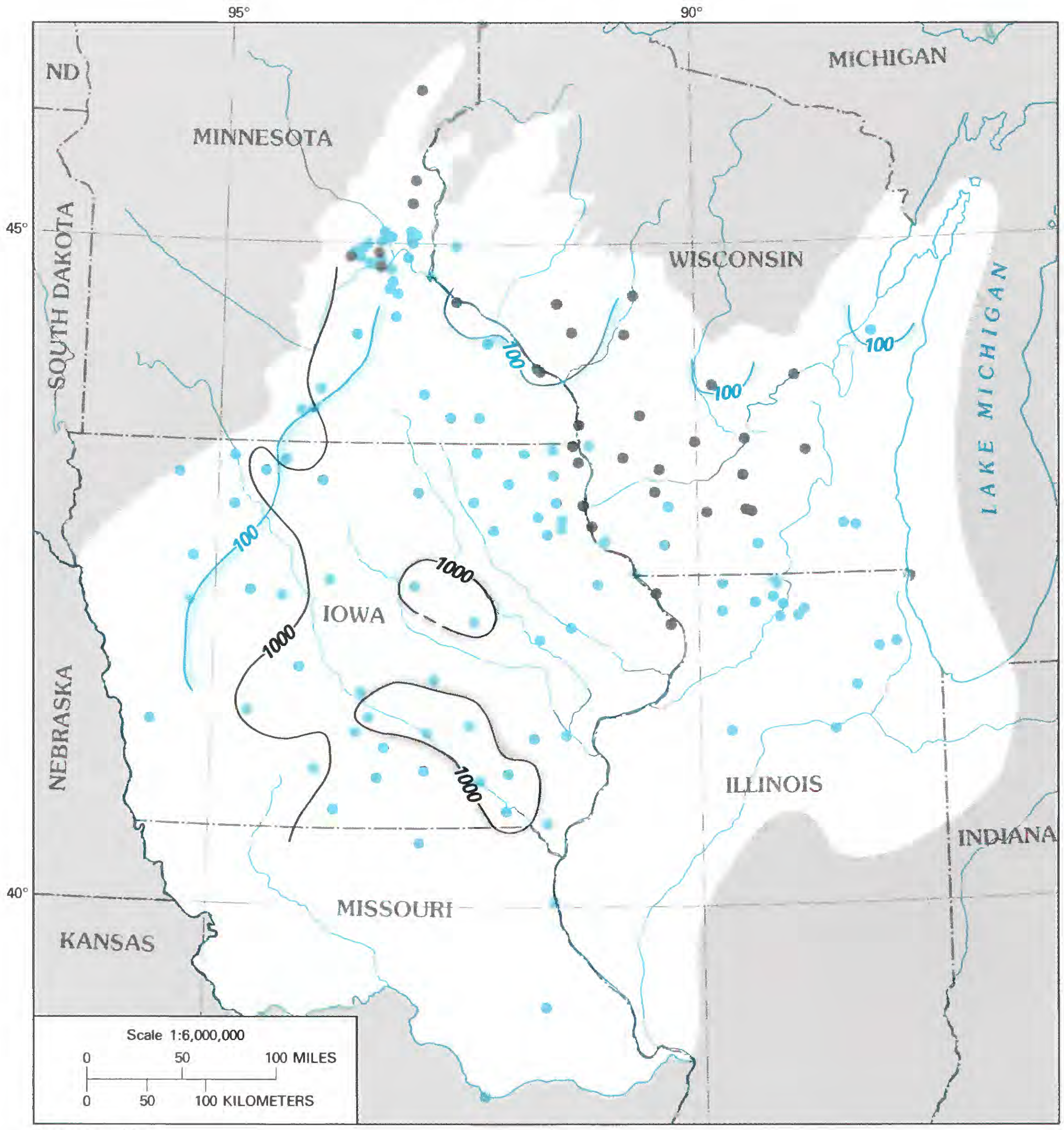
- —10— Selenium

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

● Open to aquifer layer 1

● Open to aquifer layer 3

FIGURE 20.—Distribution of dissolved cadmium, arsenic, and selenium in aquifer layers 1 and 3.



Base enlarged from
U.S.Geological Survey
1:7,500,000, 1970

EXPLANATION

LINES OF EQUAL CONCENTRATION—Stippled in direction of lower concentration. Dashed where approximate. Interval, in micrograms per liter, is variable

--*1000*— Iron

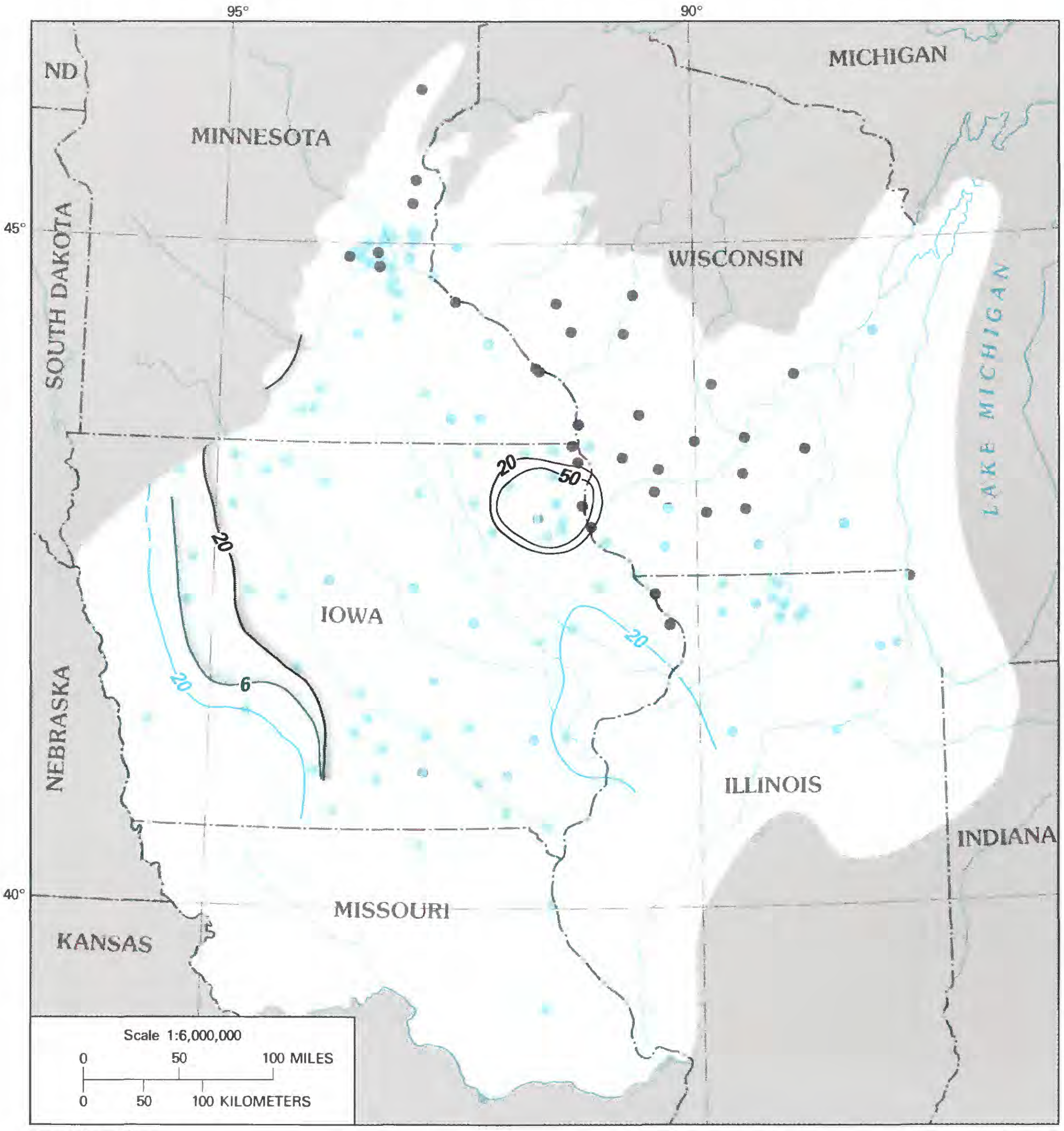
—*100*— Manganese

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

● Open to aquifer layer 1

● Open to aquifer layer 3

FIGURE 21.—Distribution of dissolved iron and manganese in aquifer layers 1 and 3.



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1:7,500,000, 1970

EXPLANATION

LINES OF EQUAL CONCENTRATION—Stippled in direction of lower concentration. Dashed where approximate. Interval, in micrograms per liter, is variable

—20— Copper

—20— Lead

—6— Cobalt

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

● Open to aquifer layer 1

● Open to aquifer layer 3

FIGURE 22.—Distribution of dissolved copper, lead, and cobalt in aquifer layers 1 and 3.

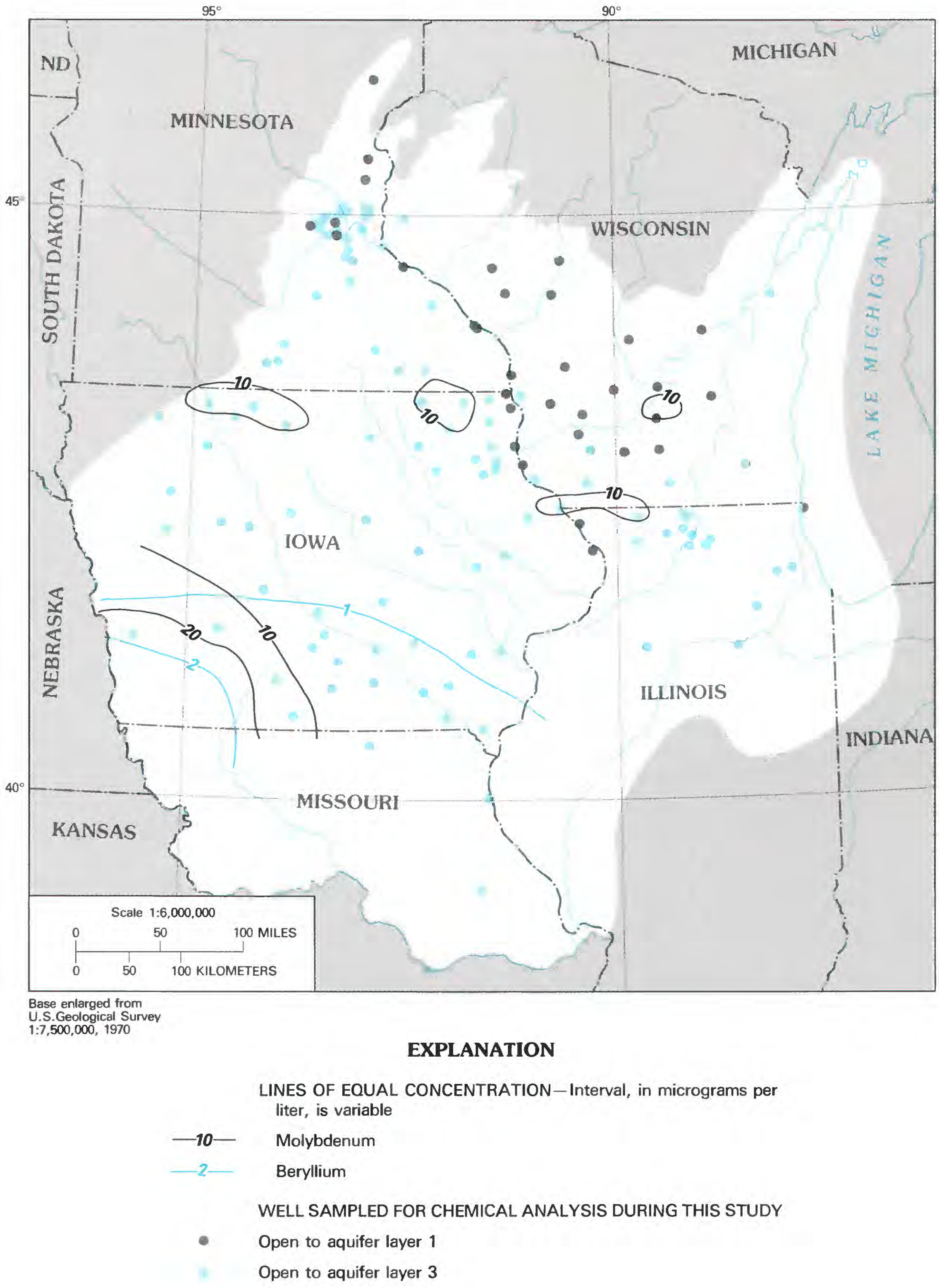

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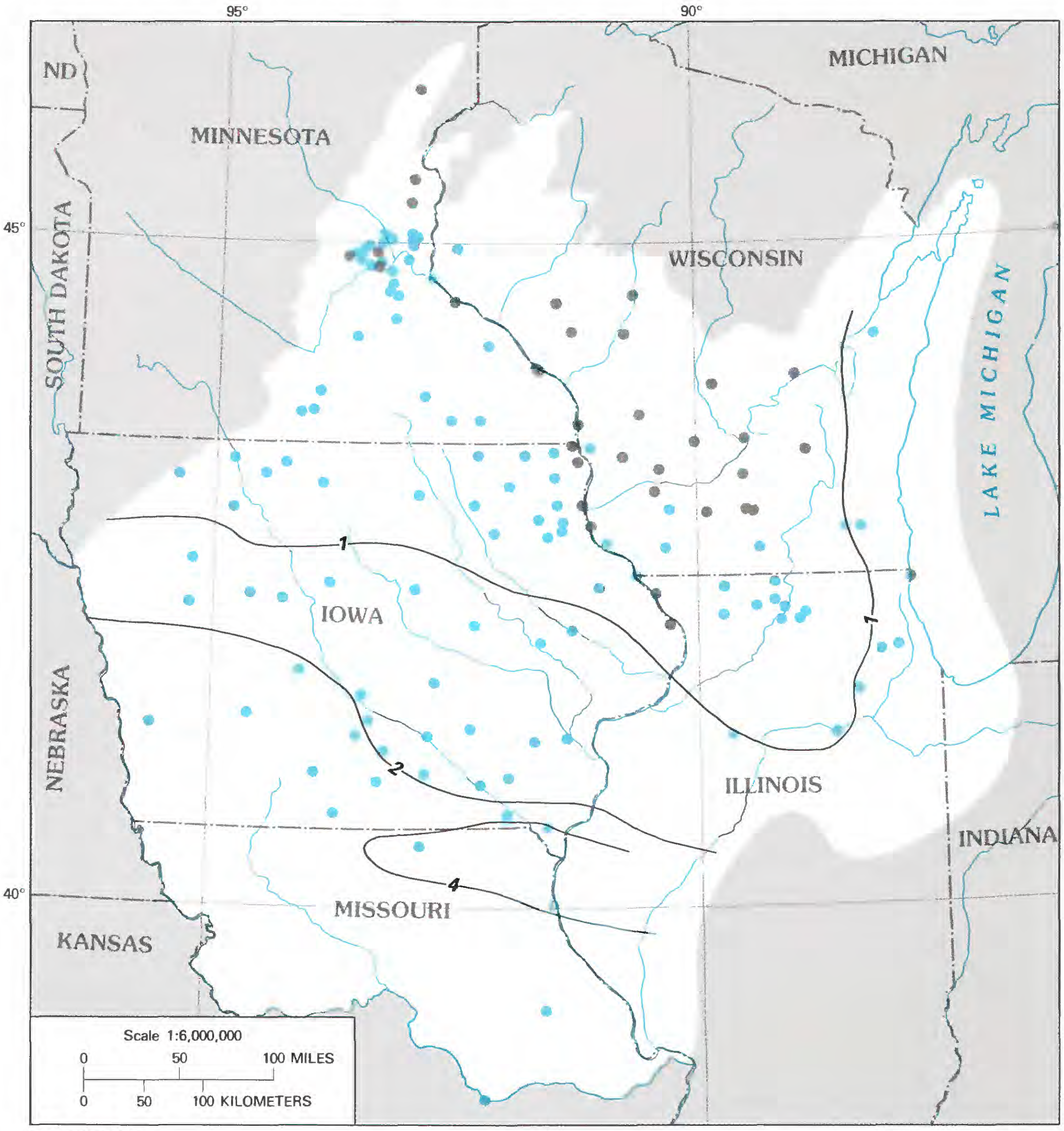
FIGURE 23.—Distribution of dissolved molybdenum and beryllium in aquifer layers 1 and 3.



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EXPLANATION

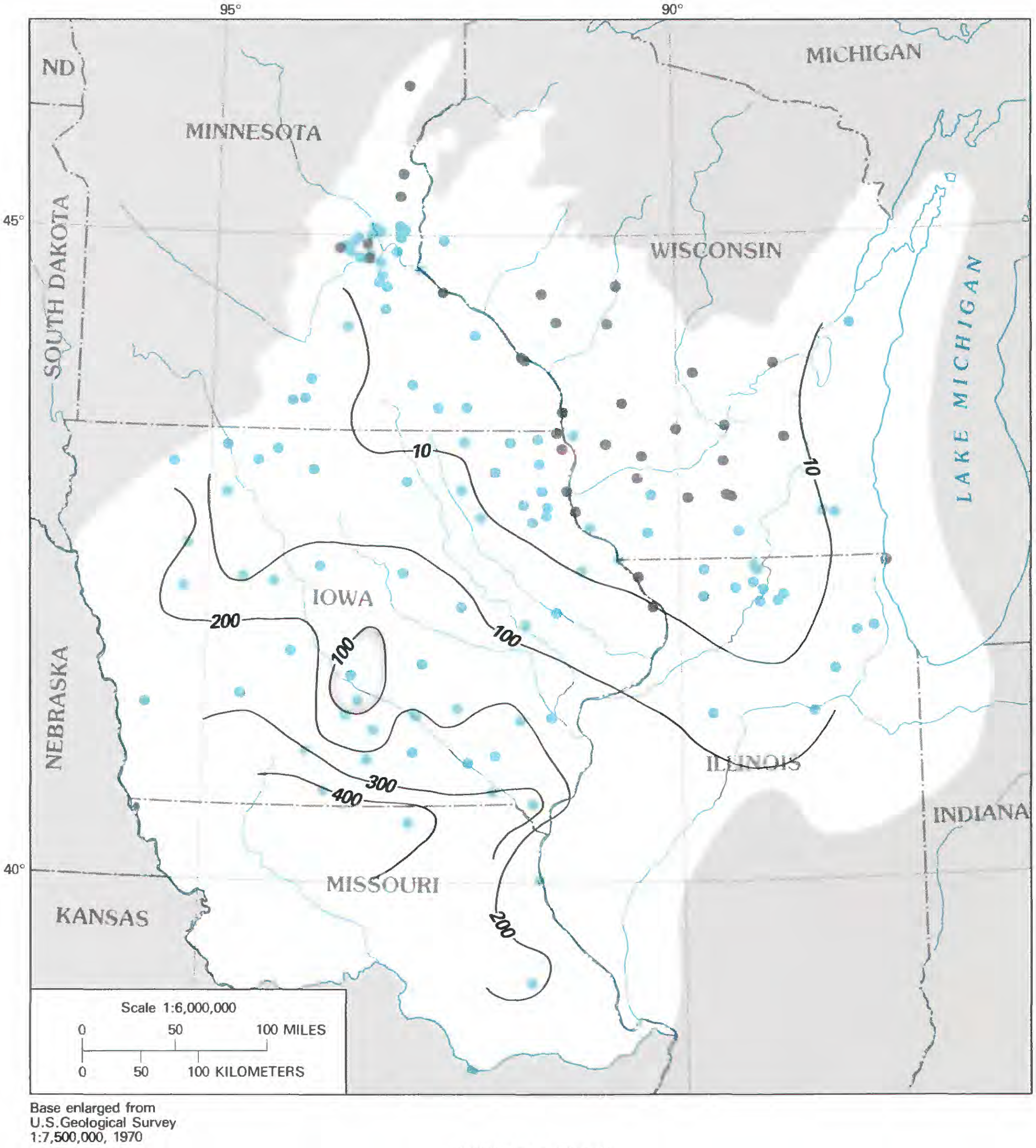
—4— LINE OF EQUAL FLUORIDE CONCENTRATION—Interval, in milligrams per liter, is variable

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

● Open to aquifer layer 1

● Open to aquifer layer 3

FIGURE 24.—Distribution of dissolved fluoride in aquifer layers 1 and 3.



EXPLANATION

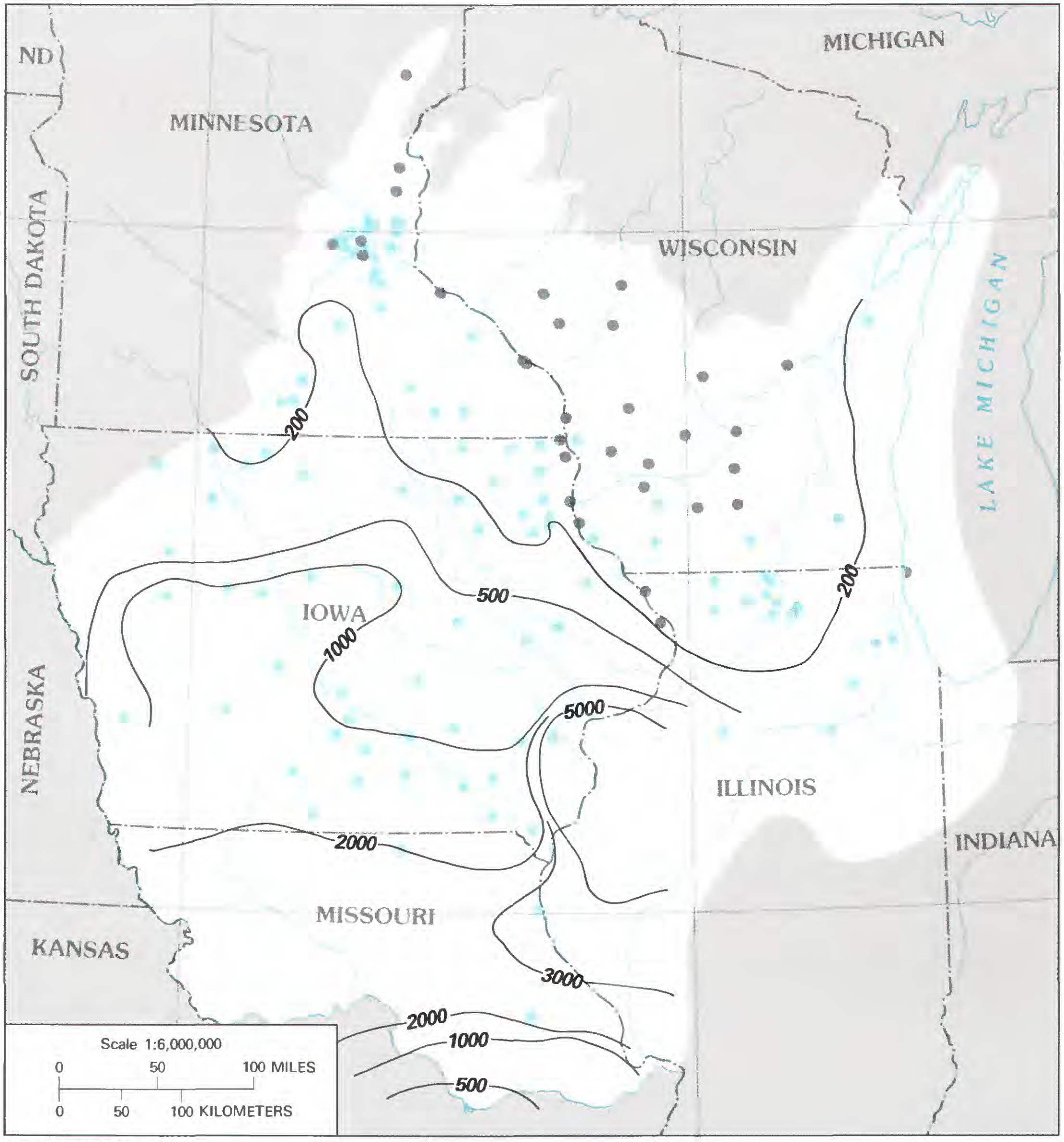
—100— LINE OF EQUAL DISSOLVED LITHIUM CONCENTRATION—Stippled in direction of lower concentration. Interval, in micrograms per liter, is variable

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

● Open to aquifer layer 1

● Open to aquifer layer 3

FIGURE 25.—Distribution of dissolved lithium in aquifer layers 1 and 3.



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EXPLANATION

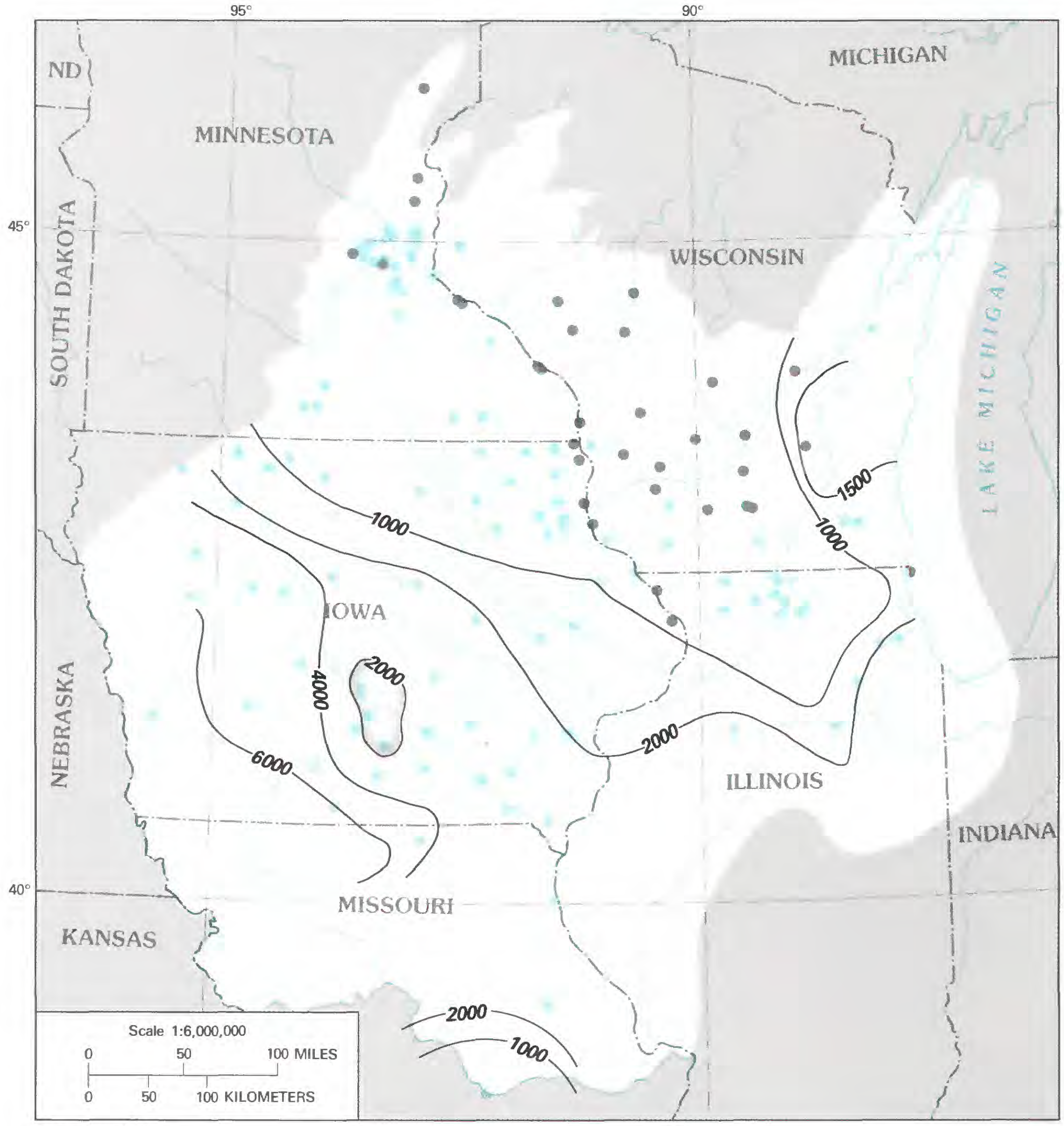
—200— LINE OF EQUAL BORON CONCENTRATION—Interval, in micrograms per liter, is variable

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

● Open to aquifer layer 1

● Open to aquifer layer 3

FIGURE 26.—Distribution of dissolved boron in aquifer layers 1 and 3.



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EXPLANATION

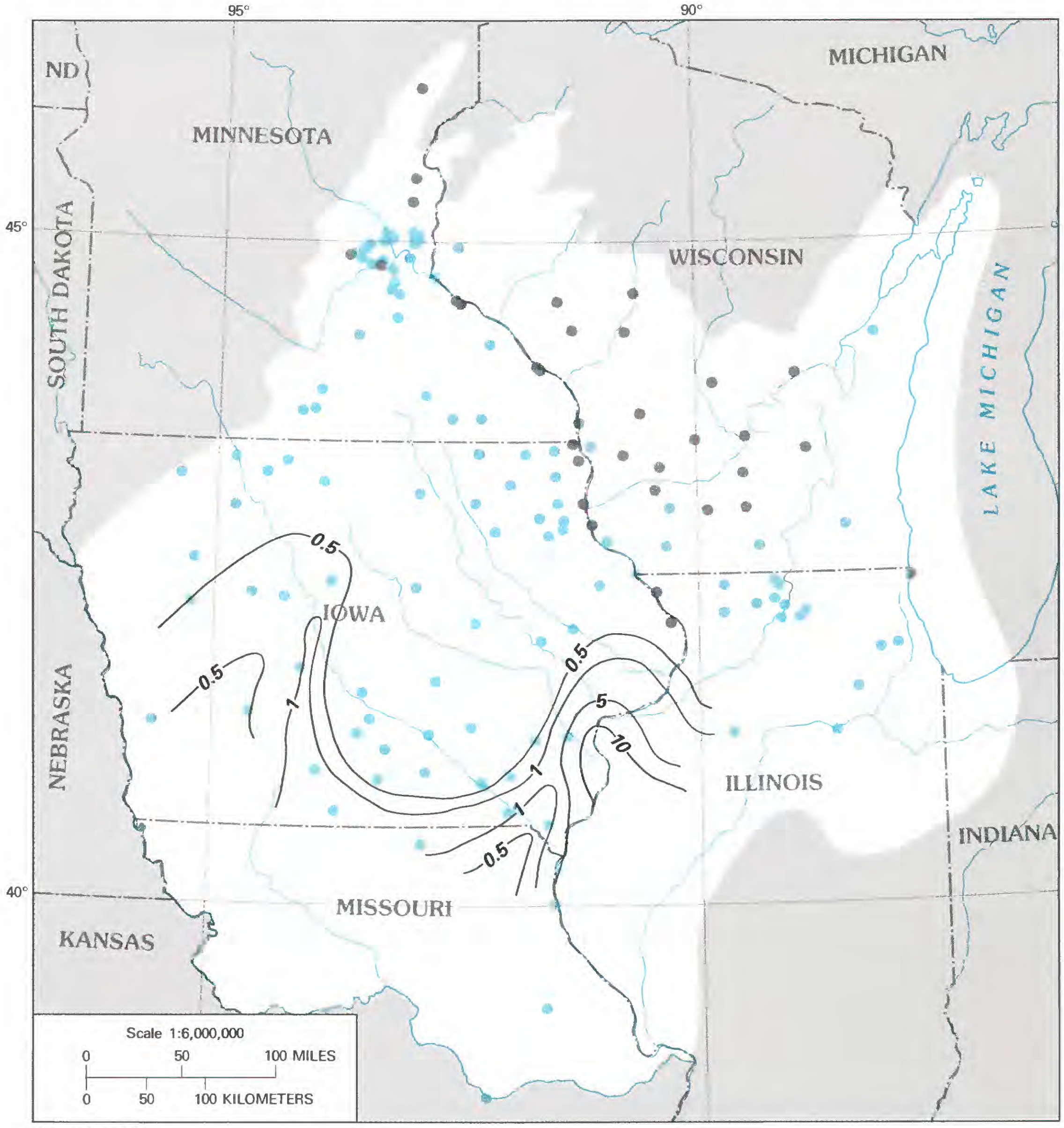
—1000— LINE OF EQUAL DISSOLVED STRONTIUM CONCENTRATION—Stippled in direction of lower concentration. Interval, in micrograms per liter, is variable

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

● Open to aquifer layer 1

● Open to aquifer layer 3

FIGURE 27.—Distribution of dissolved strontium in aquifer layers 1 and 3.



Base enlarged from
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EXPLANATION

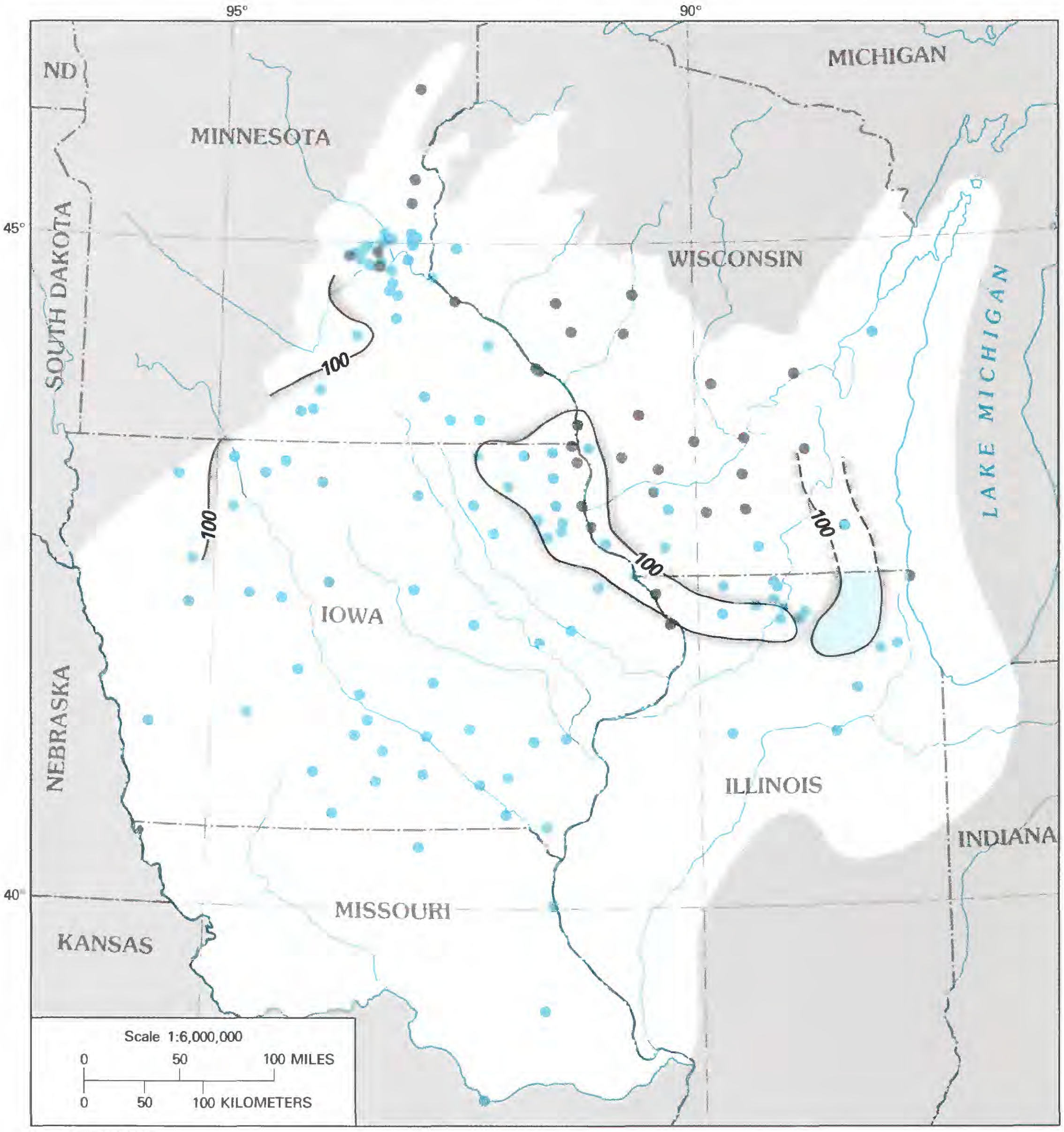
—5— LINE OF EQUAL BROMIDE CONCENTRATION—Interval, in milligrams per liter, is variable

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

● Open to aquifer layer 1

● Open to aquifer layer 3

FIGURE 28.—Distribution of dissolved bromide in aquifer layers 1 and 3.



Base enlarged from
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1:7,500,000, 1970

EXPLANATION

—100-- LINE OF EQUAL DISSOLVED BARIUM CONCENTRATION—Stippled in direction of lower concentration. Dashed where approximate. Interval 100 micrograms per liter

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

● Open to aquifer layer 1

● Open to aquifer layer 3

▭ DATA FROM GILKESON AND OTHERS (1981)

FIGURE 29.—Distribution of dissolved barium in aquifer layers 1 and 3.

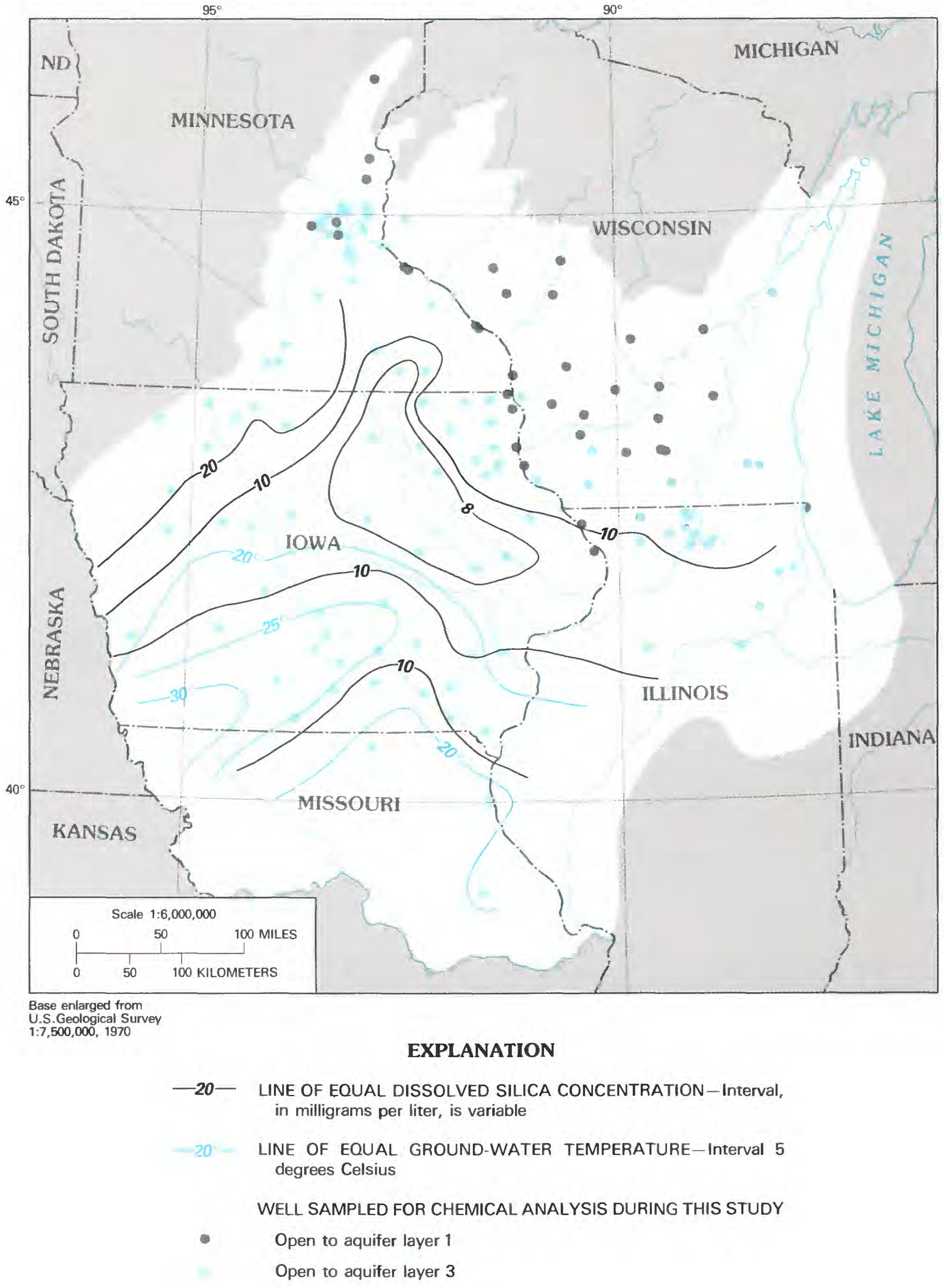

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FIGURE 30.—Distribution of dissolved silica and ground-water temperature in aquifer layers 1 and 3.

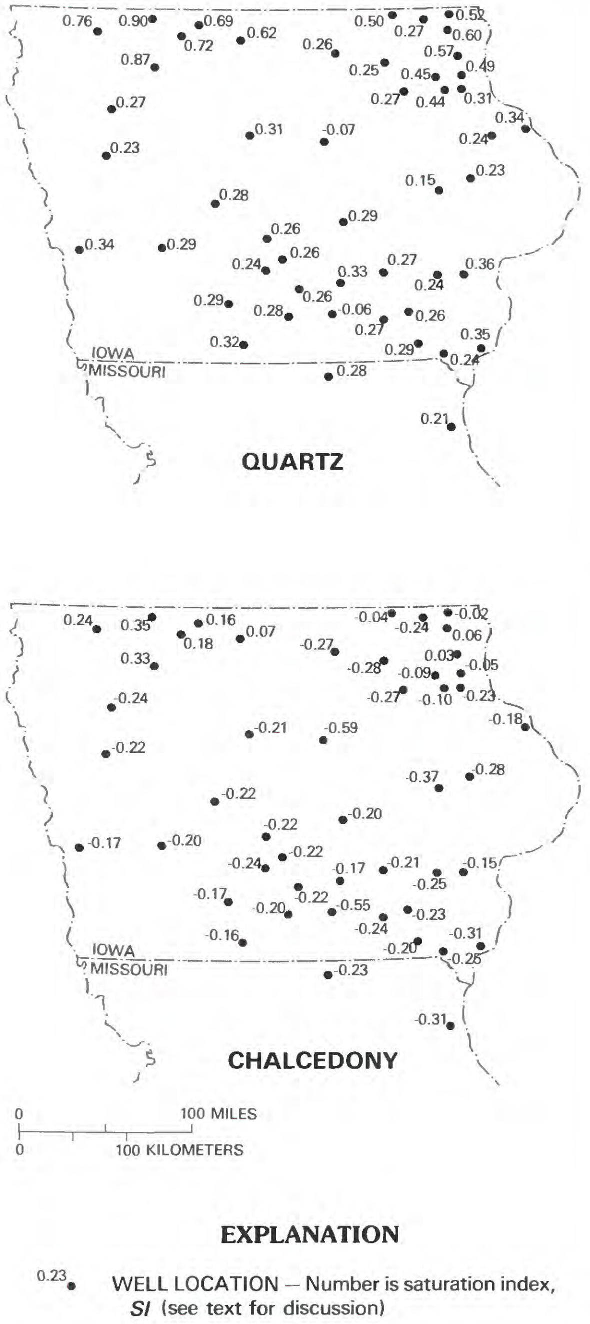


FIGURE 31.—Saturation indices for quartz and chalcedony in water from selected wells in aquifer layer 3 in Iowa and northeastern Missouri.

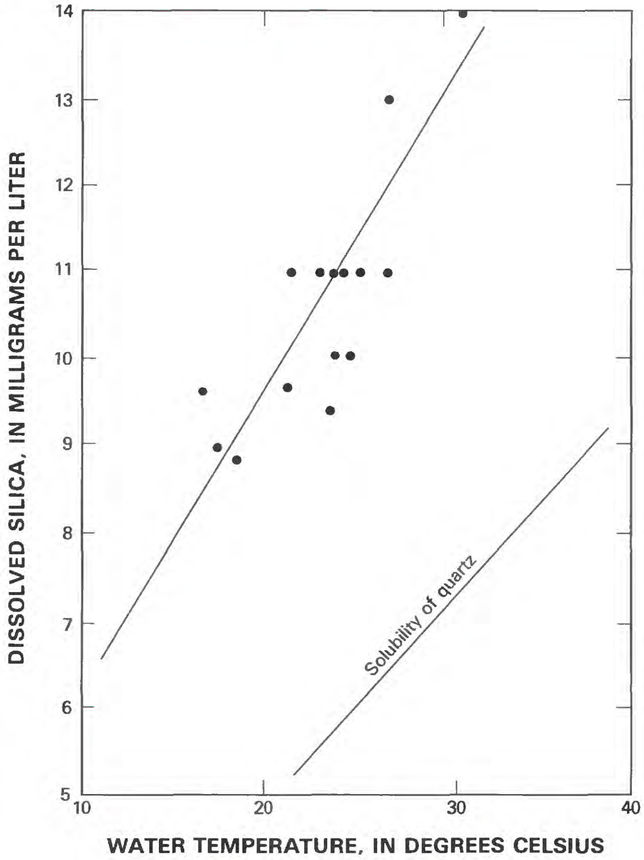
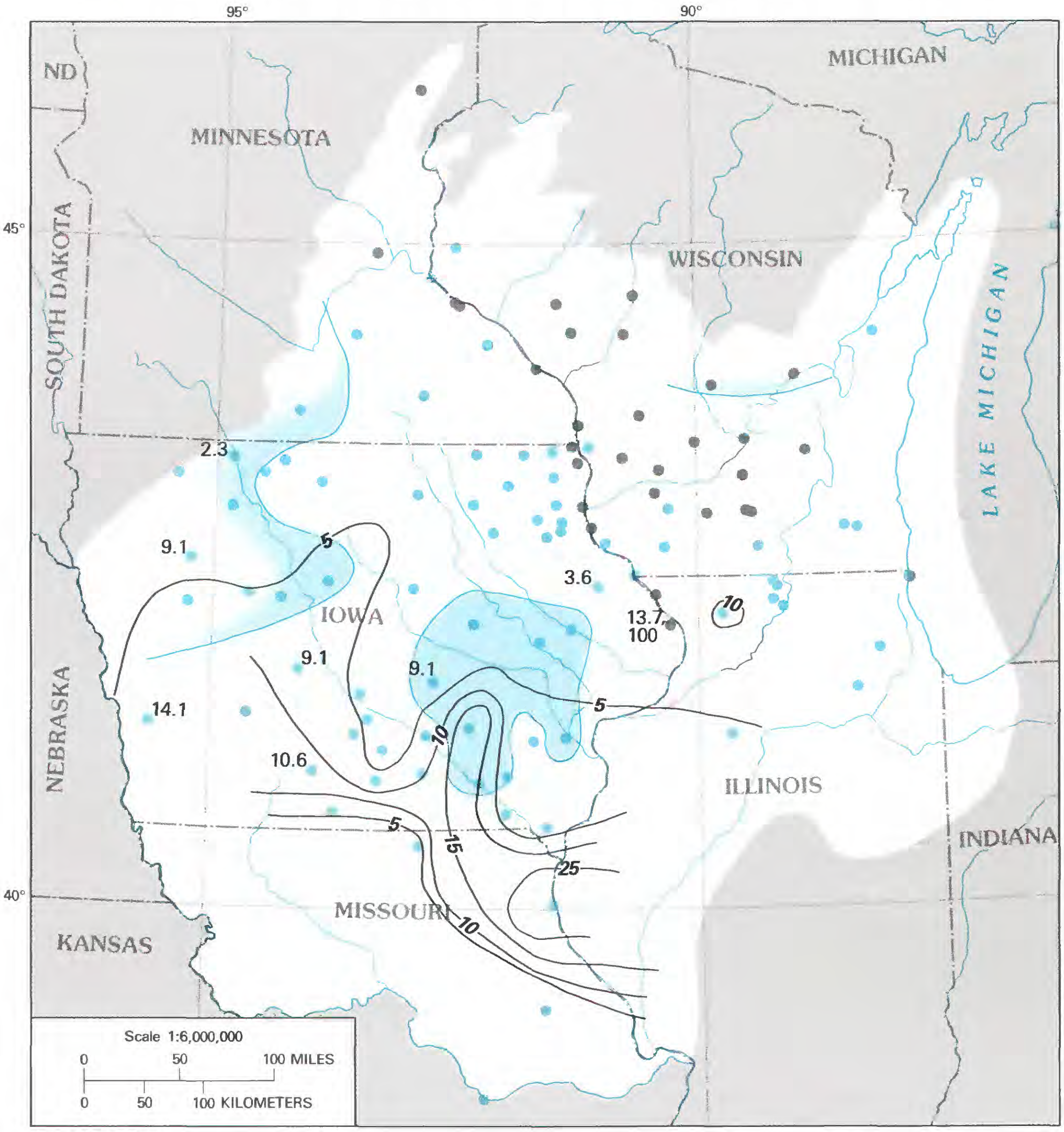


FIGURE 32.—Comparison of dissolved silica concentration and the solubility of quartz with water temperature in southwestern and southern Iowa and northeastern Missouri.

Concentrations of silica in the aquifer system range from less than 8 to more than 20 mg/L (fig. 30). The differences in silica content are related to the solubility of silicate phases in the aquifer matrix. Saturation indices show oversaturation of quartz and undersaturation of chalcedony (fig. 31); this is a typical occurrence in many waters. The solubility of silica in surface and ground water is related to solid-phase products of aluminosilicate mineral dissolution, but no aluminum data are available to test the thermodynamic models of such dissolution in a formal sense.

Concentrations of silica greater than 20 mg/L are present in the recharge area in northwestern Iowa, where the Dakota Formation and the overlying drift contain siliceous shales. Concentrations decrease downgradient to less than 10 mg/L in central Iowa, increase to more than 10 mg/L in south-central Iowa, and then decrease to less than 10 mg/L in southeastern Iowa. The distribution patterns of silica and temperature are very similar, showing the direct relationship of silica solubility to water temperature. However, the data in figure 32 indicate that the relationship of quartz solubility with temperature is not the control on dissolved silica (Helgeson, 1969). This suggests that silica phases other than quartz are contributing silica to the ground water.



Base enlarged from
U.S.Geological Survey
1:7,500,000, 1970

EXPLANATION

—*10*— LINE OF EQUAL RADIUM-226 CONCENTRATION—Interval, in picocuries per liter, is variable

▭ AREA WHERE DISSOLVED URANIUM CONCENTRATION EXCEEDS 1 MICROGRAM PER LITER

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY
Number is activity ratio of $^{234}U/^{238}U$

● 13.7 Open to aquifer layer 1

● 9.1 Open to aquifer layer 3

FIGURE 33.—Distribution of dissolved uranium and radium-226 in aquifer layers 1 and 3.

The distribution of uranium and radium-226 in the aquifer system shows the effects of the dilution plume in Iowa (fig. 33) on the concentration of these constituents. Uranium exceeds 1 μg/L in northwestern and southeastern Iowa but is less than 1 μg/L in central and southern Iowa and in northern Missouri in the vicinity of the plume of low dissolved solids. The 5-pCi/L line of radium-226 activity clearly defines the shape of the plume. Activity increases to more than 15 pCi/L southward near the Iowa-Missouri border, but the scant available data show a decrease to 5 pCi/L in northern Missouri.

High radium activities have been identified in Iowa (Brown and Morris, 1959; Lucas, 1960, 1985; Morris and Klinsky, 1962; Horick and Steinhilber, 1978; Cochran and Hahne, 1979), eastern Wisconsin (Lucas, 1960, 1985; Hahn, 1984), and northeastern Illinois (Lucas and Ilcewicz, 1958; Krause, 1959, 1960; Larson and Weatherford, 1960; Lucas, 1960, 1985; Emrich and Lucas, 1963; Kristoff and others, 1975; Gilkeson and Cowart, 1982; Gilkeson and others, 1983).

The sources of the high radium concentrations in the ground water are probably related to uranium-238 and thorium-232 in the aquifer matrix. These radioisotopes decay to radium-226 and 228, respectively. In Illinois, Gilkeson and others (1978) used radium-226 and radium-228 concentrations in 33 samples of Cambrian and Ordovician rocks to estimate the equivalent amounts of uranium-238 and thorium-232, assuming equilibrium between the parent-daughter nuclides. Calculated average uranium-238 concentrations ranged from about 1 ppm in sandstone to about 3 ppm in shale. Direct determinations of uranium-238 indicated that uranium-238 and radium-226 are in equilibrium or near equilibrium in the Cambrian-Ordovician rocks.

The activity of radium-226 and concentrations of uranium in solution may not be directly correlated, however, because of restraints on the solubility of uranium in different redox (reduction-oxidation) environments. Uranium is mobile in oxidizing environments and immobile in reducing environments (Hostetler and Garrels, 1962; Langmuir, 1978). Gilkeson and Cowart (1982) observed a decrease in total uranium concentrations from a few tenths μg/L to less than 0.01 μg/L across a reduction front along a flow path in the Cambrian-Ordovician aquifer system in northeastern Illinois. Downgradient from the reduction front, however, uranium increased to more than 0.3 μg/L under oxidizing conditions. The decrease in uranium in the central part of Iowa also could be due partly to more reducing conditions along the major flow paths. The increase in uranium in southeastern Iowa, however, probably is not caused by increased uranium solubility in oxidizing conditions, because other chemical constituents, such as dissolved sulfide, indicate probable reducing conditions.

Radium-226 activity can be increased in the ground water along a reducing front because of decay of uranium in the water and uranium previously precipitated in the aquifer matrix. The decrease in uranium in Iowa is not accompanied by an increase in radium-226 from northeast to southwest. Therefore, concentrations of uranium and radium-226 in central Iowa seem to be related more to the dilution events than to geochemical processes in the aquifer system.

The activity ratio of ^{234}U/^{238}U generally increases across a reducing front because of alpha-recoil transfer (Kronfeld and others, 1975; Cowart and Osmond, 1977). No such increase in the activity ratio is apparent from the data in central Iowa. However, to relate redox relationships to uranium and radium in ground water, more detailed sampling is necessary at a closer spacing than for the reconnaissance purposes of this study. Defining sources and sinks for radium and uranium in the study area would require more detailed information on the concentrations and isotopic variability of these constituents and thorium in aquifer matrices and ground water. For example, in a more detailed study, Gilkeson and Cowart (1982) determined ^{234}U/^{238}U alpha-activity ratios in ground water from the aquifer system along a flow path from the unconfined to confined system in northeastern Illinois. Where the aquifer is confined by the Maquoketa Shale, ratios exceed 20, but in the unconfined area, ratios are generally less than 5. The disequilibrium in the confined area is pronounced, and Gilkeson and Cowart (1982) suggest that dissolved uranium was emplaced in the aquifer during Pleistocene glaciation when flow directions may have been different from those of today. Uranium-234 could then have been leached from glacial till and the Maquoketa Shale. However, the observed disequilibrium still is problematical, because the role of geochemical and radiogenic mechanisms in enriching the isotopic ratio is not fully understood (Gilkeson and others, 1978).

Similar disequilibria are found in selected samples of water from aquifer layer 3 in Iowa. ^{234}U/^{238}U activity ratios determined from a few selected water samples showed disequilibrium and range from 2.3 to 14.1 with no discernible pattern (fig. 33). For example, the ratio is 9.1 for water in the northwest recharge area associated with the Dakota Formation as well as for water in the central dilute plume area. The scant data suggest that the ratio in Iowa increases generally toward the south, but additional data are needed to verify the trend.

A water sample from a 2,673-ft-deep test well drilled during this study at Green Island in extreme eastern Iowa is of particular interest. The sample from the interval 1,741 to 2,673 ft in the Mount Simon Sandstone had the extraordinarily high ratio of 100 (fig. 33). This may be the largest known uranium disequilibrium in an aquifer system. Gilkeson and Cowart (1982) indicate that the highest reported ratio prior to their work was 12.3. They measured activity ratios as high as 28.6 in the Cambrian-Ordovician aquifer system in northeastern Illinois and activity ratios "greater than 40" in the aquifer system in other parts of Illinois.

Gilkson and Cowart (1982) hypothesize that such extreme disequilibrium may be related to influx of uranium-234-enriched uranium derived from fine-grained materials during the emplacement of glacial meltwater during the Pleistocene. The uranium-234-enriched ground water could be further enriched by isotopic fractionation caused by precipitation of the uranium in the reducing zone downgradient from the meltwater recharge front. Unfortunately, the scant areal distribution of the uranium isotope data for this study is not sufficient to evaluate this hypothesis further, and the causes of the isotopic enrichment are still unknown.

ISOTOPIC COMPOSITION OF WATER AND PLEISTOCENE RECHARGE MODEL

The direction of the dilute plume, from northeastern Iowa to south-southwestern Iowa, suggests a flow system having recharge areas in southeastern Minnesota and northeastern Iowa and discharge areas in Missouri or farther south. The study region was glaciated numerous times during the Pleistocene Epoch. Work by Boellstorff (1976, 1980) indicates that at least Nebraska and Iowa were glaciated as long ago as 2.5 m.y. (million years) and that the classic Nebraskan-Kansan sequence of glaciation—now referred to as Pre-Illinoian (Richmond and Fullerton, 1986)—occurred 1.0 to 0.4 m.y. ago. At least five ice advances occurred in Iowa and Nebraska during this time. No similar sequence of glaciation has been identified in Wisconsin and Illinois to date, but evidence of such glaciation could be obscured by glaciation during Illinoian and Wisconsin time, from about 100,000 to 12,000 yr B.P. (years before present).

The extent of major glaciations (fig. 34) has been estimated from the stratigraphic relationships among glacial deposits (Flint, 1972). Pre-Illinoian advances extended almost to the Missouri River and covered much of the study area. Later advances during Illinoian time covered most of Illinois and parts of Wisconsin. During Wisconsin time, numerous ice lobes advanced into Wisconsin, Minnesota, Iowa, and Illinois.

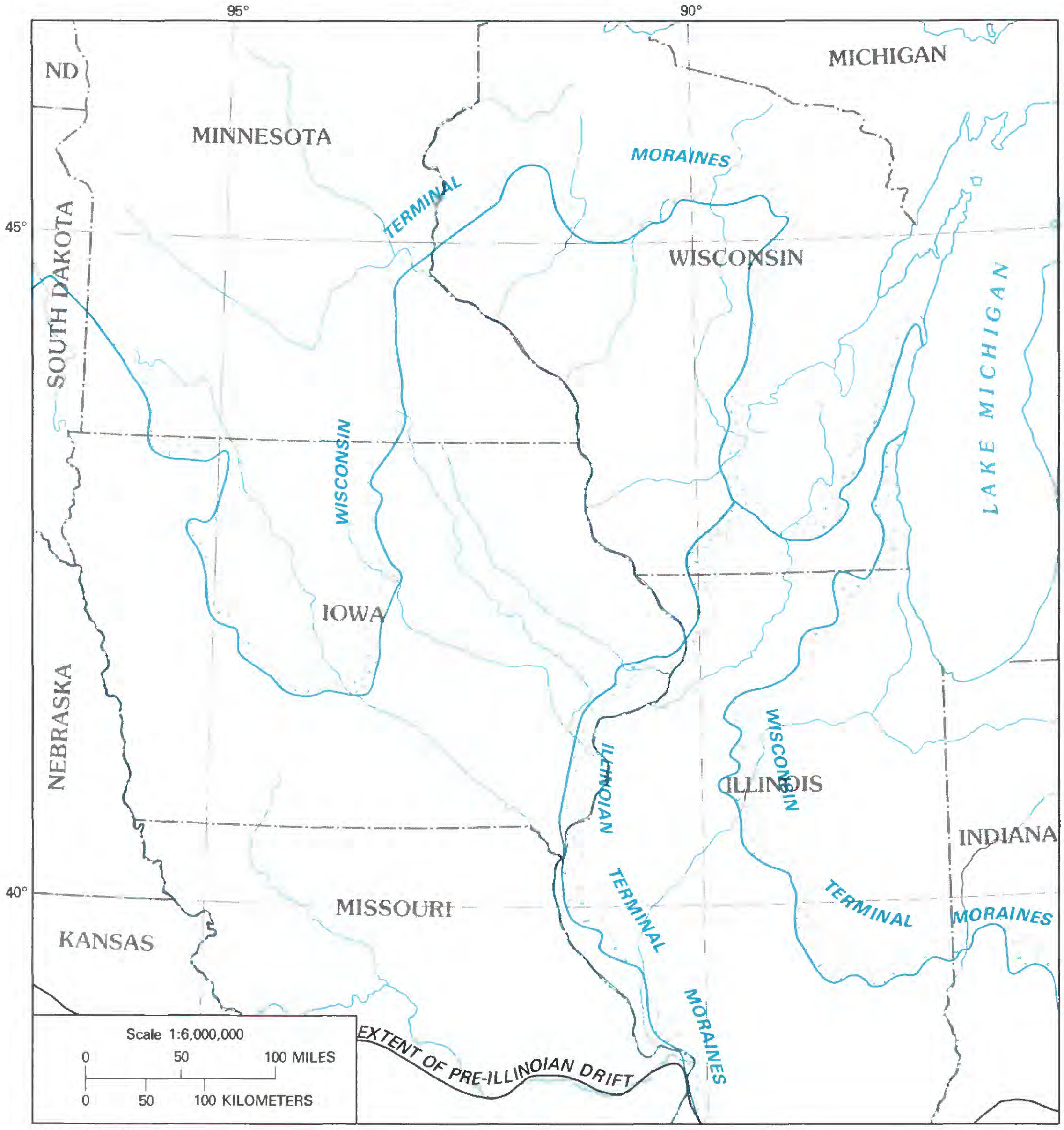
Theoretical reconstructions of the temperature distribution in continental Pleistocene glaciers have indicated that a pressure-melting zone probably was extensive in the basal part of the ablation zone. The zone may have extended upgradient for a few hundred miles from frozen ice margins (Hooke, 1977; Sugden, 1977; Moran and others, 1980). Glacial movement in these unfrozen areas involved basal sliding (Weertman, 1957, 1961, 1964; Clayton and Moran, 1974). Landforms such as drumlins, tunnel valleys, and streamlined ridges are field evidence for basal melting (Wright, 1973; Clayton and Moran, 1974; Moran and others, 1980) where meltwater under high hydrostatic head could have recharged the Cambrian-Ordovician aquifer system in outcrop areas.

The isotopic composition of oxygen and hydrogen in the ground water in the aquifer system is important geochemical evidence for such recharge. The distribution of $\delta^{18}O$ and δD in modern precipitation shows excellent covariation with both mean annual air temperature and latitude because of isotope fractionation by the Raleigh distillation effect (Dansgaard, 1964). Covariation between $\delta^{18}O$ and δD of modern precipitation defines an average meteoric water line (Craig, 1961), expressed as

$$\delta D = 8\ \delta^{18}O + 10, \tag{13}$$

to which the isotopic content of ground water can be compared. If past ground-water recharge occurred under climatic conditions similar to those of today, then the isotopic composition of the ground water should be similar to that of modern recharge. However, if the ground water originally precipitated at temperatures colder than today, its isotopic composition should be lighter than modern recharge but should still plot near the meteoric water line (eq. 13). Deviations of the data from the trend of the line indicate that geochemical processes, such as water-rock interaction, evaporation, or ultrafiltration, have modified the isotopic composition of the water.

The relationship of $\delta^{18}O$ to δD in ground water in the Cambrian-Ordovician aquifer system exclusive of the Illinois basin is similar to the isotopic composition of modern precipitation (fig. 35). This indicates that the water in the Cambrian-Ordovician aquifer system outside the Illinois basin retains its meteoric nature and has been relatively unaltered by significant reactions with the aquifer matrix. Water in the Illinois basin is enriched in oxygen-18 because of probable exchanges between carbonate rock and water at temperatures more than twice the temperature in the fresher and shallower parts of the aquifer system (Clayton and others, 1966). The average $\delta^{18}O$ and δD of modern precipitation in the study area ranges from about −8 to −6 o/oo and from −70 to −50 o/oo, respectively, from



Base enlarged from
U.S.Geological Survey
1:7,500,000, 1970

FIGURE 34.—Extent of major glaciations in the northern Midwest during the Pleistocene Epoch.

north to south (Yurtsever, 1975). The difference in $\delta^{18}O$ and δD between water in the aquifer and in modern precipitation, as much as −9 and −70 ⁰/oo, respectively, indicates past recharge to the aquifer system that is isotopically similar to water now precipitated at colder latitudes hundreds of miles north of the study area. No shift occurs in the isotopic content of water across the Holocene-Pleistocene boundary in regional aquifers unaffected by glaciation (Hanshaw and others, 1978). This suggests that the light isotopic composition of the ground water is not a result of continental differences in the isotopic composition of interstadial precipitation.

Isotopically light ground water in the aquifer system in northern Illinois has been described previously and explained as Pleistocene recharge (Clayton and others, 1966; Gilkeson and others, 1981; Perry and others, 1982). Regional distribution of the isotopic composition of water in the aquifer system (figs. 36, 37) closely approximates the distribution of dissolved solids (fig.

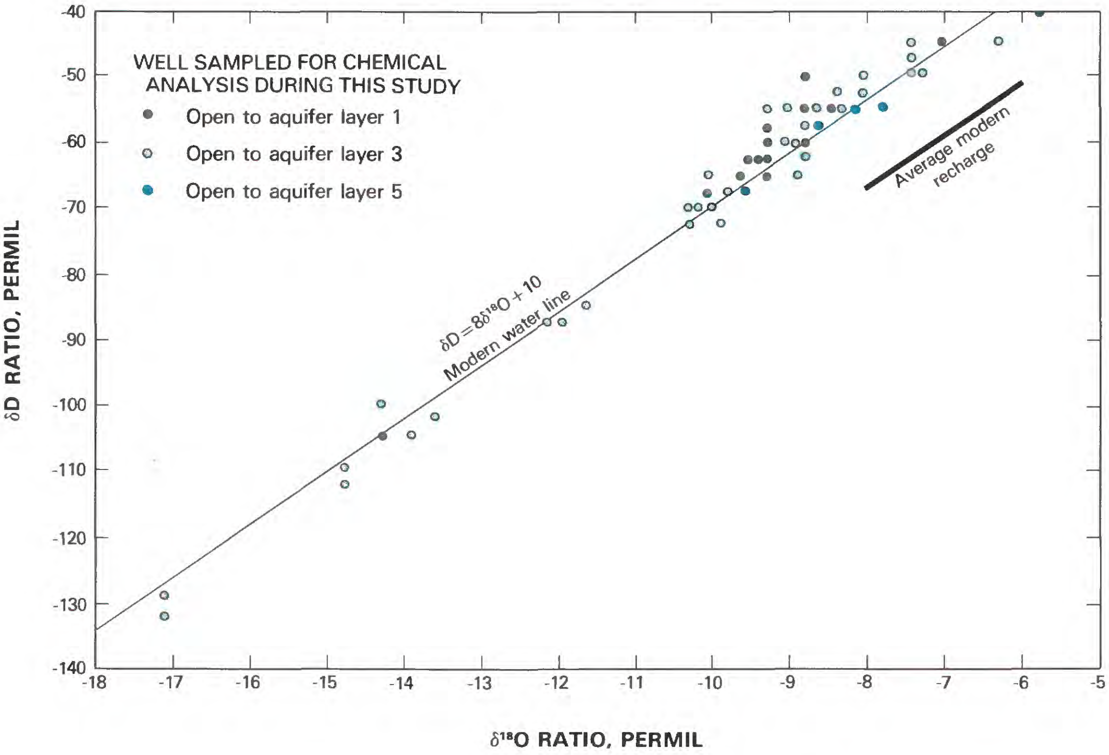


FIGURE 35.—δ^{18}O-δD relationship for ground water in the northern Midwest.

7). In Iowa and Missouri, ground water is isotopically lighter toward the south, approximately perpendicular to the direction of the modern hydraulic gradient. The boundary of the dilute plume in central Iowa is coincident with the −10 ‰ δ^{18}O isoline. The plume, although isotopically about 2 to 4 ‰ lighter with respect to δ^{18}O than modern recharge at the same latitude, is isotopically heavier than surrounding ground water. The extension of the −10 ‰ line into south-central Iowa and the distribution of dissolved solids suggest a ground-water flow direction approximately perpendicular to that of today.

The δ^{18}O content of North American ice sheets could have ranged from about −40 ‰ (Dansgaard and Tauber, 1969) to −9 ‰ (Emiliani, 1971). Yapp and Epstein (1977), using calculations from δD of cellulose in plant material entrained in drift, suggest an intermediate δ^{18}O of −15 ‰ for the ice of the latest Wisconsin advance. If the isotopically lightest water in the aquifer system in southern Iowa were emplaced during this time, virtually all the ground water in the southwestern part of the study area would be recharged from glacial meltwater. This is unlikely because the dissolution of carbonate and silicate minerals at aquifer temperatures (less than 40 °C) would not produce concentrations of dissolved solids exceeding 2,500 mg/L or the large equivalent percentages of chloride and sodium found in the southwestern part of the aquifer. Therefore, the isotopic content of the ground water probably represents a mixture of meltwater with δ^{18}O depleted to less than −17 ‰ and pre-Pleistocene ground water with δ^{18}O enriched to more than −17 ‰, and perhaps similar to the isotopic content of modern recharge.

The shape of the dilute plume looks similar to the shape of the Des Moines lobe which covered part of north-central Iowa during the last advance of Wisconsin ice. This suggests that the plume may be related to this ice advance. The isotopic content of water in the dilute plume would be lighter than −10 ‰ if the plume were caused by meltwater recharge under the lobe through the outcrop area in southern Minnesota. However, the possible displacement of ground water having low dissolved solids from overlying Paleozoic aquifers to aquifer layer 3 by vertical leakage of subglacial meltwater cannot be ruled out unequivocally at this time.

Scant data indicate that dissolved-solids concentrations in aquifer layer 4 are generally more than 1,000 mg/L where the aquifer is overlain by Mississippian rocks in central Iowa but are generally less than 500 mg/L in outcrop areas north of the Mississippian erosional edge (U.S. Geological Survey, unpub. data).

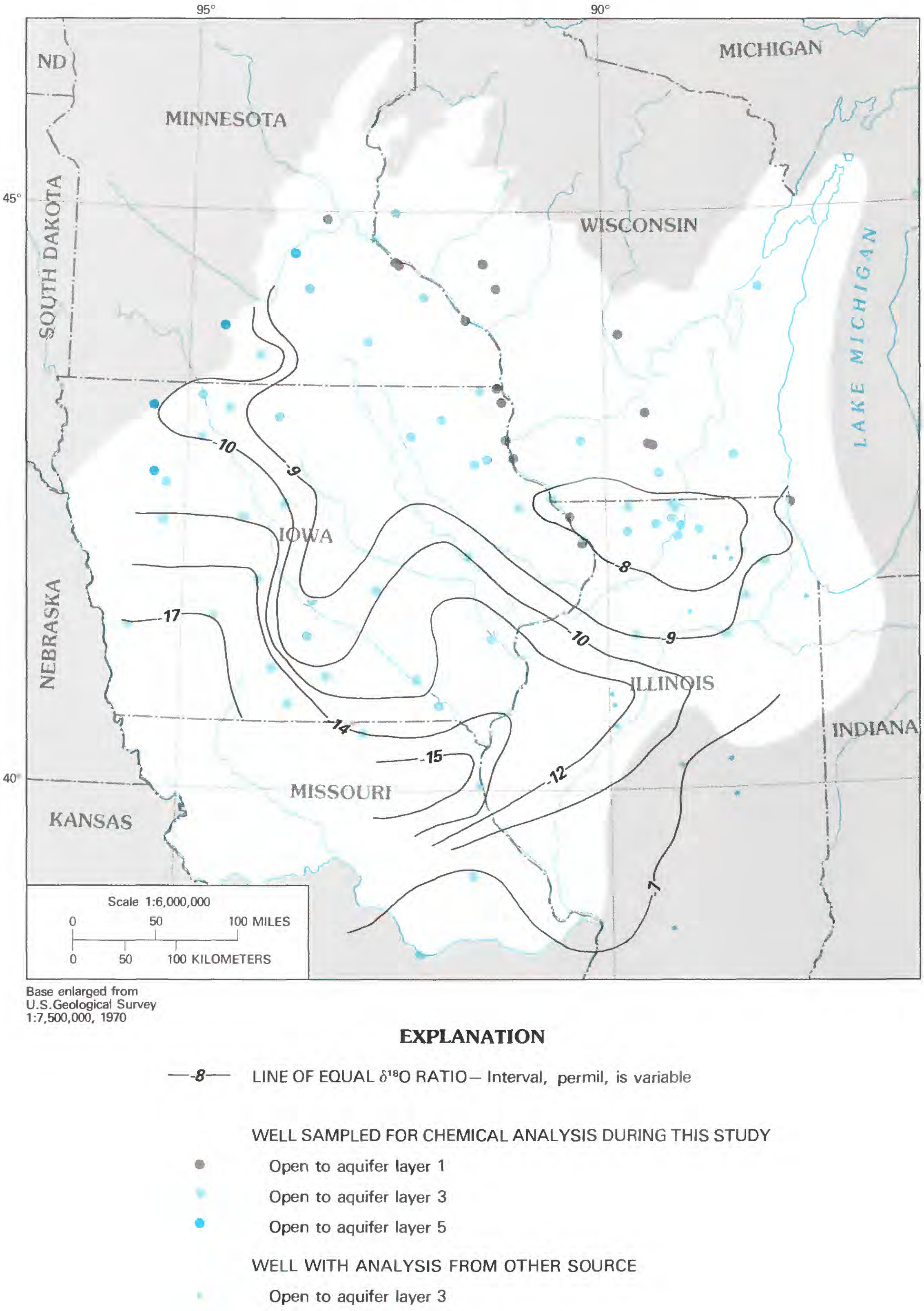


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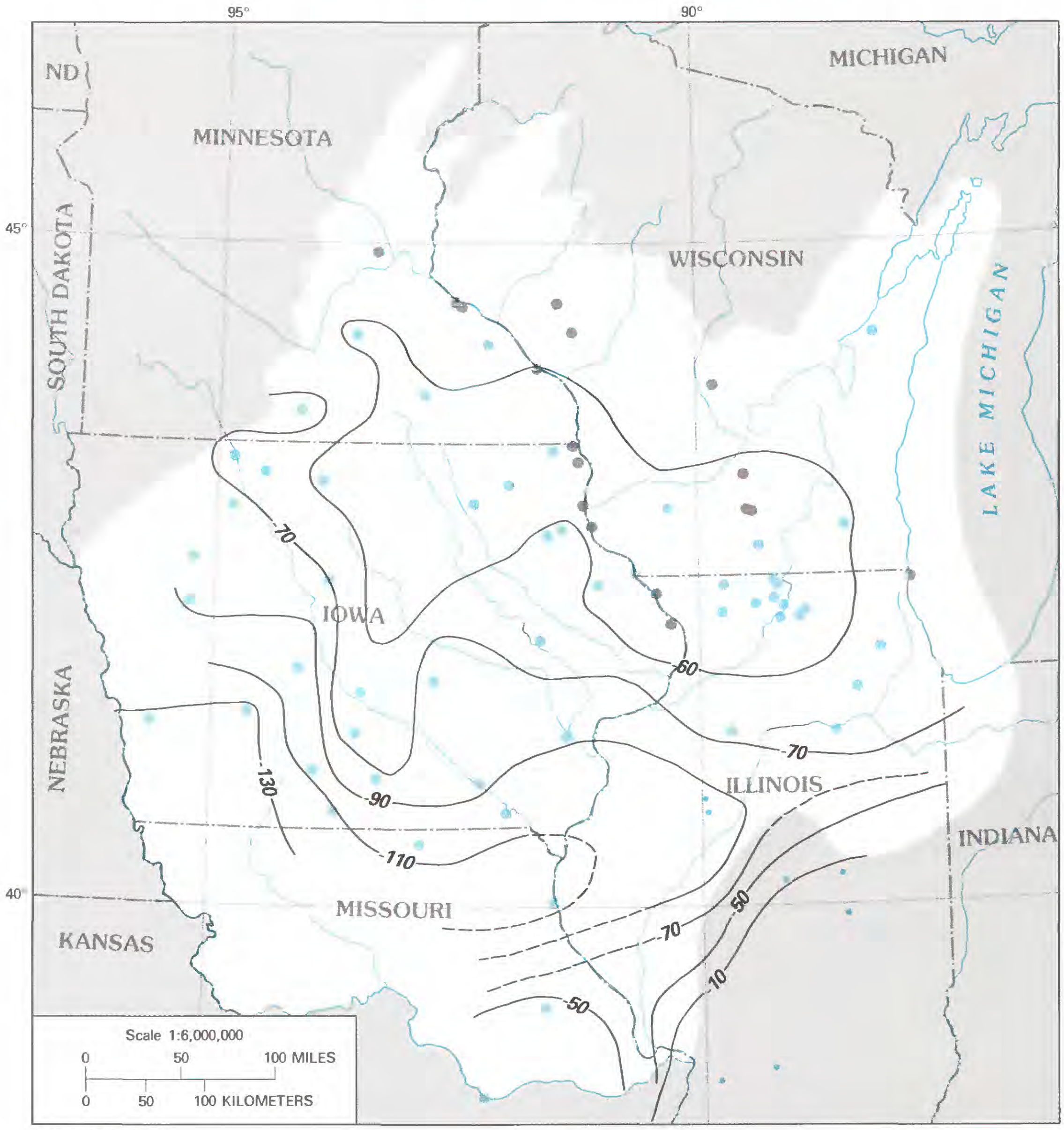
FIGURE 36.—Distribution of $\delta^{18}O$ ratio in aquifer layers 1, 3, and 5.



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EXPLANATION

---*70*— LINE OF EQUAL δD RATIO—Dashed where approximate. Interval, permil, is variable

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

● Open to aquifer layer 1

● Open to aquifer layer 3

WELL WITH ANALYSIS FROM OTHER SOURCE

• Open to aquifer layer 3

FIGURE 37.—Distribution of δD ratio in aquifer layers 1 and 3.

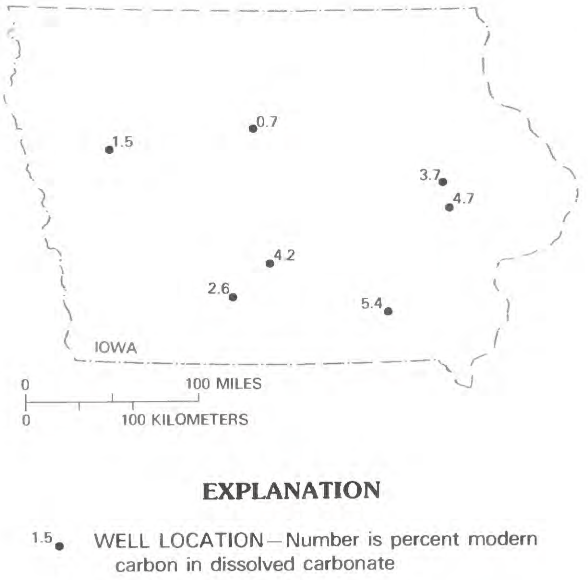


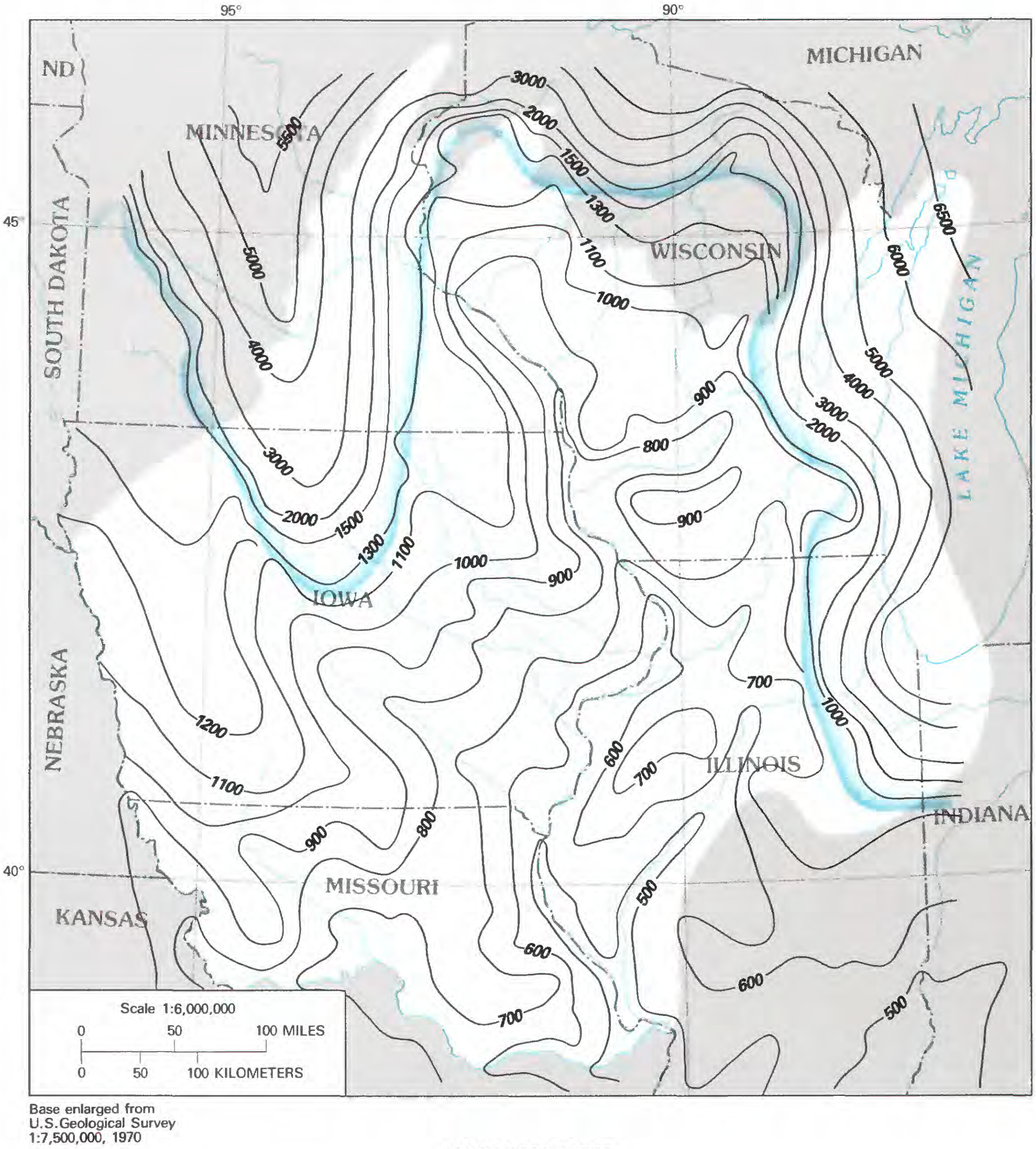
FIGURE 38.—Carbon-14 data for water from selected wells in aquifer layer 3 in Iowa.

Dissolved-solids concentration in ground water from Mississippian rocks in north-central Iowa is more than 500 mg/L. The 1,000-mg/L isoline of dissolved solids in the Mississippian rocks roughly outlines a dilute plume trending from north-central to southwestern Iowa (Horick and Steinhilber, 1973), similar to the plume in aquifer layer 3.

Downward movement of meltwater from the base of the Des Moines lobe into the Mississippian rocks could have started a series of downward displacements of water from layer to layer: recharge of water with low dissolved solids into the Mississippian; higher disolved-solids water (more than 1,000 mg/L) from the Mississippian into aquifer layer 4; and water with low dissolved solids from aquifer layer 4 into aquifer layer 3, forming the dilute plume. Water in aquifer layer 4 could have had a $\delta^{18}O$ content ranging from -8 to -6 o/oo if it were not mixed with meltwater recharge from previous glaciations. Downward flow of water from aquifer layer 4 to aquifer layer 3 could have resulted in both dilution and isotopic enrichment. However, additional isotopic data for ground water from aquifer layer 4 and the Mississippian in central Iowa are needed to evaluate better the influence of the Des Moines lobe on the Cambrian-Ordovician aquifer system.

The time, or times, of meltwater emplacement is unknown. Seven carbon-14 analyses of ground water from aquifer layer 3 in Iowa have a range of 0.7 to 5.4 percent modern carbon (fig. 38). These values correspond to apparent ages ranging from more than 30,000 to about 15,000 yr B.P., respectively, corrected for isotopic dilution by dissolution of carbonate aquifer minerals. The smallest amount of modern carbon occurs in central Iowa within the dilute plume. This could reflect either the age of water in aquifer layer 3 or a composite age of water from aquifer layers 3 and 4, if vertical recharge occurred beneath the ice of the Des Moines lobe. A small amount of modern carbon may have been introduced in the sampling procedure at other sites as contamination from atmospheric carbon dioxide (E.C. Alexander, University of Minnesota, written commun., 1982; L.N. Plummer, U.S. Geological Survey, oral commun., 1982). Water in aquifer layer 1 at St. Paul, Minn., has an apparent age of more than 35,000 yr B.P. (Alexander and others, 1983), and very likely water in the Cambrian-Ordovician aquifer system in southern Iowa and northern Missouri also contains little or no measurable carbon-14 because flow paths are many times longer than in Minnesota.

The possible emplacement of meltwater during the late Pleistocene was independently tested using the steady-state three-dimensional ground-water flow model of Mandle and Kontis (in press) to simulate the Cambrian-Ordovician aquifer system under the pressure head caused by the weight of the glacial ice about 18,000 yr B.P. The head values for the water-table aquifer (aquifer layer 5) in the ice-covered areas (fig. 39) were estimated as the sum of the elevation head at the land surface and the pressure head from the ice. The water-table aquifer is represented by constant-head nodes in the model and provides the hydraulic driving force to simulate ground-water flow. An average Wisconsin glacial ice-sheet configuration was assumed similar to that described by Denton and Hughes (1981). The static steady-state topography of the ice sheets at maximum advance calculated by Denton and Hughes (1981) was based on the modern analog of the Greenland and Antarctic ice sheets. This may be incorrect because geologic evidence suggests that the Laurentide ice sheet did not attain a steady-state profile everywhere but may have been highly dynamic (Clark, 1980; Andrews, 1982). Nevertheless, the Denton and Hughes (1981) model is probably a first approximation for the general morphometry of the major ice lobes that entered the northern Midwest during Wisconsin time. Hydraulic parameters, boundaries, and nodal distribution for all aquifer layers were those used in a steady-state flow model of the modern Cambrian-Ordovician aquifer system described by Mandle and Kontis (in press). The position of the ancestral Mississippi River was assumed to be similar to its present position. Although the ancestral Mississippi River was displaced in some areas during the late Pleistocene, the displacement did not significantly alter the general drainage pattern from



Base enlarged from U.S.Geological Survey 1:7,500,000, 1970

EXPLANATION

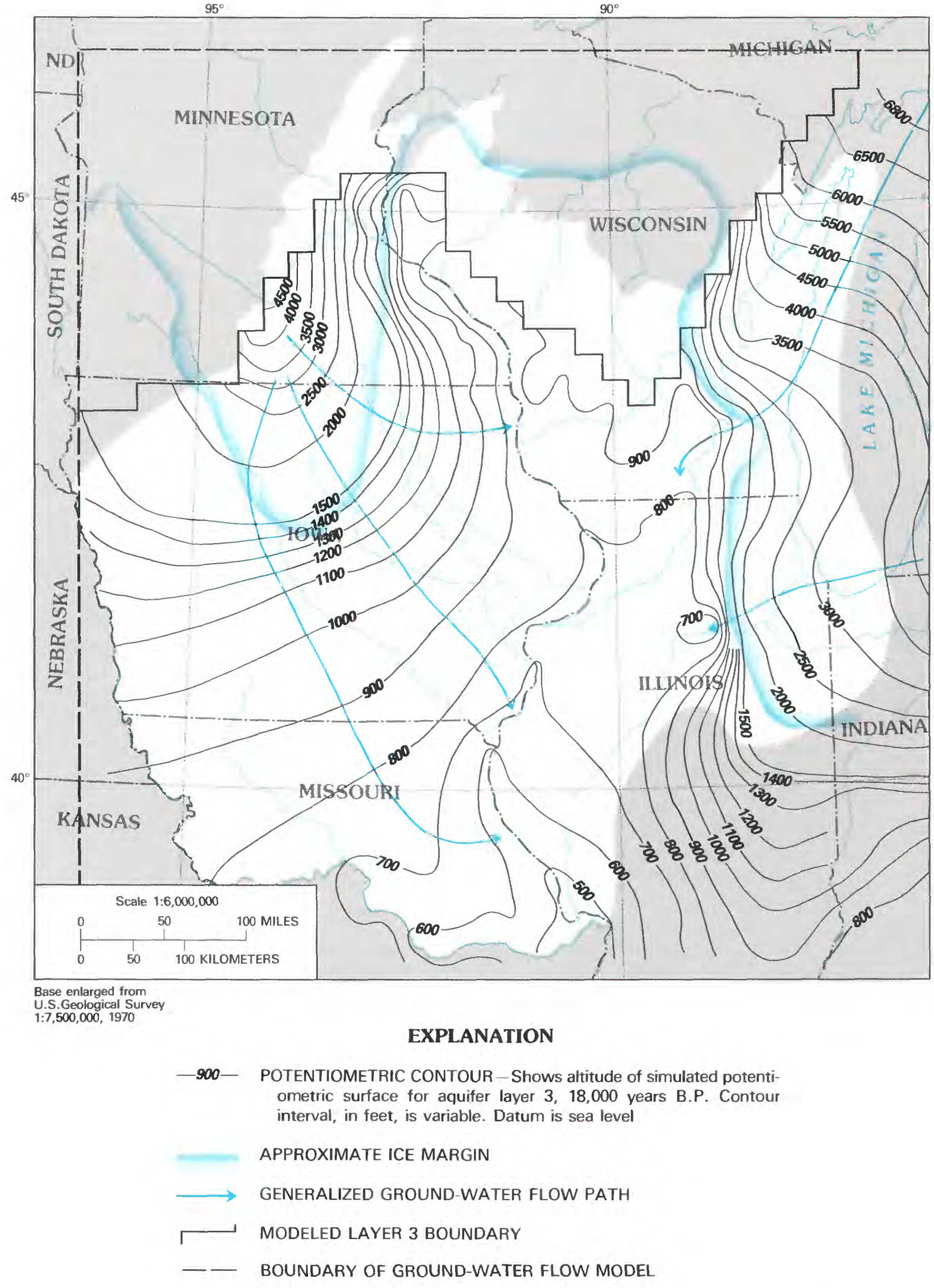
—800— POTENTIOMETRIC CONTOUR—Shows altitude of assumed potentiometric surface for aquifer layer 5, 18,000 years B.P. Contour interval, in feet, is variable. Datum is sea level

APPROXIMATE ICE MARGIN

FIGURE 39.—Assumed hydraulic head for aquifer layer 5 incorporating effects of ice thickness at the average advance of ice, about 18,000 yr B.P., during late Wisconsin time.

north to south near the border of Iowa and Illinois (Flint, 1972).

Results of the steady-state flow model show that the distribution of ice at the average Wisconsin advance probably did not significantly change the direction of ground-water flow in most of Iowa and Missouri (fig. 40). Ground-water flow paths, in general, were from northwestern Iowa southeastward to the Illinois basin.



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EXPLANATION

—900— POTENTIOMETRIC CONTOUR—Shows altitude of simulated potentiometric surface for aquifer layer 3, 18,000 years B.P. Contour interval, in feet, is variable. Datum is sea level

APPROXIMATE ICE MARGIN

GENERALIZED GROUND-WATER FLOW PATH

MODELED LAYER 3 BOUNDARY

BOUNDARY OF GROUND-WATER FLOW MODEL

FIGURE 40.—Simulated hydraulic head in aquifer layer 3 at the average advance of ice, about 18,000 yr B.P., during late Wisconsin time.

Some ground-water flow was diverted from central to northeastern Iowa from a local ground-water divide that is symmetrical with the axis of the Des Moines lobe in Iowa. In eastern Wisconsin and Illinois, simulated ground-water flow was opposite from that of today: ground-water recharge zones were in the vicinity of Lake Michigan, and discharge zones were the outcrop areas in Wisconsin, northeastern Iowa, southeastern Minnesota, and northern Illinois. Results of the flow model show that, during late Wisconsin time, the net movement of ground water was not in the direction of the dilute plume, from northeastern to southwestern Iowa. Much of the outcrop area of the aquifer in Wisconsin, Iowa, and Illinois was probably a discharge zone, as suggested by the results of the flow model, and not a recharge zone, as suggested by the geochemical data.

Model-calculated horizontal flow rates of the present flow system in Iowa are extremely slow, ranging from a few feet per year in the recharge area in northwestern Iowa to less than 1 ft/yr in deeper parts of the aquifer (Mandle and Kontis, in press). These flow rates indicate that residence time for most of the water in the aquifer system could be tens of thousands to hundreds of thousands of years. The slow flow rates compare favorably with the carbon-14 date of more than 35,000 yr B.P. for water in aquifer layer 1 from a well in St. Paul, Minn. (Alexander and others, 1983).

Model-calculated horizontal flow rates under the Des Moines lobe are about 10 times larger than present flow rates. Model-calculated vertical leakage from aquifer layer 4 to aquifer layer 3 in the confined part of Iowa is less than 5,000 $(\mathrm{ft}^3/\mathrm{mi}^2)/\mathrm{yr}$, even under simulated glacial head from the Des Moines lobe. This amount of vertical leakage is insignificant with respect to the total amount of water in aquifer layer 5. The volume of water per square mile in aquifer layer 3 is approximately $2\times10^9\ \mathrm{ft}^3$, assuming an average thickness of 300 ft and a porosity of 0.25. Only about 2.5 percent of the water in the aquifer would be replaced in 10,000 yr at the maximum calculated flow rates owing to glacial-ice loading.

This computed result suggests that downward leakage from younger Paleozoic rocks to aquifer layer 3 probably did not cause the dilute (low dissolved solids) plume in Iowa. However, fracture permeability in younger confining units and in the carbonate rocks of the aquifer system was not specifically addressed in the model because of the paucity of field data needed to define fracture locations and patterns. Consequently, the possibility of larger amounts of vertical leakage during glaciation still exists and needs to be tested by additional isotopic data, as discussed previously.

An alternative hypothesis to explain the isotopically defined plume in Iowa is a southerly displacement of ground water having an isotopic content similar to that of modern recharge from the outcrop area in southern Minnesota. Model-calculated flow rates in aquifer layer 3 for the average ice advance in south-central Minnesota range from 10^{-6} to 10^{-5} ft/s. At the fastest rate, meltwater would move downgradient about 60 mi in 1,000 yr. The Des Moines lobe probably was on the outcrop area in southern Minnesota for 2,000 yr, from about 16,000 to 14,000 yr B.P. (Wright, 1972), so the model results indicate that it is possible to have had significant meltwater displacement of ground water (δ^{18}O content of about −8 o/oo) toward Iowa. The meltwater that replaced the ambient ground water would be isotopically very light. This characteristic should be identifiable today in southern Minnesota, where the aquifer is confined and flow rates are low. On the contrary, δ^{18}O content of water in aquifer layer 3 in south-central Minnesota is about −9 o/oo; this δ^{18}O content is only slightly depleted relative to modern recharge and is not characteristic of isotopically depleted water, such as is found in southern Iowa and central Illinois.

The hypothetical steady-state model of the ground-water flow system at the maximum glacial advance during Wisconsin time shows that flow rates are increased significantly only under, and immediately next to, the ice sheets. The simulated effect of the additional pressure head on the potentiometric gradient contributed by the ice sheets is dampened considerably within 30 to 50 mi from the edge of the ice (fig. 40). The steady-state model simulations of predevelopment conditions and with glacial-ice loading during Wisconsin time suggest that the time necessary for a unit volume of recharge in northeastern Iowa and in southern Minnesota to reach north-central Missouri would have been at least tens of thousands of years. Confinement by the ice could accelerate flow rates in Iowa south of the Maquoketa Shale outcrop.

HYPOTHETICAL GEOCHEMICAL MODELS

Previous studies of the chemistry of regional aquifer systems have used mass-balance and reaction models to evalute, at least semiquantitatively, the extent of chemical mass transfer from solid to aqueous phases and the evolution of different water types—for example, Thorstenson and others (1979), Plummer (1977), Chapelle (1983), Plummer and Back (1980), and Plummer and others (1983). These models have been particularly useful for evaluating chemical changes associated with mixing of different water types—for example, Plummer (1975) and Wigley and Plummer (1976).

The extent to which these approaches can be successfully used in the present study of the geochemistry of the Cambrian-Ordovician aquifer system is limited, because critical data are still unavailable on the solid phases in the aquifer, the isotopic composition of Pleistocene glacial meltwater and precipitation, the pre-Pleistocene topography and water table, and local values for hydraulic characteristics.

The chemical composition of major solid phases, such as calcite, in the aquifer matrices in central Iowa is unknown. Information on bulk chemistry of the rocks and petrographic information on the type and nature of cementation in the rocks are necessary to check the accuracy of mass-balance calculations of net dissolution or precipitation of carbonate minerals (Chapelle, 1983). Identification of clay minerals in the aquifer matrix also is needed to determine appropriate ion-exchange selectivity coefficients for use in thermodynamic models of reaction progress. Estimates of ion-exchange selectivity coefficients from water chemistry (Thorstenson and others, 1979) are not applicable because of possible multiple sources and mechanisms for observed increases in sodium concentrations in southern Iowa and northern Missouri. No direct information is available on the isotopic composition of carbon in the aquifer matrix. Such data are critical to the use of $\delta^{13}C$ information to check the mass-balance models. Furthermore, detailed mass-transfer models that have been used to evaluate carbon isotopes in other aquifer systems (Wigley and others, 1978) cannot be applied to the Cambrian-Ordovician aquifer system because location and magnitude of past recharge were pulselike, depending on the configuration, timing, and duration of the ice sheets during the Pleistocene. Present-day concentrations of solutes may not represent steady-state conditions, and effects of hydrodynamic dispersion on the isotopic composition of ground water during recharge events cannot be excluded.

The $\delta^{18}O$ and δD composition of ground water in the Cambrian-Ordovician aquifer system is probably a composite derived from numerous episodes of Pleistocene recharge to the aquifer system. Assuming that the isotopic composition of the water is conservative, based on the clustering of data around the modern meteoric water line discussed previously (fig. 35), a mixing model can be prepared. However, to prepare such a model, the isotopic composition of both the pre-Pleistocene ground water and the Pleistocene recharge must be known. Within the aquifer system, the isotopic gradient toward lighter water from central to southwestern Iowa shows *no reversal* in trend (figs. 36, 37). The isotopically lightest water may, consequently, be even more depleted in $\delta^{18}O$ than −17 o/oo. Estimation of the $\delta^{18}O$ of Pleistocene recharge is also difficult because the $\delta^{18}O$ of meltwater from glacial ice could have ranged at least from −40 to −15 o/oo. The isotopic composition of precipitation in the region during the Pleistocene may have been different from what it is today.

A mixing model of a chemically conservative constituent is made using the generalized equation

$$C_1(1-Q_2)+C_2Q_2=C_{mixture}, \tag{14}$$

where

C_1=concentration in water 1,

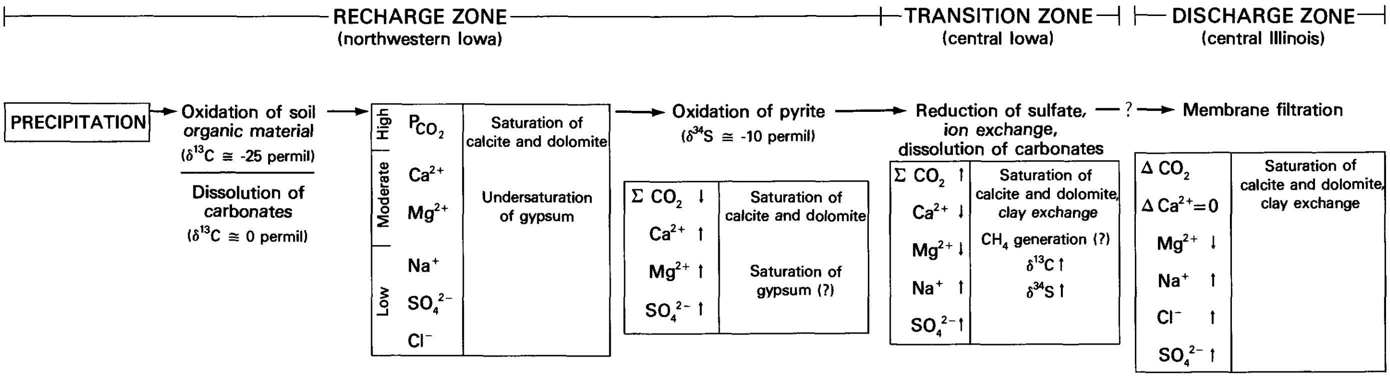
C_2=concentration in water 2, and

Q_2=fraction of water 2 in the mixture.

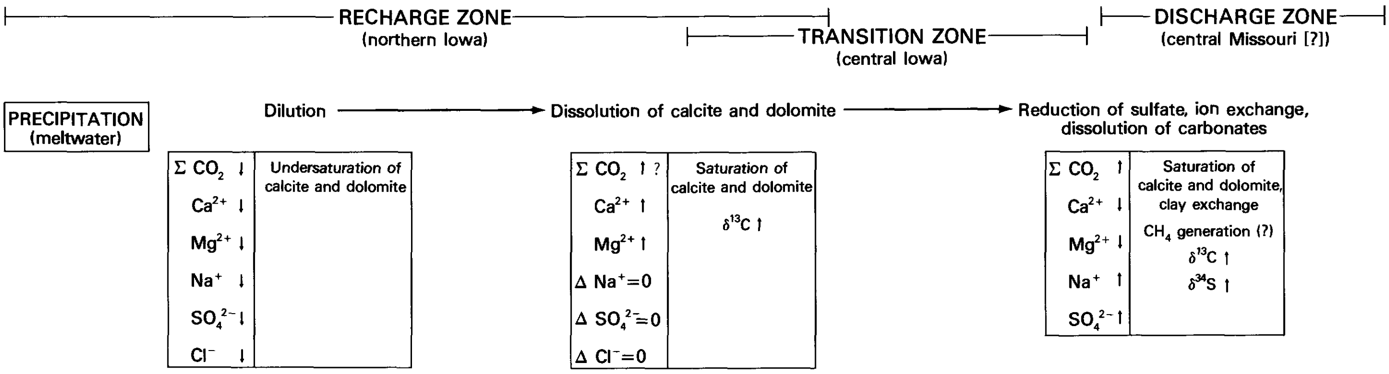
As an example of a mixing model, the following conditions were assumed:

1. Pre-Pleistocene ground water had an istotopic composition similar to the present-day recharge water of about −7 o/oo of $\delta^{18}O$.
2. Glacial meltwater entered the aquifer, resulting in a $\delta^{18}O$ of −17 o/oo, the most isotopically depleted water identified.
3. Subsequent recharge southwestward caused the plume outlined by the −10 o/oo line of $\delta^{18}O$. This recharge water is assumed to have a $\delta^{18}O$ value of −8 o/oo, which is about 1 o/oo lighter than modern recharge.

It follows from these assumptions and for equation 14 that a 1:2.3 mixture of meltwater ($\delta^{18}O$ of −40 o/oo) and pre-Pleistocene ground water ($\delta^{18}O$ of −7 o/oo) would produce an observed $\delta^{18}O$ of −17 o/oo. This first-phase mixture subsequently would have had to be mixed with Pleistocene recharge ($\delta^{18}O$ of −8 o/oo) at ratios of up to 1:9 to produce the present isotopically heavier plume in central Iowa. If the $\delta^{18}O$ of the first mixture were lighter than −17 o/oo, the second-phase dilution would be larger. If recharge in the second mixing phase was isotopically heavier, that is, derived from precipitation during warm interstadial periods (Emiliani, 1955; Ruddiman and McIntyre, 1976), a smaller volume of recharge would have been required. For example, if in the hypothesized second mixing phase $\delta^{18}O$ of Pleistocene recharge in the plume area was about 1 o/oo heavier than in modern precipitation (−6 rather than −7 o/oo), the mixing ratio of ground water with $\delta^{18}O$ of −17 o/oo and recharge with −6 o/oo would have been about 1:2 to produce the heavier plume. These exercises indicate that the amount of Pleistocene meltwater currently in the plume area of aquifer layer 3 could be as much as 90 percent, depending on which isotopic values were chosen in the calculations. If the



EVOLUTION OF WATER CHEMISTRY FROM NORMAL RECHARGE



EVOLUTION OF WATER CHEMISTRY FROM MELTWATER RECHARGE

FIGURE 41.—Hypothetical geochemical models for the evolution of water chemistry in the Cambrian-Ordovician aquifer system.

$\delta^{18}O$ of the pre-Pleistocene ground water was heavier than that of modern precipitation, the total percentage of Pleistocene glacial meltwater in the aquifer system would be less.

The hypothetical hydrologic and geochemical processes that may have affected the water quality of the Cambrian-Ordovician aquifer system are illustrated in figure 41. Preglacial water quality in the major recharge areas in Wisconsin, Minnesota, and northeastern Iowa may be controlled by dissolution of carbonate minerals in the aquifer matrix. Dissolution of carbonate minerals, ion exchange, and oxidation of pyrite may modify the water quality in northwestern Iowa and southwestern Minnesota. Oxidation of pyrite in the Dakota Formation and in glacial till derived from the Dakota Formation produces sulfuric acid (eq. 7) that would increase both the dissolution of carbonate minerals and the concentration of sulfate. Activities of sulfate and calcium may locally approach the solubility of gypsum, although, generally, ground water in the aquifer system and the overlying Dakota Formation and glacial drift is undersaturated with respect to gypsum and other evaporite minerals. Sulfate reduction, oxidation of organic material, and methane generation decrease concentrations of sulfate and increase inorganic carbon content. Downgradient into the transition zones of Ca-Na-SO_4-HCO_3 and Na-Ca-SO_4-HCO_3 facies in Iowa, additional sulfate reduction, unaccompanied by ion exchange, could cause carbonate precipitation. Membrane filtration near and in the Illinois basin may have caused precipitation of calcite, possible dolomitization of the aquifer matrix in the Illinois basin (Graf and others, 1966; Nesbitt, 1980; R. Shedlock, U.S. Geological Survey, written commun., 1982), and increases in sodium and chloride concentrations.

Glaciation and emplacement of Pleistocene meltwater in the aquifer system in Iowa and Missouri could cause dilution of all ground-water solutes. Although concentrations of conservative solutes, such as bromide and chloride, remained low, redissolution of carbonate minerals in the aquifer matrix increased the bicarbonate, calcium, and magnesium until equilibrium with the carbonate minerals was reestablished. This dilution and reequilibration process could have occurred many times. Glaciation also could temporarily enhance the extent of pyrite oxidation in Iowa because additional pyrite was exposed to the atmosphere by glacial erosion of the Dakota Formation.

The hypothetical model can be tested by evaluating the variations in $\delta^{13}C$ in dissolved inorganic carbon. $\delta^{13}C$ inorganic carbon in ground water from wells in aquifer layer 1 in southeastern Minnesota, southern Wisconsin, and northeastern Iowa ranges from about −14 to −8 ⁰/oo (fig. 42). $\delta^{13}C$ is more than −9 ⁰/oo in aquifer layer 3 in northern Illinois and less than −17 ⁰/oo in northwestern Iowa. Of major interest is the enrichment of $\delta^{13}C$ from about −11 to more than −8 ⁰/oo from northeast to southwest in Iowa, approximately perpendicular to the direction of the present hydraulic gradient.

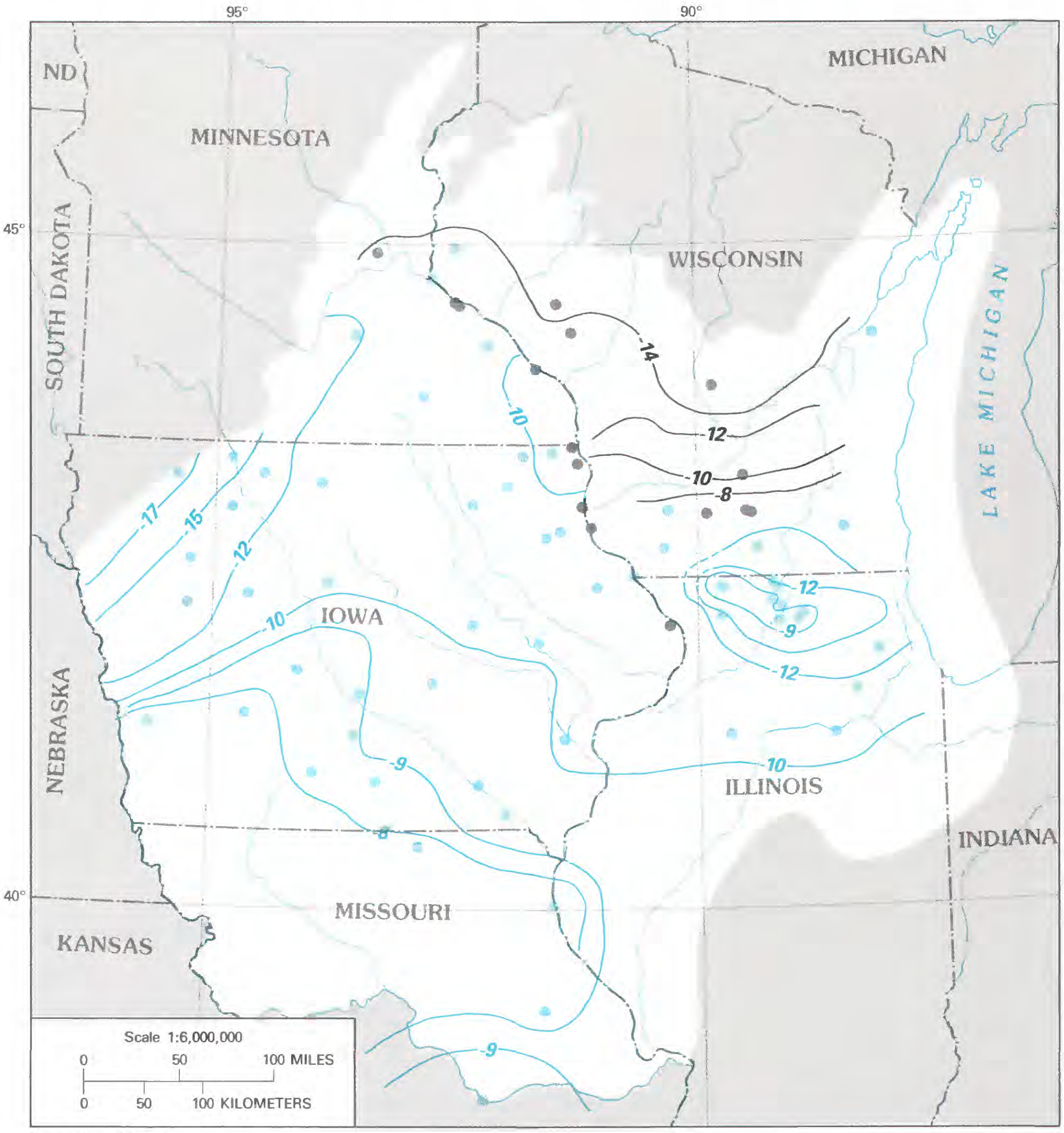
The average of $\delta^{13}C$ in the major recharge areas in Minnesota and Wisconsin is close to −12 ⁰/oo in aquifer layer 1, a value that is typically obtained by the simple closed-system dissolution of carbonate minerals with $\delta^{13}C$ of 0 ⁰/oo (Wigley and others, 1978) by soil carbon dioxide with $\delta^{13}C$ of about −25 ⁰/oo. Recharge to the aquifer system through the Dakota Formation in northwestern Iowa would obtain dissolved carbon from the oxidation of isotopically depleted organic material from both soils and lignite. The $\delta^{13}C$ of the lignite is also probably about −25 ⁰/oo, and consequently the observed −17 to −18 ⁰/oo $\delta^{13}C$ of inorganic carbon in the ground water in aquifer layer 3 is probably caused by fractionation processes. One likely process is bacterially mediated oxidation of methane, which would produce isotopically depleted carbon dioxide with $\delta^{13}C$ of less than −25 ⁰/oo (Fenchel and Blackburn, 1979), and ultimately result in $\delta^{13}C$ of dissolved inorganic carbon in the ground water of less than −12 ⁰/oo. However, sulfate reduction followed by methane production can also enrich the $\delta^{13}C$ of inorganic carbon (Nissenbaum and others, 1972; Claypool and Kaplan, 1974).

The enrichment in $\delta^{13}C$ in aquifer layer 3 from about −11 ⁰/oo in northeastern Iowa to more than −8 ⁰/oo in southwestern Iowa can be explained by successive episodes of glacial-meltwater dilution, dissolution of carbonate minerals in the aquifer matrix, and reequilibration of ground water with respect to the carbonate system. However, it is necessary to assume that the inorganic carbon in the meltwater that recharged the aquifer system had a $\delta^{13}C$ of more than −10 ⁰/oo. The involvement of organic carbon in the dissolution of carbonate rock beneath modern glaciers is minimal, although the presence of atmospheric carbon dioxide in meltwater cannot be overlooked (Hanshaw and Hallet, 1978). The $\delta^{13}C$ of modern atmospheric carbon dioxide is about −7 ⁰/oo (Hoefs, 1980). If most of the meltwater recharge occurred subglacially and if the carbon isotopic composition of Pleistocene atmospheric carbon dioxide was similar to that of today, then the observed enrichment of $\delta^{13}C$ from −11 to −8 ⁰/oo of the dissolved inorganic carbon in the ground water would be conceptually consistent with the meltwater recharge model. During glacial-meltwater emplacement, $\delta^{13}C$ of inorganic carbon also could be enriched by sulfate reduction followed by methane production, as discussed earlier.

Infiltration of meltwater through soils could result in soil carbon dioxide of varying isotopic composition depending on the type of vegetation (Fontes, 1980; Hoefs, 1980). Studies of plant succession after the latest Wisconsin glacial retreat in the Midwest indicate that many stages in plant succession can occur after glaciation and could range from black spruce forests to open woodlands (Wright, 1976). These vegetation types can develop even on the mantle of rock debris that covers stagnant ice. The simplest interpretation of the succession in central Minnesota, for example, is probably that the earlier colonization of herb tundra vegetation was followed by shrub and forest tundra, spruce forest, and, ultimately, pine (Birks, 1975; Gordon and Birks, 1982). These types of vegetation, as well as prairie grasses, have $\delta^{13}C$ values between about −37 and −24 ⁰/oo (Hoefs, 1980). The isotopic composition of carbon dioxide derived from the oxidation of this vegetation would not be too different from that of modern soils. Repeated dissolution of carbonate minerals by meltwater with such dissolved soil carbon dioxide would result in $\delta^{13}C$ of dissolved inorganic carbon of about −12 ⁰/oo, rather than the observed enriched values of carbon-13.

SUMMARY AND CONCLUSIONS

The evolution of the water quality in the Cambrian-Ordovician aquifer system in the northern Midwest United States is complicated because of many possible geochemical processes and the probable effects of Pleistocene glaciation on the aquifer system. Modern



Base enlarged from
U.S.Geological Survey
1:7,500,000, 1970

EXPLANATION

LINES OF EQUAL $\delta^{13}C$ RATIO—Dashed where uncertain. Interval, permil, is variable

—-10— Aquifer layer 1

—-12-- Aquifer layer 3

WELL SAMPLED FOR CHEMICAL ANALYSIS DURING THIS STUDY

● Open to aquifer layer 1

● Open to aquifer layer 3

FIGURE 42.—Distribution of $\delta^{13}C$ ratio in aquifer layers 1 and 3.

ground-water types may be, in part, a result of ground-water types prior to Pleistocene ice advances.

Ground water in recharge areas in Wisconsin, southern Minnesota, northeastern Iowa, and north-central Illinois is the Ca-Mg-HCO_3 type and is identical in both the glacial drift and the underlying Cambrian-Ordovician aquifer system. Dissolved-solids concentrations are less than 500 mg/L, and the major geochemical process probably is dissolution of carbonate minerals by soil carbon dioxide. In northwestern Iowa and southwestern Minnesota, however, the ground-water type in both the drift and the Cambrian-Ordovician aquifer system is Ca-Na-SO_4-HCO_3 because of the oxidation of pyrite in the Dakota Formation that overlies the aquifer system. Ground water is generally undersaturated with gypsum, and the negative $\delta^{34}S$ values in sulfate indicate that pyrite is a primary sulfur source. Dissolved-solids concentrations in places exceed 1,000 mg/L.

Ground-water type changes from Na-Ca-SO_4-HCO_3 to Na-Cl along the major flow path from northwestern Iowa to the Illinois basin. This is probably due to membrane filtration that would result in calcite precipitation coincident with increases in sodium and chloride.

A plume of dilute water containing less than 500 mg/L of dissolved solids trends north to south in central Iowa under the confining Maquoketa Shale. The plume suggests that paleo-ground-water flow probably was perpendicular to the present hydraulic gradient. This interpretation also is suggested by the general trend of increasing dissolved solids perpendicular to the present hydraulic gradient in Iowa and Missouri.

Ground water in southern Iowa and northern Missouri is considerably more depleted in the heavier stable isotopes, oxygen-18 and hydrogen-2, than is modern recharge water. This evidence may suggest a Pleistocene, and probably a glacial-meltwater, origin of recharge. A plume of ground water isotopically heavier than ground water in southern Iowa, but isotopically lighter than modern recharge, is coincident with the plume of low-dissolved-solids water in central Iowa. It is hypothesized that the isotopic content and dilution of ground water in Iowa and Missouri probably was caused by glacial meltwater emplaced in the aquifer system when glacial ice covered the present recharge areas in northeastern Iowa and southern Minnesota. The emplaced water extends hundreds of miles from the recharge areas. This may suggest that some of the recharge occurred subglacially, under considerably steeper hydraulic gradients than those of the present.

Dilution by the emplaced water decreased the concentrations of solutes such as chloride and sulfate in central Iowa, but bicarbonate concentrations remained about the same. Reequilibration of ground water with carbonate minerals in aquifer matrices, suggested by marked enrichment of $\delta^{13}C$ in dissolved inorganic carbon, could have maintained the level of bicarbonate concentrations. Dilution and re-reaction of the water with the aquifer matrix did not significantly change the ground-water types that are present down the modern hydraulic gradient. The overall chemical character of the ground water in the aquifer system in Iowa was probably established prior to glaciation and the recharge of meltwater.

Reconnaissance data on the distribution of trace solutes show that concentrations of cadmium, arsenic, and selenium seem to be related to the proximity of the Dakota Formation, which onlaps the western edge of the aquifer system in northwestern Iowa and southwestern Minnesota. Iron, manganese, cobalt, cadmium, copper, and lead concentrations are higher in proximity to the Dakota Formation in northwestern Iowa and on the edge of the Forest City basin in southwestern Iowa. Concentrations of beryllium and molybdenum are generally higher near the Forest City basin than elsewhere in the aquifer system. Silica concentrations correlate roughly with ground-water temperature in south-central Iowa and northern Missouri; however, the solid phases controlling the solubility of silica are unknown.

Concentrations of lithium, strontium, boron, and fluoride increase from north to south in Iowa and northern Missouri in a direction perpendicular to the present hydraulic gradient. Distributions of lithium, radium-226, and bromide show a plume of lower concentration similar to the plumes of low dissolved solids and the distribution of stable isotopes of water. Uranium isotopes are at disequilibrium and show activity ratios of uranium-234 to uranium-238 as large as 100. High barium concentrations in northern Illinois and eastern Wisconsin are probably due to a zone of reducing conditions that markedly lower the sulfate concentration. Thus, barium concentrations increase until the solubility limit of barite is reached. Increased concentrations of sulfate and positive $\delta^{34}S$ values of sulfur in sulfate east of the reducing zone in eastern Wisconsin and northeastern Illinois probably indicate emplacement of sulfate derived from evaporitic gypsum. This may have occurred during Pleistocene glaciation, when the load of glacial ice could have reversed ground-water flow from east to west. Ground water from the Michigan basin could have discharged through the present recharge area in central Wisconsin and northern Illinois, where the aquifer either crops out at the land surface or subcrops beneath glacial drift.

It is possible to derive scenarios for the net dilution and dissolution process from calculations using data on the stable isotopes of the water. Such calculations are nonunique and are used only for the hypothetical interpretation of geochemical data because (1) the number of glacial advances in Wisconsin and Minnesota prior to Wisconsin time is uncertain, (2) the pre-Pleistocene regional ground-water flow system and topography are unknown, (3) information on the chemical and clay-mineral composition of the aquifer matrix in central Iowa is scant, (4) estimates of the isotopic composition of Pleistocene ice sheets have a large range, (5) different interpretations are made of the shape of the continental ice lobes, (6) no direct information is available on the leakance of younger rocks that overlie the aquifer south of the Maquoketa Shale outcrop, and (7) the extent of isotopic depletion in ground water south of the study area is unknown.

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CHEMICAL AND ISOTOPIC ANALYSES OF GROUND WATER SAMPLED DURING THE STUDY (TABLES 1-3)

TABLE 1.—*Chemical analyses of major constituents in water from wells sampled for this study*

[Results in milligrams per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of collection	Field pH (standard units)	Calcium, Ca	Magnesium, Mg	Sodium, Na	Potassium, K	Field alkalinity, as HCO_3	Sulfate, SO_4	Chloride, Cl	Silica, SiO_2	Dissolved solids, sum of constituents
Aquifer layer 1, Illinois												
118	422418090255501	10-23-80	7.4	50	26	1.3	2.8	--	5.9	1.3	7.7	230
130	422803087475303	12-10-80	7.2	310	39	440	16	--	1300	370	7.5	2600
131	422803087475304	01-14-81	--	1000	930	15000	270	--	1400	37000	4.4	56000
Aquifer layer 1, Iowa												
71	432953091172001	06-24-80	7.5	37	45	2.7	1.9	317	19	2.9	8.2	270
73	432206091130301	06-10-80	7.9	31	18	99	4.7	245	52	45	8.0	410
102	430240091110001	06-09-80	7.7	62	27	55	4.0	323	52	59	8.6	430
119	420842090165702	05-15-81	7.6	57	37	9.3	5.9	366	20	8.7	10	330
Aquifer layer 1, Minnesota												
1	461209093550701	02-21-80	6.5	13	4.4	3.8	1.3	50	5.2	--	19	--
3	453038092584301	05-13-80	7.0	64	22	9.6	2.4	340	<5.0	2.7	20	--
4	452008092595001	05-13-80	7.3	52	14	5.0	1.6	241	<5.0	1.0	13	--
5	445648093395101	05-19-80	7.4	68	24	23	5.4	368	30	6.5	11	350
19	445704093215611	09-04-80	7.8	58	19	33	7.6	244	47	33	7.2	330
21	445153093202101	05-20-80	--	39	13	29	6.7	239	<5.0	20	7.6	--
30	443354092323201	02-12-80	6.7	64	27	53	6.8	276	34	80	8.3	410
31	443407092315501	02-12-80	6.8	40	19	79	4.4	250	27	98	9.2	400
32	443300092302901	02-12-80	7.0	80	44	250	7.9	262	36	550	8.6	1100
50	440324091404001	02-13-80	7.4	56	20	130	8.1	364	85	99	7.0	590
51	440324091401501	02-13-80	7.0	60	21	180	9.0	362	180	140	7.4	760
52	440318091388180	02-13-80	6.9	52	20	80	6.3	351	57	56	8.4	450
53	440312091381201	02-13-80	7.2	56	21	49	6.2	312	37	28	8.3	360
Aquifer layer 1, Wisconsin												
33	443436091281401	08-06-80	6.8	13	5.9	2.0	1.7	65	11	1.2	16	84
34	443841090393001	08-20-80	6.7	34	8.9	7.7	1.0	99	14	17	20	180
38	442141091185601	08-13-80	7.2	16	6.7	3.8	3.6	68	19	4.2	17	110
39	442045090453601	08-20-80	6.4	2.8	1.2	1.2	1.4	16	6.1	1.3	11	36
54	435743089485701	08-21-80	7.8	21	9.0	1.6	.4	110	4.2	.7	8.9	100
55	440219088555701	08-19-80	8.0	27	34	15	1.8	256	27	2.3	21	260
56	434312090353901	08-22-80	7.8	51	27	1.2	1.0	268	19	1.0	9.8	240
57	433921091132101	10-08-81	7.6	45	29	1.9	1.3	294	11	2.6	9.9	250
75	432336090460601	08-28-80	7.6	50	28	1.7	1.0	268	17	.9	11	240
76	432042090231701	08-28-80	7.7	55	26	2.7	1.0	232	18	3.2	12	230
77	433144089595901	09-05-80	7.2	22	11	3.9	2.5	--	13	7.1	11	--
78	433220089282601	09-05-80	7.4	65	42	1.8	.6	378	32	5.0	7.1	340
79	431849089311002	07-24-80	7.7	51	29	2.5	.9	329	3.0	.8	13	260
80	432717088501701	09-05-80	7.3	60	31	3.7	1.7	--	21	3.7	9.4	--
103	425246091042101	08-19-81	7.3	180	40	140	12	280	370	180	8.7	1100
105	431108090263101	08-29-80	7.4	57	32	5.2	1.5	305	6.0	5.3	12	270
108	430055089534001	07-18-80	7.3	67	37	6.0	1.0	354	28	13	6.7	360
110	430058089251401	07-22-80	7.6	54	31	2.9	1.8	329	6.4	1.8	9.0	270
Aquifer layer 3, Illinois												
120	422606089434501	08-29-80	7.6	66	34	3.2	.6	341	5.2	.6	13	290
121	421331089442201	08-29-80	7.4	74	42	9.8	3.0	329	3.2	1.1	9.5	330
122	421658089235101	08-20-80	7.4	110	50	25	1.5	256	86	39	21	530
123	422738089114601	08-23-80	7.1	81	41	3.5	1.8	402	29	7.2	11	390
124	422545089103301	08-23-80	7.4	91	49	5.7	.6	451	32	20	8.7	440
125	421855089121601	08-23-80	7.3	62	29	2.9	.7	329	11	.8	12	280
126	421614089062301	09-03-80	6.7	120	57	59	4.9	232	140	120	16	650
127	420953089080501	09-05-80	7.4	65	32	5.0	.5	232	16	2.3	15	250
128	421025088564401	09-04-80	7.0	67	34	3.7	1.0	244	14	1.9	14	260
129	421329088531701	09-05-80	7.1	95	47	14	1.8	207	74	38	13	440
132	422803087475306	09-01-81	7.2	94	23	41	11	--	150	13	8.0	510
133	415632088071201	06-21-80	8.3	74	23	52	18	597	170	18	7.0	660
134	415818087565201	05-02-80	--	24	7.2	85	4.3	268	44	22	7.1	330
135	413847088214801	08-27-80	7.3	54	27	64	1.9	280	69	20	7.5	390
136	411858088363401	08-28-80	7.4	71	35	97	12	195	110	90	7.8	520
137	411933089403701	08-28-80	7.0	38	19	370	12	317	200	350	9.3	1200

TABLE 1.—*Chemical analyses of major constituents in water from wells sampled for this study*—Continued

[Results in milligrams per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of collection	Field pH (standard units)	Calcium, Ca	Magnesium, Mg	Sodium, Na	Potassium, K	Field alkalinity, as HCO_3	Sulfate, SO_4	Chloride, Cl	Silica, SiO_2	Dissolved solids, sum of constituents
Aquifer layer 3, Iowa												
59	431620095250201	09-03-80	8.0	340	130	190	10	505	1400	26	22	2400
61	432412094503301	09-09-81	7.3	240	74	50	6.0	841	570	2.6	27	1400
62	431750094303001	09-08-81	7.4	180	61	63	5.0	744	440	2.3	18	1100
63	432256094183301	06-25-80	7.3	110	35	58	3.1	441	200	1.9	18	650
64	431350093544201	06-25-80	7.3	78	27	19	4.0	421	17	1.1	14	370
65	430800092540301	06-26-80	7.8	66	26	16	6.8	317	48	2.0	7.0	330
66	432650092170201	06-24-80	7.4	60	18	4.2	1.7	274	14	1.3	11	250
67	430337092190701	06-25-80	7.5	52	21	6.9	4.3	263	27	.9	6.8	250
68	431216091572001	06-23-80	7.5	69	29	3.5	1.1	297	37	9.4	11	320
69	432606091470301	06-23-80	7.2	93	24	5.0	1.6	386	10	9.4	18	370
70	432800091295301	06-24-80	7.5	56	28	3.5	.8	366	3.6	2.1	12	300
72	431638091284102	06-24-80	7.3	86	21	3.2	.9	341	24	6.5	14	330
84	430210094500001	09-08-81	7.6	240	78	100	7.3	744	800	6.6	26	1600
88	423840095135001	09-04-80	7.2	280	64	170	43	329	1100	30	8.3	1900
91	421831095152101	09-04-80	7.5	190	48	150	32	282	730	32	9.3	1300
92	422339094375101	09-02-80	7.2	170	59	98	26	317	590	14	9.0	1100
93	422136094173401	09-05-80	7.5	120	44	92	25	372	390	20	9.0	890
94	422855093481501	09-02-80	7.3	120	43	140	20	363	370	71	8.4	960
95	422611092552501	09-02-80	7.4	78	32	74	21	329	180	11	8.0	570
96	425049092063801	06-11-80	7.7	50	24	15	6.6	293	39	1.3	6.6	290
97	425708091383001	06-10-80	7.3	82	27	6.0	2.6	347	47	13	10	370
98	424820091324001	06-09-80	7.6	65	27	4.5	1.6	293	43	8.9	10	310
99	425138091234901	06-09-80	7.5	62	29	6.7	5.0	293	54	1.7	7.4	310
100	425550091233001	06-09-80	7.5	60	27	4.6	2.8	317	28	1.9	11	290
101	430330091264301	06-24-80	7.5	87	39	7.4	1.2	366	75	14	13	420
116	423141090385801	08-26-81	7.6	52	33	2.2	2.2	329	16	2.5	9.5	280
117	422640091002701	08-26-81	7.8	50	24	62	11	329	90	21	8.3	430
138	421010092180301	06-23-80	7.5	83	40	73	14	400	200	6.8	7.2	630
139	420200091363001	07-21-80	7.4	59	31	74	13	341	170	10	7.8	540
140	420718091165401	07-23-80	7.5	62	30	68	13	341	160	14	7.9	530
141	412407095391201	09-02-81	7.7	190	55	210	36	244	690	240	9.7	1600
142	413015094391302	09-02-81	7.8	170	63	330	35	219	750	380	11	1900
143	415021094072801	09-02-81	7.5	110	44	240	28	317	590	140	9.7	1300
144	413931093292001	09-01-81	7.6	58	24	53	12	305	110	14	11	440
145	414430092433001	09-01-81	7.5	79	37	100	16	354	270	21	11	710
146	412736093241201	07-30-81	7.5	61	26	83	13	329	150	28	11	540
147	412025093322201	06-10-81	7.7	55	22	140	17	305	240	30	12	670
148	410235093564901	06-10-81	7.6	130	44	360	28	244	740	250	14	1700
149	404422093445602	07-28-81	7.4	170	56	520	26	232	700	410	13	2000
150	405858093175701	06-10-81	7.8	60	23	200	19	317	300	110	11	890
151	411332093142101	06-10-81	7.8	57	22	140	17	317	190	75	11	680
152	412020092471001	08-12-81	7.6	86	37	200	22	329	440	62	11	1000
153	410305092490701	07-28-81	7.5	65	26	190	17	317	320	130	4.8	910
154	412356092211001	07-30-81	7.4	100	46	150	15	341	430	34	11	960
155	405750092142001	06-09-81	8.0	74	32	250	20	293	470	140	8.7	1100
156	410115091571801	06-09-81	7.5	75	31	240	20	280	470	130	10	1100
157	411812091412601	08-05-80	7.3	93	46	240	20	286	550	63	10	1200
158	411907091220001	10-29-80	7.2	530	78	2500	70	295	2200	3600	10	9200
159	404421091575801	06-09-81	7.5	69	28	330	20	305	410	250	11	1300
160	403839091333801	08-05-80	7.6	62	28	490	17	312	400	370	9.5	1500
Aquifer layer 3, Minnesota												
6	445607093364701	05-19-80	7.6	84	44	25	3.8	535	26	.9	20	470
7	445409093342801	05-19-80	7.7	52	29	4.1	4.0	312	<5.0	2.9	17	--
8	445831093305701	05-19-80	7.5	80	34	6.4	2.2	406	8.0	6.2	23	360
9	450015093280001	05-14-80	7.6	76	34	3.7	2.2	358	28	5.5	23	350
10	450127093204201	05-14-80	7.3	88	41	5.3	2.6	447	12	.50	20	390
11	450510093172501	05-14-80	--	64	24	5.6	1.8	302	9.5	3.1	21	280
12	450337093130901	05-14-80	6.8	68	29	5.4	1.5	269	61	8.2	19	330
13	450532093000301	05-12-80	7.3	48	17	4.1	1.8	213	8.0	3.2	15	200
14	450532093000302	05-12-80	7.2	56	18	7.9	3.7	233	<5.0	1.7	8.9	--
15	450417092570401	05-12-80	--	40	16	3.2	1.2	212	<5.0	<.5	15	--
16	450238093000401	05-12-80	7.0	56	18	5.4	1.8	219	8.3	4.7	16	220
17	450039092594501	05-14-80	6.8	56	19	7.9	1.7	232	35	6.2	19	260

TABLE 1.—*Chemical analyses of major constituents in water from wells sampled for this study*—Continued

[Results in milligrams per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of collection	Field pH (standard units)	Calcium, Ca	Magnesium, Mg	Sodium, Na	Potassium, K	Field alkalinity, as HCO_3	Sulfate, SO_4	Chloride, Cl	Silica, SiO_2	Dissolved solids, sum of constituents
20	445124093270801	05-20-80	7.6	68	27	5.5	1.7	347	12	2.9	22	310
22	445153093202102	05-20-80	7.6	76	32	5.2	1.4	371	11	3.3	17	330
23	444825093125001	05-22-80	--	68	27	3.7	1.7	--	11	<.5	23	--
24	445348093022901	05-21-80	--	100	36	14	1.9	--	71	45	22	470
25	444227093125201	05-21-80	--	65	20	4.8	1.1	305	10	.5	14	260
27	443849093143601	01-30-80	6.6	140	36	45	11	394	300	7.8	21	760
28	443806093085901	05-21-80	7.6	68	24	2.8	1.1	322	10	<.5	15	--
35	442648093091301	05-21-80	--	76	29	3.0	1.3	--	35	.6	15	330
36	441851093341801	09-03-80	--	90	35	22	4.2	378	33	1.6	22	400
37	441454092101001	02-12-80	--	72	27	9.1	.8	--	18	24	17	310
42	435542093570501	02-29-80	7.0	140	41	65	4.3	452	340	1.3	15	830
43	434547094095802	01-29-80	7.5	160	44	68	4.9	428	450	1.5	15	960
44	434601094010001	02-29-80	7.4	110	32	30	4.6	472	69	.6	23	510
46	435333092503901	09-02-80	--	72	20	4.3	3.1	317	21	1.1	7.6	290
47	434221092341701	05-07-80	--	60	22	3.1	2.8	260	34	.9	7.6	260
48	434235092340201	05-07-80	--	64	22	3.0	2.5	269	34	.8	8.3	270
49	434242092160503	05-06-80	--	56	21	2.3	1.1	262	12	2.6	9.3	230
Aquifer layer 3, Missouri												
161	402842092511801	04-07-81	7.4	110	49	710	25	319	1200	450	8.6	2700
162	400217091295201	04-07-81	7.3	210	100	2000	46	300	1200	3000	6.7	6700
163	391622091343301	04-06-81	7.5	72	36	280	19	450	280	190	8.5	1100
164	383543092103001	04-06-81	7.4	51	23	43	5.6	360	36	27	8.0	370
Aquifer layer 3, Wisconsin												
18	445910092331301	08-04-80	7.8	36	20	2.9	.8	195	6.5	3.5	19	200
29	444504092473601	08-14-80	7.5	13	5.8	2.5	.8	46	13	2.3	19	94
40	441849088051801	08-08-80	7.3	300	48	110	15	195	870	170	9.8	1600
74	432800091062501	11-10-81	7.7	61	35	4.2	.6	304	8.0	8.6	18	290
104	424423090552801	08-26-80	7.1	120	57	17	.7	439	47	41	26	640
106	430117090173201	08-27-80	7.6	63	33	2.3	.8	329	16	4.5	13	310
107	430132090172601	08-27-80	6.8	12	6.1	3.2	.7	51	13	2.8	22	89
109	430136089274301	05-12-80	7.5	94	49	21	1.1	390	34	91	20	520
112	425245088274701	05-29-80	7.5	56	28	4.4	1.8	305	2.2	1.3	9.9	260
113	425153088195501	10-21-82	7.6	53	22	7.0	1.6	266	19	1.7	10	250
114	424407090200001	08-26-80	7.6	66	37	3.8	.5	341	19	3.1	11	310
115	424404089204701	09-04-80	7.5	57	30	20	3.9	280	31	41	15	340
Aquifer layer 4, Minnesota												
45	433615093403001	09-02-80	--	58	20	100	2.6	512	66	2.1	22	520
Aquifer layer 4, Wisconsin												
111	430618087571001	11-21-80	7.7	68	28	35	2.6	--	240	15	9.8	510
Aquifer layer 5, Iowa												
58	425526096210711	09-03-80	8.0	250	97	170	16	305	1100	21	14	1800
60	431620095250511	09-03-80	8.0	300	110	150	8.8	442	1200	30	23	2000
81	430512095371801	02-23-82	7.4	--	--	--	--	--	--	--	10	--
82	425824095300901	02-23-82	7.3	320	80	96	--	--	930	6.7	11	--
83	430745094541101	02-23-82	7.5	220	58	100	--	--	520	5.0	11	--
85	424348095231601	04-15-80	8.0	120	38	74	9.9	355	260	18	9.0	710
86	424348095231602	09-04-80	8.1	97	35	25	3.0	396	170	1.6	27	560
87	423618095194511	09-04-80	8.0	180	42	28	3.7	397	370	1.1	24	850
89	422950095174301	02-22-82	7.5	310	100	190	--	1200	16	12	--	--
90	422009095210101	02-22-82	7.4	260	63	140	--	850	8.5	5.0	--	--
Aquifer layer 5, Minnesota												
2	462710092454001	02-21-80	--	60	15	13	1.7	--	15	39	19	270
26	443710093453501	09-03-80	--	82	35	80	3.6	378	100	36	24	550
41	440026094355401	09-03-80	--	87	24	18	2.2	268	130	5.0	29	430

TABLE 2.—*Chemical analyses of selected trace constituents in water from wells sampled for this study*

[Results in micrograms per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of sample	Arsenic, As	Boron, B	Barium, Ba	Bromide, Br (mg/L)	Cadmium, Cd	Cobalt, Co	Chromium, Cr	Copper, Cu
Aquifer layer 1, Illinois										
118	422418090255501	10-23-80	<1	20	160	.20	<1	4	--	<10
130	422803087475303	12-10-80	<1	1000	10	1.4	5	6	--	<10
131	422803087475304	01-14-81	2	11000	50	.20	10	<3	--	36
Aquifer layer 1, Iowa										
71	432953091172001	06-24-80	1	30	130	<.10	2	<3	--	<10
73	432206091130301	06-10-80	2	220	60	<.10	<1	<3	--	13
102	430240091110001	06-09-80	1	160	80	<.10	2	<3	--	<10
119	420842090165702	05-15-81	1	10	160	<.10	<1	<3	--	<10
Aquifer layer 1, Minnesota										
1	461209093550701	02-21-80	<1	<50	18	--	<1	<3	<1	<10
3	453038092584301	05-13-80	<1	60	48	--	<1	<3	<1	<10
4	452008092595001	05-13-80	<1	<50	37	--	<1	<3	<1	<10
5	445648093395101	05-19-80	1	250	150	--	<1	<3	<1	11
19	445704093215611	09-04-80	1	210	150	.30	8	<3	--	<10
21	445153093202101	05-20-80	<1	20	280	--	<1	<1	<1	<10
30	443354092323201	02-12-80	<1	210	520	--	<1	<3	<1	<10
31	443407092315501	02-12-80	<1	--	33	--	2	<3	2	<10
50	440324091404001	02-13-80	<1	620	32	--	<1	<3	<1	20
51	440324091401501	02-13-80	<1	80	37	--	<1	<3	<1	<10
52	440318091388180	02-13-80	<1	43	33	--	<1	<3	<1	<10
53	440312091381201	02-13-80	<1	32	40	--	<1	<3	<1	1
Aquifer layer 1, Wisconsin										
33	443436091281401	08-06-80	1	<20	20	.40	5	<3	--	10
34	443841090393001	08-20-80	1	10	60	.10	6	<3	--	10
38	442141091185601	08-13-80	<1	40	20	.70	5	<3	--	<10
39	442045090453601	08-20-80	2	10	20	<.10	2	<3	--	<10
54	435743089485701	08-21-80	1	<20	40	<.10	2	<3	--	<10
55	440219088555701	08-19-80	6	50	80	.20	3	<3	--	<10
56	434312090353901	08-22-80	1	<20	20	.30	<1	<3	--	<10
57	433921091132101	10-08-81	1	10	40	.10	1	10	--	10
75	432336090460601	08-28-80	1	20	50	.30	3	<3	--	<10
76	432042090231701	08-28-80	2	30	30	.20	4	<3	--	<10
77	433144089595901	09-05-80	1	20	40	.40	2	<3	--	<10
78	433220089282601	09-05-80	1	<20	40	.40	3	<3	--	11
79	431849089311002	07-24-80	4	<20	30	.20	3	<3	--	<10
80	432717088501701	09-05-80	1	30	250	.30	2	<3	--	<10
103	425246091042101	08-19-81	1	190	20	.90	2	10	--	10
105	431108090263101	08-29-80	1	50	50	.20	3	<3	--	<10
108	430055089534001	07-18-80	1	<20	60	.90	3	<3	--	<10
110	430058089251401	07-22-80	2	30	20	.30	<1	<3	--	<10
Aquifer layer 3, Illinois										
120	422606089434501	08-29-80	1	20	20	.20	4	<3	--	<10
121	421331089442201	08-29-80	2	80	21000	.20	3	<3	--	<10
122	421658089235101	08-20-80	1	40	110	.60	3	<3	--	<10
123	422738089114601	08-23-80	<1	<20	40	.10	<2	<3	--	<20
124	422545089103301	08-23-80	<1	--	40	.10	<2	<3	--	<20
125	421855089121601	08-23-80	1	<20	130	.20	<2	<3	--	<20
126	421614089062301	09-03-80	1	270	80	.60	4	<3	10	<10
127	420953089080501	09-05-80	2	20	100	.70	3	<3	--	<10
128	421025088564401	09-04-80	1	50	110	.30	4	<3	--	<10

TABLE 2.—*Chemical analyses of selected trace constituents in water from wells sampled for this study*—Continued

[Results in micrograms per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Fluoride, F (mg/L)	Iron, Fe	Lithium, Li	Manganese, Mn	Molybdenum, Mo	Lead, Pb	Selenium, Se	Strontium, Sr	Vanadium, Va	Beryllium, Be	Sulfide, S (mg/L)
Aquifer layer 1, Illinois											
118	.30	670	<4	10	<10	<10	<1	46	<6	<.7	--
130	1.0	2700	180	190	<10	17	<1	13000	<6	<.7	<.1
131	.30	8500	2100	9800	<10	170	<1	100000	<6	<1.0	<.1
Aquifer layer 1, Iowa											
71	.20	220	7	9	<10	<10	<1	100	<6	<.7	--
73	.20	170	15	15	<10	<10	<1	230	<6	.7	--
102	.30	250	18	14	<10	62	<1	360	<6	<.7	--
119	.10	11	13	14	<10	<10	<1	960	<6	<1.0	--
Aquifer layer 1, Minnesota											
1	.10	4800	2	450	<1	<10	<1	--	--	--	--
3	.26	1100	5	70	2	<10	<1	--	--	--	--
4	.20	550	4	90	2	<10	<1	--	--	--	--
5	.72	2200	11	30	<1	<10	1	--	--	--	--
19	.40	610	20	14	<10	34	<10	690	<6	<.7	--
21	.30	380	18	20	<1	<1	2	--	--	--	--
30	.18	<50	29	59	2	<1	3	--	--	--	--
31	.28	300	20	38	<1	<10	--	--	--	--	--
50	.56	200	56	25	<1	<1	<1	--	--	--	--
51	.04	580	63	<20	<1	<1	<1	--	--	--	--
52	1.3	340	31	21	<1	<1	1	--	--	--	--
53	.39	340	22	24	<1	30	4	--	--	--	--
Aquifer layer 1, Wisconsin											
33	.50	6	0	210	0	10	<1	24	<6	<.7	<.1
34	.20	<3	5	5	<10	13	<1	58	<6	<.7	<.1
38	.60	6500	<4	190	<10	<10	<1	20	<6	2.0	<.1
39	.10	<3	<4	2	<10	<10	<1	12	<6	3.0	<.1
54	.20	<3	<4	260	<10	<10	<1	39	<6	3.0	<.1
55	.40	50	7	11	<10	<10	<1	1100	<6	2.0	<.1
56	.20	40	<4	29	<10	16	<1	36	<6	4.0	--
57	<.10	440	4	17	10	10	<1	59	6	1.0	--
75	.10	310	<4	14	<10	17	<1	40	<6	<.7	<.1
76	.10	150	<4	16	<10	<10	<1	45	<6	1.0	<.1
77	.10	10	<4	45	<10	<10	<1	41	<6	<.7	.2
78	.10	9	<4	5	<10	<10	<1	44	<6	<.7	<.1
79	.10	<3	<4	<1	<10	<10	<1	46	<6	<.7	<.1
80	.30	840	<4	49	<10	<10	<1	1700	<6	<.7	<.1
103	.20	1700	50	16	11	10	<1	4400	6	1.0	<.1
105	.20	750	5	26	<10	<10	<1	58	<6	<.7	.2
108	.10	8	<4	<1	10	13	<1	38	<6	<.7	<.1
110	.10	140	<4	16	<10	<10	<1	76	<6	.8	.1
Aquifer layer 3, Illinois											
120	.20	1500	<4	28	13	18	<1	61	<6	<.7	--
121	.30	270	5	13	<10	12	<1	540	<6	<.7	--
122	.20	100	5	<1	<10	14	1	110	<6	1.0	--
123	.10	3	5	<1	<10	21	<1	48	<6	<.7	--
124	.10	16	6	<1	<10	<10	<1	43	<6	<.7	--
125	.10	21	4	5	<10	<10	<1	48	<6	<.7	--
126	.20	330	6	58	<10	11	<1	160	<6	<.7	--
127	.20	1700	<4	44	<10	<10	<1	120	<6	<.7	--
128	.20	<3	<4	<1	<10	<10	<1	72	<6	<.7	--

TABLE 2.—*Chemical analyses of selected trace constituents in water from wells sampled for this study*—Continued

[Results in micrograms per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of sample	Arsenic, As	Boron, B	Barium, Ba	Bromide, Br (mg/L)	Cadmium, Cd	Cobalt, Co	Chromium, Cr	Copper, Cu
129	421329088531701	09-05-80	1	30	50	.50	3	<3	--	<10
132	422803087475306	09-01-81	1	290	2	.10	1	3	--	10
133	415632088071201	06-21-80	1	560	80	.20	1	<3	--	<10
134	415818087565201	05-02-80	1	910	20	.20	<1	<3	--	11
135	413847088214801	08-27-80	1	470	30	.40	<1	<3	--	<10
136	411858088363401	08-28-80	1	270	30	.70	2	<3	--	<10
137	411933089403701	08-28-80	<1	850	20	1.0	5	<3	--	<10
				Aquifer layer 3, Iowa						
59	431620095250201	09-03-80	3	300	20	.20	7	<3	--	<10
61	432412094503301	09-09-81	2	300	23	.10	1	<3	--	<10
62	431750094303001	09-08-81	2	210	21	<.10	1	4	--	<10
63	432256094183301	06-25-80	1	140	60	<.10	<1	<3	--	<10
64	431350093544201	06-25-80	1	70	140	<.10	<1	<3	--	<10
65	430800092540301	06-26-80	1	250	60	<.10	3	<3	--	<10
66	432650092170201	06-24-80	1	70	140	.10	<1	<3	--	<10
67	430337092190701	06-25-80	<10	310	70	<.10	<1	<3	--	<10
68	431216091572001	06-23-80	1	60	140	.10	<1	<3	--	<10
69	432606091470301	06-23-80	1	20	120	.10	<1	<3	--	<10
70	432800091295301	06-24-80	<10	<20	60	.10	2	<3	--	<10
72	431638091284102	06-24-80	<10	30	80	<.10	<1	<3	--	<10
84	430210094500001	09-08-81	1	360	31	<.10	1	<3	--	<10
88	423840095135001	09-04-80	1	2200	20	.90	6	<3	--	<10
91	421831095152101	09-04-80	1	1100	30	.50	4	<3	--	<10
92	422339094375101	09-02-80	1	990	20	.80	5	<3	--	<10
93	422136094173401	09-05-80	1	1200	20	.80	3	<3	--	<10
94	422855093481501	09-02-80	2	1100	20	.90	4	<3	--	<10
95	422611092552501	09-02-80	1	1100	30	.40	4	<3	--	<10
96	425049092063801	06-11-80	<10	220	70	<.10	<1	<3	--	<10
97	425708091383001	06-10-80	4	50	110	.10	<1	<3	--	<10
98	424820091324001	06-09-80	1	140	140	<.10	1	<3	--	<10
99	425138091234901	06-09-80	2	180	60	<.10	<1	<3	--	<10
100	425550091233001	06-09-80	<10	130	100	<.10	<1	<3	--	<10
101	430330091264301	06-24-80	<10	80	100	.10	2	<3	--	<10
116	423141090385801	08-26-81	2	<20	150	<.10	<1	<3	--	<10
117	422640091002701	08-26-81	1	460	40	.10	<1	<3	--	<10
138	421010092180301	06-23-80	<10	590	30	.10	3	<3	--	<10
139	420200091363001	07-21-80	1	610	30	.30	<1	<3	--	<10
140	420718091165401	07-23-80	1	570	40	.30	2	<3	--	<10
141	412407095391201	09-02-81	<10	820	17	.90	<2	<6	--	<20
142	413015094391302	09-02-81	1	1300	23	.20	<2	<6	--	<20
143	415021094072801	09-02-81	1	1700	21	.60	<1	<3	--	<10
144	413931093292001	09-01-81	<10	600	48	.10	<1	<3	--	<10
145	414430092433001	09-01-81	<10	1100	27	.10	<1	<3	--	<10
146	412736093241201	07-30-81	2	760	40	.20	<1	<3	--	<10
147	412025093322201	06-10-81	<10	1200	170	.20	<1	<3	--	<10
148	410235093564901	06-10-81	1	1600	310	.90	<2	<6	--	<20
149	404422093445602	07-28-81	1	1900	20	1.5	<1	<3	--	<10
150	405858093175701	06-10-81	1	1500	130	.40	<1	<3	--	<10
151	411332093142101	06-10-81	1	1100	120	.30	<1	<3	--	<10
152	412020092471001	08-12-81	1	1400	30	.30	<1	<3	--	<10
153	410305092490701	07-28-81	1	1400	30	.40	<1	<3	--	<10
154	412356092211001	07-30-81	2	870	30	.20	<1	<3	--	<10
155	405750092142001	06-09-81	1	1400	130	.50	<1	<3	--	<10
156	410115091571801	06-09-81	1	1300	100	.50	<1	<3	--	<10
157	411812091412601	08-05-80	2	670	30	.40	4	<3	--	<10
158	411907091220001	10-29-80	1	5700	30	9.8	6	10	--	24
159	404421091575801	06-09-81	1	1700	140	.80	<1	<3	--	<10
160	403839091333801	08-05-80	3	1600	30	.50	5	<3	--	<10

TABLE 2.—*Chemical analyses of selected trace constituents in water from wells sampled for this study*—Continued

[Results in micrograms per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Fluoride, F (mg/L)	Iron, Fe	Lithium, Li	Manganese, Mn	Molybdenum, Mo	Lead, Pb	Selenium, Se	Strontium, Sr	Vanadium, Va	Beryllium, Be	Sulfide, S (mg/L)
129	.20	<3	<4	<1	<10	<10	<1	83	<6	<.7	--
132	1.4	650	24	14	10	10	<1	8300	6	1.0	<.1
133	1.1	22	49	13	<10	54	<1	3900	<6	2.0	--
134	3.5	200	73	11	12	<10	<1	710	<6	4.0	--
135	1.1	4	59	48	<10	21	<1	1800	<6	<.7	--
136	.70	9	67	10	<10	18	<1	1300	<6	<.7	--
137	1.5	580	220	9	<10	<10	<1	2700	<6	<.7	--
					Aquifer layer 3, Iowa						
59	.30	82	140	550	<10	26	<1	3000	<6	<.7	--
61	.30	1500	70	330	20	<10	<1	1100	<6	<1.0	.8
62	.40	99	51	130	<10	10	<1	1100	<6	<1.0	1.0
63	.30	2600	30	36	25	<10	<1	350	<6	<.7	--
64	.40	260	23	25	17	<10	<1	320	<6	<.7	--
65	.70	380	31	8	21	<10	<1	510	<6	<.7	--
66	.60	630	10	10	<10	<10	<1	150	<6	<.7	--
67	.60	91	14	5	<10	17	<1	280	<6	<.7	--
68	.30	<3	7	2	17	<10	1	220	<6	<.7	--
69	.20	7	7	25	16	<10	<1	100	<6	<.7	--
70	.10	<3	<4	2	<10	<10	<1	52	<6	<.7	--
72	.20	15	5	3	15	<10	<1	97	<6	<.7	--
84	.30	2500	72	170	<10	10	<1	1900	<6	<1.0	.7
88	1.7	1300	210	59	<10	24	<1	9100	<6	<.7	--
91	2.0	3700	170	57	<10	22	<1	6000	<6	<.7	--
92	1.5	2100	95	39	<10	18	<1	4400	<6	<.7	--
93	1.6	2600	150	33	<10	14	<1	5200	<6	<.7	--
94	1.3	210	130	14	<10	13	<1	4000	<6	<.7	--
95	1.2	1200	120	18	<10	10	<1	2200	<6	<.7	--
96	.80	150	24	8	<10	<10	<1	530	<6	<.7	--
97	.40	6	5	4	<10	66	1	250	<6	<.7	--
98	.50	7	<4	37	<10	<10	2	150	<6	<.7	--
99	.40	22	14	8	11	78	<1	370	<6	<.7	--
100	.50	260	9	9	<10	87	<1	270	<6	2.0	--
101	.30	210	9	9	16	<10	<1	120	<6	<.7	--
116	.20	170	7	10	<10	<10	<1	92	<6	<1.0	<.1
117	.90	280	77	8	<10	<10	<1	1100	<6	<1.0	.1
138	1.1	1400	110	19	<10	<10	<1	1900	<6	<.7	--
139	1.3	170	90	3	<10	<10	<1	1500	<6	<.7	--
140	1.2	120	79	4	<10	<10	<1	1600	<6	<.7	--
141	2.9	2500	240	120	<20	<20	<1	6300	<12	<2.0	1.0
142	2.7	370	280	17	<20	<20	<1	5800	<12	<2.0	.5
143	2.3	440	270	8	<10	<10	<1	4700	<6	<1.0	.5
144	1.7	120	63	4	<10	<10	<1	1300	<6	<1.0	.5
145	1.4	320	140	5	<10	<10	<1	2300	<6	<1.0	.8
146	1.7	2000	86	18	<10	<10	<1	1700	<6	<1.0	--
147	2.7	210	150	3	<10	<10	<1	2100	<6	<1.0	.1
148	2.7	1300	350	18	<20	<20	<1	5700	<6	<2.0	.1
149	2.8	720	420	10	<10	<10	<1	6000	<6	<1.0	<.1
150	2.7	840	200	8	<10	<10	<1	2400	<6	<1.0	.9
151	2.2	800	130	12	<10	<10	<1	1800	<6	<1.0	<.1
152	1.2	2300	210	32	<10	<10	<1	2500	<6	<1.0	.2
153	1.6	51	4	<1	<10	<10	<1	44	<6	<1.0	<.1
154	1.3	2200	170	18	<10	<10	<1	2300	<6	<1.0	--
155	1.7	2100	260	91	<10	<10	<1	2700	<6	<1.0	<.1
156	1.6	530	240	8	<10	<10	<1	2500	<6	<1.0	<.1
157	1.3	290	220	4	<10	16	<1	2500	<6	<.7	--
158	1.5	10000	620	130	<10	17	<1	19000	5	<1.0	--
159	2.3	1200	290	12	<10	<10	<1	2500	<6	<1.0	<.1
160	4.1	770	360	8	<10	<10	<1	2600	<6	1.0	--

TABLE 2.—*Chemical analyses of selected trace constituents in water from wells sampled for this study*—Continued

[Results in micrograms per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of sample	Arsenic, As	Boron, B	Barium, Ba	Bromide, Br (mg/L)	Cadmium, Cd	Cobalt, Co	Chromium, Cr	Copper, Cu
Aquifer layer 3, Minnesota										
6	445607093364701	05-19-80	<1	210	110	--	<1	<3	<1	<10
7	445409093342801	05-19-80	<1	10	160	--	<1	<3	<1	21
8	445831093305701	05-19-80	11	10	270	--	<1	<3	<1	15
9	450015093280001	05-14-80	<1	80	75	--	<1	<3	<1	11
10	450127093204201	05-14-80	<1	110	11	--	<1	<3	<1	<10
11	450510093172501	05-14-80	<1	100	90	--	<1	<3	<1	<10
12	450337093130901	05-14-80	<1	80	63	--	<1	<3	<1	12
13	450532093000301	05-12-80	--	--	--	--	--	--	--	--
14	450532093000302	05-12-80	<1	<50	59	--	<1	<3	<1	<10
15	450417092570401	05-12-80	<1	<50	13	--	<1	<3	<1	<10
16	450238093000401	05-12-80	<1	<50	25	--	<1	<3	<1	<10
17	450039092594501	05-14-80	<1	90	110	--	<1	<3	<1	<10
20	445124093270801	05-20-80	1	70	190	--	<1	<3	8	<10
22	445153093202102	05-20-80	1	240	150	--	<1	<3	7.9	<10
23	444825093125001	05-22-80	2	80	190	--	<1	<3	<1	--
24	445348093022901	05-21-80	<1	80	53	--	<1	<3	<1	<10
25	444227093125201	05-21-80	<1	110	120	--	--	--	--	--
27	443849093143601	01-30-80	2	400	17	--	<1	<3	<1	<10
28	443806093085901	05-21-80	<1	70	91	--	<1	<3	<1	<10
35	442648093091301	05-21-80	<1	90	50	--	<1	<3	<1	<10
36	441851093341801	09-03-80	1	30	110	--	10	<3	--	<10
37	441454092101001	02-12-80	<1	<50	57	--	<1	<3	1	<10
42	435542093570501	02-29-80	5	20	46	--	<1	<3	1	<10
43	434547094095802	01-29-80	6	270	47	--	<1	<3	<1	<10
44	434601094010001	02-29-80	6	20	44	--	<1	<3	<1	<10
46	435333092503901	09-02-80	1	90	80	--	10	<3	<1	30
47	434221092341701	05-07-80	<1	120	48	--	<1	<3	<1	<10
48	434235092340201	05-07-80	1	80	44	--	<1	<3	--	<10
49	434242092160503	05-06-80	<1	<50	35	--	<1	<3	<1	16
Aquifer layer 3, Missouri										
161	402842092511801	04-07-81	0	2100	30	3.0	2	<3	--	0
162	400217091295201	04-07-81	0	3100	30	5.6	13	<3	--	0
163	391622091343301	04-06-81	0	2200	40	1.0	1	<3	--	0
164	383543092103001	04-06-81	0	320	100	.10	3	<3	--	0
Aquifer layer 3, Wisconsin										
18	445910092331301	08-04-80	0	<20	20	.60	2	<3	--	<10
29	444504092473601	08-14-80	1	<20	20	.90	4	<3	--	<10
40	441849088051801	08-08-80	7	400	20	.90	4	<3	--	<10
74	432800091062501	11-10-81	0	<20	30	<.10	1	3	--	10
104	424423090552801	08-26-80	1	30	160	.40	4	<3	--	<10
106	430117090173201	08-27-80	1	30	30	.30	6	4	--	<10
107	430132090172601	08-27-80	1	30	30	.30	3	<3	--	<10
109	430136089274301	05-12-80	2	30	90	<.10	6	<3	--	<10
112	425245088274701	05-29-80	0	80	950	<.10	<1	<3	--	<10
113	425153088195501	10-21-82	--	--	150	--	--	--	--	--
114	424407090200001	08-26-80	1	30	40	.10	5	4	--	<10
115	424404089204701	09-04-80	1	80	40	.30	3	<3	--	<10
Aquifer layer 4, Minnesota										
45	433615093403001	09-02-80	5	250	60	.10	11	<3	--	<10
Aquifer layer 4, Wisconsin										
111	430618087571001	11-21-80	3	180	30	.30	2	<3	--	<10

TABLE 2.—*Chemical analyses of selected trace constituents in water from wells sampled for this study*—Continued

[Results in micrograms per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Fluoride, F (mg/L)	Iron, Fe	Lithium, Li	Manganese, Mn	Molybdenum, Mo	Lead, Pb	Selenium, Se	Strontium, Sr	Vanadium, Va	Beryllium, Be	Sulfide, S (mg/L)
Aquifer layer 3, Minnesota											
6	.30	330	14	190	<10	<10	1	--	--	--	--
7	.20	1200	11	230	<10	<10	<1	--	--	--	--
8	.20	1200	6	<20	<10	<10	<1	--	--	--	--
9	.24	<50	6	320	<10	<10	1	--	--	--	--
10	.26	430	8	470	<10	--	<1	--	--	--	--
11	.18	<50	4	280	<10	<10	<1	--	--	--	--
12	.20	<50	3	320	<10	<10	<1	--	--	--	--
13	--	--	3	--	<10	<10	<1	--	--	--	--
14	.27	640	7	30	<10	<10	<1	--	--	--	--
15	.18	<50	2	70	<10	<10	<1	--	--	--	--
16	.19	50	4	<20	<10	<10	<1	--	--	--	--
17	.18	<50	2	<50	<1	--	<1	--	--	--	--
20	.18	590	5	70	3	<10	<1	--	--	--	--
22	.24	430	5	30	3	<10	<1	--	--	--	--
23	.12	<50	5	140	2	<10	<1	--	--	--	--
24	.12	<50	12	20	1	<10	2	--	--	--	--
25	.14	130	7	1000	<1	<10	<1	--	--	--	--
27	.15	1120	7	22	<1	<10	1	--	--	--	--
28	.12	200	5	40	2	<10	<1	--	--	--	--
35	.14	160	7	90	<10	<10	<1	--	--	--	--
36	.40	39	29	330	<10	44	<1	450	<6	<.7	--
37	.17	<50	5	<20	<1	<10	<1	--	--	--	--
42	.43	660	29	190	15	<10	3	--	--	--	--
43	.18	2200	29	200	2	<10	2	--	--	--	--
44	.28	2400	17	300	4	<10	2	--	--	--	--
46	.40	200	8	22	<10	51	1	320	<6	<.7	--
47	.37	320	8	20	<1	<10	<1	--	--	--	--
48	.40	150	8	20	1	<10	1	--	--	--	--
49	.24	240	3	20	<1	1	<1	--	--	--	--
Aquifer layer 3, Missouri											
161	5.1	110	390	21	0	<10	<1	4500	0	<.7	--
162	4.7	12	680	19	0	25	<1	9300	0	<.7	--
163	2.7	140	230	9	0	<10	<1	2400	0	<.7	--
164	1.2	130	37	18	0	<10	<1	570	0	<.7	--
Aquifer layer 3, Wisconsin											
18	.20	<3	<4	<1	<10	<10	<1	34	<6	<.7	<.1
29	.10	<3	<4	1	<10	14	<1	21	<6	2.0	<.1
40	1.3	2500	90	65	<10	18	<1	15000	<6	<.7	<.1
74	.10	6	4	1	10	10	<1	62	6	1.0	<.1
104	.20	<3	5	2	<10	13	<1	120	<6	<.7	<.1
106	.20	7	<4	1	<10	17	<1	50	<6	<.7	<.1
107	.10	45	<4	7	<10	<10	<1	15	<6	<.7	<.1
109	.10	14	<4	2	21	<10	<1	78	<6	<.7	--
112	.30	440	8	6	<10	<10	<1	1200	<6	<.7	.6
113	.30	120	4	21	--	--	--	1200	--	--	--
114	.20	3	<4	2	<10	<10	<1	58	<6	<.7	<.1
115	.10	59	<4	190	<10	<10	<1	58	<6	<.7	<.1
Aquifer layer 4, Minnesota											
45	.30	210	22	100	<10	55	<1	190	<6	<.7	--
Aquifer layer 4, Wisconsin											
111	.90	150	12	12	12	16	1	13000	<6	<1.0	.2

TABLE 2.—*Chemical analyses of selected trace constituents in water from wells sampled for this study*—Continued

[Results in micrograms per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of sample	Arsenic, As	Boron, B	Barium, Ba	Bromide, Br (mg/L)	Cadmium, Cd	Cobalt, Co	Chromium, Cr	Copper, Cu
					Aquifer layer 5, Iowa					
58	425526096210711	09-03-80	2	480	20	.60	6	<3	--	<10
60	431620095250511	09-03-80	3	280	20	.10	6	<3	--	13
81	430512095371801	02-23-82	<50	--	9	--	<2	--	<5	<10
82	425824095300901	02-23-82	<50	--	9	--	<2	--	<5	<10
83	430745094541101	02-23-82	<50	--	13	--	<2	--	<5	<10
85	424348095231601	04-15-80	<10	--	<100	--	1	--	<1	<10
86	424348095231602	09-04-80	2	150	30	<.10	4	<3	--	<10
87	423618095194511	09-04-80	10	340	30	.20	6	6	--	<10
89	422950095174301	02-22-82	<50	--	8	--	<2	--	<5	<10
90	422009095210101	02-22-82	<50	--	10	--	<2	--	<5	<10
					Aquifer layer 5, Minnesota					
2	462710092454001	02-21-80	<1	120	49	--	<1	<3	<1	<10
26	443710093453501	09-03-80	5	220	70	.40	9	<3	--	<10
41	440026094355401	09-03-80	9	110	160	<.10	11	<3	--	<10

TABLE 2.—*Chemical analyses of selected trace constituents in water from wells sampled for this study*—Continued

[Results in micrograms per liter, except as indicated. Analyses by U.S. Geological Survey, except Minnesota analyses by Minnesota Department of Health. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Fluoride, F (mg/L)	Iron, Fe	Lithium, Li	Manganese, Mn	Molybdenum, Mo	Lead, Pb	Selenium, Se	Strontium, Sr	Vanadium, Va	Beryllium, Be	Sulfide, S (mg/L)
Aquifer layer 5, Iowa											
58	.80	140	170	230	<10	22	<1	4300	<6	<.7	--
60	.30	78	110	720	<10	28	<1	2600	<6	<.7	--
81	--	1400	--	--	--	--	<5	--	--	--	<.1
82	.57	2500	--	640	--	<50	<5	--	--	--	<.1
83	.36	4200	--	270	--	<50	<5	--	--	--	<.1
85	2.0	30	--	130	--	<10	<10	--	--	--	--
86	.40	34	33	210	<10	20	<1	770	<6	<.7	--
87	.50	27	45	220	<10	20	<1	1100	<6	<.7	--
89	.43	71	--	2600	--	<50	<5	--	--	--	<.1
90	.82	2900	--	460	--	<50	<5	--	--	--	<.1
Aquifer layer 5, Minnesota											
2	.15	<0	6	<0	<1	<10	3	--	--	--	--
26	.30	1500	20	710	<10	34	0	370	<6	<.7	--
41	.20	1800	17	320	<10	34	1	240	<6	<.7	--

TABLE 3.—*Analyses of stable isotopes, uranium, and radium-226 in water from selected wells sampled for this study*

[Analyses by U.S. Geological Survey. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of collection	Stable isotope ratios (permil)				Uranium, U (μg/L)	Radium-226, Ra (pCi/L)	Carbon-14 (percent modern)
			$\delta^{18}O$	δD	$\delta^{13}C$	$\delta^{34}S$			
			Aquifer layer 1, Illinois						
118	422418090255501	10-23-80	-8.4	-54.0	--	--	<.6	1.1	--
130	422803087475303	12-10-80	-9.3	-63.0	--	8.7	<.6	6.9	--
131	422803087475304	01-14-81	-9.0	-57.5	--	--	28.9	99	--
			Aquifer layer 1, Iowa						
71	432953091172001	06-24-80	-8.4	-55.0	-11.7	--	<.3	1.4	--
73	432206091130301	06-10-80	-8.8	-54.5	-11.3	--	.5	2.0	--
102	430240091110001	06-09-80	-9.2	-56.5	-10.0	--	<.5	2.0	--
119	420842090165702	05-15-81	-8.4	-58.0	-11.1	--	<.6	2.2	--
			Aquifer layer 1, Minnesota						
1	461209093550701	02-21-80	--	--	--	--	<.6	1.7	--
19	445704093215611	09-04-80	-9.6	-64.5	-13.2	--	<.5	2.8	--
30	443354092323201	02-12-80	-10.0	-67.0	-9.9	--	<.6	5.5	--
32	443300092302901	02-12-80	-10.2	-68.0	-10.2	--	<.6	11	--
51	440324091401501	02-13-80	-9.2	-60.5	-12.4	--	<.5	4.6	--
52	440318091388180	02-13-80	-9.5	-61.5	-12.5	--	<.6	2.8	--
			Aquifer layer 1, Wisconsin						
33	443436091281401	08-06-80	-9.2	-65.5	-14.4	--	<.6	.2	--
34	443841090393001	08-20-80	--	--	--	--	<.6	.4	--
38	442141091185601	08-13-80	-9.2	-63.0	-12.3	--	<.7	.5	--
39	442045090453601	08-20-80	--	--	--	--	<.6	.3	--
54	435743089485701	08-21-80	-9.4	-62.5	-14.2	--	2.0	.5	--
55	440219088555701	08-19-80	--	--	--	--	3.7	.5	--
56	434312090353901	08-22-80	--	--	--	--	<.5	.2	--
57	433921091132101	10-08-81	--	--	--	--	<.6	2.2	--
75	432336090460601	08-28-80	--	--	--	--	<.6	.9	--
76	432042090231701	08-28-80	--	--	--	--	<.6	.7	--
77	433144089595901	09-05-80	--	--	--	--	<.6	.5	--
78	433220089282601	09-05-80	--	--	--	--	<.6	.2	--
79	431849089311002	07-24-80	-8.8	-60.0	-8.2	--	.9	<.1	--
80	432717088501701	09-05-80	--	--	--	--	<.6	5.9	--
103	425246091042101	08-19-81	-8.6	-56.5	-11.0	--	.7	2.8	--
105	431108090263101	08-29-80	--	--	--	--	<.5	1.7	--
108	430055089534001	07-18-80	--	--	--	--	.7	.8	--
109	430136089274301	05-12-80	-9.4	-60.0	-13.1	--	22	<.1	--
110	430058089251401	07-22-80	-8.8	-51.0	-8.6	--	.8	1.2	--
			Aquifer layer 3, Illinois						
120	422606089434501	08-29-80	-7.4	-47.5	-8.4	--	--	--	--
121	421331089442201	08-29-80	-8.0	-50.5	-12.6	--	<.6	13	--
122	421658089235101	08-20-80	-8.4	-52.5	--	--	--	--	--
123	422738089114601	08-23-80	-8.8	-58.0	-14.0	--	<.6	.1	--
124	422545089103301	08-23-80	-8.6	-56.0	-12.3	--	<.6	.1	--
125	421855089121601	08-23-80	-7.4	-49.5	-7.3	--	<.6	.8	--
126	421614089062301	09-03-80	-8.4	-54.5	-14.0	--	.9	.5	--
127	420953089080501	09-05-80	-7.4	-46.0	-8.2	--	--	--	--
128	421025088564401	09-04-80	--	--	-7.9	--	--	--	--
129	421329088531701	09-05-80	-8.4	-51.5	-9.4	--	--	--	--
132	422803087475306	09-01-81	-9.6	-68.5	--	15.5	.7	6.0	--
133	415632088071201	06-21-80	-8.9	-64.0	-14.6	--	<1.6	2.7	--
135	413847088214801	08-27-80	-9.5	-61.5	-11.8	--	<.6	2.2	--
136	411858088363401	08-28-80	-9.0	-60.5	-10.6	--	--	--	--
137	411933089403701	08-28-80	-9.4	-61.5	-11.3	--	<.6	5.8	--

TABLE 3—*Analyses of stable isotopes, uranium, and radium-226 in water from selected wells sampled for this study*—Continued

[Analyses by U.S. Geological Survey. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of collection	Stable isotope ratios (permil) $\delta^{18}O$	δD	$\delta^{13}C$	$\delta^{34}S$	Uranium, U (µg/L)	Radium-226, Ra (pCi/L)	Carbon-14 (percent modern)
Aquifer layer 3, Iowa									
59	431620095250201	09-03-80	-10.2	-71.5	-17.2	--	3.7	2.7	--
61	432412094503301	09-09-81	-9.4	-68.5	-13.8	-10.0	2.6	5.8	--
62	431750094303001	09-08-81	-9.0	-64.5	-16.0	-9.9	<.6	1.9	--
63	432256094183301	06-25-80	--	--	--	--	.6	1.6	--
64	431350093544201	06-25-80	-6.3	-45.5	-11.2	--	<.6	1.2	--
65	430800092540301	06-26-80	--	--	--	--	<.5	2.0	--
66	432650092170201	06-24-80	--	--	--	--	<.5	.4	--
67	430337092190701	06-25-80	-8.3	-54.5	-10.2	--	.4	1.1	--
68	431216091572001	06-23-80	-9.2	-54.0	-10.6	--	.8	.3	--
69	432606091470301	06-23-80	--	--	--	--	.9	<.1	--
70	432800091295301	06-24-80	-8.9	-59.5	-10.0	--	.7	<.1	--
72	431638091284102	06-24-80	--	--	--	--	.5	.2	--
84	430210094500001	09-08-81	-9.9	-70.0	-18.8	-8.5	<.7	.4	--
88	423840095135001	09-04-80	--	--	--	--	.7	8.0	--
		09-08-81	-10.8	-78.5	-14.7	-9.2	--	--	--
91	421831095152101	09-04-80	-12.0	-87.0	-12.5	-1.1	.6	7.3	1.5
92	422339094375101	09-02-80	--	--	-10.1	-4.4	1.2	5.0	--
93	422136094173401	09-05-80	-12.3	--	--	-1.0	1.1	9.1	--
94	422855093481501	09-02-80	-10.0	-70.0	-11.4	--	1.2	6.5	<0.7
95	422611092552501	09-02-80	--	--	--	--	.7	3.6	--
96	425049092063801	06-11-80	--	--	--	--	.5	2.4	--
97	425708091383001	06-10-80	--	--	--	--	2.4	.6	--
98	424820091324001	06-09-80	-8.6	-54.0	-10.0	--	4.9	.8	--
99	425138091234901	06-09-80	-9.0	-54.5	-11.2	--	<.5	1.8	--
100	425550091233001	06-09-80	--	--	--	--	.4	1.7	--
101	430330091264301	06-24-80	--	--	--	--	1.4	1.4	--
116	423141090385801	08-26-81	-8.2	-54.5	-11.2	3.9	.8	2.0	--
117	422640091002701	08-26-81	-8.8	-61.5	-10.2	-8.4	<.6	1.8	--
138	421010092180301	06-23-80	--	--	-10.1	--	1.1	2.7	--
139	420200091363001	07-21-80	-10.0	-66.0	-10.1	--	<7.0	2.8	3.7
140	420718091165401	07-23-80	--	--	--	--	1.6	1.8	--
141	412407095391201	09-02-81	-17.1	-131.0	-7.3	11.8	<.6	6.2	--
142	413015094391302	09-02-81	-17.1	-132.0	-6.9	13.6	<.5	12	--
143	415021094072801	09-02-81	-13.6	-103.0	-8.6	6.5	.7	9.4	--
144	413931093292001	09-01-81	--	--	-8.9	--	<.6	6.5	--
		09-08-81	-8.6	-61.0	-9.2	2.5	--	--	--
145	414430092433001	09-01-81	-9.9	-72.5	-9.3	1.8	<1.1	3.2	--
146	412736093241201	07-30-81	--	--	--	--	<.6	3.3	--
147	412025093322201	06-10-81	-9.6	-64.5	-9.0	6.6	<.5	4.7	4.2
148	410235093564901	06-10-81	-14.7	-109.0	-8.1	-2.0	<.5	13	2.6
149	404422093445602	07-28-81	-16.5	-124.0	-7.7	16.2	<.6	7.1	--
150	405858093175701	06-10-81	-10.3	-72.0	-8.9	-4.6	<.5	5.8	--
151	411332093142101	06-10-81	--	--	--	--	<.6	3.9	--
152	412020092471001	08-12-81	--	--	--	--	<.6	9.0	--
153	410305092490701	07-28-81	--	--	--	--	<.5	11	--
154	412356092211001	07-30-81	--	--	--	--	.9	17	--
155	405750092142001	06-09-81	-12.1	-88.5	-9.3	7.7	1.2	16	5.4
156	410115091571801	06-09-81	--	--	--	--	1.3	9.6	--
157	411812091412601	08-05-80	--	--	--	--	<.5	7.1	--
158	411907091220001	10-29-80	-19.4	-86.5	-10.6	--	<1.6	8.2	--
160	403839091333801	08-05-80	--	--	--	--	.9	9.9	--
Aquifer layer 3, Minnesota									
36	441851093341801	09-03-80	-7.6	-54.5	-12.4	--	3.1	.4	--
37	441454092101001	02-12-80	-9.5	-62.5	-9.0	--	1.2	.3	--
43	434547094095802	01-29-80	-10.2	-70.0	--	--	1.0	3.7	--
46	435333092503901	09-02-80	-9.0	-59.0	-11.4	--	<.5	.8	--

TABLE 3—*Analyses of stable isotopes, uranium, and radium-226 in water from selected wells sampled for this study*—Continued

[Analyses by U.S. Geological Survey. Map number is location in figure 6. Site identification number is the well label in the U.S. Geological Survey WATSTORE data base]

Map no.	Site identification number	Date of collection	Stable isotope ratios (permil)				Uranium, U ($\mu g/L$)	Radium-226, Ra (pCi/L)	Carbon-14 (percent modern)
			$\delta^{18}O$	δD	$\delta^{13}C$	$\delta^{34}S$			
			Aquifer layer 3, Missouri						
161	402842092511801	04-07-81	-13.9	-104.0	-6.2	--	<.6	3.3	--
162	400217091295201	04-07-81	-14.8	-112.0	-6.1	--	<.6	31	--
163	391622091343301	04-06-81	-7.2	-49.0	-7.6	--	1.9	3.4	--
164	383543092103001	04-06-81	-7.0	-46.0	-9.0	--	.8	2.1	--
			Aquifer layer 3, Wisconsin						
18	445910092331301	08-04-80	-10.5	--	-13.4	--	<.6	<.1	--
29	444504092473601	08-14-80	-9.4	--	-6.2	--	1.5	.5	--
40	441849088051801	08-08-80	-14.0	-98.0	-12.6	--	1.4	8.9	--
74	432800091062501	11-10-81	--	--	--	--	<.6	<.1	--
104	424423090552801	08-26-80	--	--	--	--	.9	<.1	--
106	430117090173201	08-27-80	-9.0	-59.0	-10.7	--	<.5	<.1	--
107	430132090172601	08-27-80	--	--	-6.2	--	<.6	.2	--
112	425245088274701	05-29-80	-8.6	-56.5	-9.0	--	<.5	3.3	--
113	425153088195501	10-21-82	--	--	--	--	--	3.0	--
114	424407090200001	08-26-80	--	--	-6.1	--	1.0	.5	--
115	424404089204701	09-04-80	-9.2	-62.0	-13.0	--	<.6	.1	--
			Aquifer layer 4, Minnesota						
45	433615093403001	09-02-80	-9.6	-63.0	-14.4	--	1.2	.3	--
			Aquifer layer 4, Wisconsin						
111	430618087571001	11-21-80	--	--	--	--	.8	.3	--
			Aquifer layer 5, Iowa						
58	425526096210711	09-03-80	--	--	--	--	<.5	.8	--
60	431620095250511	09-03-80	--	--	--	--	1.6	.8	--
81	430512095371801	02=23-82	--	--	--	-7.5	--	--	--
82	425824095300901	02-23-82	--	--	--	-10.0	--	--	--
83	430745094541101	02-23-82	--	--	--	-7.5	--	--	--
85	424348095231601	09-04-80	-8.1	-55.5	-14.2	--	<.5	.1	--
86	424348095231602	09-04-80	-8.6	-57.5	-7.6	--	6.1	.1	--
87	423618095194511	09-04-80	--	--	--	--	1.3	.3	--
89	422950095174301	02-22-82	--	--	--	-8.0	--	--	--
90	422009095210101	02-22-82	--	--	--	-10.8	--	--	--
			Aquifer layer 5, Minnesota						
2	462710092454001	02-20-80	--	--	--	--	1.1	.1	--
26	443710093453501	09-03-80	-7.8	-55.5	-13.8	--	3.2	.2	--
41	440026094355401	09-03-80	-9.5	-67.0	-10.2	--	<.6	.2	--

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