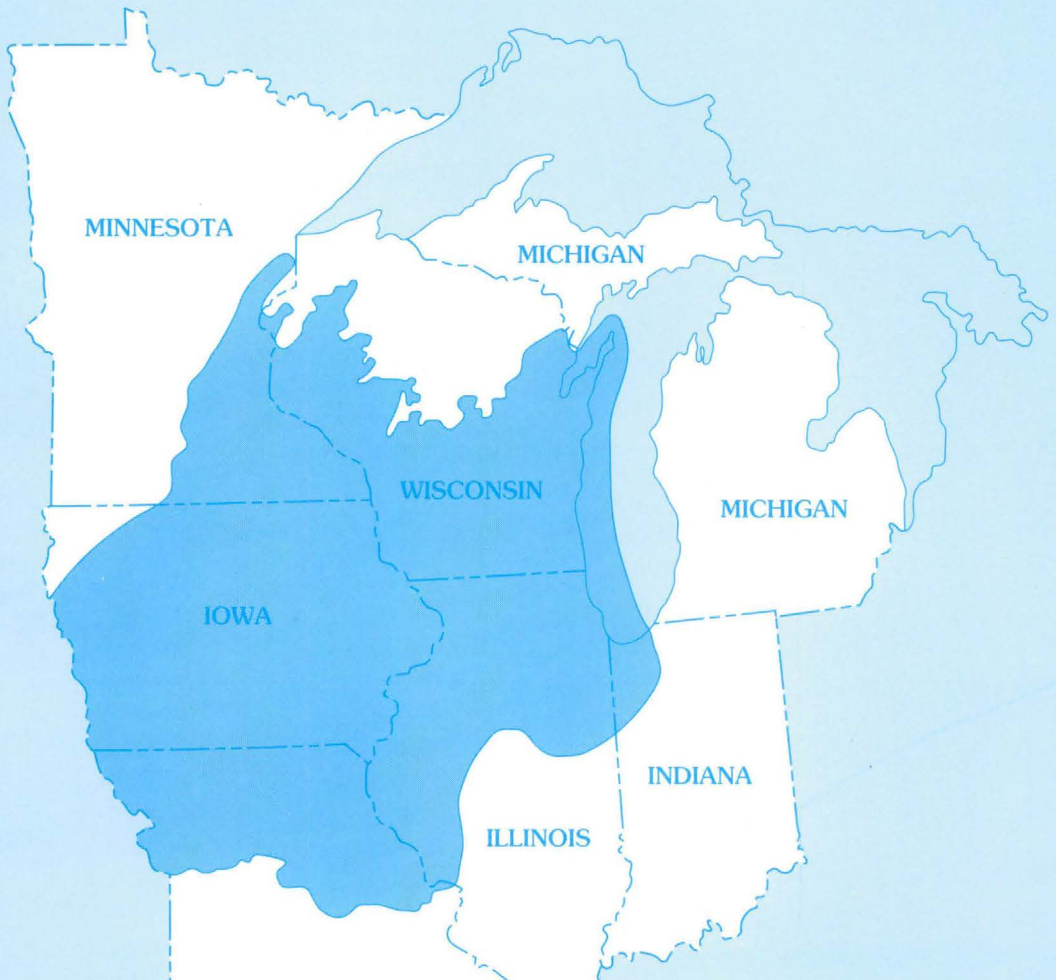
HYDROGEOLOGY OF THE CAMBRIAN-ORDOVICIAN AQUIFER SYSTEM IN THE NORTHERN MIDWEST, UNITED STATES

REGIONAL AQUIFER-SYSTEM ANALYSIS



U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1405-B

Hydrogeology of the Cambrian-Ordovician Aquifer System in the Northern Midwest, United States

By H.L. YOUNG

With a section on GROUND-WATER QUALITY

By D.I. SIEGEL

REGIONAL AQUIFER SYSTEM ANALYSIS—NORTHERN MIDWEST

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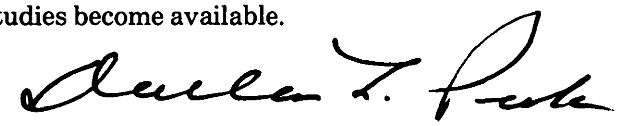
FOREWORD

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
Director

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply inch-pound unit	By	To obtain metric units
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter(m)
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.2832	cubic meter (m^3)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow	
cubic foot per second (ft^3/s)	0.2832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Hydraulic conductivity	
foot per second (ft/s)	0.3048	meter per second (m/s)
	Transimissivity	
foot squared per day (ft^2/d)	0.0920	meter squared per day (m^2/d)

For temperature, degrees Farenheit (°F) may be converted to degrees Celsius (°C) by using the formula °C=0.5556(°F–32).

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."

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

By H.L. Young

ABSTRACT

The Cambrian-Ordovician aquifer system contains the most extensive and continuous aquifers in the northern Midwest of the United States. It is the source of water for many municipalities, industries, and rural water users. Since the beginning of ground-water development from the aquifer system in the late 1800's, hydraulic heads have declined hundreds of feet in the heavily pumped Chicago-Milwaukee area and somewhat less in other metropolitan areas. The U.S. Geological Survey has completed a regional assessment of this aquifer system within a 161,000-square-mile area encompassing northern Illinois, northwestern Indiana, Iowa, southeastern Minnesota, northern Missouri, and Wisconsin.

Consolidated sedimentary rocks in the northern Midwest range in age from Precambrian to Cretaceous and crop out in generally concentric, arcuate patterns, dipping away from structural highs (arches) on the Precambrian basement in northern Minnesota and Wisconsin toward structural lows (basins) to the south and east. The sedimentary bedrock is generally overlain by a veneer of glacial drift. Thickness of the sedimentary sequence increases to about 5,000 feet in the Forest City basin of southwestern Iowa and to about 14,000 and more than 15,000 feet in the Illinois and Michigan basins, respectively.

Cambrian and Ordovician age rocks, mainly marine sandstone and carbonate rocks, compose much of the sedimentary sequence and form the Cambrian-Ordovician aquifer system. The aquifer system lies on the Precambrian basement, regarded as a regional confining unit. Six hydrogeologic units are defined; they are arranged as alternating pairs of an aquifer and an overlying confining unit. The units are named using the predominant geologic nomenclature of the upper Mississippi Valley, which includes most of the study area. In the southern quarter of the area, the hydrogeologic units consist of equivalent formations of the Ozark area (mostly carbonate rocks). The uppermost part of the aquifer system is the Maquoketa confining unit, which consists of the Maquoketa Shale and the underlying dolomite and shale of the Galena Dolomite and the Decorah, Platteville, and Glenwood Formations.

The underlying St. Peter-Prairie du Chien-Jordan aquifer is an important source of ground water in the western part of the area in Iowa and Minnesota, where the uniform Jordan Sandstone is hydraulically connected to overlying fractured dolomite of the Prairie du Chien Group. The unit is less important in the eastern part of Wisconsin and Illinois because the Jordan Sandstone is absent and the Prairie du Chien Group is thin or absent due to pre-St. Peter Sandstone erosion. Equivalent rocks in northern Missouri—the Roubidoux Formation and the Gasconade and Eminence Dolomites—are mainly carbonate rocks that are somewhat permeable and contain some sandstone.

The St. Lawrence and Franconia Formations underlying the St. Peter-Prairie du Chien-Jordan aquifer consist generally of silty and shaly, fine-grained, poorly sorted, and dolomitic sandstones that restrict vertical movement of ground water and form a regional confining unit. In the southern and eastern parts of the area, the Potosi and Derby-Doerun Dolomites and the upper part of the Davis Formation are the equivalent rocks (mainly carbonate rocks).

In the east-central part of the area in Illinois and Wisconsin, the Ironton-Galesville aquifer forms the most important aquifer of the Cambrian-Ordovician aquifer system, contributing about one-third of the yield from wells in the aquifer system in the Chicago area. The aquifer terminates to the west, south, and east, where the sandstones grade into less permeable carbonate rocks in central Iowa, central Illinois, and northwestern Indiana, respectively.

The underlying Eau Claire Formation and its partial equivalent to the southwest, the Bonneterre Formation, form an important confining unit above the Mount Simon aquifer throughout much of the study area. Siltstone and shale are fairly common in the upper part of the Eau Claire Formation but less so in its northernmost extent in Wisconsin. Dolomite content increases southward and westward, where a middle dolomite facies grades laterally into the Bonneterre in Missouri, southwestern Minnesota, extreme south-central Wisconsin, and possibly in western Iowa.

The basal unit in the Cambrian-Ordovician aquifer system, the Mount Simon aquifer, is present throughout the study area, except where it is absent over local highs of the Precambrian basement. It consists primarily of the Mount Simon Sandstone in the north and its equivalent in northern Missouri, the Lamotte Sandstone. The underlying Hinckley Sandstone of Precambrian age is included in Minnesota, as is the overlying Elmhurst Sandstone Member of the Eau Claire Formation in northern Illinois. The aquifer increases greatly in thickness and the water is progressively more saline away from the northern structural highs toward the basins.

Much of the movement and discharge of ground water in the northern Midwest occurs in local, unconfined, shallow flow systems within a few miles of points of recharge. The rest of the water is semiconfined or confined in intermediate or regional flow systems within the bedrock, where flow is deeper, slower,

and traverses much longer distances from recharge areas to discharge areas. The major areas of recharge to regional confined flow are in northwestern Iowa, southeastern Minnesota, western, southern, and eastern Wisconsin, and northern Illinois. Although the rate of flow is small, significant recharge to the Cambrian-Ordovician aquifer system also occurs as leakage through the Maquoketa confining unit, where the vertical hydraulic gradient is downward.

Ground water in much of the confined aquifer system moves laterally from recharge areas toward the major river valleys and Lake Michigan or down dip toward the structural basins. The longest flow paths extend as much as 400 miles from northwestern Iowa southeast toward the Illinois basin or to the Mississippi River and Missouri River valleys near their confluence. Other major confined flow is from eastern Wisconsin toward the Michigan basin and southward flow from northeastern Illinois toward the Illinois basin.

Regional ground-water discharge from the aquifer system is mainly diffuse upward leakage from confined aquifers along flow paths toward the structural basins. Very saline water around and brines within the basins restrict regional flow into the basins, forcing ground water to discharge upward. Water in intermediate flow systems discharges upward to the major river valleys.

Original heads of more than 100 feet above land surface were recorded in the aquifer system near Lake Michigan in eastern Wisconsin and at Dubuque, Iowa, along the Mississippi River. The Cambrian-Ordovician aquifer system was developed rapidly in the late 1800's after the first deep well was drilled in Chicago in 1864. Many flowing wells were not controlled, which caused water levels in deep wells to decline, and many no longer flowed by the early 1900's.

Heads in the aquifers have declined very little in most of the recharge or unconfined areas since ground-water withdrawal began, but major declines have occurred in confined areas. The largest declines in head are at Chicago, Illinois, Milwaukee and Green Bay, Wisconsin, and Mason City, Iowa, where the aquifer system is confined by the Maquoketa confining unit. The composite head in the aquifer system declined more than 900 feet in the deepest cones of depression in the Chicago area from 1864 to 1980 and about 375 feet in the cone at Milwaukee from 1880 to 1980. More than 200 feet of decline has occurred at Mason City. The head declined as much as 440 feet in Green Bay from 1886 to 1957, when the city discontinued use of its deep wells and began using water from Lake Michigan.

The largest centers of pumping are in the Chicago and Twin Cities (Minneapolis-St. Paul, Minnesota) metropolitan areas—about 180 million gallons per day each in 1980. Pumpage exceeded 10 million gallons per day in only a few other areas in 1980.

Ground water in the Cambrian-Ordovician aquifer system in the northern Midwest is characterized by an extreme range of mineralization, but its quality in most of the area is good. The major cations are calcium, magnesium, and sodium, and the major anions are bicarbonate, sulfate, and chloride. Sodium, sulfate, and chloride distributions are closely related to the distribution pattern of dissolved solids but not in the same proportion. Dissolved-solids concentration is generally less than 1,000 milligrams per liter in the recharge areas of Wisconsin, southern Minnesota, northeastern Iowa, and north-central Illinois where the aquifer system crops out or subcrops beneath glacial drift. Ground water there is the Ca-Mg-HCO_3 type, derived from and identical to that in the overlying glacial drift.

In northwestern Iowa and southwestern Minnesota, the water in both the glacial drift and the Cambrian-Ordovician aquifer system is a Ca-Na-SO_4-HCO_3 type, derived from oxidation of pyrite in the overlying Cretaceous Dakota Formation.

Transition to higher dissolved solids in the confined areas commonly is accompanied by increased sulfate concentration and the occurrence of Ca-Na-SO_4-type water. Salinity of the ground water increases progressively toward the basins, where dissolved solids exceed 200,000 milligrams per liter. Saline water is present in the Mount Simon aquifer near Lake Michigan in eastern Wisconsin and northeastern Illinois but occurs in successively younger rocks to the east and south as they dip toward the basins. Similarly, salinity increases down dip in Iowa to the southwest and south; however, regional ground-water flow in Iowa is from northwest to southeast.

Much of the ground water in the confined aquifer system is isotopically depleted in $\delta^{18}O$ and δD with respect to modern precipitation—an indication that the water originated as precipitation in a much colder climate than the present and probably was derived from recharge of glacial meltwater. On the basis of $\delta^{34}S$ values for sulfur in sulfate, it is believed that isostatic loading from glacial ice over the Michigan basin reversed the hydraulic gradient to trend westward, opposite from the present gradient, causing saline water in the Michigan basin to discharge westward through the present recharge areas.

Natural water-quality problems in the Cambrian-Ordovician aquifer system are mainly the high dissolved-solids concentrations and associated high concentrations of sulfate and chloride, which limit the use of the water for municipal and domestic purposes in much of the confined aquifer system in central and southern Illinois, Indiana, southern and western Iowa, and northern Missouri. Another concern is that radium activity exceeds normal background concentrations of a few picocuries per liter in much of the confined aquifer system in eastern Wisconsin, northeastern Illinois, and central Iowa. Other common problems are high hardness and locally excessive concentrations of iron and hydrogen sulfide.

INTRODUCTION

BACKGROUND

Sandstone and carbonate rocks of Cambrian and Ordovician age compose 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 (USGS) 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).

This report describes the regional hydrogeology and ground-water quality of the Cambrian-Ordovician aquifer system in the northern Midwest. Other regional reports on the aquifer system are being published as independent chapters of U.S. Geological Survey Professional Paper 1405. They are as follows: chapter A, which is a summary of the Northern Midwest RASA (Young, in press); chapter C, which describes regional simulation of the aquifer system

(Mandle and Kontis, in press); chapter D, which describes the hydrologic and geochemical mechanisms that cause regional differences in ground-water quality (Siegel, 1989); and chapter E, which describes flow simulation in the Chicago-Milwaukee area (H.L. Young and A.J. MacKenzie, U.S. Geological Survey, written commun., 1988).

Several reports describing the geology or hydrogeology of States within the study area are also products of this project:

Illinois—Fassnacht (1982), Visocky and others (1985), and Nicholas and others (1987);

Minnesota—Mossler (1983a, b), Woodward (1983, 1986), and Delin and Woodward (1984); and

Missouri—Imes (1985).

The Cambrian-Ordovician aquifer system supplies a major part of the water needs in the northern Midwest. Many metropolitan areas depend on the aquifer system for all or part of their water supplies. Hydraulic heads in the system have declined hundreds of feet since the late 1800's in the heavily pumped Chicago-Milwaukee area and to a somewhat lesser extent in other major metropolitan areas, such as Minneapolis-St. Paul, Minnesota; Green Bay, Wisconsin; and Des Moines, Mason City, and Cedar Rapids, Iowa. Projections of future water needs indicate continuing or increasing demands and, therefore, continuing head declines.

The aquifer system contains highly mineralized water in several places, especially in its deepest parts, that generally coincide with regional discharge or structurally low areas (basins); this water is mainly in the southwestern, southern, and eastern parts of the study area. Water from the highly mineralized zones may be induced into freshwater zones by large withdrawals of freshwater, such as occurs in northeastern Illinois, eastern Wisconsin, and central Iowa.

PURPOSE AND SCOPE

This report describes the hydrogeology of the Cambrian-Ordovician aquifer system in the northern Midwest, including the ground-water flow system and the effects of ground-water withdrawal on the system. The chemical quality of ground water in the aquifer system also is described to show the water's suitability for use and the relation of major quality characteristics to present and past patterns of regional flow. Chapter D of this professional paper (Siegel, 1989) presents a more detailed geochemical study of the water in the aquifer system.

STUDY AREA

The study area includes about 161,000 mi^2 (square miles) in northern Illinois, northwestern Indiana, Iowa, southeastern Minnesota, northern Missouri, and Wisconsin (fig. 1). The border of the study area delimits either the natural geologic 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 eroded 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. The study area is not extended from Wisconsin into the Upper Peninsula of Michigan because the Menominee River (the Michigan-Wisconsin State line) probably is a local line of ground-water discharge and the aquifer system also is not extensive there.

Cambrian and Ordovician rocks form the dominant aquifer system in the study area. They are bounded below by Precambrian basement rocks, which have very low permeability, and above generally by the Maquoketa Shale of Ordovician age. Other rocks are minor aquifers regionally but are very important in particular areas. The major secondary aquifers consist of Silurian and Devonian carbonate rocks and Quaternary sand and gravel. The former are included in this study because some wells open to the Cambrian-Ordovician aquifer system are open also to the Silurian-Devonian aquifer.

METHOD OF INVESTIGATION

The major effort in this study was the formulation of several computer flow models of the Cambrian-Ordovician aquifer system. These models simulate all or parts of the regional flow system and can be used to estimate water-level changes from projected future pumping. A nine-layer, three-dimensional flow model with a uniform node spacing of 16 mi (miles) was developed for the entire study area and is described in Professional Paper 1405–C (Mandle and Kontis, in press). In addition, a more detailed, three-dimensional flow model of the Chicago-Milwaukee area is described in Professional Paper 1405–E (H.L. Young and A.J. MacKenzie, U.S. Geological Survey, written commun., 1988).

Local models of the Cambrian-Ordovician aquifer system were constructed during the project by U.S. Geological Survey district personnel: (1) a two-dimensional model of northeastern Missouri (Imes, 1985), (2) a three-dimensional model of northeastern Wisconsin (Emmons, 1987), and (3) a two-dimensional model of the Jordan aquifer in Iowa (M.R. Burkart and R.C. Buchmiller, U.S. Geological Survey, written commun., 1988). In addition, two flow-model studies conducted under the Geological Survey's cooperative program benefited from joint data-collection efforts. The studies are of the Minneapolis-St. Paul area (Guswa and others, 1982) and of Brown County, Wisconsin (Krohelski, 1986).

The major hydrogeologic data needed for these models are:

1. Structure contour maps of the top and maps of the thickness of each aquifer and confining layer;
2. Water-level and pumpage data for each aquifer;
3. A series of potentiometric surface maps for each aquifer representing predevelopment and recent head conditions;

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

4. Hydraulic conductivity and storage coefficient of each aquifer and vertical hydraulic conductivity of each confining unit; and
5. Dissolved-solids concentration of the ground water in each aquifer.

This information has been generated from existing files, publications, and newly gathered and interpreted data from several State agencies and the USGS district office in each of the six States. Regional geologic and hydrologic maps for the study area were prepared by the central RASA staff in Madison, Wisconsin, using the individual State maps and data. A computerized data-base system was developed (Kontis and Mandle, 1980) to efficiently store, edit, and access the data to provide input to the model.

Contour maps of the altitude of rock-unit tops in this report were prepared from computer files of digitized point data using the MInimum curvature SPline (MISP) interpolation technique (Kontis and Mandle, 1980). A major advantage of MISP is that it reflects the short-wavelength characteristics of input data but produces a smooth surface based on regional characteristics in areas with sparse data. Each map represents the maximum areal extent of a unit or combination of units and includes the areas of erosional outcrop or subcrop of the units. No attempt is made to delineate eroded areas.

Although fairly complete geologic data are available for each rock formation, very little information exists on vertical variation in hydraulic properties, head distribution, or water-quality characteristics for individual units within the aquifer system, except in areas where the formations crop out. This lack of specific information is because (1) wells generally are drilled only as deep as needed to obtain a desired well yield, and (2) deep wells commonly are cased only as deep as is necessary to provide sound construction, thus leaving the well open to several formations.

To obtain data on individual formations at various points in the regional flow system, deep test wells were drilled at seven sites (see fig. 21). Data on hydraulic conductivity, hydraulic heads, and water quality were obtained for individual aquifers in these and several other existing wells using inflatable hydraulic packers, pressure transducers, and submersible pumps. Nests of three or four piezometers were installed by isolating specific zones with grout plugs in five of the test wells, and two piezometers were drilled near each of the wells in Minnesota. These piezometers are now part of the U.S. Geological Survey's ground-water and water-quality monitoring programs. The deepest well, 3,475 ft (feet) deep near Zion, Illinois, is described by Nicholas and others (1987).

PREVIOUS INVESTIGATIONS

The hydrogeology and water quality of the rocks composing the Cambrian-Ordovician aquifer system have been described in many reports, primarily as a result of the U.S. Geological Survey's Cooperative Program with the States of Iowa, Minnesota, Missouri, and Wisconsin, and by the State Geological Survey and State Water Survey in Illinois. Most of these reports pertain to the aquifer system or parts of the system within a particular State and, commonly, in very local areas. These reports could provide the basis for a regional description of the aquifer system; however, this has not been done. These reports are too numerous to reference in this report, but a few of the major reports are listed here:

Illinois—Anderson (1919), Suter and others (1959), Walton and Csallany (1962), and Schicht and others (1976);

Iowa—Norton and others (1912), Norton (1928), and Horick and Steinhilber (1978);

Minnesota—Hall and others (1911), Thiel (1944), and Norvitch and others (1973); and

Wisconsin—Weidman and Schultz (1915) and Foley and others (1953).

Most of the study area is described in comprehensive framework studies of the upper Mississippi River basin (U.S. Corps of Engineers, 1970) and the Great Lakes basin (Great Lakes Basin Commission, 1976). These studies present background information on the basins' water and land-related resources in a management and development context. The same boundaries are used for summary appraisals of the basins' ground-water resources (Bloyd, 1975; Weist, 1978).

ACKNOWLEDGMENTS

As previously stated, much of the information used in this study was obtained from State agencies and from the U.S. Geological Survey district office in each State. I appreciate the personal contributions made by Heidi Minc, Robert Ringler, and Michael Sargent (Illinois State Geological Survey); Robert Sasman (Illinois State Water Survey); John Mossler (Minnesota Geological Survey); and Roger Peters (Wisconsin Geological and Natural History Survey).

PHYSICAL SETTING

The study area is almost entirely within the Central Lowland physiographic province, except for parts in northern Minnesota and Wisconsin that are in the Superior Upland province (Fenneman, 1946). Surface topography is mainly smooth to irregular plains with gently rolling hills and some dissected uplands. The latter are most prominent in the Driftless Area (fig. 3) of southwestern Wisconsin, northeastern Iowa, and extreme northwestern Illinois, where narrow valley bottoms and ridgetops are connected by steep valley walls. Altitude of the land surface ranges from about 400 ft above sea level near the confluence of the Missouri and Mississippi Rivers to about 1,600 ft in northwestern Iowa.

Surface drainage (fig. 1) is mainly to the Mississippi River, either directly or by way of its major tributaries, including the Missouri River. A small part of the area is in the Lake Michigan drainage basin.

The continental climate of the northern Midwest ranges from cold winters and relatively cool summers in the north to mild winters and hot summers in the south. Average annual precipitation increases from 24 to 44 in. (inches) from northwest to southeast (fig. 2). However, the range in the study area is mainly 30 to 36 in., averaging about 32 in. The precipitation is fairly well distributed seasonally, although the winter months are generally the driest. Although evapotranspiration consumes a large part of the water from precipitation, a significant surplus runs off to streams or recharges ground water. Average annual runoff in west-central Minnesota is only 1 to 2 in. but increases steadily to 15 in. eastward to northern Wisconsin and southeastward to southern Illinois.

GEOLOGIC FRAMEWORK

GEOLOGIC SETTING

The land surface of the northern Midwest generally is the result of continental glaciation during the Pleistocene Epoch. One or more of the major ice advances covered most of the area (fig. 3), leaving an almost continuous veneer of unconsolidated sediment on the bedrock surface. A diverse group of depositional and erosional landforms was created. This glacial drift is absent or very thin on some uplands, particularly in the Driftless Area, but may be several hundred feet in thickness in buried valleys on the bedrock surface and in some terminal moraines.

Bedrock in the area consists of crystalline basement rocks of Precambrian age that underlie the entire area and marine sedimentary rocks that overlie the basement in most of the area. The rocks range in age from Precambrian to Cretaceous (fig. 4). Sandstone, dolomite, limestone, and shale were deposited mainly in a marine environment on the broad stable shelf that covered most or all of the area, lapping onto the Wisconsin and Transcontinental arches (higher areas of Precambrian basement to the north). The rocks crop out from oldest to youngest in generally concentric belts away from the arches (pl. 1) because they dip gently away from the arches at a gradient slightly steeper than the general land surface (pl. 1). Similarly, these rocks are at the surface near the Missouri River in northern Missouri, dipping northward away from the Precambrian high of the Ozark uplift in southeastern Missouri. The thickest sequences of sedimentary strata occur in three major areas of subsidence: about 14,000 ft in the Illinois basin (Willman and others, 1975), more than 15,000 ft in the Michigan basin (Hinze and others, 1975), and about 5,000 ft in the Forest City basin of southwestern Iowa. The Illinois and Michigan basins are separated by the Kankakee arch.

The following description of the geologic stratigraphy and structure of the northern Midwest specifically describes the Cambrian-Ordovician aquifer system and associated rocks in more detail than most of the other rocks. Although the varied distribution and lithology of rock units in the study area have produced differences in geologic nomenclature from State to State, a fairly consistent set of nomenclature can be derived from the most commonly used rock names. The rock-stratigraphic nomenclature in this report, therefore, does not necessarily follow that approved by the U.S. Geological Survey or a particular State Survey. All are not cited, but the published works of each State Geological Survey are the major basis for the following description of the geologic framework. The most comprehensive for each State are:

Illinois—Buschbach (1964), Willman (1971), and Willman and others (1975);

Indiana—Droste and Patton (1985) and Shaver and others (1986);

Minnesota—Austin (1969), Sims and Morey (1972), and Mossler (1987);

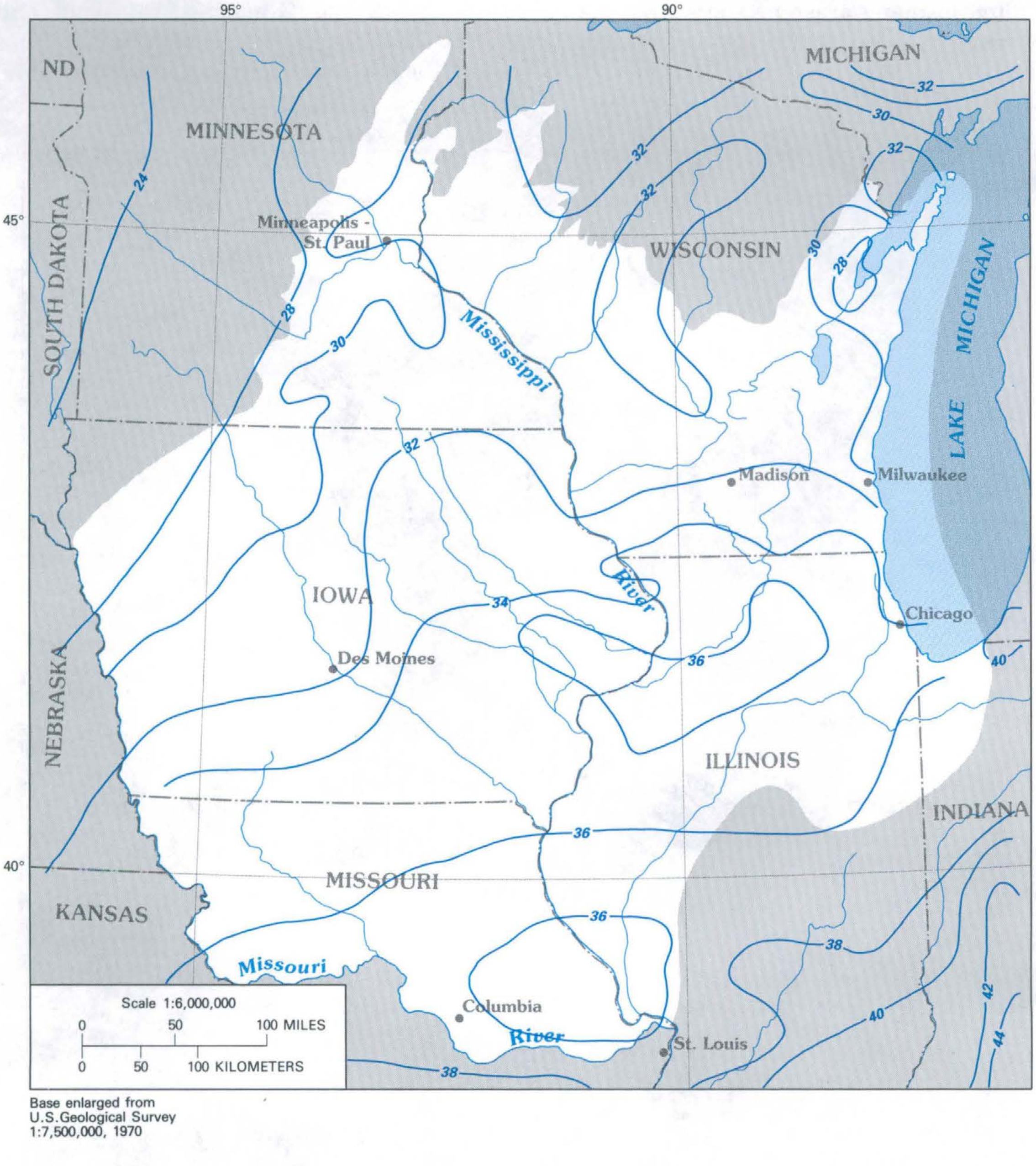
Missouri—Howe and others (1961, 1972); and

Wisconsin—Ostrom (1964, 1978).

Figures 5 and 8–17 show structure contours of formation tops. These maps are mainly computer generated from the regional data base, as described in the section "Method of Investigation," during the process of preparing input arrays for the regional ground-water flow model.

PRECAMBRIAN ROCKS

The basement beneath the northern Midwest is composed primarily of Precambrian crystalline igneous and metamorphic rocks. They are generally from 1,100 to 3,500 million years in age (Denison and others, 1984) and form the North American Craton—the more permanent nucleus of the continent. The craton is exposed as a broad, smooth, low-relief surface called the Canadian Shield, which extends southward into northern Minnesota and Wisconsin where it generally is covered with glacial drift. The surface



EXPLANATION

36 LINE OF EQUAL AVERAGE ANNUAL PRECIPITATION — Interval, in inches, is variable

FIGURE 2.—Average annual precipitation, 1951–80. Modified from Wendland and others (1985).

slopes to the south and east into the Forest City, Illinois, and Michigan basins, where it is buried progressively deeper by Paleozoic rocks (fig. 5). The Precambrian basement is higher in the vicinity of the Ozark uplift in southeastern Missouri (just south of the area shown in fig. 5), where igneous rocks crop out over a large area in the St. Francois Mountains. Accuracy of the depiction of the surface where deeply buried is limited in many areas by the sparse number of deep wells that penetrate to the basement. Seismic-refraction investigations provide some additional data. Isolated exposures of Precambrian rocks occur in southern Wisconsin, southwestern Minnesota, and northwestern Iowa. These are primarily quartzite bodies, resistant to weathering, that formed islands in the early Paleozoic seas.

About 1,100 million years ago, a large continental rift-fault zone, termed the Midcontinent Rift System, developed from northeastern Kansas to Lake Superior (Chase and Gilmer, 1973; Wold and Hinze, 1982). Thousands of feet of basalt were extruded along the rift in the Precambrian basement, typically

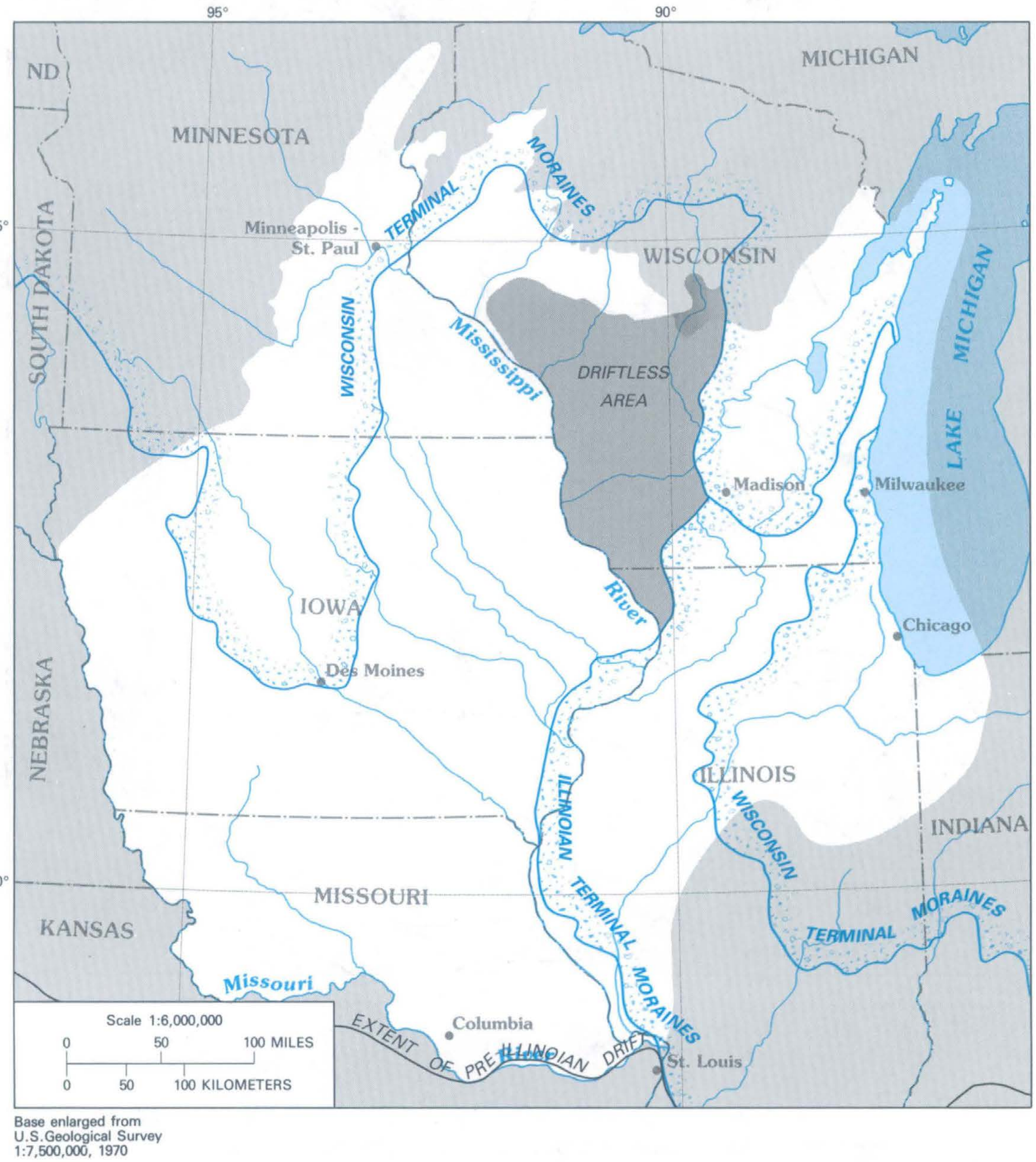


FIGURE 3.—Extent of major glaciations during the Pleistocene Epoch. Modified from Willman and Frye (1970), Hadley and Pelham (1976), and Siegel (1989).

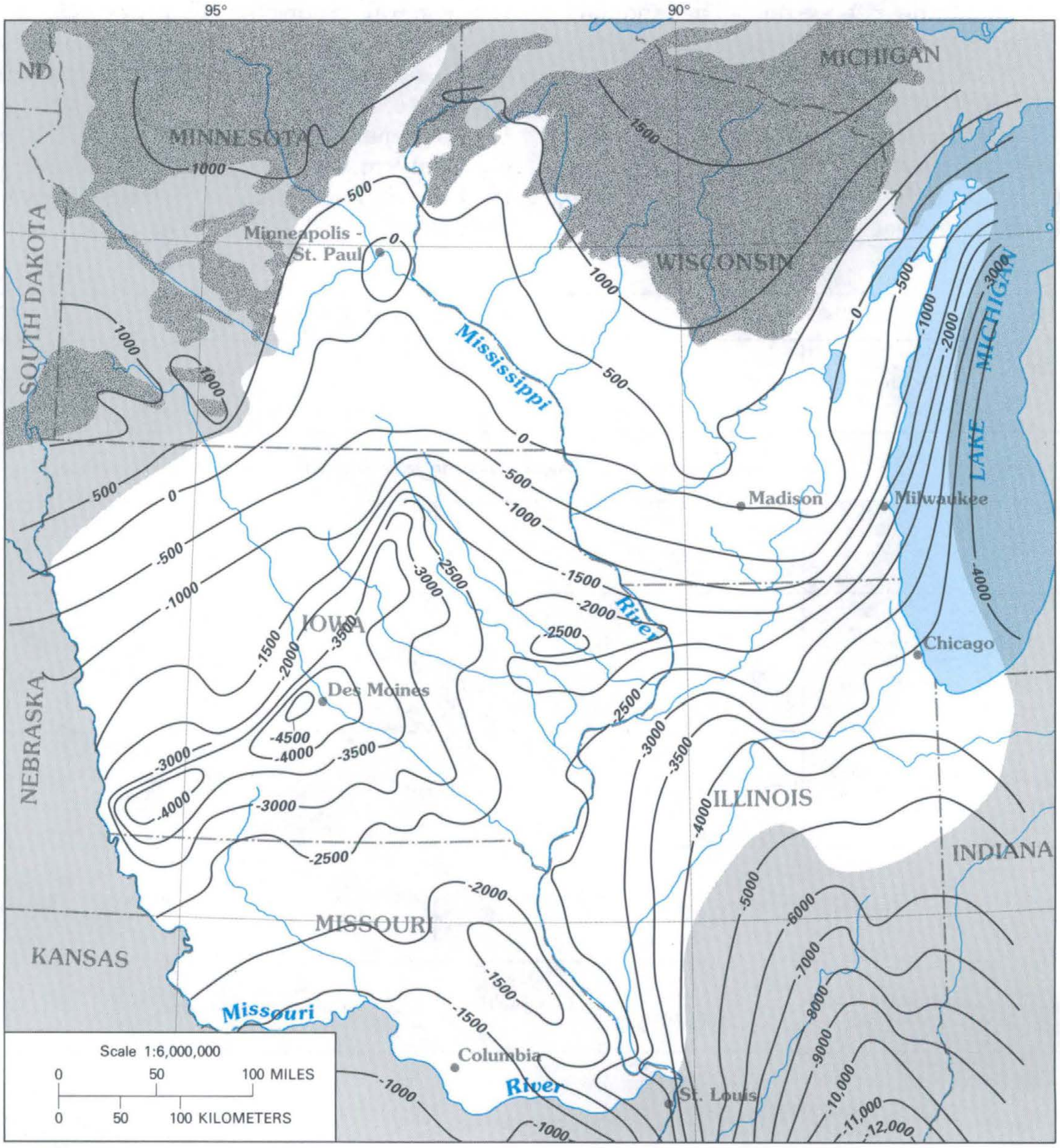
uplifted in a central horst that is flanked by thousands of feet of younger Precambrian sedimentary rocks. The uplifted basalts and associated intrusive gabbros produce the most prominent positive gravity anomaly in the United States, which was the basis for identification of the rift system. The anomaly, termed the Midcontinent Gravity High, is generally a few tens of miles in width and merges northeastward with the axis of the Lake Superior syncline (just north of northwestern Wisconsin off plate 1). The Precambrian closed in the northern Midwest with more than 500 million years of crustal upwarp, volcanism, erosion, and sedimentation.

Precambrian sedimentary rocks extend northeastward in a narrow belt along the rift zone to the southern shore of Lake Superior and to the Keweenaw Peninsula of northern Michigan (Sims, 1985). The rocks in the Lake Superior region were divided into two general groups by Thwaites (1912). The older Oronto Group consists of many thousands of feet of poorly sorted, reddish-brown, arkosic sandstone, conglomerate, siltstone, and shale. The younger Bayfield Group is mainly sandstone that is much less arkosic, especially in the upper part. In eastern Minnesota, the Fond du Lac Formation and the overlying Hinckley Sandstone are believed to be equivalent to the Bayfield

<table>
<tr><th rowspan="2">Erathem</th><th rowspan="2">System</th><th colspan="6">Major rock types</th></tr>
<tr><th>Northern Missouri</th><th>Iowa</th><th>Southern Minnesota</th><th>Wisconsin</th><th>Northern Illinois</th><th>Northwestern Indiana</th></tr>
<tr><td>Cenozoic</td><td>Quaternary</td><td colspan="6">Unconsolidated deposits of clay, silt, sand, gravel, and boulders; degree of sorting variable</td></tr>
<tr><td>Mesozoic</td><td>Cretaceous</td><td>Absent</td><td colspan="2">Sandstone, shale, and limestone</td><td colspan="2">Isolated deposits of clayey sand or gravel</td><td>Absent</td></tr>
<tr><td rowspan="6">Paleozoic</td><td>Pennsylvanian</td><td>Shale, sandstone, siltstone, limestone, coal, and clay</td><td>Shale, sandstone, and limestone</td><td colspan="2">Absent</td><td>Shale, sandstone, siltstone, limestone, coal, and clay</td><td>Absent</td></tr>
<tr><td>Mississippian</td><td>Limestone, sandstone, siltstone, and shale</td><td>Limestone and shale</td><td colspan="2">Absent</td><td>Limestone, sandstone, siltstone, and shale</td><td>Shale</td></tr>
<tr><td>Devonian</td><td colspan="2">Limestone and shale</td><td>Dolomite and limestone</td><td>Dolomite, shale, and limestone</td><td>Limestone, shale, and dolomite</td><td>Shale and dolomite</td></tr>
<tr><td>Silurian</td><td>Limestone and dolomite</td><td>Dolomite</td><td>Absent</td><td colspan="2">Dolomite and limestone</td><td>Dolomite</td></tr>
<tr><td>Ordovician</td><td>Dolomite, sandstone, and shale</td><td colspan="3">Dolomite, shale, sandstone, and limestone</td><td>Dolomite, limestone, and shale</td><td>Dolomite, limestone, sandstone, and shale</td></tr>
<tr><td>Cambrian</td><td>Dolomite, sandstone, and shale</td><td colspan="3">Sandstone, shale, and dolomite</td><td colspan="2">Sandstone, dolomite, and shale</td></tr>
<tr><td colspan="2" rowspan="2">Precambrian</td><td></td><td colspan="3">Sandstone and siltstone on crystalline rocks</td><td colspan="2"></td></tr>
<tr><td colspan="6">Igneous and metamorphic crystalline rocks</td></tr>
</table>

FIGURE 4.—General lithology of rock units in the northern Midwest.

Group (Morey, 1977). The Hinckley is a fine- to coarse-grained, well-sorted, quartzose sandstone that is as much as 500 ft thick. It is an aquifer, either alone or in combination with the Mount Simon Sandstone (the lowermost Cambrian unit in the study area) and thus is included in this regional study. Morey (1977) defined



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

EXPLANATION

—500— STRUCTURE CONTOUR — Shows altitude of the top of Precambrian rocks. Contour interval, in feet, is variable. Datum is sea level

AREA OF OUTCROP OR SUBCROP OF PRECAMBRIAN ROCKS BENEATH GLACIAL DRIFT

FIGURE 5.—Altitude of the Precambrian basement surface.

a new unit, the Solor Church Formation, comprised of a great thickness of arkosic sandstone, siltstone, and shale beneath the Fond du Lac in southeastern Minnesota. The Solor Church is equivalent to the Oronto Group.

PALEOZOIC ROCKS

The large thickness of sedimentary rock that overlies the Precambrian surface in the northern Midwest was deposited during the Paleozoic Era, which began about 570 million years ago. All time periods of the era are represented in the rocks of the northern Midwest (pl. 1). The era began and ended with uplift and long periods of erosion or nondeposition. These major unconformities account for the absence of rocks that would represent the Early and Middle Cambrian Epochs and large intervals of later time periods.

The Paleozoic rocks are the result primarily of repeated transgression and regression of shallow marine seas, mainly from the south, that lapped onto the uplifted Precambrian paleosurface in the continental interior. Thousands of feet of sediment were deposited from adjacent land areas, primarily from uplifted areas of the craton to the north. The Ozark uplift in southeastern Missouri (pl. 1) was another source area for Paleozoic sediment. Paleozoic seas undoubtedly covered a much more extensive area in Minnesota and Wisconsin than is apparent from the present distribution of Paleozoic rocks. This is indicated by the thickness and topographic elevation of several units near their eroded edges. The major basins and bordering arches began forming early in Paleozoic time. Moderate vertical movement of the basement created varying depositional and erosional environments during the era, resulting in many minor and several major unconformities. Although the majority of the Paleozoic rocks are marine in origin, some are a result of continental deposition processes.

The concept of a rock sequence, as applied to the stratigraphy of central North America, was introduced by Sloss and others (1949) and later reviewed and modified by Sloss (1963). This new rock-stratigraphic term was applied to very large sections of the geologic column that were deposited during major cycles of transgression-regression and were bounded by major, interregional unconformities. In the present study area, the first sequence, the Sauk, includes the late Precambrian sedimentary rocks, all Cambrian rocks, and much of the Ordovician rocks. The boundary between the Sauk and the overlying Tippecanoe sequences is a major unconformity at the base of the Middle Ordovician St. Peter Sandstone. A third sequence, the Kaskaskia, includes rocks of Early Devonian through Late Mississippian age.

Upper Cambrian rocks in the upper Misssissippi Valley are mainly sandstone but grade into carbonate rocks to the south. Carbonate rocks are also more abundant throughout the northern Midwest in the Ordovician, Silurian, Devonian, and Lower Mississippian rocks. Upper Mississippian and Pennsylvanian rocks are mainly shale and sandstone. Sandstones in the Cambrian and Ordovician Systems are generally orthoquartzites with relatively well-sorted and well-rounded grains, but basal rocks deposited on the Precambrian surface commonly are arkosic or conglomeratic. The original source of the sand is the crystalline rocks of the Precambrian basement; however, the grains are abraded and frosted, indicating a history of extensive transportation. These sand grains in their final form are derived mainly from the weathering and reworking of the upper Precambrian sandstones and have probably gone through a number of erosion and transportation cycles (Potter and Pryor, 1961).

CYCLIC DEPOSITION

A prominent feature of the lower Paleozoic rocks is a series of cyclic depositional patterns of shorter frequency than the sequences of Sloss (1963). This feature had been recognized by early investigators, but it was not studied in any detail until the investigations of Berg and others (1956). Ostrom (1964, 1965, 1970) expanded the concept to include five full cycles of marine transgression and regression from the beginning of the Late Cambrian through the end of the Middle Ordovician (fig. 6). Each cycle of deposition consists of four environments or lithotopes: (1) quartz sandstone in the littoral zone, (2) quartz sandstone interbedded with layers of poorly sorted sediment or sandy carbonates in the nondepositional shelf zone, (3) fine-grained clastics in the depositional shelf zone, and (4) reef carbonates in the biogenic zone (Ostrom, 1970; 1978). Recent investigations (Driese and others, 1981; Dott and others, 1986) have identified some continental deposits in sandstones of the littoral lithotope.

At a given time, deposition occurred in belts parallel to the shoreline, but over the course of a cycle of transgression and regression, each environment migrated over the shelf surface, producing a stack of thin, sheetlike formations commonly traceable over long distances. Potter and Pryor (1961) believe that the consistent directional pattern of sediment transport and slope of the post-Precambrian depositional surface indicates major tectonic control of the area by the movements of the North American Craton—a factor in the development and building of the continent.

Sequence	Cycle	Rock type	Depositional zone	Geologic unit		
Tippecanoe	5	Carbonate	Biogenic	Sinnipee Group		
		Shaly sandstone and/or shale	Depositional shelf	Glenwood Formation	Hennepin Member	
					Harmony Hill Member	
		Reworked quartz sandstone	Nondepositional shelf		Nokomis Member	
		Quartz sandstone	Shallow marine littoral	St. Peter Sandstone		
Sauk	4	Carbonate	Biogenic	Prairie du Chien Group	Shakopee Formation	Willow River Member
		Shaly sandstone and/or shale	Depositional shelf			New Richmond Sandstone Member
		Reworked quartz sandstone	Nondepositional shelf			
		Quartz sandstone	Shallow marine littoral			
	3	Carbonate	Biogenic		Oneota Dolomite	
		Shaly sandstone and/or shale	Depositional shelf	Jordan Sandstone	Coon Valley Member	
		Reworked quartz sandstone	Nondepositional shelf			
		Quartz sandstone	Shallow marine littoral		Van Oser Member	
					Norwalk Member	
	2	Carbonate	Biogenic	St. Lawrence Formation	Lodi Member	Black Earth Member
		Shaly sandstone and/or shale	Depositional shelf	Tunnel City Group	Mazomanie Formation	Lone Rock Formation
		Reworked quartz sandstone	Nondepositional shelf	Wonewoc Sandstone	Ironton Sandstone Member	
		Quartz sandstone	Shallow marine littoral		Galesville Sandstone Member	
	1	Carbonate	Biogenic	Bonneterre Formation		
		Shaly sandstone and/or shale	Depositional shelf	Eau Claire Formation		
		Reworked quartz sandstone	Nondepositional shelf	Mount Simon Sandstone		
		Quartz sandstone	Shallow marine littoral			

FIGURE 6.—Cycles of depositional environment in the lower Paleozoic of the northern Midwest. From Ostrom (1978).

CAMBRIAN SYSTEM

Rocks of the Cambrian System in the study area are all of Late Cambrian age. Walcott (1912) proposed the term St. Croixan Series (for the St. Croix River, which forms the Minnesota-Wisconsin border north of its confluence with the Mississippi River) for rocks with Upper Cambrian fauna. The entire series crops out within the St. Croix River valley, which is the type locality for Upper Cambrian rocks in North America. The rock-stratigraphic nomenclature of the upper Mississippi Valley is the primary one used in this report (fig. 7) because the distinctive lithologies there persist widely across and beyond the study area. Many facies changes are present, however, as a result of the various depositional environments. Faunal zones (especially trilobites) are also persistent and provide the necessary correlation across facies changes and distance between outcrops or drillholes. The Upper Cambrian contains two complete cycles of sedimentation, plus most of a third (see fig. 6). In most of Missouri, southern Illinois, and Indiana, carbonate facies are most abundant.

MOUNT SIMON AND LAMOTTE SANDSTONES

The basal Cambrian strata are composed of sandstone in most of the study area. These strata lie on and commonly contain fragments of the Precambrian crystalline basement rock. Sediment, deposited in shallow seas on this paleosurface, dips gently and thickens toward the structural basins. These rocks crop out in large areas of northern Wisconsin and eastern Minnesota, where their erosional edge lies on the Precambrian basement. Some local topographic highs on the Precambrian surface were islands during this deposition, resulting in the absence or very local thinning of the deposits, particularly near quartzite ridges and knobs in south-central and southeastern Wisconsin and southwestern Minnesota and near resistant lava flows in east-central Minnesota. Most of this basal deposit is called the Mount Simon Sandstone; however, it grades into the Lamotte Sandstone in northern Missouri (see plate 1). The base of the Mount Simon and Lamotte is not everywhere clearly the base of the Upper Cambrian rocks. Lack of fossils and exposures of the basal contact, as well as the similarity of these formations to the Hinckley Sandstone of known Precambrian age, make it difficult to be certain of the age of parts of the basal sandstones. According to Howe and others (1972), some of the Lamotte probably is older than Upper Cambrian. Likewise, some basal rocks in southern Illinois and Indiana may be Precambrian sedimentary rocks preserved in grabens related to the Reelfoot Rift zone (Droste and Patton, 1985).

The Mount Simon Sandstone generally is a medium- to coarse-grained, poorly to moderately sorted, sometimes pebbly, white to gray, quartzose sandstone. Sand grains range in size from fine to very coarse and in degree of roundness from angular to rounded. The formation tends to be arkosic, coarse grained, and locally conglomeratic with igneous pebbles near its base. Lenticular beds of gray, green, and red shale commonly occur in the upper part of the formation throughout the study area and also in the lower part of the formation in Illinois. Hematitic staining of sand grains at the upper contact in several wells in northern Iowa has been reported (R.M. McKay, Iowa Geological Survey, oral commun., 1984). Cross bedding is common, especially in the upper part, indicating a high-energy depositional environment. Conversely, the thin interbedded shale beds represent intermittent periods of lower energy deposition (Austin, 1972). The bulk of the Mount Simon comprises the first quartz sandstone lithotope of Ostrom (1978), but the upper 20 to 40 ft in Wisconsin are medium and fine grained with shale partings, are burrowed, and contain phosphatic brachiopods (M.E. Ostrom, Wisconsin Geological and Natural History Survey, written commun., 1987); these strata compose the reworked quartz sandstone lithotope (fig. 6).

The Mount Simon Sandstone thickens progressively southward from its erosional boundary in the north to maximums of about 2,600 ft in northeastern Illinois and more than 2,000 ft in central and north-central Iowa. The thickest area in Illinois does not coincide with the center of the Illinois basin, but rather is on the extreme northern edge of the basin. The Precambrian surface in the Illinois basin was much higher prior to deposition of the Mount Simon, so the thickest Mount Simon deposits probably result from deposition on a low part of the pre-Mount Simon topographic surface and indicate the major locus of downwarp during deposition of the Mount Simon. Only the younger Ironton and Galesville Sandstones exhibit a similar depositional pattern. The maximum thicknesses of other Cambrian and Ordovician formations generally coincide with the center of the Illinois basin. Similarly, in the Michigan basin, the Mount Simon is thickest (more than 1,000 ft) on the western edge of the basin (Catacosinos, 1973). The large thicknesses in Iowa are in deep depressions in the Precambrian surface along the Midcontinent Rift System.

The configuration of the top of the Mount Simon Sandstone generally resembles that of the Precambrian basement, dipping steeply into the Illinois and

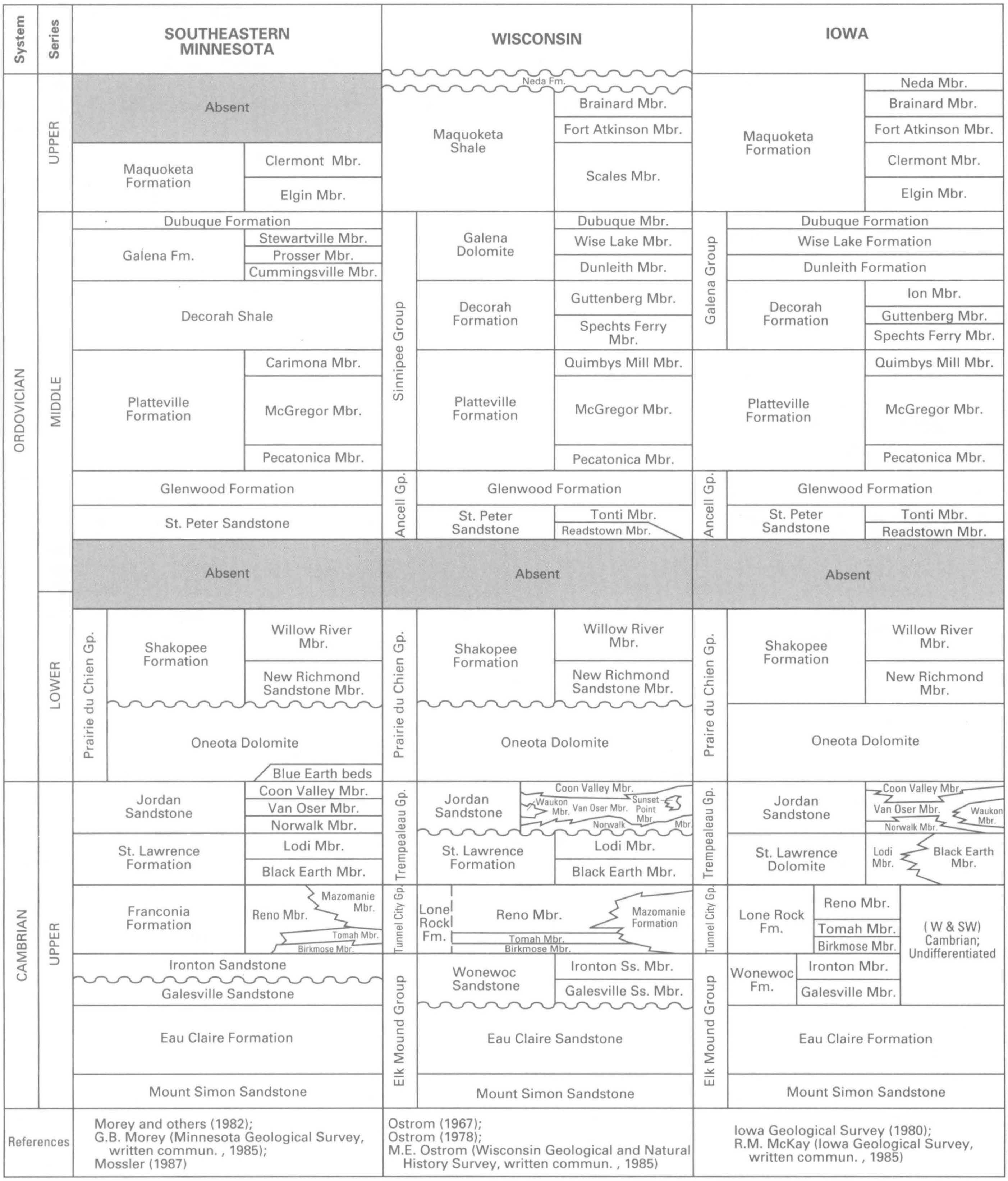


FIGURE 7.—Generalized correlation chart of Cambrian and Ordovician rock units in the northern Midwest. Dol., Dolomite; Fm., Formation; Gp., Group; Ls., Limestone; Mbr., Member; Sh., Shale; Slts., Siltstone; Ss., Sandstone.

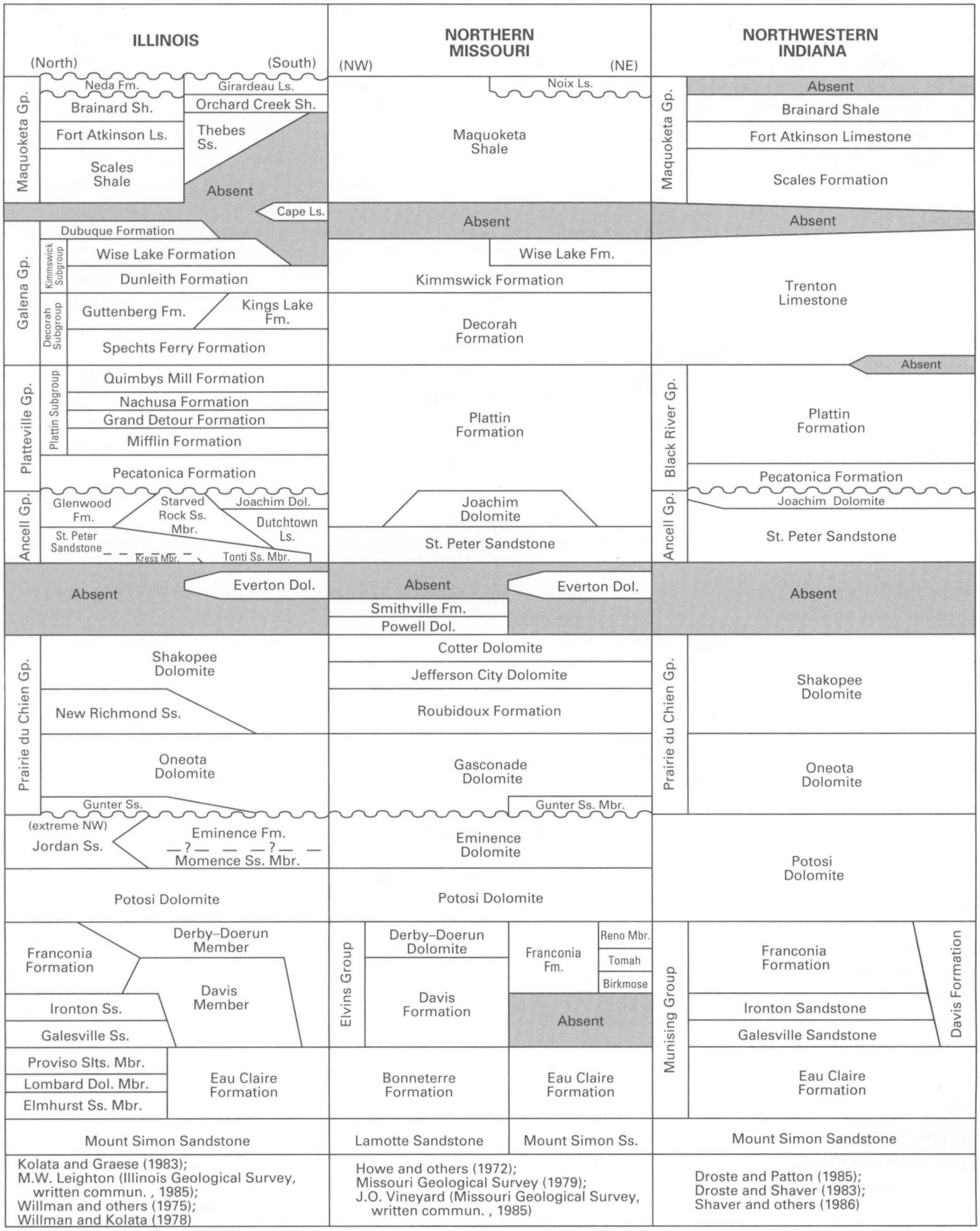


FIGURE 7.—Continued.

Michigan basins but less steeply into the Forest City basin (fig. 8). The top is about 2,000 to 2,500 ft below sea level in the Forest City basin and about 2,500 ft below sea level along the northern perimeter of the Illinois basin in north-central Illinois. The base is about 4,500 ft below sea level in both these areas. Maximum depths to the top are more than 12,000 ft below sea level in both the Illinois and Michigan basins. The upper contact with the overlying Eau Claire or Bonneterre Formations seems to be essentially conformable, even though a sharp lithologic change is usual.

EAU CLAIRE AND BONNETERRE FORMATIONS

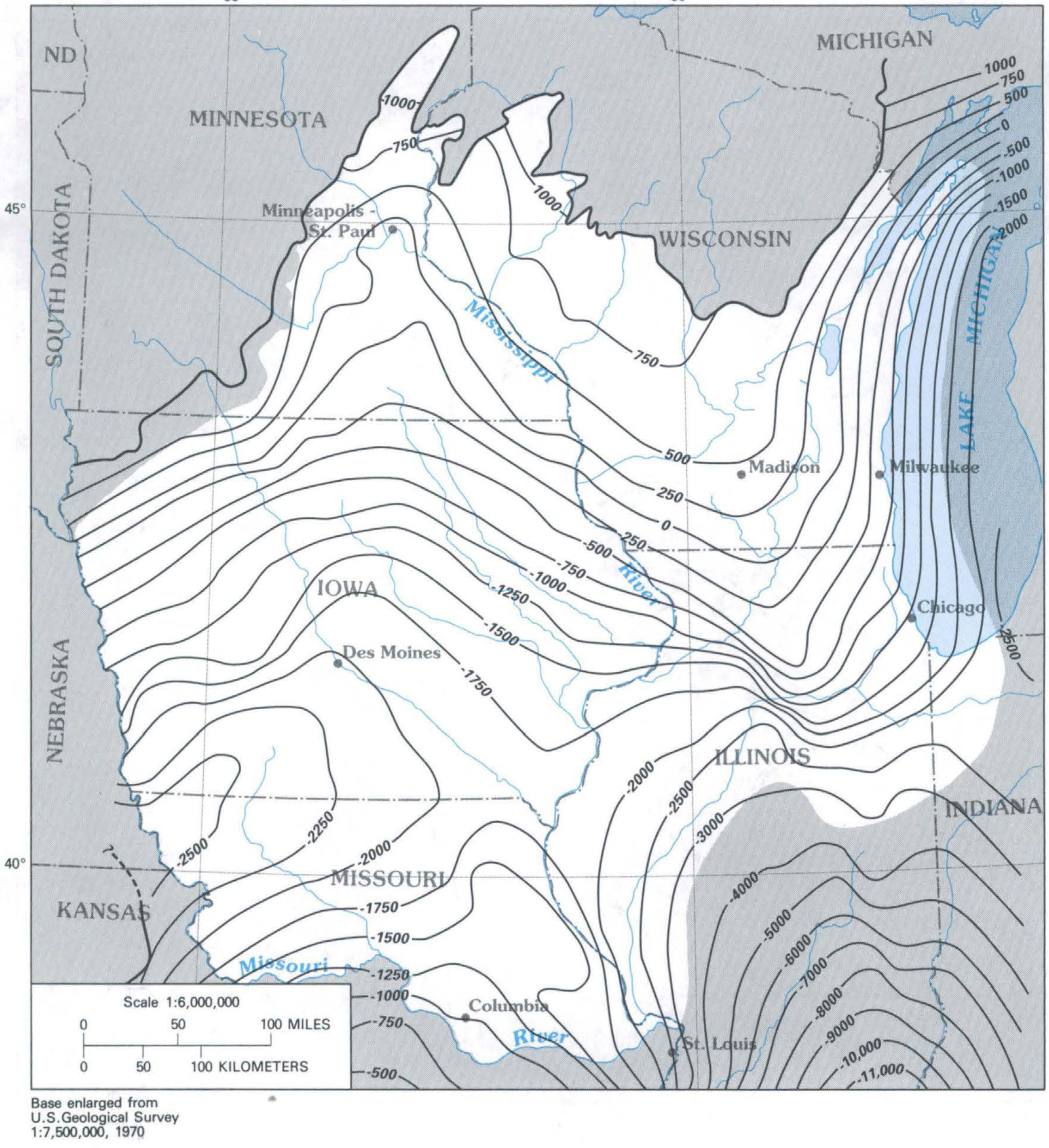
The Eau Claire Formation consists generally of very fine grained and fine- to medium-grained, silty, commonly glauconitic, yellow to gray, quartzose sandstone or shaly siltstone, with various amounts of green to black shale or dolomite. The Eau Claire formed in an offshore marine environment that migrated shoreward with transgression of the sea during Dresbachian time. The sandstone facies is dominant in the northern part of the area, but siltstone and shale and then dolomite become dominant southward and toward the structural basins. In the Hollandale embayment of southeastern Minnesota and in west-central Wisconsin, five informal units are recognized based primarily on their content of shale and glauconite (Morrison, 1968; Austin, 1969). In Wisconsin and extreme northern and western Illinois, the formation has little dolomite but is commonly very silty and shaly. Three members are recognized in the Eau Claire in Illinois (Buschbach, 1964): the basal Elmhurst Sandstone Member, the middle Lombard Dolomite Member, and the Proviso Siltstone Member.

The middle dolomitic facies becomes dominant to the south and west, becoming the Bonneterre Formation in Missouri and possibly in western Iowa. A thin carbonate unit thought to be equivalent to the Bonneterre is reported from extreme south-central Wisconsin (Ostrom, 1964) and southwestern Minnesota (Mossler, 1987). The Bonneterre generally is a fine- to coarse-grained, shaly, dolomitized calcarenite with much oolitic and stromatolitic material (Howe and others, 1972). R.M. McKay (Iowa Geological Survey, written commun., 1984) describes the Eau Claire as a silty dolomite in central Iowa. These strata compose the biogenic carbonate facies that completes the first depositional cycle of Ostrom (1978).

A difference in interpretation of the lower Eau Claire Formation contact by the State Geological Surveys of Illinois and Wisconsin complicates the regionalization of Mount Simon Sandstone and Eau Claire stratigraphy. The Eau Claire in the outcrop and in the subsurface in Wisconsin is presently distinguished from the Mount Simon by a sharp textural change; the Eau Claire is much finer textured and contains shale and carbonate (M.E. Ostrom, Wisconsin Geological and Natural History Survey, written commun., 1987). A distinct, strongly positive pattern on natural-gamma geophysical well logs delineates the shaly and silty strata of the Eau Claire. In southeastern Wisconsin, the strata now classified as Eau Claire may be equivalent primarily to the Proviso Siltstone Member of the Eau Claire in Illinois, resulting in a much thinner Eau Claire than in northern Illinois. This problem is being addressed currently (1987) by the Illinois and Wisconsin Geological Surveys (B.A. Brown, Wisconsin Geological and Natural History Survey, written commun., 1987).

These differences may be attributed primarily to two factors. First, the dolomitic facies in Illinois seems to thin to extinction in the extreme north near the Wisconsin border, which, along with the shaly nature of the upper Mount Simon Sandstone, makes it difficult to recognize the members of the Illinois classification in the subsurface in Wisconsin. Second, whereas the Eau Claire Formation is thin or absent on and east of the Wisconsin arch because of pre-Galesville Sandstone erosion, it thickens greatly toward the Illinois basin. Thus, thickening of the Eau Claire near the State line also may contribute to the classification problem. North of Milwaukee, the Eau Claire, or its silty, shaly facies, is commonly absent, and it is not possible to differentiate the sandstone formations of the Elk Mound Group in well-drilling cuttings. Similarly in Indiana, the Eau Claire generally is not differentiated from the Ironton and Galesville Sandstones and the Franconia Formation, all of which are assigned there to the Munising Group by Droste and Patton (1985) as defined by Catacosinos (1973) for the Michigan basin.

The top of the Eau Claire Formation, like that of the Mount Simon Sandstone, reflects the major structural features on the Precambrian surface. However, the Eau Claire is thickest and deepest in the center of the Illinois basin (see figs. 8, 9). The partially equivalent Bonneterre Formation thins southward from the northern edge to the center of the Forest City basin, which began to form in Middle Ordovician time (McCracken, 1967). The upper contact of the Eau Claire may be conformable in the subsurface toward the basins (Willman and others, 1975); however, it is unconformable

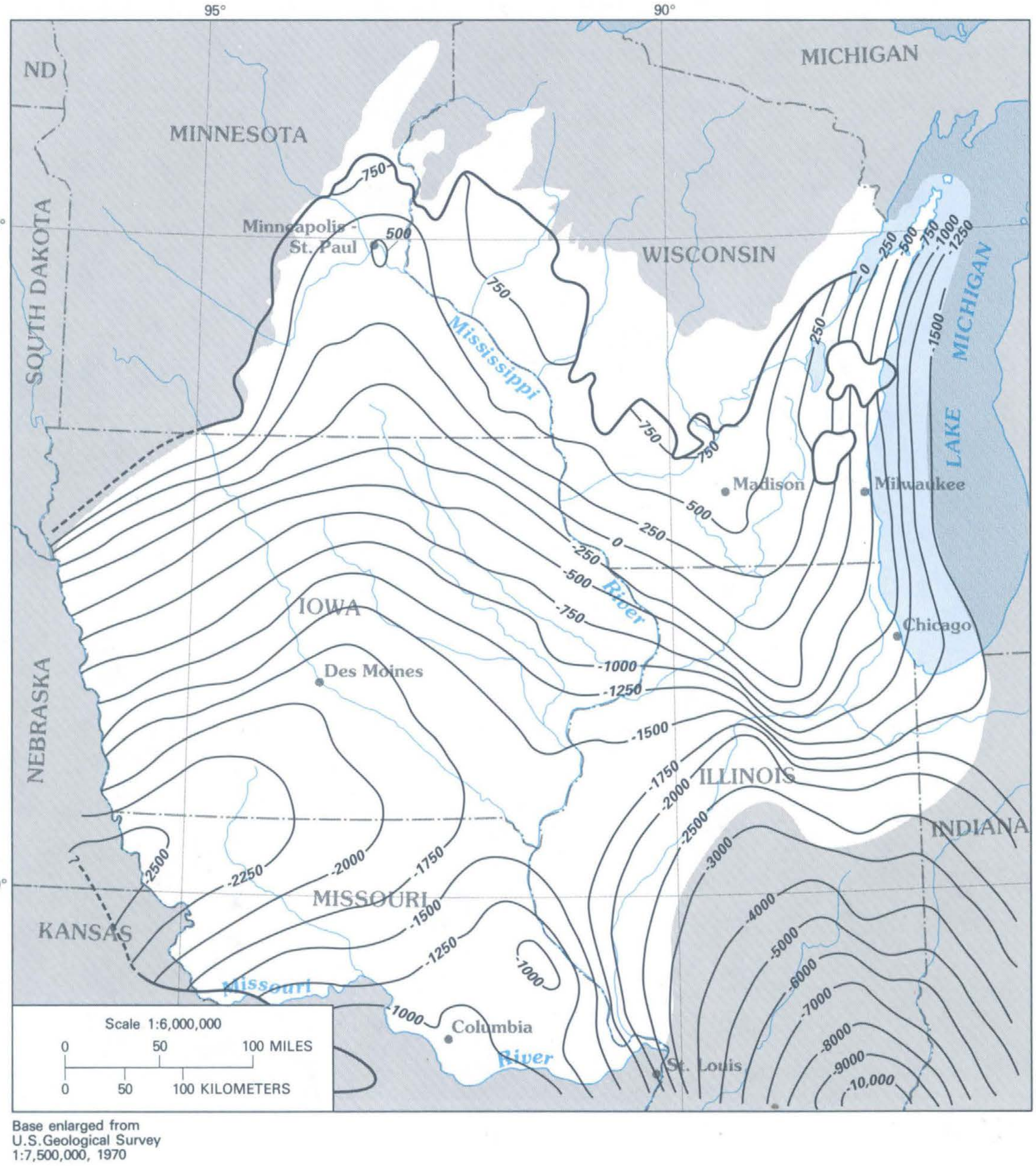


EXPLANATION

—500— STRUCTURE CONTOUR — Shows altitude of the top of the Mount Simon Sandstone or Lamotte Sandstone. Includes areas of eroded surface. Contour interval, in feet, is variable. Datum is sea level

——--? EROSIONAL BOUNDARY OF MOUNT SIMON SANDSTONE OR LAMOTTE SANDSTONE — Dashed where inferred; queried where unknown. See figure 7 for general areal distribution of rock units

FIGURE 8.—Altitude of the top of the Mount Simon Sandstone or Lamotte Sandstone.



EXPLANATION

—500— STRUCTURE CONTOUR — Shows altitude of the top of the Eau Claire Formation or Bonneterre Formation. Includes areas of eroded surface. Contour interval, in feet, is variable. Datum is sea level

——--? EROSIONAL BOUNDARY OF EAU CLAIRE FORMATION OR BONNETERRE FORMATION — Dashed where inferred; queried where unknown. See figure 7 for general areal distribution of rock units

FIGURE 9.—Altitude of the top of the Eau Claire Formation or Bonneterre Formation.

and thinner owing to pre-Galesville Sandstone erosion near uplifted parts of the craton in eastern Minnesota, Wisconsin, and southern Missouri. Ostrom (1964, fig. 1) shows the upper part of the Eau Claire grading into the lower part (Davis Formation) of the Elvins Group in eastern Missouri and southwestern Illinois.

In northern Illinois, the basal Elmhurst Sandstone Member of the Eau Claire Formation is included with the Mount Simon Sandstone (see fig. 18) to compose the basal Elmhurst-Mount Simon aquifer (Visocky and others, 1985).

GALESVILLE AND IRONTON SANDSTONES

The Galesville and Ironton Sandstones generally are medium- to coarse-grained, quartzose sandstones that can be difficult to distinguish in the subsurface. In some early classifications of Cambrian stratigraphy, these sandstones were not divided and were referred to as the Dresbach Sandstone or Galesville Sandstone. Because of their similarity and the practical need for a mappable unit in Wisconsin, the Galesville and Ironton were assigned as members of the Wonewoc Sandstone (Ostrom, 1966). The Mount Simon Sandstone, Eau Claire Formation, and Galesville Sandstone traditionally have composed the Dresbach Group (rock-stratigraphic term) of the Dresbachian Stage (time-stratigraphic term). The Ironton Sandstone also is classified variously as a formation or as a member at the base of the overlying Franconia Formation of the Franconian Stage. Ostrom (1966) believed that the rock-stratigraphic terminology should be independent of the biostratigraphic and time-stratigraphic terminology. Thus he proposed the term Elk Mound Group, which consists of the Mount Simon Sandstone, the Eau Claire Formation, and the Wonewoc Sandstone. The Elk Mound overlaps the Dresbachian-Franconian Stage boundary and replaces the term Dresbach Group.

The Galesville Sandstone is a fine- to medium-grained, moderately to well-sorted, white to buff, quartzose sandstone. It may be slightly glauconitic, but it is generally nondolomitic. The clean sand is a nearshore, high-energy deposit that represents the beginning of the second cycle of Paleozoic sedimentation (Ostrom, 1978). As previously noted, the basal contact may be transitional with the Eau Claire Formation in the basins, where interbedded fine-grained sandstone is present in the lower part. Because of erosion or nondeposition of the Eau Claire, coarser upper Galesville beds lie unconformably on older strata in the higher areas.

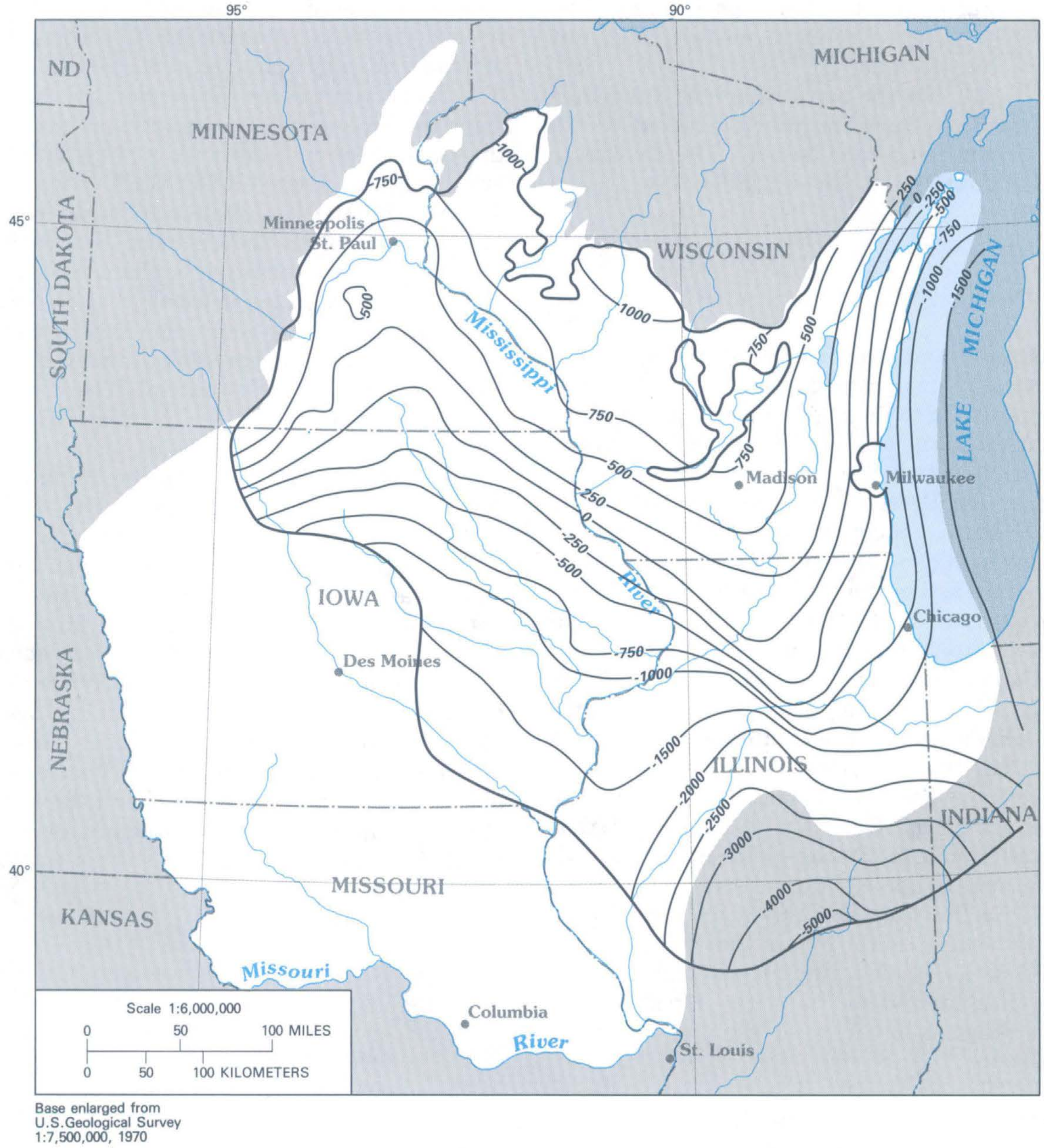
The Ironton Sandstone is a medium- to coarse-grained, poorly to moderately sorted, locally very silty, white to light gray, quartzose sandstone. It locally is glauconitic, especially near the top, and commonly is dolomitic, grading to a sandy dolomite toward the basins. Emrich (1966) reports the coating of sand grains by hematite and limonite in the upper 5 ft. Its poorer sorting and large amount of silt characterize the low-energy depositional environment of the nondepositional shelf. According to Berg (1954) and Berg and others (1956), the Ironton lies disconformably on the Galesville Sandstone in the upper Mississippi Valley. The evidence is a zone of intraclasts and ferroan crusting at the base of the Ironton (J.H. Mossler, Minnesota Geological Survey, written commun., 1987). A similar zone is described by Moretti (1971) in core samples from a deep well in Sheboygan County, east-central Wisconsin. It is not recognized in Wisconsin by Ostrom (1978) or in Illinois (Willman and others, 1975).

These units, like the Mount Simon Sandstone, are thickest on the northern edge of the Illinois basin and in the Michigan basin, where they represent areas of greatest subsidence during deposition. Sediment was transported south and southwest from highland source areas in northern Minnesota, Wisconsin, and Michigan. The formations terminate to the south and southwest (fig. 10), where the sandy facies grades into dolomite in central Iowa, central Illinois, and northwestern Indiana. This dolomitic facies is recognized as the Davis Formation, except in Iowa. As a unit, the Ironton and Galesville Sandstones compose the most productive zone in the Cambrian-Ordovician aquifer system in Illinois and Wisconsin.

FRANCONIA FORMATION AND EQUIVALENTS

The Franconia Formation is a complex of poorly sorted, glauconitic, fine-grained clastics and dolomite in the upper Mississippi Valley that grade laterally to the south into a purer dolomite, the Derby-Doerun Dolomite (usage of the Missouri Geological Survey, 1979), and into the sandy, argillaceous dolomite of the upper part of the Davis Formation. The nomenclature and rank of these rocks and equivalents vary throughout the study area (see fig. 7). Four units, generally termed members, are recognized in the Franconia: Birkmose, Tomah, Reno, and Mazomanie. The Mazomanie is classified as a formation in Wisconsin and is recognized elsewhere only in Minnesota, where it is a member. The other three units are grouped as members of the Lone Rock Formation in

Wisconsin and eastern Iowa. Ostrom (1966) introduced the name Lone Rock in his revision of St. Croixan stratigraphy in Wisconsin. He replaced the name Franconia Formation with Tunnel City Group (now also used in Iowa), feeling that the term Franconian was more established as the biostratigraphic



EXPLANATION

—500— STRUCTURE CONTOUR — Shows altitude of the top of the combined Ironton and Galesville Sandstones. Includes areas of eroded surface. Contour interval, in feet, is variable. Datum is sea level

—— EROSIONAL BOUNDARY OF COMBINED IRONTON AND GALESVILLE SANDSTONES — See figure 7 for general areal distribution of rock units

FIGURE 10.—Altitude of the top of the combined Ironton and Galesville Sandstones.

name of the stage and that the duplicity was confusing. However, the original, more familiar name is used in this report as a matter of convenience because it has been retained by the other four States and is the most commonly used term. The Franconia Formation is not subdivided in northwestern Indiana and in extreme northern Illinois. In Indiana, the Franconia is present only in the northwest, and it grades southward first into the upper part of the Davis Formation. In the rest of Illinois, the Franconia is subdivided, in descending order, into the Derby-Doerun and Davis Members. The latter two units are formations in the equivalent Elvins Group of northwestern Missouri. In northeastern Missouri the Franconia is divided into the Birkmose, Tomah, and Reno Members. The Lone Rock Formation of eastern Iowa grades westward into carbonate of the Davis Formation.

The Birkmose Member is a widespread basal deposit of the Franconia Formation and consists of very fine grained to fine-grained, glauconitic, feldspathic, dolomitic sandstone, sandy dolomite, and flat-pebble conglomerate. It was deposited offshore in relatively shallow water, as evidenced by the intraformational clasts of the flat-pebble conglomerate and abundant cross bedding and ripple marks. The Birkmose is thickest in the Hollandale embayment and thinnest shoreward on the Wisconsin arch.

Overlying the Birkmose Member is the Tomah Member—a very fine grained, mostly feldspathic, micaceous sandstone with interbedded shale. The Tomah thickens to the south and grades into shale and dolomite of the Davis Formation in northern Missouri (Howe and others, 1972).

The Reno Member is very similar to the Birkmose Member, but it is much less dolomitic. It is an intermediate facies between the Tomah and Mazomanie Members. It is the major facies in southeastern Minnesota, eastern Iowa, and western and southeastern Wisconsin, and it probably is the shaly, glauconitic, dolomitic siltstone and sandstone classified as the Franconia Formation in northern Illinois and northwestern Indiana. It is very similar in northeastern Missouri, where it grades southward into the lower part of the Derby-Doerun Dolomite.

In the upper Mississippi Valley, the Mazomanie (Formation or Member) is a fine- to coarse-grained, generally nonglauconitic sandstone facies with dolomitic cement. The Mazomanie intertongues southward in the Lone Rock Formation in Wisconsin and interfingers laterally with and progressively replaces the Reno and Tomah Members shoreward from the Hollandale embayment. It has a quartzose facies on the eastern side of the Wisconsin arch that is the result of high-energy deposition on the shelf (Odom, 1978), but the most extensive facies is highly feldspathic and was deposited in a narrow arc around the Wisconsin arch, parallel to the shore.

The Davis Formation in Missouri consists of silty to sandy shale and limestone or dolomite, with beds of flat-pebble conglomerate. Where the Davis is the basal member of the Franconia Formation in Illinois, it changes from a shaly sandstone in the north to a silty, sandy, clayey, glauconitic dolomite to the south. In western Iowa, shale and bioclastic carbonate rocks, similar to the Davis, contain much skeletal and algal material (R.M. McKay, Iowa Geological Survey, written commun., 1984). A thin interval of algal-laminated dolomite in the basal Franconia of south-central Minnesota may be equivalent to the Davis (Mossler, 1987).

The Franconia and Davis Formation strata result from fairly uniform rates of deposition on a relatively stable shelf, with minor fluctuations in subsidence and sediment supply. Thickness of the strata is generally 100 to 200 ft in the northern part of the area but increases rapidly from central Illinois to more than 700 ft in extreme southern Illinois. Most of the increase is attributable to thickening of the Derby-Doerun Member to more than 500 ft. The upper contact is conformable with the overlying Potosi Dolomite (equivalent to St. Lawrence Formation elsewhere) and often is difficult to distinguish in the subsurface.

ST. LAWRENCE FORMATION AND EQUIVALENTS

The St. Lawrence Formation is much more silty than the underlying Franconia Formation but has a similar depositional pattern throughout the upper Mississippi Valley. Clastic rocks are prevalent nearshore (along the northern outcrop belt) but grade into pure carbonate rocks seaward (to the south and west). The carbonate rocks form the Potosi Dolomite in Illinois, Indiana, and Missouri. The St. Lawrence is subdivided into the Black Earth and Lodi Members, whose facies indicate distinct patterns of deposition. The St. Lawrence Formation and the overlying Jordan Sandstone compose the Trempealeau Group—the last Cambrian rocks deposited.

The Black Earth Member is the closest to being a dolostone of all the Upper Cambrian rocks in the upper Mississippi Valley (Byers, 1978). It is a silty or sandy, clayey, glauconitic dolomite that was deposited offshore in somewhat deeper water. The Black Earth is a wedge-shaped facies that extends northward (shoreward) and is gradually replaced laterally by the overlying Lodi Member (Nelson, 1956; Ostrom, 1964).

The Lodi Member, therefore, becomes the dominant St. Lawrence Formation facies shoreward and is variously a very fine grained sandstone; a sandy, clayey, dolomitic siltstone; or a silty, clayey dolomite. This member thins to extinction on the Wisconsin arch, where the younger Jordan Sandstone locally lies directly on the Franconia Formation.

In Missouri, Illinois, and Indiana, the Potosi Dolomite is the lateral equivalent of the St. Lawrence Formation. Both are fine- to medium-crystalline dolomites that contain algal material. The base of the Potosi is characterized by shaly or sandy, glauconitic beds. The upper contact is conformable except toward the north, where the surface was eroded prior to deposition of the St. Peter Sandstone.

These lower dolomites of Trempealeauan age are Ostrom's (1978) biogenic carbonate lithotope that closes his second cycle of Paleozoic sedimentation. The St. Lawrence Formation generally is less than 200 ft thick, but the Potosi Dolomite thickness increases southward to more than 350 ft.

The shape of the structure contours depicting the top of the combined Franconia and St. Lawrence Formations or equivalents (fig. 11) is very similar to those of the formations below, although the surface is affected locally by pre-Jordan Sandstone erosion. Similarly, the Franconia and St. Lawrence are also deepest in the structural basins. The Franconia and St. Lawrence form a confining unit between the underlying Ironton and Galesville Sandstones and the overlying Jordan Sandstone.

JORDAN SANDSTONE AND EMINENCE DOLOMITE

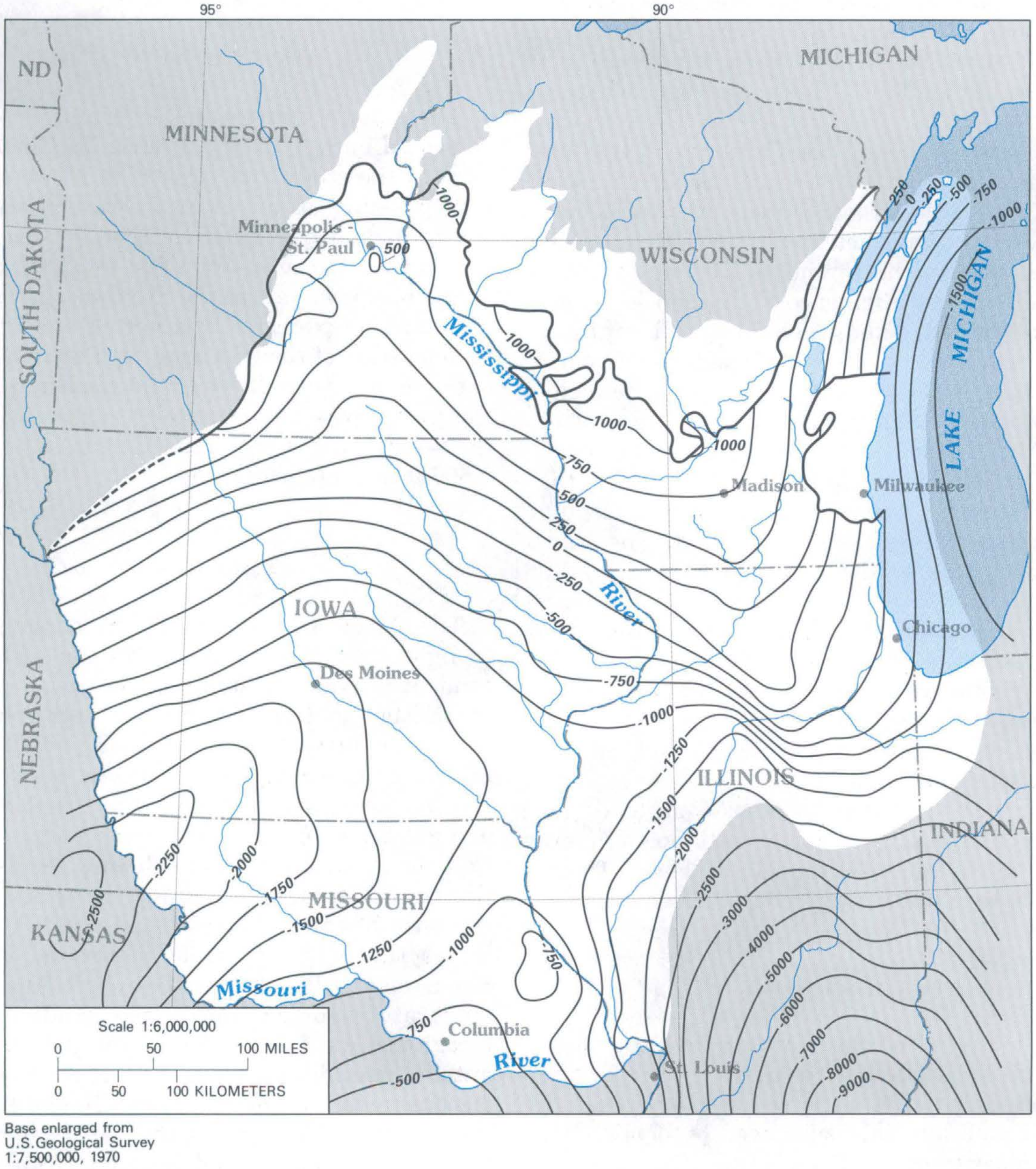
In the upper Mississippi Valley, the Cambrian Period closed with the deposition of the Jordan Sandstone, a massive to well-bedded, fine- to coarse-grained, generally quartzose sandstone. It is somewhat loosely cemented in the north, but dolomitic cementation increases progressively to the south (Horick and Steinhilber, 1978). Sediment from a northeastern source was deposited in a broad tongue covering central and western Wisconsin, southeastern Minnesota, extreme western Illinois, and most of Iowa and Missouri (Ostrom, 1970). Deposition in most areas was transitional into the following Ordovician Period, producing the overlying Oneota Dolomite. Three major and two minor members are generally recognized in the Jordan. They show an upward progression from very fine grained, silty sandstone to medium- to coarse-grained sandstone and sandy dolomite. This configuration is common in Minnesota, Wisconsin, eastern Iowa, and extreme northwestern Illinois. To the west, south, and east, the Jordan grades laterally into the Eminence Dolomite, which was deposited farther offshore.

The basal Norwalk Member is a very fine grained to fine-grained, poorly sorted, silty, feldspathic, quartzose sandstone. It is fairly well cemented with dolomite and contains some interbedded layers of medium-grained sand, the proportion of which increases upward.

Intermediate strata are the Van Oser Member, which intertongues with minor members, the Waukon and Sunset Point Members (Odom and Ostrom, 1978), in its upper part. The Van Oser is a medium- to coarse-grained, moderately sorted, white to yellow or brown, quartzose sandstone, which also coarsens upward. The Waukon and Sunset Point Members are very fine grained, feldspathic sandstones of limited extent.

Odom and Ostrom (1978) proposed a revision of the classification of the uppermost Jordan Sandstone strata that are transitional to the overlying Oneota Dolomite, the basal unit of the Ordovician System. They proposed the name Coon Valley Member for the sequence of poorly sorted, shaly dolomitic sandstones and sandy dolomites above the Van Oser Member and below the fairly pure dolomite of the Oneota. This sequence includes strata in western Wisconsin that Raasch (1951, 1952) called the Sunset Point Formation, and which he thought were equivalent to the type Sunset Point facies at Madison, Wisconsin, plus the lower part of his Oneota Dolomite. The Coon Valley Member contains several lithologies, which locally change rapidly within short distances. These lithologies are mainly fine- to medium-grained, poorly sorted, dolomitic, quartzose sandstones and sandy oolitic dolomites, which are distributed, respectively, from west to east across the Wisconsin arch.

Ostrom (1978) includes the first three lithotopes of his third Paleozoic depositional cycle in the Jordan Sandstone (fig. 6). The quartzose sandstone lithotope is represented by the Norwalk and Van Oser Members, although the Norwalk may have been deposited in a subtidal lagoon (Odom and Ostrom, 1978). The Coon Valley Member represents both the nondepositional and depositional shelf environments. The latter informally refers to the Blue Earth beds, which are assigned to the overlying Oneota Dolomite in Minnesota (fig. 7), but whose equivalent in Wisconsin is included in the upper part of the Coon Valley



EXPLANATION

—500— STRUCTURE CONTOUR — Shows altitude of the top of the combined St. Lawrence and Franconia Formations or the combined Potosi and Derby-Doerun Dolomites. Includes areas of eroded surface. Contour interval, in feet, is variable. Datum is sea level

——--- EROSIONAL BOUNDARY OF COMBINED ST. LAWRENCE AND FRANCONIA FORMATIONS — Dashed where inferred. See figure 7 for general areal distribution of rock units

FIGURE 11.—Altitude of the top of the combined St. Lawrence and Franconia Formations or the combined Potosi and Derby-Doerun Dolomites.

by Ostrom (1978). The Jordan is generally about 50 to 100 ft thick but exceeds 140 ft in northeastern and east-central Iowa (Horick and Steinhilber, 1978).

Either alone or in combination with the overlying Prairie du Chien Group, the Jordan Sandstone is a very important aquifer in Iowa and southeastern Minnesota.

As with most of the Upper Cambrian rocks, the Jordan Sandstone also grades into carbonate rocks to the south in Missouri and Illinois, westward from central Iowa, and southeastward in Indiana. The carbonate is termed the Eminence Dolomite in Missouri. In Illinois, the Eminence Formation is a fine- to medium-grained, sandy dolomite and contains some oolitic chert and thin beds of sandstone, including a very thin, discontinuous basal sandstone member, the Momence Sandstone Member. The latter consists of light gray, poorly sorted, dolomitic sandstone with some interbedded sandy shale. It is the only formal member recognized in the Eminence and has a maximum thickness of only 15 ft. The Eminence is much less sandy in the south and grades laterally into undifferentiated dolomite in southern Illinois (Willman and others, 1975) and grades into the Potosi Dolomite in Indiana (Droste and Patton, 1985). The Eminence in Missouri is mainly a dolomitized, oolitic to coquinoidal calcarenite, but it also contains much stromatolitic material and, in the upper part, some quartzose sand layers.

The Eminence Formation thickens from less than 50 ft in the outcrop area of northern Illinois to more than 200 ft in the center of the Illinois basin. Thicknesses of 150 to 300 ft are common in Missouri.

ORDOVICIAN SYSTEM

The Cambrian Period closed with a smooth transition into the subsequent Ordovician Period in the central United States. Clastic sedimentary rocks of the Upper Cambrian were succeeded by dominantly carbonate deposits of the Ordovician. Most of these are widespread deposits formed in moderately deep, broad, marine seas open to the south; however, along the northern part of the area, shallower carbonate banks and intertidal conditions were common. A prominent exception to the carbonate facies is the St. Peter Sandstone—a very well sorted, pure quartzose sandstone that is very extensive and uniform throughout the northern Midwest. The entire Ordovician System is represented in the study area and is subdivided into Lower, Middle, and Upper Ordovician Series (fig. 7) based on faunal evidence and lithologic correlation from type sections east of the area.

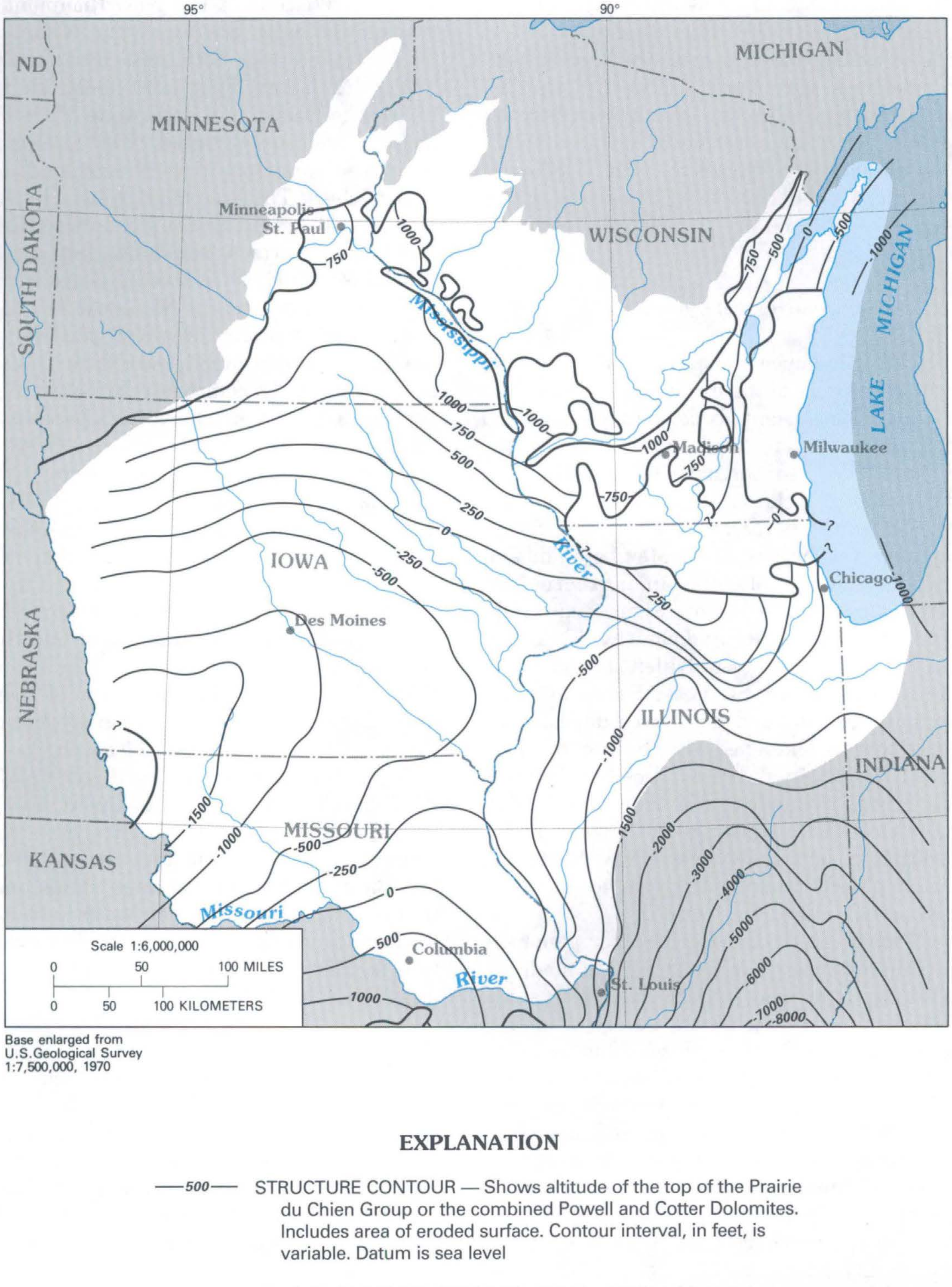
LOWER ORDOVICIAN SERIES

The Lower Ordovician, or Canadian, Series is composed entirely of the Prairie du Chien Group in most of the study area, except in Missouri, and consists generally of the Oneota Dolomite and the overlying Shakopee Formation. The Prairie du Chien Group usually ranges from 200 to 300 ft in thickness in the northern part of the area, except where it was subjected to extensive weathering and erosion prior to deposition of the overlying St. Peter Sandstone. In extreme northern Illinois and southern Wisconsin, the group was almost totally removed (fig. 12). It thickens greatly toward the Illinois basin, exceeding 2,500 ft in southern Illinois.

ONEOTA AND GASCONADE DOLOMITES

The Oneota Dolomite is fine to coarse grained, tan to light gray, with variable amounts of chert and sand. It is typically sandy in the lower part in Wisconsin, but in Illinois the lower part is very cherty with very little sand. The Gasconade Dolomite in Missouri, equivalent to the Oneota, is coarse grained and very cherty in the lower part and fine grained and much less cherty in the upper part.

A thin, discontinuous basal sandstone, the Gunter Sandstone, may underlie or be included at the base of these dolomites, in which case it comprises the oldest Ordovician strata. The Gunter Sandstone in Illinois is a fine- to medium-grained, moderately sorted, quartzose sandstone that is recognized as a formation below the Oneota Dolomite. It usually is less than 20 ft thick and is most discontinuous in northeastern Illinois. In Missouri, the Gunter Sandstone is the basal member of the Gasconade Dolomite and is about 25 to 30 ft thick. It is medium grained and quartzose from central Missouri to the south but is a sandy dolomite to the east and west. In Minnesota, a few feet of sandstone similar to the underlying Jordan Sandstone occur intermittently near the base of the Oneota Dolomite. The term Kasota beds was previously applied to this sandstone but recently has been abandoned (Mossler, 1987). These basal sandstones are probably equivalent to Raasch's (1952) Hickory Ridge Member of the Oneota Dolomite in western Wisconsin.



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

EXPLANATION

—500— STRUCTURE CONTOUR — Shows altitude of the top of the Prairie du Chien Group or the combined Powell and Cotter Dolomites. Includes area of eroded surface. Contour interval, in feet, is variable. Datum is sea level

——--? EROSIONAL BOUNDARY OF PRAIRIE DU CHIEN GROUP OR COMBINED POWELL AND COTTER DOLOMITES — Dashed where inferred; queried where unknown. See figure 7 for general areal distribution of rock units

FIGURE 12.—Altitude of the top of the Prairie du Chien Group or the combined Powell and Cotter Dolomites.

The Oneota Dolomite represents the biogenic carbonate lithotope that completes the third depositional cycle of Ostrom (1978). It is commonly 150 to 250 ft thick in the northern part of the area but increases in thickness southward to 500 ft in the Illinois basin in southern Illinois. It is absent because of pre-St. Peter Sandstone erosion in extreme northern Illinois and southern Wisconsin. The Gasconade Dolomite averages about 300 ft in thickness in the Ozark area.

Shakopee Formation and Equivalents

The overlying Shakopee Formation (or Dolomite) comprises the remainder of the Prairie du Chien Group where the Oneota is present. It consists of the basal New Richmond Sandstone Member overlain by the Willow River Member. In northern Illinois, the New Richmond Sandstone is classified as a formation, and the Shakopee Dolomite is restricted to the strata that are equivalent to the Willow River Member. The Jefferson City and Cotter Dolomites in northern Missouri are equivalent to the Willow River (see fig. 7). The younger Powell Dolomite and Smithville Formation in Missouri may have no equivalent to the north, presumably because of pre-St. Peter Sandstone erosion. Ostrom (1978) assigned his fourth depositional cycle entirely to the Shakopee, attributing the first three of its lithotopes (fig. 6) to the three lithologies of the New Richmond Sandstone Member. The Willow River and the Oneota Dolomite are not always distinguishable in the subsurface where the New Richmond is very thin or absent, making the Prairie du Chien Group the practical unit of correlation.

The New Richmond Sandstone Member generally consists of three lithologies: a lower fine- to medium-grained, white to light gray or tan, quartzose sandstone; a transitional fine-grained, sandy dolomite; and an upper very thin (1 ft or less), blue to green shale or sandy shale (M.E. Ostrom, Wisconsin Geological and Natural History Survey, written commun., 1987). It was previously termed the Root Valley Sandstone in Iowa and southeastern Minnesota. The New Richmond becomes increasingly dolomitic and more tightly cemented to the south. It is thin to absent in the northern part of the study area, where it is usually less than 50 ft thick, but it increases in thickness to more than 150 ft in north-central Illinois. It wedges out rapidly and is absent in the east-central and southern parts of Illinois (Willman and others, 1975). Along with the rest of the Prairie du Chien Group, the New Richmond is deeply channeled and removed by pre-St. Peter Sandstone erosion in extreme northern Illinois and southern Wisconsin. The New Richmond seems to be transitional with the overlying Willow River Member, grading into it both laterally and vertically.

The Roubidoux Formation in Missouri, equivalent to the New Richmond Sandstone Member, consists of fine- to medium-grained, white, partly dolomitic, quartzose sandstone and fine-grained dolomite with beds of chert. The Roubidoux ranges in thickness from 100 to 250 ft and is thinnest in northeastern Missouri. The quartzose-sandstone facies is dominant in central Missouri but is much less prevalent elsewhere.

The major part of the Shakopee Formation consists of the Willow River Member, generally a very fine grained to fine-grained, sandy, light gray to tan or buff dolomite. It commonly contains algal beds and various amounts of chert. It represents the closing biogenic carbonate lithotope of the fourth depositional cycle of Ostrom (1978) as well as the end of the Sauk sequence (Sloss, 1963). In the northern part of the area, its thickness generally is less than 100 ft but reaches 240 ft in the Hollandale embayment. Its thickness increases southward from less than 100 ft near the eroded area of northern Illinois to more than 2,500 ft in extreme southern Illinois, accounting for 75 percent or more of the thickness of the Prairie du Chien Group in southern Illinois. Most of this increase is due to the progressive addition of younger strata to the top of the formation in the south.

In northern Missouri, the Jefferson City and Cotter Dolomites, equivalent to the Willow River Member, consist primarily of fine- to medium-grained dolomite with variable amounts of chert and thin beds of shale and fine-grained sandstone. Identification of the units in the subsurface may be difficult by lithologic examination only; however, identification in Missouri is based on study of insoluble residues (Howe and others, 1961).

MIDDLE ORDOVICIAN SERIES

The Middle Ordovician Series generally is represented in the northern part of the study area by five main units: the St. Peter Sandstone, the Glenwood, Platteville, and Decorah Formations, and the Galena Dolomite. However, their classification is quite varied from State to State (see fig. 7). The equivalent strata to the south consist of the St. Peter Sandstone, Dutchtown Limestone, Joachim Dolomite, and Plattin, Decorah, and Kimmswick Formations. A remnant of an older Middle Ordovician rock unit, the Everton Dolomite, is present in extreme southeastern Missouri and southwestern Illinois. The series is divided into the Ancell, Platteville, and Galena Groups in Illinois, and modifications of this grouping are used elsewhere. The rocks are mostly carbonate, except for the St. Peter Sandstone.

Pre-St. Peter Sandstone Unconformity

The base of the St. Peter Sandstone in most of the study area lies on a major unconformity caused by extensive weathering and erosion that exposed much older strata. The underlying surface is very irregular, formed primarily on carbonate rocks of the Prairie du Chien Group, the Franconia Formation, and the Eminence and Potosi Dolomites, which may have contained extensive karst topography. Basal St. Peter in Illinois and Wisconsin commonly is a rubbly deposit that is interpreted by Buschbach (1964) as residuum from a lengthy period of weathering, rather than as stream-laid channel deposits as commonly had been believed. The base of the St. Peter lies on strata as old as the Franconia Formation in extreme northern Illinois (Willman and others, 1975) and the Precambrian basement in eastern Wisconsin (Mai and Dott, 1985). The thickness of the St. Peter is highly variable locally because of the irregular surface on which it was deposited.

The remnant of the Everton Dolomite lies unconformably beneath the St. Peter Sandstone and is also highly unconformable over the Lower Ordovician Series. This indicates that the widespread, well-developed pre-St. Peter unconformity may result from more than one period of erosion.

This major unconformity marks the end of the Sauk sequence and the beginning of the Tippecanoe sequence (Sloss, 1963).

Everton Dolomite

The Everton Dolomite is mostly a sandy dolomite with some beds of very fine grained to fine-grained sandstone, limestone, and chert. It is 400 to 500 ft thick in extreme southeastern Missouri but tapers steeply northward to extinction south of St. Louis.

St. Peter Sandstone

The St. Peter Sandstone is present throughout most of the northern Midwest south of its northern outcrop belt and general erosional limit. It thins to extinction northeastward in the subsurface in extreme southwestern Michigan. The St. Peter and overlying Glenwood Formation compose the Ancell Group (Templeton and Willman, 1963) in northern Illinois, Iowa, and Wisconsin (fig. 7). Their contact commonly is not obvious in well cuttings, so the Glenwood strata have been logged with the St. Peter in many well records. Two members generally are recognized in the St. Peter in Wisconsin and Iowa and three in Illinois.

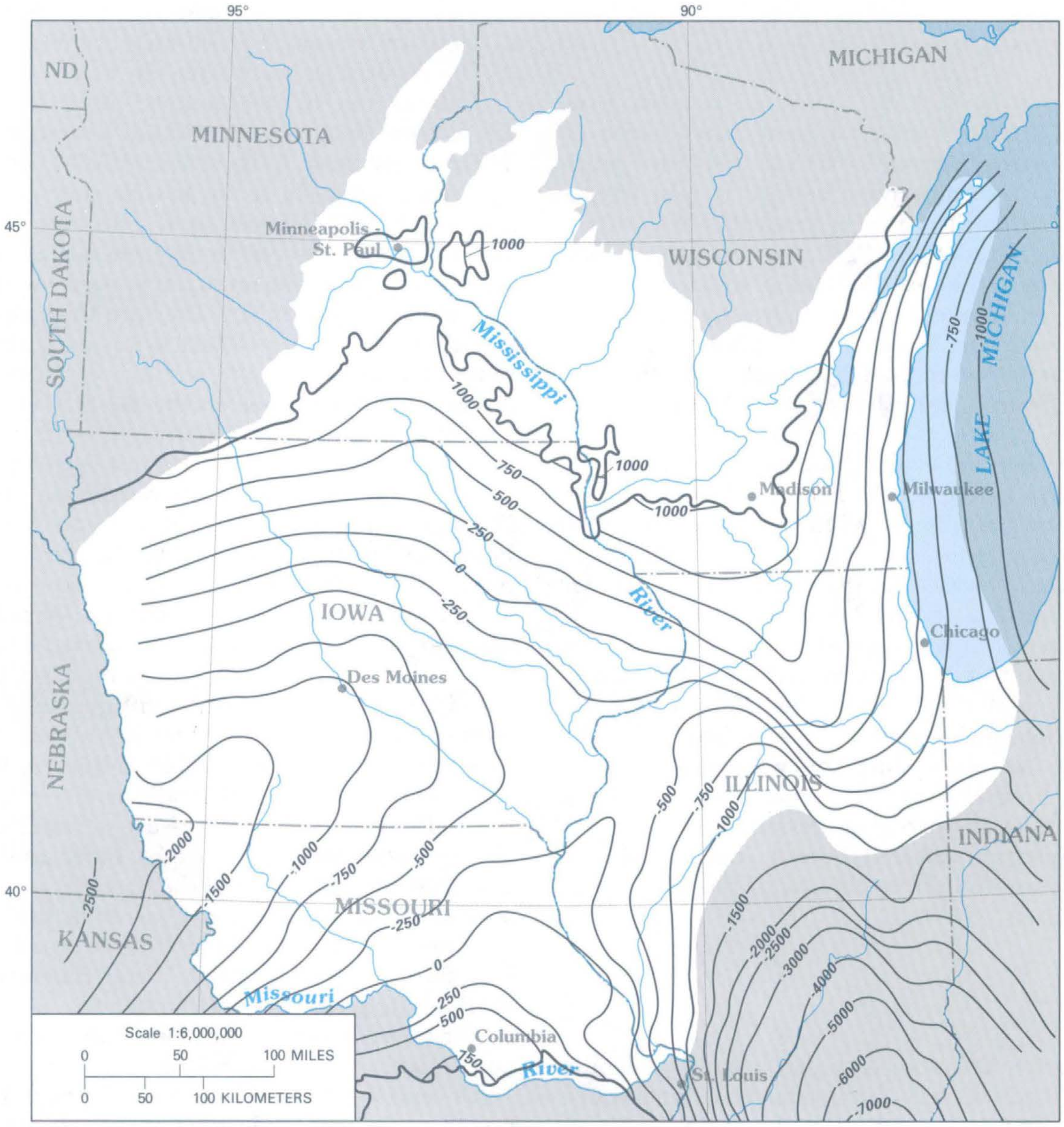
The lowermost part of the St. Peter Sandstone in Illinois is the Kress Member, equivalent to the Readstown Member of Iowa and Wisconsin (Ostrom, 1967). These basal units consist of very poorly sorted deposits of white to red or orange cherty conglomerate and clayey sandstone, and red to brown or green shale that are the residuum from the pre-St. Peter weathering cycle. The units are present intermittently in Illinois and Wisconsin. They are thickest in northern Illinois and southwestern Wisconsin, where maximum thicknesses are 170 and 275 ft, respectively, in the deepest depressions on the pre-St. Peter surface. The Kress is present as far south as central Illinois in sections as thin as a few inches to a few feet.

The Tonti Member (Tonti Sandstone Member in Illinois) is the facies typically recognized as the St. Peter Sandstone and constitutes the bulk of the formation throughout the area except in central Illinois. It is a fine- to medium-grained, well-sorted, friable, white to yellow or red, very pure quartzose sandstone. The sand grains are usually well rounded, frosted or pitted, and more than 99 percent quartz. A few thin beds of green shale occur, commonly near the base. The Tonti is usually 100 to 200 ft thick in Wisconsin and northern Illinois but locally is more than 500 ft thick. The larger thicknesses are a result of deposition in depressions in the pre-St. Peter erosional surface. The other members of the St. Peter are absent or poorly represented in many areas; thus, the Tonti may comprise the entire St. Peter in those areas.

A third member of the St. Peter Sandstone is the Starved Rock Sandstone Member in Illinois. The Starved Rock overlies the Tonti Sandstone Member and is deposited in a band 70 to 100 mi wide across north-central Illinois, southwest of Chicago. It is interpreted as an offshore-bar facies that separated deposition of the Glenwood Formation to the north from deposition of the Dutchtown Limestone and Joachim Dolomite to the south (Templeton and Willman, 1963). The Starved Rock is a medium-grained, quartzose sandstone that is generally 60 to 100 ft thick.

The St. Peter Sandstone is a good example of a shallow marine littoral lithotope and marks the beginning of the fifth Paleozoic depositional cycle of Ostrom (1978). The unit is time transgressive, deposited as the sea advanced northward. The deeper water carbonate facies of the Dutchtown Limestone and Joachim Dolomite also are transgressive northward, overlapping the St. Peter.

The top surface of the St. Peter Sandstone (fig. 13) shows the effect of strong postdepositional downwarping of the structural basins. The top is more than 7,500 ft below sea level in the Illinois basin. The structure-contour map is generalized and does not show where the St. Peter is dissected or removed in some



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

EXPLANATION

—500— STRUCTURE CONTOUR — Shows altitude of the top of the St. Peter Sandstone. Includes areas of eroded surface. Contour interval, in feet, is variable. Datum is sea level

——— EROSIONAL BOUNDARY OF ST. PETER SANDSTONE — See figure 7 for general areal distribution of rock units

FIGURE 13.—Altitude of the top of the St. Peter Sandstone.

outcrop areas, especially along the Mississippi River and its tributaries in and adjacent to western Wisconsin. In those areas, erosion of the St. Peter usually has formed valleys, and the ridgetops are capped with the younger, more resistant carbonate rocks of the Galena Dolomite and Platteville Formation.

Glenwood Formation

The Glenwood Formation generally consists of blue- or gray-green shale underlain by very fine grained and medium-grained, poorly sorted, clayey, silty and/or dolomitic sandstone. Its subdivision into members differs from State to State. For example, five members of the Glenwood are recognized in Illinois, but it is not subdivided in Minnesota. As previously stated, the Glenwood is difficult to distinguish from the St. Peter Sandstone in places and may not be separated in some well logs. It is recognized on natural-gamma geophysical well logs. Presence of the Glenwood is uncertain in Indiana (Droste and others, 1982). The Glenwood generally is a thin unit, especially in the northern part of the area. It averages only 5 ft in thickness in Minnesota and is absent on the Wisconsin arch. It increases to 25 to 50 ft in thickness in Iowa and Illinois before terminating in a vertical cutoff against the Starved Rock Sandstone Member of the St. Peter in central Illinois. Ostrom (1969) classified three members in the Glenwood. The lowermost, the Nokomis Member, represents the intermediate nondepositional lithotope of his fifth cycle of deposition. The Harmony Hill and the overlying Hennepin Members represent the depositional shelf lithotope. To the south and east in Missouri, southern Illinois, and Indiana, the Glenwood is replaced by the Joachim Dolomite.

Dutchtown Limestone

The Dutchtown Limestone is mainly dark gray or black, clayey, very fine grained limestone and dolomite, with variable amounts of sandstone, siltstone, and shale; it grades northward into the St. Peter Sandstone. It is present only in southeastern Missouri, extreme southern Illinois, and the southern one-half of Indiana. It has a maximum thickness of about 170 ft near Cape Girardeau in southeastern Missouri, but rapidly thins to extinction northward. The Dutchtown is conformably overlain by the Joachim Dolomite but unconformably overlaps the Everton Dolomite.

Joachim Dolomite

The younger Joachim Dolomite is a clayey, yellowish-brown dolomite with various beds of pure sandstone, shale, and limestone. It is mainly noncherty and contains some algal domes of dolomite. Its maximum thickness is about 385 ft in extreme southern Illinois, but it progressively thins to extinction northward in northeastern Missouri, in central Illinois, and in extreme northwestern Indiana. In the north, where the Dutchtown Limestone is absent, the Joachim grades into the St. Peter Sandstone.

Platteville Formation

The Platteville Formation generally is recognized as containing 3 members, except in Illinois, where it is elevated to the status of a group containing 5 formations with 24 members. In Wisconsin, it is the oldest of three formations, including the overlying Decorah Formation and Galena Dolomite, that compose the Sinnipee Group of Ostrom (1967). Units of the Platteville are widespread and laterally continuous throughout the northern Midwest. The lowermost member of the Platteville, the Pecatonica Member, is mainly a yellowish- to grayish-brown, fine- to medium-grained, medium-bedded to massive dolomite that commonly contains some sand near its base. The dolomite grades into limestone in southern Illinois. Strata of the middle McGregor Member and equivalents form the bulk of the Platteville and are very fine grained to fine-grained, gray to buff, thin-bedded limestone. The McGregor is mostly dolomitized in Wisconsin and is partially dolomitized locally elsewhere. The uppermost part of the Platteville is a thin, very fine grained, brown limestone unit, the Quimbys Mill Member, but this unit is not recognized in Minnesota. A similar unit, the Carimona Member, is uppermost in Minnesota. The Platteville is usually less than 50 ft thick in Iowa, Minnesota, and extreme western Illinois but progressively thickens to the east and southeast in Illinois, to more than 600 ft in the extreme south.

Ostrom (1978) attributes the entire Sinnipee Group, which represents a biogenic carbonate lithotope, to the fifth cycle of deposition.

PLATTIN FORMATION

In Indiana and Missouri, the Plattin Formation is equivalent to that part of the Platteville Formation above the Pecatonica Dolomite Member in Wisconsin and Minnesota. This interval in Illinois is named the Plattin Subgroup of the Platteville Group. The Plattin Formation is generally a fine-grained, dark gray, cherty limestone in Missouri but is mostly dolomite in the east and northeast. It contains minor amounts of shale and has a shaly, pebble conglomerate basal unit. The Plattin thickens from less than 100 ft in northeastern Missouri to 450 ft in the southeast. The Decorah Formation apparently overlies it unconformably.

DECORAH FORMATION

The Decorah Formation is recognized as a unit throughout the study area, except in Indiana. It is divided into three members in Iowa and two members in Wisconsin. It is mostly dolomitic limestone with variable amounts of thin shale beds. The lower part of the Decorah is mainly shale in Missouri and Illinois. It is a greenish-gray to olive-brown shale with some thin limestone beds in Minnesota, where it is thickest (80 ft) in the Twin Cities basin and thins to 25 to 35 ft near the Iowa border (Mossler, 1987). It characteristically is a brown to dark brown or gray clayey dolomite in Wisconsin, where it commonly is difficult to recognize in the subsurface. The Decorah generally is less than 50 ft thick and thins to less than 5 ft in central and eastern Illinois.

GALENA DOLOMITE AND KIMMSWICK FORMATION

The term “Galena Group” is used in Illinois and Iowa to include the Decorah Formation and younger strata of the Middle Ordovician. In northwestern Indiana, the equivalent rocks are termed the Trenton Limestone. In Minnesota and Wisconsin, the Galena is classified as a formation, although it is not divided into exactly the same members in each State (fig. 7). The Galena Dolomite of Wisconsin is the rock-stratigraphic equivalent of the Kimmswick Formation of Missouri. The Decorah and three additional formations above it are assigned to the Galena Group in Illinois and Iowa (fig. 7).

The Galena Dolomite is primarily carbonate, either dolomitic limestone or interbedded limestone and dolomite. Dolomite is the predominant lithology only in Wisconsin, northern Illinois, and north-central and northwestern Missouri. Thin shale beds are common in the lower part of the Galena in Minnesota and Wisconsin, as well as in the Dubuque Formation of Minnesota (uppermost Galena elsewhere). The Galena is about 200 to 250 ft thick in much of the area but decreases to almost 100 ft from northern to southern Illinois. Likewise, the Kimmswick Formation decreases from more than 250 ft in northwestern Missouri to 50 to 150 ft in eastern Missouri. As with the Ancell Group (Templeton and Willman, 1963), the top of the Galena (fig. 14) shows the effects of strong structural downwarping in the basins. It is 6,600 ft below sea level in the Illinois basin in southern Illinois. The Galena strata are truncated by pre-Cincinnatian erosion from central Illinois to the south, especially evident where the Galena thickness decreases in Illinois and Missouri. In Minnesota and Iowa, the overlying Maquoketa Formation is considered to be conformable.

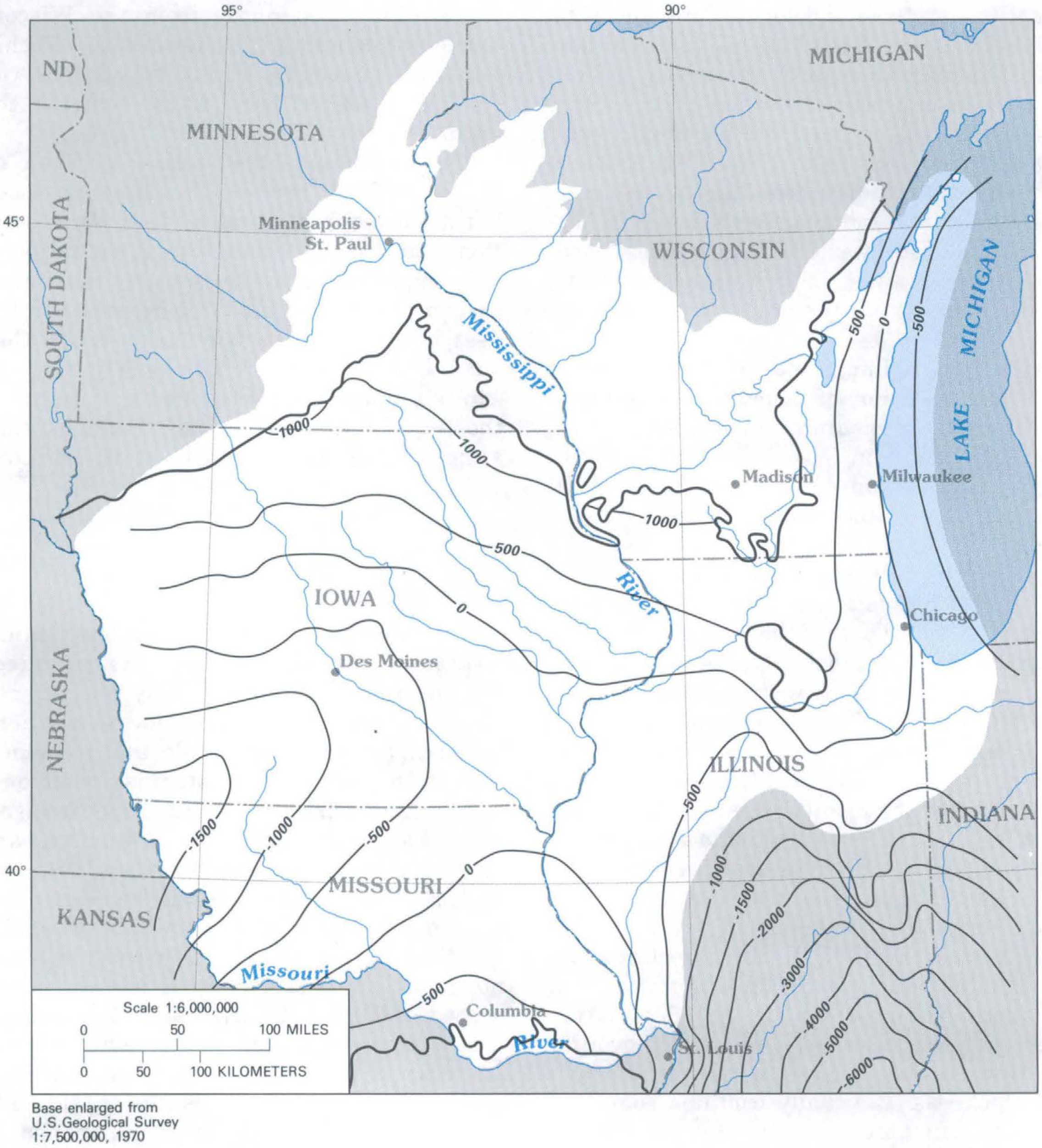
UPPER ORDOVICIAN SERIES

The Upper Ordovician, or Cincinnatian, Series in the study area consists primarily of the Maquoketa Shale but probably includes some of the uppermost Galena Dolomite in at least the eastern part of the area (Kolata and Graese, 1983). The source of the Maquoketa sediment was from the Appalachian region to the east, and Froming (1971) and Gray (1972), based on conodont correlation, considered the unit time transgressive from east to west. In Missouri, the Maquoketa is present only in the northwestern corner and near the Mississippi River on the eastern side. It also is missing in most of Minnesota, Wisconsin, and north-central Illinois due to both erosion and the probable lack of deposition in the structurally high areas.

In the southern parts of Illinois and Missouri, the Maquoketa Shale is underlain by the thin, patchily distributed Cape Limestone and is overlain by another thin unit, the Girardeau Limestone (Willman and others, 1975). The Cape is a coarse-grained, clayey, light to reddish-gray calcarenite that is usually less than 10 ft thick and is preceded and followed by significant erosional unconformities.

MAQUOKETA SHALE

The Maquoketa Shale consists primarily of calcareous, silty, dark colored shale with variable amounts of interbedded dolomite and limestone. The unit is a formation subdivided variously into two to five members in most of the study area but is a group of three or four formations in Illinois and Indiana (fig. 7). The primary units, in ascending order, are the Scales Shale, the Fort Atkinson Limestone, and the Brainard Shale of either member or formation rank.



EXPLANATION

—500— STRUCTURE CONTOUR — Shows altitude of the top of the Galena Dolomite or the Kimmswick Formation. Includes areas of eroded surface. Contour interval, in feet, is variable. Datum is sea level

——— EROSIONAL BOUNDARY OF GALENA DOLOMITE OR KIMMSWICK FORMATION

FIGURE 14.—Altitude of the top of the Galena Dolomite or Kimmswick Formation.

The Scales Shale or Member is equivalent to the Elgin Limestone Member and the overlying Clermont Shale Member of the Maquoketa Shale. These or equivalent strata occur throughout most of the area and are mainly silty, calcareous, brownish-gray to black shale with some beds of dolomite. Only the Elgin and Clermont Members of the Maquoketa Formation, consisting primarily of limestone, are present in Minnesota as a result of extensive erosion that occurred prior to deposition of the overlying Devonian rocks. The Scales is a member of the Maquoketa Shale in Wisconsin and a formation of the Maquoketa Group in northern Illinois and Indiana. To the south in Missouri and extreme southwestern Illinois, the Thebes Sandstone, a fine-grained, silty, micaceous, gray, quartzose sandstone, is partly equivalent to the Scales Shale.

The Fort Atkinson Limestone or Member varies from a pure to clayey lime or dolomitic packstone in most of Illinois to a medium- to coarse-grained, cherty, shaly dolomite in Wisconsin and Iowa. In northwestern Illinois and central and east-central Iowa it, as well as the other units in the Maquoketa Formation or Group, is primarily shale; thus the Maquoketa is generally undifferentiated in those areas (Parker, 1971; Kolata and Graese, 1983).

The uppermost major part of the Maquoketa Shale, the Brainard Shale or Member, consists of silty, dolomitic, green to dark gray shale with some interbedded limestone and dolomite. The upper few feet of the shale in northern Illinois generally is grayish-red to grayish-red purple where the Brainard is fairly thick. The color is probably the result of pre-Silurian weathering of the Maquoketa surface (Kolata and Graese, 1983). Much of the Brainard in southwestern Iowa was removed by pre-Silurian erosion.

The Neda Formation or Member is a thin, red to reddish-brown or blackish-red, hematitic, oolitic shale at the top of the Maquoketa Group or Formation in northern Illinois and Iowa and overlies the Maquoketa Shale in eastern Wisconsin. It conformably overlies the Brainard where the Maquoketa reaches its maximum local thickness. It usually contains some red shale at the top. The unit was originally described as an "iron ore" and was correlated with the iron ore of the Silurian Clinton Formation of the Appalachians (Chamberlin, 1877). It was mined locally in eastern Wisconsin from 1849 to 1928, but its distribution was too erratic and its phosphorus content was undesirable (Ostrom, 1976). The age of the Neda is still somewhat uncertain, but its similarity to the Maquoketa and its position below the pre-Silurian unconformity support its placement in the Ordovician rather than the Silurian.

An extensive period of erosion prior to deposition of the overlying Silurian left the Maquoketa Shale with a very irregular upper surface and thickness. However, the general trend of the surface (fig. 15) is very similar to the top of the preceding older formations, dipping strongly from the Wisconsin and Transcontinental arches toward the Michigan, Illinois, and Forest City basins. It is deepest (more than 6,000 ft below sea level) in the center of the Illinois basin.

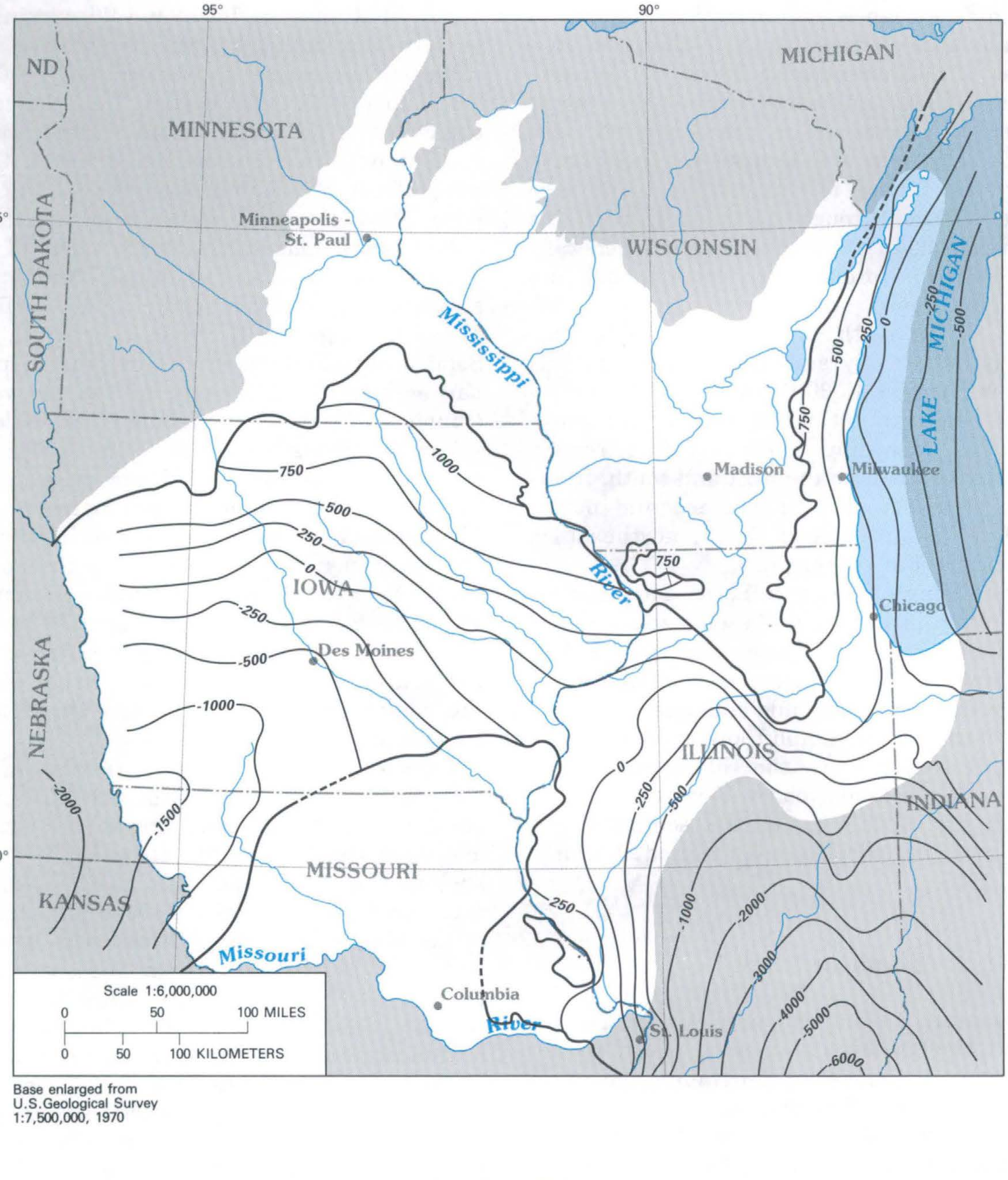
The thickness of the Maquoketa Shale commonly is 150 to 250 ft over most of its area of occurrence, but it ranges from about 80 ft in Minnesota to more than 300 ft in the Forest City basin in Iowa and 800 ft in the Michigan basin (south of Saginaw Bay, just east of the area of pl. 1). It exceeds 450 ft in thickness in northeastern Wisconsin on the Door Peninsula. The Maquoketa thickens greatly eastward across Indiana toward the source of sedimentation in the Appalachian region; the maximum thickness is almost 1,000 ft in southeastern Indiana (Gray, 1972).

SILURIAN SYSTEM

The Silurian System in the northern Midwest consists primarily of carbonate rocks deposited in shallow marine conditions, mainly as reef complexes. Most of the rock is dolomite in the northern part of the area, but limestone, shale, and siltstone are common in the south. The system is divisible into three series: Alexandrian, Niagaran, and Cayugan. Silurian rocks are not present in Minnesota and northwestern and southeastern Iowa, and they are present in Wisconsin only along the eastern edge and as caps on a few high hills in the southwest. The Upper Silurian Cayugan Series is missing in Missouri and northeastern Wisconsin and is only poorly represented in Illinois. Silurian seas, however, covered a much larger area than the present extent of Silurian rocks in the northern Midwest. Large-scale erosion occurred prior to deposition of Middle Devonian rocks. Reef building was a prominent feature of the Silurian. Rapid lithologic changes near the reefs and widespread areas of absence due to erosion make correlation difficult and have produced differing nomenclature. The stratigraphy of the Silurian is not as important as the stratigraphy of the Cambrian and Ordovician to the purpose of this study and is not described here in detail.

Beginning with the lowermost Silurian rocks, carbonate rocks are dominant in a thick sequence through the Middle Devonian Series and are termed the Silurian-Devonian aquifer in this project. This sequence is termed the Hunton Limestone Megagroup (Willman and others, 1975) in Illinois and generally is bounded by fine-grained clastic rocks of the Upper Ordovician Maquoketa Shale below and by Upper Devonian shales above.

The Lower Silurian Alexandrian Series is named from exposures in Alexander County at the extreme



EXPLANATION

—500— STRUCTURE CONTOUR — Shows altitude of the top of the Maquoketa Shale. Includes areas of eroded surface. Contour interval, in feet, is variable. Datum is sea level

——--- EXTENT OF MAQUOKETA SHALE — Dashed where inferred

FIGURE 15.—Altitude of the top of the Maquoketa Shale.

southwestern tip of Illinois. It generally consists of shaly, silty, cherty dolomite in the northern part of the area, with limestone common to the south. Thickness generally is less than 100 ft but reaches 150 to 200 ft where the Alexandrian fills deep erosional channels on the top of the Maquoketa Shale.

The Middle Silurian Niagaran Series, however, is the dominant part of the Silurian in the area. It is mainly fine- to medium-grained dolomite in Wisconsin, northern Illinois, and eastern Iowa. Most of the Silurian reef structures are in the Niagaran, especially in a belt from the Ozarks northeastward across southern Illinois to Ontario and in an area from eastern Iowa through northern Illinois and eastern Wisconsin. In the north, the reefs generally consist of mottled, porous, pure dolomite and are surrounded by dense, silty, cherty dolomite with some shale. To the south, the series is mainly limestone and is more shaly and silty, with major reef structures as much as 1,000 ft thick in south-central Illinois. The Niagaran is thickest in east- and south-central Illinois, exceeding 600 and 700 ft, respectively, but thins rapidly to the west and south. It has been removed by erosion in western and north-central Illinois, southeastern Iowa, northeastern Missouri, and most of Wisconsin.

The Upper Silurian Cayugan Series has been removed by erosion in Iowa and Missouri and is poorly represented in Illinois and Wisconsin. It is mainly dolomitic in the north and calcareous in the south but also contains some shale and siltstone.

Because of the extensive uplift and erosion preceding Middle Devonian time, the Silurian-Devonian contact is mainly unconformable. However, the sea remained in the Illinois basin, and sedimentation was continuous into the Devonian Period (Willman and others, 1975).

DEVONIAN SYSTEM

The Devonian System consists of the Lower, Middle, and Upper Devonian Series, which do not have equivalent provincial or geographic names in the northern Midwest. The extensive period of erosion prior to Middle Devonian time removed strata as old as the Ordovician Galena Group in eastern Iowa and western Illinois.

Lower Devonian strata are present only in the Illinois basin in southern Illinois and southeastern Missouri. They consist mainly of cherty limestone with some shale and dolomite. As stated before, the Devonian is conformable on the Silurian in the Illinois basin, but the Lower Devonian probably was not deposited in higher areas. Thickness increases southward from the erosional edge in south-central Illinois to more than 1,200 ft at the southern tip of Illinois.

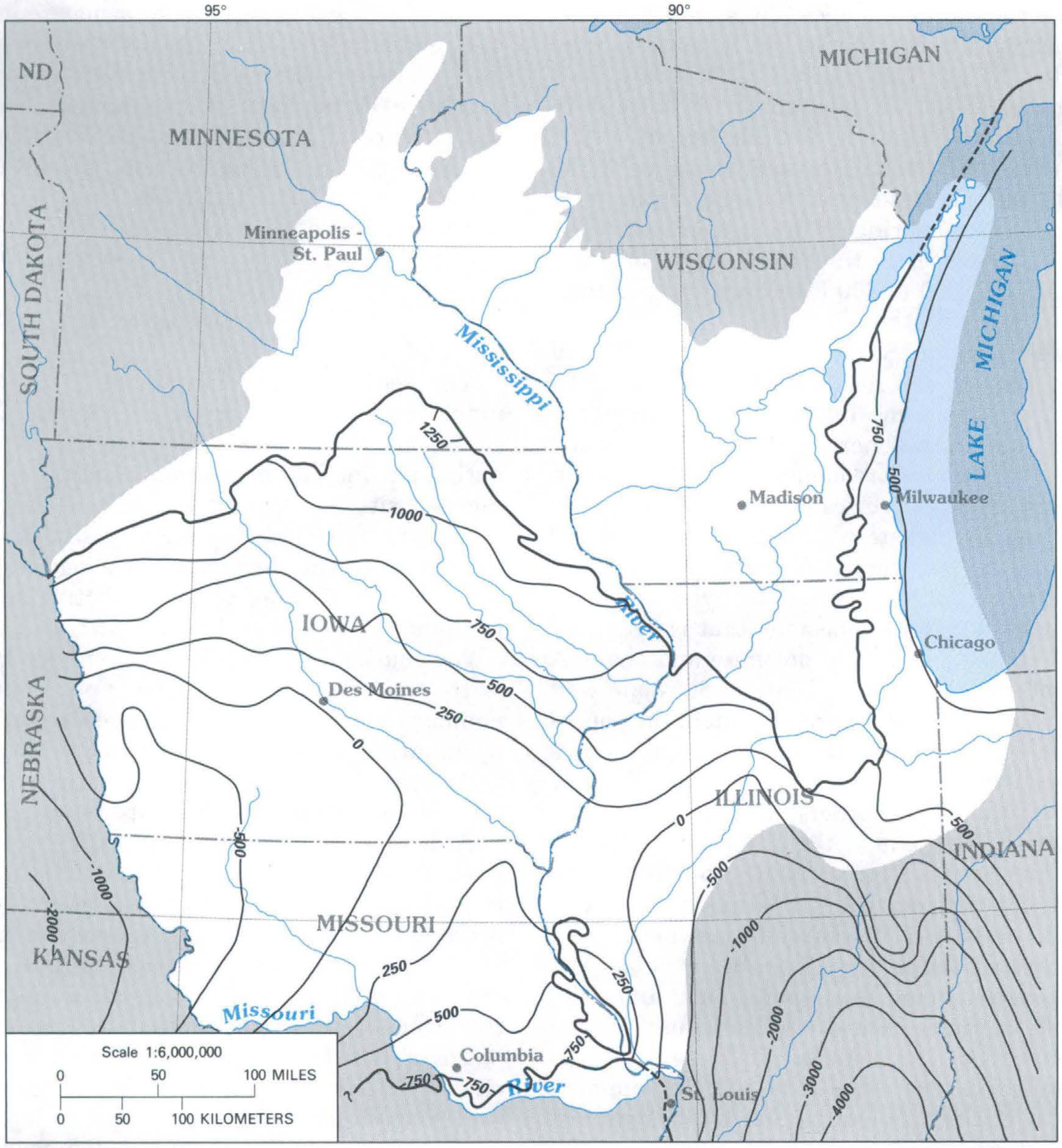
The Middle Devonian Series is present in all the States of the study area and is the primary Devonian strata in Minnesota, Iowa, and Wisconsin. In southeastern Minnesota, it is mainly dolomite with some shale and limestone and is generally 100 to 250 ft thick. In Wisconsin, it is shaly limestone or calcareous dolomite, generally less than 200 ft thick, and is present only in a narrow band about 45 mi long north from Milwaukee along the Lake Michigan shore. The Devonian is not present in the extreme northeastern and northwestern parts of Iowa and the northern one-third of Illinois. Middle Devonian strata in Iowa and the northern parts of Illinois and Missouri are generally crystalline marine limestone. Some interbedded evaporites are present in the lower part of the Middle Devonian in Iowa and west-central Illinois, and some dolomite and black shale are present in the upper part in the Illinois basin. The top of the Hunton Limestone Megagroup in Illinois is the top of the Middle Devonian carbonate rocks. Thickness of the Middle Devonian in Illinois generally increases from 40 to 100 ft in the north to 100 to 300 ft in the south. The Middle Devonian generally is conformable with the Upper Devonian, but a minor unconformity occurs in Missouri and western and southwestern Illinois. The altitude of the top of the combined Middle Devonian through Silurian rocks is shown in figure 16.

Upper Devonian strata are primarily dark-colored shale that contains various amounts of siltstone, sandstone, and limestone. Clastic rocks are more common in the structurally high areas, such as the Ozark uplift and the Mississippi River arch. Distribution of these rocks is similar to that of the Middle Devonian. Thicknesses generally are less than 100 ft in northern Missouri, southwestern Illinois, most of southwestern Iowa, and Wisconsin. They increase to about 300 ft in thickness at the outcrop area in east-central Iowa and are generally 100 to 200 ft thick in the rest of Illinois. The Upper Devonian is overlain conformably by the Lower Mississippian in the Illinois basin but generally is unconformable elsewhere, especially around the Ozark uplift.

MISSISSIPPIAN SYSTEM

The Mississippian System consists of three to four distinctly different series in the northern Midwest.

The classification traditionally recognized by the U.S. Geological Survey is, from oldest to youngest, the Kinderhookian, Osagean, Meremecian, and Chesterian Series. In Illinois and Indiana, the Osagean and Meremecian Series are renamed collectively the Valmeyeran Series.



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

EXPLANATION

—500— STRUCTURE CONTOUR — Shows altitude of the top of the combined Middle and Lower Devonian and Silurian rocks. Includes areas of eroded surface. Contour interval, in feet, is variable. Datum is sea level

———--? EROSIONAL BOUNDARY OF COMBINED MIDDLE AND LOWER DEVONIAN AND SILURIAN ROCKS — Dashed where inferred; queried where unknown

FIGURE 16.—Altitude of the top of the combined Middle Devonian through Silurian rocks.

Mississippian rocks are missing in Minnesota, Wisconsin, the northern one-third of Illinois, most of northern and eastern Iowa and Indiana, and southeastern Missouri. However, they were deposited over a much larger area, as evidenced by as much as 700 ft of Mississippian strata preserved in down-faulted blocks in the 25-mi^2 Des Plaines "Disturbance"—a cryptoexplosion structure just north of Chicago in northeastern Illinois (Emrich and Bergstrom, 1962). The uppermost of these Mississippian rocks is Osagean in age. In addition, a small amount of Pennsylvanian coal-bearing strata are present. The Mississippian increases in thickness southward from a general range of 200 to 600 ft in Iowa to more than 3,200 ft in extreme southern Illinois.

The Kinderhookian Series is mainly shale and siltstone in Illinois and northern Missouri, but the upper part contains some limestone. The limestone increases in abundance northwestward. Limestone and cherty dolomite are predominant in the series in Iowa. Thickness of the series also increases to the northwest from southeastern Illinois, where it is less than 25 ft thick. Its maximum thickness is about 300 ft in central Iowa.

The Osagean is mainly limestone that is generally cherty, with minor amounts of dolomite and shale. A major exception is the thick Borden Siltstone and minor sandstone beds that are dominant in south-central Illinois. These clastic deltaic deposits are from a large river that flowed southwestward into an inland sea (Willman and others, 1975). The Borden is 500 to 600 ft thick and is the thickest part of the Osagean. The series is commonly 150 to 200 ft thick in Iowa, but there it includes the Warsaw Limestone that is considered basal Meremecian elsewhere.

Meremecian strata also are mainly limestone but in addition contain some sandstone, shale, and dolomite. Chert is much less abundant than in the Osagean. In part of southeastern Iowa, beds of gypsum and anhydrite evaporite minerals are common. The series is thickest (almost 1,800 ft) in southern Illinois, where carbonate rocks filled a basin southeast of the Borden Siltstone delta. Upper units of the series are not restricted to the basin and are more extensive over the study area. Thickness decreases northward to about 150 ft in northeastern Missouri and less than 100 ft in central Iowa.

The uppermost series in the Mississippian, the Chesterian Series, is present only in the southern parts of Missouri, Illinois, and Indiana. It consists of repetitive beds of sandstone, shale, and limestone that are classified into 20 formations in southern Illinois. This sediment was derived from a major river flowing southwesterly into southern Illinois, similar to the one that deposited the Borden Siltstone during the Osagean. Units are persistent but may interfinger and be present as lenses. The thickness of the series increases steadily southward from its northern erosional edge to a maximum thickness of more than 1,400 ft at its southern erosional edge. Major erosion occurred prior to deposition of the overlying Pennsylvanian sediments, accounting for the absence of the youngest Mississippian rocks in much of the study area. Deep, southwest-trending channels on the surface of the Chesterian Series in southern Illinois also record this erosional interval.

PENNSYLVANIAN SYSTEM

The sedimentary environment in the Pennsylvanian Period changed from the dominantly marine conditions of previous periods to a pattern of alternating marine and nonmarine conditions. The resulting deposits are mainly clastic sediment, but some limestone and, more conspicuously, coal beds are present. Vertical changes in lithology are extremely numerous, with more than 500 distinguishable units in Illinois (Willman and others, 1975).

A remarkable feature of the Pennsylvanian strata is the cyclothem—a repetitive upward sequence of nonmarine sediment, coal, marine sediment, and a terminating erosional unconformity. More than 50 cyclothems are named in Illinois, but the number decreases away from the Illinois basin.

Although the Pennsylvanian, like the Mississippian, is not present in Wisconsin and Minnesota, it is slightly more extensive in northern Illinois. It is present also in the northwestern one-half of Missouri, in the adjoining area of southern, southwestern, and central Iowa, and in a narrow band along the Illinois border in southwestern Indiana.

The Pennsylvanian System is divided into five series: the Morrowan, Atokan, Desmoinesian, Missourian, and Virgilian Series.

The lowermost series in the Pennsylvanian, the Morrowan Series, is mainly massive, cross-bedded, locally conglomeratic, quartzose sandstone with much siltstone and shale and a few thin coal beds. It is present mainly in southern Illinois and south of the Missouri River in Missouri. It was deposited on an erosional surface with a few hundred feet of relief; thus, its thickness is quite variable. Its maximum thickness in Missouri is 65 ft, but the local maximum thickness is about 350 ft in the Illinois basin.

The overlying Atokan Series is similar to the Morrowan, but the sandstones are generally finer grained and have only a few quartz granules and pebbles. Coal beds also are thicker and more widespread. Shale comprises about one-half of the series in Illinois and is the dominant lithology in Missouri. The Atokan is present over the full extent of the Pennsylvanian in Illinois, thickening similarly to the Morrowan to 300 to 350 ft in the Illinois basin.

The middle Desmoinesian Series is dominated by and contains the most representative cyclothems. It is marked by many thin units, which are very extensive and persistent regionally. Limestone and coal are more abundant than in the older series of the Pennsylvanian. The sandstones contain more clay and detrital minerals, whose abundance increases upward to the extent that shale becomes the main lithology. The series is thickest in the Illinois basin, increasing to about 700 ft from central and western Illinois, where it is generally less than about 200 to 250 ft.

The overlying Missourian Series is somewhat similar to the Desmoinesian but contains more limestone. In Illinois, it is present only in the southeast in the center of the Illinois basin. Its maximum thickness exceeds 500 ft there and in Missouri.

The uppermost Pennsylvanian is the Virgilian Series. It is mainly shale with much sandstone or siltstone in the lower part. Limestone and coal beds present are thin and not as common as in the underlying Missourian. The series has a maximum thickness of about 700 ft in Missouri and about 300 ft in Illinois, where it is present only in the southeast.

The Pennsylvanian Period was the last time widespread seas covered most of the northern Midwest included in this study. Although much of the area was subject to subaerial erosion long before the Pennsylvanian, the present bedrock surface is primarily a product of post-Pennsylvanian erosion and Pleistocene glaciation. Structural contours on the top of the combined Pennsylvanian, Mississippian, and Upper Devonian rocks are shown in figure 17—a depiction of much of the bedrock surface in the southern part of the area. For the present study, this sequence of strata is regarded as a regional confining unit over the Silurian-Devonian aquifer (fig. 18).

PERMIAN SYSTEM

Rocks of Permian age occur in the study area only as isolated channel-fill sandstone deposits in the extreme northwestern corner of Missouri. Permian seas to the west apparently did not encroach significantly on the area of the northern Midwest described in this study.

MESOZOIC ROCKS

Within the study area, the Mesozoic Era is represented only by Jurassic and Cretaceous sedimentary rocks (pl. 1). Jurassic shale, sandstone, and gypsum occur locally in central Iowa, and Upper Jurassic sandstone and shale form the bedrock surface near the center of the Lower Peninsula of Michigan, just east of the study area. Cretaceous sandstone, siltstone, and shale compose the uppermost bedrock in much of southwestern Minnesota and western Iowa. The Dakota Formation is an important Cretaceous unit that consists of fine- to medium-grained, poorly cemented sandstone and shale. The Dakota averages about 150 ft in thickness but attains a maximum of about 400 ft (Munter and others, 1983). It was deposited unconformably on the outcropping surfaces of rocks ranging in age from Precambrian to Pennsylvanian. Cretaceous seas west of the area encroached onto the highland of the Transcontinental arch and deposited fine-grained clastic sediment derived from the Cordilleran mountain building in the Western United States. In extreme west-central Illinois, as much as 100 ft of sand containing clay beds and a basal gravel is assigned to the Upper Cretaceous. The deposits generally are nonindurated and resemble the Dakota sediment in Iowa (Willman and others, 1975). Isolated deposits of nonmarine gravel and iron-rich clay on upland surfaces near the Mississippi River in Iowa, Minnesota, and Wisconsin generally are classified as Cretaceous in age (Andrews, 1958).

CENOZOIC ROCKS

Tertiary rocks in the study area consist only of local deposits of gravel in western Illinois, similar to the Cretaceous gravels in Iowa and Wisconsin. The age of all of the gravels is somewhat speculative.

QUATERNARY SYSTEM

PLEISTOCENE SERIES

Continental ice sheets spread into the area from centers of snow accumulation in Canada during the Pleistocene Epoch [2,000,000 to 10,000 yr B.P. (before present)]. At least three major periods of glaciation are presently recognized and are referred to as pre-Illinoian, Illinoian, and Wisconsin (Richmond and Fullerton, 1986); ice advanced as far south as the southern parts of Illinois and Indiana and to the

Missouri River in Missouri (fig. 3). Interstadials (warmer periods of ice retreat) separated the periods of glaciation. The ice advanced at various rates as lobes from different ice centers, which only partially covered the study area at a given time. An area of southwestern Wisconsin and northwestern Illinois

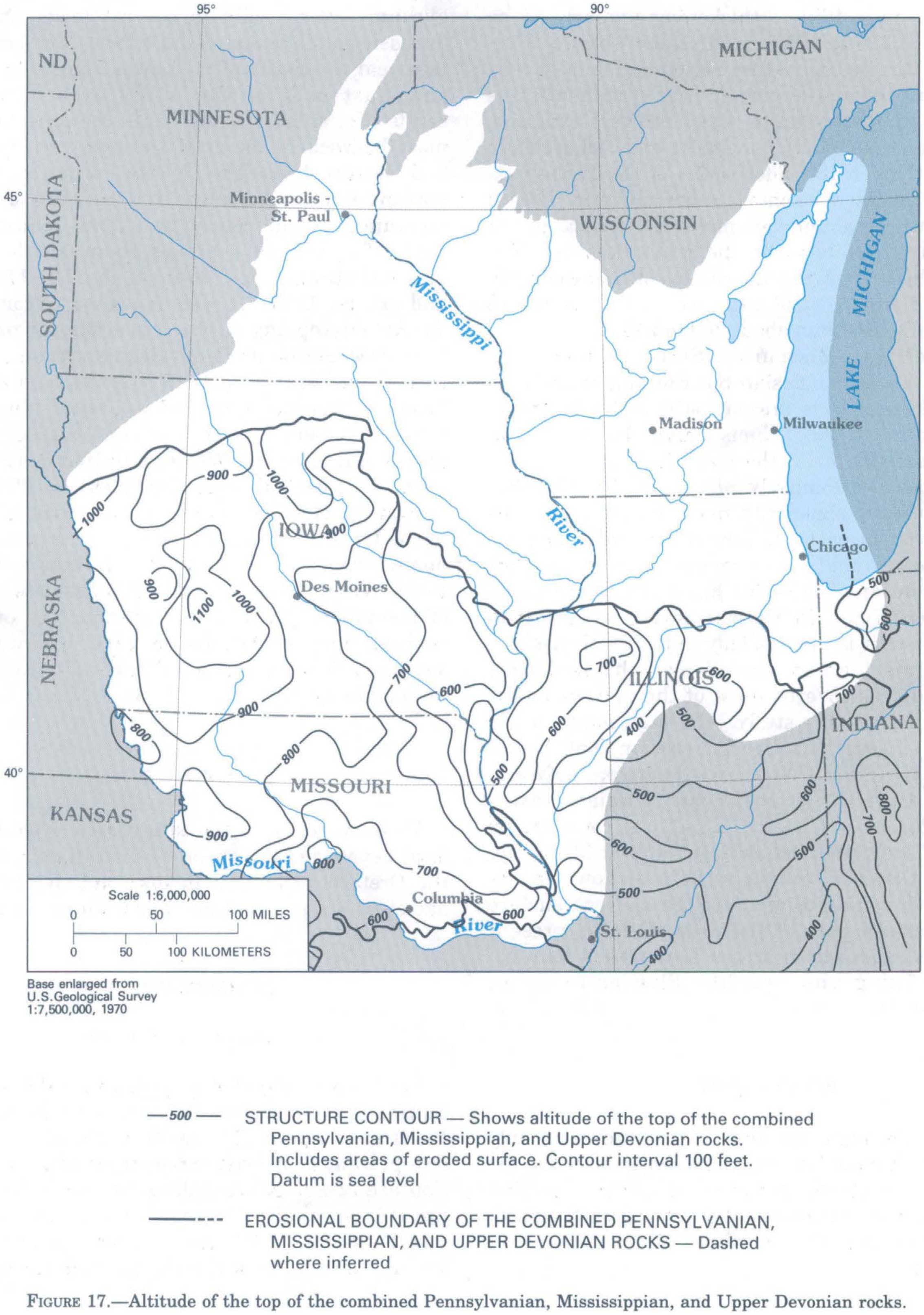


FIGURE 17.—Altitude of the top of the combined Pennsylvanian, Mississippian, and Upper Devonian rocks.

shows no evidence of having been glaciated and is termed the Driftless Area. An adjacent area of southeastern Minnesota and northeastern Iowa contains patchy remnants of pre-Illinoian drift whose easternmost limit coincides approximately with the Mississippi River (H.C. Hobbs, Minnesota Geological Survey, written commun., 1987).

The pre-Illinoian drift in Iowa and southeastern Minnesota shows evidence of other glaciations. This drift is more than 300 ft thick in places, especially in bedrock valleys or beneath end moraines. The valleys are part of extensive drainage networks carved on the pre-Pleistocene bedrock surface.

Illinoian ice covered mainly the State of Illinois, where as much as 150 ft of drift was deposited. The drift consists variously of calcareous, clayey to sandy, gravelly till layers, interbedded sands and gravels, and beds of loess silt. Only loess and alluvial deposits represent this glaciation in Missouri and most of Iowa. The Illinoian drift forms the land surface of most of western and south-central Illinois.

The drift and resultant topography from the last glaciation, the Wisconsin, are much less altered than those from the older glaciations. Classic features of continental glaciation are therefore abundant and well preserved in the Wisconsin drift, especially in Minnesota and Wisconsin. Much of the older drift in the path of the Wisconsin glaciers was incorporated into the newer drift and is not commonly distinguished beneath the Wisconsin drift in Minnesota and Wisconsin. However, in Iowa and Illinois toward the perimeter of the Wisconsin ice, the older drift was not obliterated and commonly occurs beneath the Wisconsin drift, especially in buried bedrock valleys. Sorted sand and gravel of Wisconsin age is common as surficial or near-surface deposits of outwash from meltwater streams.

Drift thickness over the area is quite variable because of the configuration of the underlying bedrock topography and depositional processes. Average thickness probably ranges from 50 to 100 ft and is least in areas of ground moraine. Locally, in terminal moraines and buried bedrock valleys, thickness commonly ranges from 200 to 400 ft and is more than 600 ft in places.

HOLOCENE SERIES

The present climatic and depositional environments have developed during the Holocene Epoch, which began after the last Wisconsin glaciers retreated as recently as 10,000 yr B.P. Major rivers have deposited alluvial sediment in their valleys, which locally may add appreciable thickness above the Pleistocene valley fill.

GROUND-WATER HYDROLOGY

Ground water is generally plentiful in the northern Midwest because the area receives abundant precipitation ranging from 24 to 44 in. annually (fig. 2) and is widely underlain by large amounts of permeable, unconsolidated rocks (glacial drift and alluvial deposits) and bedrock aquifers that store large quantities of ground water. Availability of ground water is very limited in areas where these aquifers are absent, especially along the northern fringes of the study area, where Precambrian crystalline rocks are at or near the land surface.

Local, intermediate, and regional patterns of ground-water flow control the occurrence of ground water in the northern Midwest. The local and intermediate ground-water flow systems are closely related to the water table and local topographic and surface drainage features. Regional flow is controlled mainly by elevation differences between the major regional topographic features and by the regional framework of aquifers and confining units. The public generally does not understand the basic principles of ground-water occurrence and have many misconceptions. Water from deep wells in the study area commonly is thought to be derived from Lake Superior.

AQUIFERS AND CONFINING UNITS

The rocks in the northern Midwest are subdivided into 11 regional hydrogeologic units on the basis of their geologic and hydraulic characteristics (fig. 18). These hydrogeologic units were used in model simulations discussed in chapter C of this Professional Paper (Mandle and Kontis, in press). The two uppermost hydrogeologic units, the drift and the Cretaceous aquifers, generally are unconfined and are the top layer of the regional flow model (Mandle and Kontis, in press). The consolidated sedimentary rocks below the drift and Cretaceous aquifers are subdivided into four regional aquifers, each overlain by a confining unit. The great thickness of rocks in the southern part of the study area that are older than Cretaceous and younger than Middle Devonian is collectively delineated as the Pennsylvanian-Mississippian-Devonian confining unit, although parts of this rock sequence are local aquifers. Underlying this confining unit is the Silurian-Devonian aquifer, composed of Silurian and Lower and Middle Devonian rocks, which are primarily dolomite.

The lower three aquifers and their associated confining units, composed of rocks of Cambrian and Ordovician ages (primarily the Upper Cambrian

Time-stratigraphic unit: System	Time-stratigraphic unit: Series	Rock-stratigraphic unit *	Southeastern Minnesota	Wisconsin	Iowa
Quaternary	Holocene	Undifferentiated	Undifferentiated drift aquifer	Sand and gravel aquifer	Surficial aquifer
Quaternary	Pleistocene	Undifferentiated	Undifferentiated drift aquifer	Sand and gravel aquifer	Surficial aquifer
Cretaceous			Cretaceous aquifer (local)	Absent	Cretaceous aquifer
Pennsylvanian	Virgilian, Missourian, Desmoinesian, Atokan, Morrowan	Undifferentiated	Absent	Absent	Confining beds
Mississippian	Chesterian	Undifferentiated	Absent	Absent	Absent
Mississippian	Meramecian	Ste. Genevieve Ls., St. Louis Ls., Salem Ls., Warsaw Ls.	Absent	Absent	Mississippian aquifer
Mississippian	Osagean	Keokuk Ls., Burlington Ls.	Absent	Absent	Mississippian aquifer
Mississippian	Kinderhookian	Undifferentiated	Absent	Absent	Mississippian aquifer
Devonian	Upper	Undifferentiated	Absent	Absent	Confining bed
Devonian	Middle	Undifferentiated	Devonian (Upper carbonate aquifer)	Silurian dolomite aquifer	Silurian–Devonian aquifer
Devonian	Lower	Undifferentiated	Absent (Upper carbonate aquifer)	Absent (Silurian dolomite aquifer)	Absent (Silurian–Devonian aquifer)
Silurian	Cayugan	Undifferentiated	Absent (Upper carbonate aquifer)	Silurian dolomite aquifer	Silurian–Devonian aquifer
Silurian	Niagaran	Undifferentiated	Absent (Upper carbonate aquifer)	Silurian dolomite aquifer	Silurian–Devonian aquifer
Silurian	Alexandrian	Undifferentiated	Absent (Upper carbonate aquifer)	Silurian dolomite aquifer	Silurian–Devonian aquifer
Ordovician	Cincinnatian	Maquoketa Shale	Maquoketa, Dubuque, and Galena Fm. (Upper carbonate aquifer)	Maquoketa Shale	Confining bed
Ordovician	Mohawkian	Galena Dol., Decorah Fm., Platteville Fm.	Maquoketa, Dubuque, and Galena Fm. (Upper carbonate aquifer); Decorah–Platteville–Glenwood confining bed	Galena–Platteville aquifer	Water bearing; Confining bed
Ordovician	Mohawkian	Glenwood Fm.	Decorah–Platteville–Glenwood confining bed	Sandstone aquifer	Confining bed
Ordovician	Chazyan	St. Peter Ss.	St. Peter aquifer; Basal St. Peter confining bed	Sandstone aquifer	Water bearing; Confining bed (Cambrian–Ordovician aquifer system)
Ordovician	Canadian	Prairie du Chien Gp.: Shakopee Fm.	Prairie du Chien–Jordan aquifer	Sandstone aquifer	Jordan aquifer (Cambrian–Ordovician aquifer system)
Ordovician	Canadian	Prairie du Chien Gp.: Oneota Dol.	Prairie du Chien–Jordan aquifer	Sandstone aquifer	Jordan aquifer (Cambrian–Ordovician aquifer system)
Cambrian	St. Croixan	Jordan Ss.	Prairie du Chien–Jordan aquifer	Sandstone aquifer	Jordan aquifer (Cambrian–Ordovician aquifer system)
Cambrian	St. Croixan	St. Lawrence Fm.	St. Lawrence–Franconia confining bed	Sandstone aquifer	Confining bed
Cambrian	St. Croixan	Franconia Fm.	St. Lawrence–Franconia confining bed	Sandstone aquifer	Confining bed
Cambrian	St. Croixan	Ironton Ss.	Ironton–Galesville aquifer	Sandstone aquifer	Water bearing (Dresbach aquifer)
Cambrian	St. Croixan	Galesville Ss.	Ironton–Galesville aquifer	Sandstone aquifer	Water bearing (Dresbach aquifer)
Cambrian	St. Croixan	Eau Claire Formation	Eau Claire confining bed	Sandstone aquifer	Confining bed (Dresbach aquifer)
Cambrian	St. Croixan	Mount Simon Sandstone	Mount Simon–Hinckley aquifer	Sandstone aquifer	Water bearing (Dresbach aquifer)
Precambrian		Bayfield Gp.: Hinckley Ss.	Mount Simon–Hinckley aquifer ? — — — ?	Lake Superior sandstones and lava flows	(little information)
Precambrian		Bayfield Gp.: Fond du Lac Fm.	Confining bed	Lake Superior sandstones and lava flows	(little information)
Precambrian		Oronto Gp.: Solor Church Fm.	Confining bed	Lake Superior sandstones and lava flows	(little information)
Precambrian		Crystalline rocks	Confining bed	Confining unit	Confining bed
References			Delin and Woodward (1984)	Kammerer (1984)	Horick and Steinhilber (1973, 1978); Horick (1984)

* General geologic nomenclature of the upper Mississippi Valley

FIGURE 18.—Hydrogeologic unit nomenclature in the northern Midwest. Aquifer units are shaded. Dol., Dolomite; Fm., Formation; Gp., Group; Ls., Limestone; Mbr., Member; Sh., Shale; Ss., Sandstone.

Northern Illinois	Northern Illinois: Aquigroup	Northern Illinois: Aquifer or aquitard	Northern Missouri	Hydrogeologic unit *	Layer number in digital flow model *
Glacial drift aquifers	Prairie	Pleistocene	Drift (minor aquifers in buried valleys)	Drift aquifer	Aquifer layer 5
Absent		Absent	Absent	Cretaceous aquifer	
Shallow bedrock aquifers	Upper Bedrock; Mississippi Valley Bedrock	Pennsylvanian	(Poor aquifer)	Pennsylvanian–Mississippian–Devonian confining unit	Confining layer 4–5
		Absent	Absent		
		St. Louis–Salem aquifer	(Poor aquifer)		
		Confining unit			
		Keokuk–Burlington aquifer	Mississippian aquifer		
		Confining unit	(Confining bed) — Upper confining bed		
		Devonian		Silurian–Devonian aquifer	Aquifer layer 4
		Silurian Dolomite aquifer	(Poor aquifer)		
Confining bed		Maquoketa confining unit	(Confining bed)	Maquoketa confining unit (Cambrian–Ordovician aquifer system)	Confining layer 3–4
Cambrian–Ordovician aquifer	Midwest Bedrock	Galena–Platteville unit	Kimmswick Fm. (minor aquifer) (Cambrian–Ordovician aquifer)		
			Decorah Fm. Plattin Fm. Joachim Dol. (confining bed)		
		Ancell aquifer	St. Peter Ss. Everton Dol. (moderate aquifer)	St. Peter–Prairie du Chien–Jordan aquifer	Aquifer layer 3
		Middle confining unit: Prairie du Chien Group	Confining bed		
			Roubidoux Fm. Gasconade Dol.		
		Eminence Fm. Potosi Dol.	Eminence Dol. Potosi Dol. (good aquifer)		
		Franconia Fm.	Derby–Doerun Dol. (poor aquifer)	St. Lawrence–Franconia confining unit	Confining layer 2–3
		Ironton–Galesville aquifer	Davis Formation (Lower confining bed)	Ironton–Galesville aquifer	Aquifer layer 2
Confining bed	Basal Bedrock	Eau Claire confining unit	Bonneterre Fm. (little information)	Eau Claire confining unit	Confining layer 1–2
Elmhurst–Mount Simon aquifer		Elmhurst–Mount Simon aquifer	Lamotte Ss. (probable aquifer)	Mount Simon aquifer	Aquifer layer 1
Absent	Absent		Absent (?)	Confining unit	Impermeable boundary
Confining bed	Confining unit		Confining bed		
Schicht and others (1976); Sasman and others (1982)	Visocky and others (1985)		Imes (1985)		Mandle and Kontis (in press)

* Nomenclature of the Northern Midwest Regional Aquifer-System Analysis

FIGURE 18.—Continued.

sandstones), are the Cambrian-Ordovician aquifer system of this study. These hydrogeologic units are named (fig. 18) for their primary stratigraphic components in the northern part of the area, using the generalized upper Mississippi Valley nomenclature as described previously. Rocks younger than Cambrian or Ordovician age overlie the aquifer system in more than one-half of the study area, mainly in the west, south, and east.

The lowermost hydrogeologic unit is a confining unit that consists of generally very low permeability crystalline rocks of the Precambrian basement and, in Minnesota, most of the Precambrian sedimentary rocks below the Hinckley Sandstone. Significant ground-water flow in the dense crystalline rocks occurs only in fractures and joints within a few to several tens of feet below the top of these rocks. This confining unit is considered to be an impermeable boundary beneath the Cambrian-Ordovician aquifer system in the regional flow model (Mandle and Kontis, in press).

As is shown in figure 18, rocks of the hydrogeologic units are grouped into somewhat different and, in some cases, more detailed aquifer configurations in some States. Aside from the obvious factor of variation in lithology, other factors have affected the importance or utilization of an aquifer in a particular area. These include depth below land surface, stratigraphic position, structural configuration, water quality, and prevalent local drilling and well-completion practices.

Most wells in the study area are finished in more than one aquifer; therefore hydraulic characteristics from pumping tests generally are not available for a particular aquifer, except in areas where the aquifer is at or near the surface. The most abundant and readily available data on hydraulic characteristics are specific capacities from well-completion or production tests. Using the method of Theis and others (1963), Mandle and Kontis (in press) estimate transmissivities and hydraulic conductivities from specific capacities of about 2,500 single-aquifer wells in the study area. Geometric means and standard deviations of the hydraulic conductivities were computed for each aquifer and were used as a guide for input to the regional flow model. The values required for model calibration generally were only slightly lower than the values derived from specific capacities, except for the specific capacity of the Silurian-Devonian aquifer, for which the model value was more than one standard deviation less than the geometric mean determined from more than 1,800 values.

DRIFT AQUIFER

Because glacial drift is almost universally present in the study area and is the shallowest permeable rock material, it provides a ready source of ground water. Ground-water availability from the drift is directly proportional to the amount of permeable, well-sorted sand and gravel within the drift. The large variety of sediment types in the drift have a wide range of sorting and depositional form; however, the drift is mainly ground or end moraine, which consists of much fine-grained sediment, either as the main component or as the matrix between larger sized sediment. Sand and gravel is less abundant, present as discontinuous lenses within or beneath moraine or as more extensive outwash and ice-contact deposits.

The drift is not considered in detail because of the emphasis in this study on the Cambrian-Ordovician aquifer system; however, it is a very important hydrogeologic unit. It generally contains the water table and is a large reservoir for ground-water storage. The permeability of the drift is a controlling factor in ground-water recharge and discharge, not only directly to and from the water table but, more importantly to this study, through the top of the bedrock where it subcrops beneath the drift.

The drift and Cretaceous are represented in the regional flow model as an upper constant-head boundary (constant water-table altitude) and, thus, are constrained to function only as a flux source or sink for the layers below. General hydraulic characteristics of the drift are incorporated in the regional flow model to control simulated vertical flow to or from the glacial drift where it directly overlies an aquifer.

CRETACEOUS AQUIFER

Sandstone of the Cretaceous Dakota Formation forms an important artesian aquifer in North and South Dakota and in northwestern Iowa. It is confined by interbedded and overlying Cretaceous shales and siltstones and by fine sediment in the glacial drift. The sandstone of the Dakota in northwestern Iowa is generally 100 to 200 ft thick but attains a maximum thickness of more than 300 ft (Burkart, 1984). The shale averages 100 to 150 ft in thickness but is discontinuous. Lowermost Cretaceous rocks lie directly on the eroded edge of rock units ranging in age from Precambrian to Pennsylvanian. For purposes of the regional flow model, all

Cretaceous rocks in northwestern Iowa are included with the glacial drift to compose a single water-table aquifer. This aquifer was not studied in any detail during this study, but the Dakota aquifer in Nebraska and Kansas is described in the adjacent Central Midwest RASA project (Jorgensen and Signor, 1981).

PENNSYLVANIAN-MISSISSIPPIAN-DEVONIAN CONFINING UNIT

The thick sequence of Pennsylvanian, Mississippian, and Upper Devonian rocks in the study area consists mainly of shales and carbonate rocks, which generally have low permeability. They underlie most of the southern part of the study area but are absent in Minnesota, Wisconsin, northeastern Iowa, northern Illinois, and northwestern Indiana. They gradually increase in thickness away from these areas to more than 3,000 ft in the Illinois and Michigan basins and to more than 1,000 ft in the Forest City basin in Iowa. Although some parts of this sequence contain fairly permeable sandstone and carbonate rocks that yield small to moderate water supplies, its great thickness and the predominance of low-permeability shale and carbonate rock cause it to function as a regional confining unit between the drift and Silurian-Devonian aquifers in the southern part of the study area.

SILURIAN-DEVONIAN AQUIFER

Dolomite and limestone constitute most of the Silurian through Middle Devonian rocks in the study area, which are collectively termed the Silurian-Devonian aquifer in this study. The rock is relatively fine grained and dense, and its permeability is primarily dependent on the extent and degree of intersection of fractures and joints within it and on the subsequent solutional enlargement of these openings by weathering action and ground-water movement. This secondary permeability is best developed in the shallower parts of the aquifer where the rocks crop out or subcrop beneath glacial drift. There are three main outcrop areas: (1) a broad band from southeastern Minnesota through northeastern Iowa into northwestern Illinois, (2) a narrow strip along the western shore of Lake Michigan from the Upper Peninsula of Michigan down the eastern side of Wisconsin into northeastern Illinois, and (3) an extension of the latter area to include most of northern and eastern Indiana (pl. 1).

In southeastern Minnesota, where the intermediate rocks are missing because of erosion or nondeposition, dolomite of the Middle Devonian Cedar Valley Formation lies directly on the lower part of the Maquoketa Formation. Limestone and dolomite of these rock units and the underlying Dubuque and Galena Formations compose the upper carbonate aquifer of southeastern Minnesota (fig. 18).

Permeability differs greatly within the Silurian-Devonian aquifer, commonly decreasing with depth below the top of the aquifer as the effects of weathering decrease. Fractures and joints generally are localized and have little continuity, causing large, abrupt lateral variations in permeability. Some large-scale jointing patterns and fracture traces in outcrop areas can be mapped from aerial photography and satellite imagery in order to provide a guide to possible zones of high permeability. Down dip from the subcrop areas, the aquifer is confined by the Pennsylvanian-Mississippian-Devonian confining unit; thus, the carbonate rocks there have not been weathered, and secondary solutional permeability has not developed. In these areas, the Middle and Lower Devonian limestones function as leaky confining units, especially where they are not overlain by younger shales (Imes, 1985). Horick (1984) reports that transmissivities of the Silurian-Devonian aquifer determined from pumping tests in Iowa range from as low as 200 ft^2/d (feet squared per day), where the aquifer is confined or has few openings, to 360,000 ft^2/d in areas with large solution openings or highly fractured rock (table 1). However, most transmissivities range from about 670 to 2,000 ft^2/d. The other data given in table 1 also show a wide range of transmissivities and hydraulic conductivities for the aquifer. The following average values of hydraulic conductivity have been used for the Silurian-Devonian aquifer in various models of ground-water flow in the study area.

1. Northern Midwest regional model (Mandle and Kontis, in press)—an average value of 0.39 ft/d (feet per day) for the aquifer in the entire study area.
2. Northeastern Wisconsin (Emmons, 1987) and Brown County, Wisconsin (Krohelski, 1986)—an average of 7.9 ft/d for the aquifer in northeastern Wisconsin.
3. Northeastern Illinois-southeastern Wisconsin (H.L. Young and A.J. MacKenzie, U.S. Geological Survey, written commun., 1988)—an average value of 0.17 ft/d for the aquifer in northeastern Illinois and southeastern Wisconsin.

TABLE 1.—*Hydraulic characteristics of the Silurian-Devonian aquifer*

[----, not available; Do. (do.), ditto]

Well or site location	No. of wells or tests	Geologic unit (nomenclature of this report)	Transmissivity, *T* (ft^2/d)		Horizontal hydraulic conductivity, *K* (ft/d)		Storage coefficient, *S* (dimensionless)		Reference or source	Remarks
			Value or range	Average	Value or range	Average	Value or range	Average		
Southeastern Minnesota	----	Devonian, Maquoketa Formation, and Galena Dolomite	1,100-23,000	----	3.3-40	----	1.0×10^{-5}-1.0×10^{-2}	----	Kanivetsky and Walton (1979)	Range of values, including estimates from specific capacities.
Iowa	----	Devonian and Silurian rocks	200-360,000	----	----	----	1.0×10^{-4}-3.2×10^{-2}	----	Horick (1984)	Numerous pumping tests Statewide.
Milwaukee, Wis.	3	Silurian rocks	67-640	330	.28-2.0	1.1	5.6×10^{-4}-4.8×10^{-3}	3.0×10^{-3}	Milwaukee Metropolitan Sewerage District (written commun., 1981)	From pumping tests.
Do.	5	-do.-	----	----	.068-1.6	0.49	----	----	-do.-	Averages of packed zone pressure tests at 20-ft intervals in 5 test borings.
Du Page Co., Ill.	5	-do.-	1,400-11,400	----	----	----	9.0×10^{-5}-3.5×10^{-4}	----	Visocky and others (1985)	
Chicago Deep Tunnel test well, Lake Calumet area, Cook Co., Ill.	1	-do.-	----	----	----	----	----	----	Papadopulos and others (1969)	9 gal/min net yield in 158 min from 435-ft-thick interval.
Glasford gas storage project, Peoria Co., Ill.	----	-do.-	----	140	----	1.2	----	----	Buschbach and Bond (1967)	Laboratory determination of *K* from drill cores.
Lincoln gas storage project, Logan Co., Ill.	----	-do.-	----	58	----	.68	----	----	Van Den Berg (1975)	Do.
C and E Power Systems, East Chicago, Lake Co., Ind.	1	-do.-	----	----	----	----	----	----	USGS packer test, 1980	Negligible yield from 277-ft-thick interval.

The Silurian-Devonian aquifer thickens from the eroded edge in the north toward the structural basins to the south and east, most prominently toward the Michigan and Illinois basins, where it exceeds 1,000 ft. It more commonly is 200 to 500 ft thick in the areas of outcrop and on the fringes of the basins.

MAQUOKETA CONFINING UNIT

Excellent confinement by the Maquoketa confining unit is the main reason why the aquifers comprised of Cambrian and Ordovician rocks are delineated as a regional aquifer system. This confining unit consists of the Maquoketa Shale, the Galena Dolomite, and the Decorah, Platteville, and Glenwood Formations or equivalents. The latter four units are included in the confining unit only where they are overlain by the Maquoketa. The Maquoketa is mainly shale but also contains significant amounts of carbonate rocks in most of the study area. As previously stated, in southeastern Minnesota the formation is dominantly limestone and, along with overlying (Devonian Cedar Valley Formation) and underlying (Dubuque and Galena Formations) carbonate rocks, forms the upper carbonate aquifer (fig. 18). The confining unit in most of the study area usually ranges from 150 to 250 ft in thickness where it has not been eroded.

The Galena, Decorah, and Platteville Formations, also referred to as the Galena-Platteville unit, consist mostly of carbonate rocks with some shale. The unit is moderately permeable in its outcrop area and is a minor aquifer. However, beneath the Maquoketa

Shale (similar to the condition of the buried Silurian-Devonian aquifer), these carbonate rocks are not weathered and generally have not developed secondary permeability, as shown by several packer pumping tests conducted in wells where the Maquoketa is present. The Galena-Platteville unit generally yielded no water during these tests in Wisconsin, northern Illinois, and northwestern Indiana. Similar results were reported by Papadopulos and others (1969) from a packer test southeast of Chicago. The Galena-Platteville unit, therefore, is considered to be part of the Maquoketa confining unit where overlain by the Maquoketa Shale. In northern Missouri, the equivalent Decorah and Plattin Formations and the Joachim Dolomite (mainly carbonate rocks) contain dolomite with various amounts of interbedded shale that restricts vertical ground-water flow (Imes, 1985). Collective thickness of the Galena-Platteville unit commonly exceeds 300 ft.

The lowermost part of the Maquoketa confining unit, the Glenwood Formation, contains shale, silty dolomite, and silty sandstone and generally is present only in northern Illinois, Wisconsin, and Iowa. It usually is much less than 50 ft thick and averages only 5 ft in thickness in Minnesota. The thickness of the Maquoketa confining unit increases to the south and east and commonly is 400 to 600 ft in eastern Iowa, eastern Wisconsin, and northeastern Illinois.

Estimates of the vertical hydraulic conductivity K' of the Maquoketa confining unit are available only indirectly from flow-net analyses or digital models. Walton (1960) derived values for the Maquoketa Shale ranging from 4.0×10^{-6} to 1.3×10^{-5} ft/d by flow-net analysis of the assumed predevelopment composite head in the Cambrian-Ordovician aquifer system in extreme northeastern Illinois. He then used 6.7×10^{-6} ft/d as an average K' value to estimate leakage through the Maquoketa in the Chicago area in 1958. This value has been used in various versions of the Illinois State Water Survey two-dimensional ground-water flow model of the Chicago area (Prickett and Lonnquist, 1971; Schicht and others, 1976; Visocky, 1982). Young (1976) used values ranging from 1.3×10^{-6} to 4.7×10^{-5} ft/d for the Maquoketa Shale in southeastern Wisconsin in calibrating a two-dimensional ground-water flow model of the Cambrian-Ordovician aquifer system in southeastern Wisconsin and northeastern Illinois. In each of these cases, the thickness b' of only the Maquoketa Shale was used in the relationship K'/b' (vertical leakance). The values are probably somewhat too large to represent only the Maquoketa Shale because the underlying Galena-Platteville unit was not considered.

Values of K' representative of the entire Maquoketa confining unit have been used in other flow models of Cambrian-Ordovician aquifers.

1. Northern Midwest regional model (Mandle and Kontis, in press)—6.9×10^{-7} to 4.3×10^{-4} ft/d.
2. Northeastern Wisconsin (Emmons, 1987)—4.0×10^{-6} ft/d.
3. Brown Co., Wisconsin (Krohelski, 1986)—7.0×10^{-6} to 7.0×10^{-5} ft/d.
4. Northeastern Illinois-southeastern Wisconsin (H.L. Young, and A.J. MacKenzie, U.S. Geological Survey, written commun., 1988)—8.6×10^{-7} to 1.7×10^{-4} ft/d.
5. Northeastern Missouri (Imes, 1985)—5.2×10^{-6} to 1.6×10^{-5} ft/d. Overlying Devonian and Mississippian shales and limestones also are included.

Vertical hydraulic conductivity of the Galena-Platteville unit, where it crops out or subcrops beneath glacial drift, also has been estimated during calibration of some of the models.

1. Southeastern Wisconsin (Young, 1976)—4.0×10^{-4} to 3.3×10^{-3} ft/d.
2. Northeastern Wisconsin (Emmons, 1987)—1.0×10^{-4} ft/d.
3. Brown Co., Wisconsin (Krohelski, 1986)—7.0×10^{-5} to 3.0×10^{-3} ft/d.
4. Northeastern Illinois-southeastern Wisconsin (H.L. Young and A.J. MacKenzie, U.S. Geological Survey, written commun., 1988)—3.0×10^{-4} to 6.9×10^{-4} ft/d.
5. Twin Cities (Minneapolis-St. Paul) area (Guswa and others, 1982)—1.0×10^{-4} to 6.0×10^{-4} ft/d.

ST. PETER-PRAIRIE DU CHIEN-JORDAN AQUIFER

Although this multiunit aquifer may be the least uniform of the bedrock aquifer units in the northern Midwest (fig. 18), it is a major source of ground water in Iowa and Minnesota. In these States, the Jordan Sandstone and all or parts of the overlying Prairie du Chien Group are in direct hydraulic connection, resulting in a highly productive aquifer. The aquifer subcrops beneath glacial drift on the edges of the Hollandale embayment in southeastern Minnesota and extreme northeastern Iowa. It is confined and dips southwestward across Iowa into the Forest City basin. The aquifer underlies the ridges of the Driftless Area and adjacent parts of Minnesota where the water table is very deep and the upper part of the aquifer is unsaturated. The St. Peter commonly is regarded as a separate aquifer from the

Prairie du Chien and Jordan in Minnesota and western Illinois.

The St. Peter Sandstone is widely distributed and recognized in wells in the area. Its thickness increases dramatically within short distances because its basal beds fill topographically low parts of the irregular erosional surface on which it was deposited. The increased thickness due to these basal beds (the poorly sorted, fine-grained Kress or Readstown Members) apparently adds little to the transmissivity of the St. Peter (Visocky and others, 1985). The Tonti and Starved Rock Members are very well sorted and fairly permeable; however, they are poorly cemented and commonly the rocks cave badly in wells, which requires some intervals to be sealed with casing or liners. Shale in the basal beds also presents caving problems. Regionally, the St. Peter Sandstone is hydraulically connected to the Prairie du Chien Group.

The underlying Prairie du Chien Group is discontinuous because rocks of the group formed much of the land surface that was deeply eroded prior to the deposition of the St. Peter Sandstone. As stated previously, the group has been mainly or entirely eroded in large areas of northern Illinois and southern Wisconsin. Some secondary porosity was created by weathering and solution of the dolomite by water during the period of subaerial erosion prior to deposition of the St. Peter. The resulting openings, such as fractures, vugs, and caverns, are common in Iowa, Minnesota, and Wisconsin and locally produce very high permeability. In places, the Prairie du Chien Group may be more permeable than the underlying Jordan Sandstone (Horick and Steinhilber, 1978). Karst topography was formed in the carbonate rocks on the pre-St. Peter erosional surface, but Visocky and others (1985) state that no remnant of increased permeability because of solution channels is apparent in northern Illinois. The New Richmond Sandstone Member of the Shakopee Formation of the Prairie du Chien Group is somewhat similar to the Jordan, but it is thinner and more variable. In some areas, the New Richmond probably contributes significantly to the yield of wells. The uppermost Prairie du Chien, the Willow River Member of the Shakopee Formation, and the basal beds of the St. Peter locally confine the Prairie du Chien and Jordan. Equivalent rocks to the Prairie du Chien in northern Missouri, the Roubidoux Formation and Gasconade Dolomite, are mainly carbonate, but they also contain enough sandstone to make them productive and important aquifers.

The Jordan Sandstone is a major component of the St. Peter-Prairie du Chien-Jordan aquifer because of its uniform lithology and consistently high permeability. As discussed in the section "Geologic Framework," the Jordan is absent in the eastern part of the study area, and thus the aquifer there is much less permeable. In Missouri, the Eminence Dolomite, equivalent to the Jordan, and the underlying Potosi Dolomite show much of the secondary permeability that is characteristic of the Prairie du Chien aquifer in Iowa and Minnesota.

Coefficients of transmissivity, hydraulic conductivity, and storage for the aquifer in various areas of the northern Midwest are listed in table 2. The highest transmissivities and hydraulic conductivities are in the Minneapolis-St. Paul area, eastern Iowa, and extreme southwestern Wisconsin, primarily because of the higher values for the Jordan Sandstone. Horick and Steinhilber (1978) show generalized zones of transmissivity for the Jordan aquifer in Iowa that decrease from 5,000 ft^2/d in the northeast and east to 500 ft^2/d in the extreme southwest. A somewhat similar pattern was used in the two-dimensional flow model in Iowa (M.R. Burkart and R.C. Buchmiller, U.S. Geological Survey, written commun., 1988), but the maximum values were about 2,000 ft^2/d in the northeast and 3,500 ft^2/d in the extreme southeast. This pattern coincides with increased cementation and depth of burial of the Jordan Sandstone to the southwest. The hydraulic conductivities used in the regional flow model of this study ranged from 0.35 to 8.2 ft/d (Mandle and Kontis, in press) and also follow that pattern. However, the majority of the hydraulic conductivities range from 1.7 to 5.2 ft/d. Similarly, hydraulic conductivities used in the Chicago-Milwaukee area model ranged mainly from 1.7 to 5.4 ft/d (H.L. Young and A.J. MacKenzie, U.S. Geological Survey, written commun., 1988). Emmons (1987) used a range of hydraulic conductivities of 2.5 to 8.2 ft/d for his model of northeastern Wisconsin. Guswa and others (1982) assigned fixed transmissivities of 6,000 and 12,000 ft^2/d to the St. Peter aquifer and the Prairie du Chien-Jordan aquifer, respectively, in a preliminary model of ground-water flow in the Twin Cities area. Dividing these values by general aquifer thicknesses produces hydraulic conductivities of about 40 to 60 ft/d, similar to reported values in that area shown in table 2.

Thickness of the aquifer increases gradually from the northern erosional edge to more than 1,500 and 1,000 ft in the Illinois and Michigan basins, respectively.

ST. LAWRENCE-FRANCONIA CONFINING UNIT

The St. Lawrence and Franconia Formations form an important regional confining unit over the Ironton-Galesville aquifer. Although these formations are dominantly sandstone in the northern part of the area, they are very silty and shaly, fine grained, poorly sorted, and dolomitic. Thus, the units are anisotropic and restrict vertical movement of ground water. They contribute some water to multiaquifer wells, but their permeability generally is too low for them to be productive aquifers. Fractures and solution channels in the upper part of the more dolomitic St. Lawrence locally form a direct hydraulic connection with the overlying Jordan Sandstone; therefore, in some places, the St. Lawrence is penetrated by wells in the Jordan aquifer. The Franconia, whose Mazomanie Member is coarse grained, has been included with the Ironton-Galesville aquifer in Minnesota by some investigators (Kanivetsky, 1978; Adolphson and others, 1981). However, natural-gamma well logs show the Franconia there to be primarily a confining unit (Woodward, 1986).

Equivalent carbonate rocks in the southern and eastern parts of the study area are the Potosi and Derby-Doerun Dolomites and the upper part of the Davis Formation. In Missouri, Imes (1985) includes the Potosi and Derby-Doerun in his Cambrian-Ordovician aquifer (fig. 18), although the Derby-Doerun is not considered to be very productive. The Davis also is a dolomite but contains as much as 50 percent shale and silt. Its confining capacity in northern Missouri is not proven; however, to the south, water levels differ by 50 ft above and below the Davis.

A few hydraulic conductivity and transmissivity values were made on the basis of packer tests in Wisconsin and Minnesota (table 3). The tests in Grant County are in the Driftless Area of southwestern Wisconsin and indicate that the St. Lawrence Formation there is much more transmissive than the St. Lawrence in eastern Wisconsin and in St. Paul, and than the Tunnel City Group (equivalent to the Franconia Formation) in general. At the St. Paul test site, Miller (1984) used packer-test data to estimate ratios of horizontal to vertical hydraulic conductivity of 10:1 in the Mazomanie Member and 100:1 in the remainder of the Franconia and the St. Lawrence; thus, the respective vertical hydraulic conductivities would be 0.2 and 0.001 ft/d. However, laboratory determinations of vertical hydraulic conductivity of cores from the lower part of the Franconia Formation there gave values of less than 0.0025 to 0.025 ft/d. In addition, Kanivetsky and Hoyer (1987) used four methods to estimate the vertical hydraulic conductivity of the St. Lawrence Formation at that site; they obtained a range of 7.9×10^{-5} to 4.6×10^{-4} ft/d.

The following vertical hydraulic conductivities were used in the three-dimensional ground-water flow models:

1. Northern Midwest regional model (Mandle and Kontis, in press)—8.6×10^{-7} to 4.3×10^{-4} ft/d.
2. Northeastern Wisconsin (Emmons, 1987)—1.0×10^{-5} ft/d.
3. Brown County, Wisconsin (Krohelski, 1986)—3.5×10^{-5} to 3.0×10^{-3} ft/d.
4. Northeastern Illinois-southeastern Wisconsin (H.L. Young and A.J. MacKenzie, U.S. Geological Survey, written commun., 1988)—4.3×10^{-4} to 1.1×10^{-3} ft/d.
5. Twin Cities area (Guswa and others, 1982)—4.0×10^{-4} to 2.0×10^{-3} ft/d.

The thickness of the St. Lawrence-Franconia confining unit in the part of the aquifer system that contains freshwater generally is about 100 to 200 ft, although it is less than 100 ft thick in most of Wisconsin.

IRONTON-GALESVILLE AQUIFER

The Ironton and Galesville Sandstones form the most important aquifer of the Cambrian-Ordovician aquifer system in the east-central part of the study area, although they generally are not the only rock units open to deep wells. In the Chicago-Milwaukee area, the Ironton-Galesville aquifer is sufficiently deep such that historical head decline because of the large-scale pumping from the Cambrian-Ordovician aquifer system has exceeded 850 ft without lowering the head in the aquifer system to the top of the Ironton. The aquifer terminates to the west, south, and east (fig. 10) as the sandstones grade into carbonate rocks, primarily dolomite. Permeability of the aquifer decreases as the carbonate content increases. The aquifer is not used in some of this transitional area because the shallower St. Peter-Prairie du Chien-Jordan aquifer is very productive in Minnesota and Iowa, and because the aquifer becomes saline where it is more deeply buried in the central parts of Iowa and Illinois. Although the Franconia Formation is less permeable than the Ironton and Galesville, it is much thicker and, as previously described, has been included with those units by Kanivetsky (1978) in Minnesota.

TABLE 2.—*Hydraulic characteristics of the St. Peter-Prairie du Chien-Jordan aquifer*

[----, not available; Do. (do.), ditto]

Well or site location	No. of wells or tests	Geologic unit (nomenclature of this report)	Transmissivity, *T* (ft^2/d)		Horizontal hydraulic conductivity, *K* (ft/d)		Storage coefficient, *S* (dimensionless)		Reference or source	Remarks
			Value or range	Average	Value or range	Average	Value or range	Average		
Southeastern Minnesota	----	St. Peter Sandstone	330-4,900	----	3.3-33	----	$1.0x10^{-5}$-$1.0x10^{-3}$	----	Kanivetsky and Walton (1979)	Range of values, including estimates from specific capacities.
Minneapolis - St. Paul area, Minn.	1	-do.-	5,000	----	----	----	----	----	Norvitch and others (1973)	
Do.	10	-do.-	----	----	.16-26.9	12.5 (median)	----	----	Norvitch and others (1973), Reeder and others (1976)	Laboratory determination of *K* from drill cores; 0.16 is for basal St. Peter.
Dousman, village well 2, Waukesha Co., Wis.	1	-do.-	350	----	3.6	----	----	----	USGS packer test, 1983	
Eagle, village well 2, Waukesha Co., Wis.	1	-do.-	120	----	1.6	----	----	----	USGS packer test, 1980	
Greenfield High School, Milwaukee Co., Wis.	1	-do.-	760	----	3.7	----	----	----	USGS packer test, 1983	
Bong Recreation Area, Kenosha Co., Wis.	1	-do.-	160	----	1.3	----	----	----	-do.-	
Mukwonago, village well 2, Waukesha Co., Wis.	1	-do.-	250	----	2.7	----	----	----	USGS packer test,1982	
Fond du Lac, city test wells, Fond du Lac Co., Wis.	1	-do.-	500	----	3.5	----	----	----	USGS packer test, 1985	
Do.	3	St. Peter Sandstone (Tonti Member)	180-420	300	3.6-5.2	4.5	----	----	-do.-	Average of values computed from specific-capacity data using minimum and maximum storage coefficient values of 0.0001 and 0.001.
Do.	2	St. Peter Sandstone (Readstown Member)	42-90	66	.93-1.4	1.2	----	----	-do.-	
USGS test well, Zion, Lake Co., Ill.	1	St. Peter Sandstone (Tonti Member)	250	----	1.8	----	----	----	USGS packer tests, 1980 and 1981	
Pontiac gas storage project, Livingston Co., Ill.	----	St. Peter Sandstone	----	48	----	.37	----	----	Bergstrom (1968)	Laboratory determination of *K* from drill cores.
Mahomet gas storage project, Champaign Co., Ill.	----	-do.-	----	250	----	1.1	----	----	-do.-	Do.
Crescent City gas storage project, Iroquois Co., Ill.	----	-do.-	----	57	----	.38	----	----	Buschbach and Bond (1967)	Do.
Chicago Deep Tunnel test well, Lake Calumet area, Cook Co., Ill.	1	Glenwood Formation, St. Peter Sandstone	67	----	.69	----	$1.3x10^{-4}$	----	Papadopulos and others (1969)	Packer test of pumped well and 2 observation wells.
Minneapolis - St. Paul area, Minn.	3	Prairie du Chien Group	6,300-7,400	6,800	----	59	$1.1x10^{-5}$-$3.4x10^{-4}$	$1.3x10^{-4}$	Norvitch and others (1973)	*K* from the average T and an average thickness of 115 ft.
West St. Paul recharge test, Dakota Co., Minn.	1	-do.-	4,500	----	30	----	$2.0x10^{-5}$-$2.0x10^{-4}$	----	Reeder and others (1976)	
Fennimore, city well 4, Grant Co., Wis.	1	-do.-	4,900	----	26	----	----	----	USGS packer test, 1983	

TABLE 2.—*Hydraulic characteristics of the St. Peter-Prairie du Chien-Jordan aquifer*—Continued

[----, not available; Do. (do.), ditto]

Well or site location	No. of wells or tests	Geologic unit (nomenclature of this report)	Transmissivity, *T* (ft^2/d)		Horizontal hydraulic conductivity, *K* (ft/d)		Storage coefficient, *S* (dimensionless)		Reference or source	Remarks
			Value or range	Average	Value or range	Average	Value or range	Average		
C and E Power Systems, East Chicago, Lake Co., Ind.	1	-do.-	----	----	----	----	----	----	USGS packer test, 1980	Negligible yield from 102-ft-thick interval.
Minneapolis-St. Paul area, Minn.	12	Jordan Sandstone	1,900-10,700	5,900	----	69	$4.9x10^{-5}$-$1.2x10^{-4}$	$7.2x10^{-5}$	Norvitch and others (1973)	*K* from the average *T* and an average thickness of 85 ft; *S* from 5 tests.
Do.	3	-do.-	----	----	4.6-166	Not meaningful	----	----	-do.-	Laboratory determination of *K* from drill cores.
USGS test well, Red Mound School, Vernon Co., Wis.	1	-do.-	670	----	8.0	----	----	----	USGS packer test, 1981	
USGS test well, Bagley, Grant Co., Wis.	1	-do.-	1,700	----	17	----	----	----	-do.-	
Fennimore, city well 4, Grant Co., Wis.	1	-do.-	2,400	----	24	----	----	----	USGS packer test, 1983	
Lake Geneva, village well 1, Walworth Co., Wis.	1	St. Peter Sandstone, Prairie du Chien Group	1,300	----	6.8	----	----	----	USGS packer test, 1982	
Southeastern Minnesota	1	Prairie du Chien Group, Jordan Sandstone	900-33,000	----	5.3-67	----	$1.0x10^{-6}$-$1.0x10^{-3}$	----	Kanivetsky and Walton (1979)	Range of values, including estimates from specific capacities.
Minneapolis-St. Paul area, Minn.	11	-do.-	5,000-26,500	11,000	----	56	$4.8x10^{-5}$-$6.5x10^{-4}$	$4.0x10^{-4}$	Norvitch and others (1973)	*K* from average *T* and average thickness of 200 ft; *S* from 5 tests.
West St. Paul recharge test, Dakota Co., Minn.	1	-do.-	7,500	----	31	----	----	----	Reeder and others (1976)	
Iowa	----	-do.-	500-5,000	----	----	----	----	$2.5x10^{-4}$	Horick and Steinhilber (1978)	Based on statewide specific capacity tests and several pumping tests in eastern Iowa.
Mason City, city well 14, Cerro Gordo Co., Iowa	1	-do.-	4,500	----	----	----	----	$2.0x10^{-4}$	Hershey and others (1970)	
Marion, city well 3, Linn Co., Iowa	1	-do.-	5,100	----	----	----	----	----	Hansen (1970)	
Limback well, Galena, Jo Daviess Co., Ill.	1	Prairie du Chien Group, Jordan Sandstone, Potosi Dolomite	300	----	1.8	----	----	----	USGS packer test, 1980	
Chicago Deep Tunnel test well, Lake Calumet area, Cook Co., Ill.	1	Prairie du Chien Group, Eminence Formation, Potosi Dolomite	2,300	----	9.3	----	$5.0x10^{-4}$	----	Papadopulos and others (1969)	Packer test of pumped well and 2 observation wells.
Fitchburg, city well 1, Dane Co., Wis.	1	Jordan Sandstone, St. Lawrence Formation	210	----	5.0	----	----	----	USGS packer test, 1980	

TABLE 3.—*Hydraulic characteristics of the St. Lawrence-Franconia confining unit*

[*K'*, vertical hydraulic conductivity; ----, not available; Do. (do.), ditto]

Well or site location	No. of wells or tests	Geologic unit (nomenclature of this report)	Transmissivity, *T* (ft^2/d)		Horizontal hydraulic conductivity, *K* (ft/d)		Storage coefficient, *S* (dimensionless)		Reference or source	Remarks
			Value or range	Average	Value or range	Average	Value or range	Average		
Aquifer Thermal-Energy Storage site, St. Paul, Minn.	2	St. Lawrence Formation	----	3.8	----	0.1	----	----	Packer tests, Miller (1984)	*K:K'* ratio estimated to be 100:1.
Do.	1	-do.-	----	----	----	----	----	----	Kanivetsky and Hoyer (1987)	*K'* estimated to be 7.9×10^{-5} to 4.6×10^{-4} ft/d.
USGS test well, Bagley, Grant Co., Wis.	1	-do.-	940	----	9.3	----	----	----	USGS packer test, 1981	
Fennimore, city well 4, Grant Co., Wis.	1	St. Lawrence Formation (Black Earth Member)	2,000	----	20	----	----	----	USGS packer test, 1983	
Aquifer Thermal-Energy Storage site, St. Paul, Minn.	2	Franconia Formation (Mazomanie Member)	----	----	----	2.0	----	----	Packer tests, Miller (1984)	*K:K'* ratio estimated to be 10:1.
Do.	1	-do.-	380	----	8.5	----	----	1.2×10^{-5}	Kanivetsky and Hoyer (1987)	
Do.	1	Remaining Franconia Formation	----	----	----	.1	----	----	Packer tests, Miller (1984)	*K:K'* ratio estimated to be 100:1.
Do.	----	-do.-	----	----	----	----	----	----	Miller (1984)	Range of laboratory determinations of *K'*: 2.5×10^{-3} to 2.5×10^{-2} ft/d.
Fennimore, city well 4, Grant Co., Wis.	1	Tunnel City Group	130	----	1.3	----	----	----	USGS packer test, 1983	
Fond du Lac, city test wells, Fond du Lac Co., Wis.	3	-do.-	46-110	78	.34-.93	.56	----	----	USGS packer tests, 1985	Averages of values computed from specific-capacity data using minimum and maximum storage coefficient values of 0.0001 and 0.001.
Greenleaf, village well 1, Brown Co., Wis.	1	-do.-	110	----	2.2	----	----	----	USGS packer test, 1980	
Bong Recreation Area, Kenosha Co., Wis.	1	St. Lawrence Formation, Tunnel City Group	120	----	1.4	----	----	----	USGS packer test, 1983	
Chicago Deep Tunnel test well, Lake Calumet area, Cook Co., Ill.	1	Franconia Formation	740	----	7.4	----	1.2×10^{-3}	----	Papadopulos and others (1969)	Packer test of pumped well and 2 observation wells.

Hydraulic conductivities determined from 16 packer tests on individual wells in the Ironton-Galesville aquifer in the northern Midwest (table 4) range from 1.0 to 31 ft/d, with a median value of 8.4 ft/d. Walton and Csallany (1962) estimated that regional hydraulic conductivity in the aquifer decreases southeastward in the Chicago area from about 5.3 to 3.3 ft/d, based on specific-capacity data

TABLE 4.—*Hydraulic characteristics of the Ironton-Galesville aquifer*

[*K'*, vertical hydraulic conductivity; ----, not available; Do. (do.), ditto]

Well or site location	No. of wells or tests	Geologic unit (nomenclature of this report)	Transmissivity, *T* (ft²/d) Value or range	Transmissivity, *T* (ft²/d) Average	Horizontal hydraulic conductivity, *K* (ft/d) Value or range	Horizontal hydraulic conductivity, *K* (ft/d) Average	Storage coefficient, *S* (dimensionless) Value or range	Storage coefficient, *S* (dimensionless) Average	Reference or source	Remarks
Aquifer Thermal-Energy Storage site, St. Paul, Minn.	2	Ironton and Galesville Sandstones	----	----	1.0-4.0	----	$2.7x10^{-5}$-$5.9x10^{-5}$	----	Packer tests, Miller (1984)	Larger *K* in upper part; *K:K'* ratio estimated to be 10:1.
Do.	1	-do.-	480-1,090	----	7.7-17	----	----	$4.5x10^{-5}$	Miller (1984)	Pumped well and 4 observation wells.
Do.		-do.-	730	----	12	----	----	$1.2x10^{-5}$	Kanivetsky and Hoyer (1987)	
Southeastern Minnesota	7	-do.-	----	----	.17-1.7	0.34 (median)	----	----	Norvitch and others (1973)	Laboratory determination of *K* from drill cores.
Do.	----	Franconia Formation, Ironton and Galesville Sandstones	530-11,000	----	4.0-83	----	$1.0x10^{-6}$	----	Kanivetsky and Walton (1979)	Range of values, including estimates from specific capacities.
USGS test well, Reno, Houston Co., Minn.	1	-do.-	860	----	7.4	----	----	----	USGS packer test, 1981	
USGS test well, Red Mound School, Vernon Co., Wis.	1	-do.-	1,900	----	10	----	----	----	-do.-	
USGS test well, Bagley, Grant Co., Wis.	1	-do.-	3,000	----	19	----	----	----	-do.-	
Fennimore, city well 4, Grant Co., Wis.	1	-do.-	1,500	----	15	----	----	----	USGS packer test, 1983	
Fitchburg, city well 1, Dane Co., Wis.	1	Tunnel City Group, Wonewoc Formation	360	----	8.4	----	----	----	USGS packer test, 1980	
Dousman, village well 2, Waukesha Co., Wis.	1	Wonewoc Formation	800	----	8.3	----	----	----	USGS packer test, 1983	
Eagle, village well 2, Waukesha Co., Wis.	1	-do.-	2,000	----	31	----	----	----	USGS packer test, 1980	
Mukwonago, village well 2, Waukesha Co. Wis.	1	-do.-	200	----	4.8	----	----	----	USGS packer test, 1982	
Greenleaf, village well 1, Brown Co., Wis.	1	-do.-	960	----	9.2	----	----	----	USGS packer test, 1980	
Bong Recreation Area, Kenosha Co., Wis.	1	-do.-	240	----	2.9	----	----	----	USGS packer test, 1983	
Limback Well, Galena, Jo Daviess Co., Ill.	1	Ironton and Galesville Sandstones	1,500	----	7.8	----	----	----	USGS packer test, 1980	
Rockford, city well 4, Winnebago Co., Ill.	1	-do.-	2,000	----	15	----	----	----	-do.-	
USGS test well, Zion, Lake Co., Ill.	1	-do.-	1,100	----	9.8	----	----	----	USGS packer test, 1980	

TABLE 4.—*Hydraulic characteristics of the Ironton-Galesville aquifer*—Continued

[K', vertical hydraulic conductivity; ----, not available; Do. (do.), ditto]

Well or site location	No. of wells or tests	Geologic unit (nomenclature of this report)	Transmissivity, T (ft²/d)		Horizontal hydraulic conductivity, K (ft/d)		Storage coefficient, S (dimensionless)		Reference or source	Remarks
			Value or range	Average	Value or range	Average	Value or range	Average		
Chicago Ill., area	11	-do.-	670-940	----	3.3-5.3	----	----	----	Walton and Csallany (1962)	Estimated regional range, decreasing to the southeast. Based on specific-capacity tests.
Chicago Deep Tunnel test well, Lake Calumet area, Cook Co., Ill.	1	-do.-	2,000	----	11	----	$7.5x10^{-5}$	----	Papadopulos and others (1969)	Packer test on pumped well and 2 observation wells.
C & E Power Systems East Chicago, Lake Co., Ind.	1	Franconia Formation, Galesville Sandstone	1,900	----	7.3	----	----	----	USGS packer test, 1980	
Leaf River gas storage project, Ogle Co., Ill.	----	Galesville Sandstone	----	----	----	1.5	----	----	Witherspoon and Neuman (1967)	Laboratory determination of K from drill cores.
Herscher gas storage project, Kankakee Co., Ill.	81	-do.-	----	470	----	3.9	----	----	Emrich (1966)	Average of laboratory determinations from drill cores, weighted on recovery. Estimated K' >1.5 ft/d.
Do.	----	-do.-	----	130	----	1.3	----	----	Buschbach and Bond (1967)	Laboratory determination of K from drill cores.
Pontiac gas storage project, Livingston Co., Ill.	----	-do.-	----	71	----	1.2	----	----	Bergstrom (1968)	Do.
Mahomet gas storage project, Champaign Co., Ill.	----	-do.-	----	120	----	2.1	----	----	-do.-	Do.

from 11 wells open only to this aquifer. Average hydraulic conductivities at three underground natural-gas storage facilities in central Illinois are in the lower range of the values from the packer tests. These values are from laboratory determinations of permeability of drill cores; such determinations typically are lower than values determined from well pumping tests. Values ranging from 4.3 to 8.6 ft/d were used in the regional flow model during this study (Mandle and Kontis, in press), and similar values were used for the combined Elk Mound Group in the northeastern Wisconsin model (Emmons, 1987). In addition, values ranging from 2.6 to 8.6 ft/d were used in the Chicago-Milwaukee area model (H.L. Young and A.J. MacKenzie, U.S. Geological Survey, written commun., 1988). Guswa and others (1982) used a uniform transmissivity of 50 ft²/d in the Twin Cities area model, which is equivalent to a range in hydraulic conductivity of about 0.42 to 1.2 ft/d, based on a range in thickness of 40 to 120 ft.

The aquifer is generally between 50 and 150 ft thick but exceeds 200 ft on the northeastern edge of the Illinois basin. The thickness of the aquifer is uncertain north of Milwaukee, where the Ironton and Galesville Sandstones and the other sandstones of the Elk Mound Group generally cannot be differentiated in the subsurface from drill cuttings or borehole geophysical logs.

EAU CLAIRE CONFINING UNIT

The Eau Claire Formation and its partial equivalent to the southwest, the Bonneterre Formation, form an extensive confining unit above the Mount Simon aquifer. The effectiveness of the Eau Claire as a confining unit depends on the relative abundance of shale, siltstone, dolomite, and sandstone in the formation. Siltstone and shale are fairly abundant in the upper part of the formation but less so in its northernmost extent in Wisconsin. Dolomite content increases to the south and west, where the Eau Claire grades laterally into the Bonneterre in Missouri and a dolomitic facies in western Iowa. The confining unit mapped on figure 9 consists of the entire Eau Claire, except in Illinois, where the lower Elmhurst Sandstone Member of the Eau Claire is included in the Mount Simon aquifer.

Verification of the confining effects of the Eau Claire is scanty, evidenced primarily by differences in potentiometric head between the Mount Simon and Ironton-Galesville aquifers during well packer tests (see table 7). Although the percentage of sand in the upper Eau Claire increases to more than 50 percent northward in Illinois, Visocky and others (1985) report that the shales in the Eau Claire are laterally persistent and provide confinement throughout the State and farther north than had generally been believed. Results of the packer tests made during this study show that the confining unit is very effective in extreme northern Illinois, southern Wisconsin, and southeastern Minnesota. Gamma-ray logs of wells in these areas indicate that 50 to 125 ft of very fine grained sediment occur within the upper part of the Eau Claire.

Very few data on hydraulic characteristics are available for the Eau Claire Formation (table 5). The unit was not isolated and pumped in most of the packer tests. Where it was pumped, the packed interval included enough sandstone of the lower Eau Claire, Mount Simon Sandstone, or Galesville Sandstone so that the hydraulic conductivity determined does not accurately reflect the permeability of the confining unit. Those results are not shown in table 5. Miller (1984) estimated the vertical anisotropy of the Eau Claire at St. Paul to be 100:1 (table 5), resulting in a vertical hydraulic conductivity of 1.0×10^{-3} ft/d. The following vertical hydraulic conductivities were used in the three-dimensional ground-water flow models:

1. Northern Midwest regional model (Mandle and Kontis, in press)—6.9×10^{-5} to 4.3×10^{-4} ft/d.
2. Northeastern Illinois-southeastern Wisconsin (H.L. Young and A.J. MacKenzie, U.S. Geological Survey, written commun., 1988)—3.2×10^{-5} to 5.2×10^{-5} ft/d.
3. Twin Cities area (Guswa and others, 1982)—8.0×10^{-4} to 3.2×10^{-3} ft/d.

Thickness of the Eau Claire confining unit increases steadily from the northern erosional limit and subcrop area to about 200 to 300 ft in central Iowa and northern Illinois and to more than 750 ft in the Illinois basin.

MOUNT SIMON AQUIFER

The lowermost aquifer of the Cambrian-Ordovician aquifer system is composed primarily of the Mount Simon Sandstone and equivalent strata, the Lamotte Sandstone, in Missouri. In Minnesota, the Mount Simon is underlain by Precambrian sedimentary rocks—the Hinckley Sandstone and the older Fond du Lac Formation. The Hinckley is permeable and in direct hydrologic connection with the Mount Simon; thus, these units compose the Mount Simon-Hinckley aquifer in Minnesota. The Fond du Lac contains much shale, siltstone, and poorly sorted sandstone and generally is considered to be a confining unit. As is customary in Illinois, the basal Elmhurst Sandstone Member of the overlying Eau Claire Formation is included in the Mount Simon aquifer. In Illinois, this combination has been termed both the Elmhurst-Mount Simon aquifer and the basal sandstone aquifer. As described earlier, the Elmhurst strata of Illinois apparently are interpreted as upper Mount Simon in southern Wisconsin. Although the Mount Simon is poorly sorted and contains much shale, its great thickness makes it a productive aquifer.

The Mount Simon aquifer is the most extensive aquifer unit in the study area by virtue of its basal position in the bedrock sequence; it is absent only on local highs of the Precambrian basement. It is not used in much of its southern and eastern extent toward the Illinois and Michigan basins and in Iowa and northern Missouri because it contains saline water. It is the primary bedrock aquifer along the northern perimeter of the study area, where it crops out or is overlain only by the Eau Claire Formation. To the south, in the remainder of Minnesota, Wisconsin, eastern Iowa, and northern Illinois, the Mount Simon aquifer is used in combination with overlying aquifers. The maximum thickness of the Mount Simon penetrated by water wells probably is at Waukesha, Wisconsin (just west of Milwaukee), where the entire thickness of about 1,000 to 1,300 ft is open in several wells.

In easternmost Wisconsin and northeastern Illinois, only the upper few hundred feet of the aquifer contain freshwater, but many wells penetrate into that freshwater zone. The base of the freshwater corresponds

TABLE 5.—*Hydraulic characteristics of the Eau Claire confining unit*

[K', vertical hydraulic conductivity; ----, not available; do., ditto]

Well or site location	No. of wells or tests	Geologic unit (nomenclature of this report)	Transmissivity, T (ft²/d)		Horizontal hydraulic conductivity, K (ft/d)		Storage coefficient, S (dimensionless)		Reference or source	Remarks
			Value or range	Average	Value or range	Average	Value or range	Average		
Aquifer thermal-energy storage site, St. Paul, Minn.	1	Eau Claire Formation	----	----	0.10	----	----	----	Packer test, Miller (1984)	K:K' ratio estimated to be 100:1; thus, K' would be $1.0x10^{-3}$ ft/d.
Dousman, village well 2, Waukesha Co., Wis.	1	-do.-	370	----	3.9	----	----	----	USGS packer test, 1983	
Bong Recreation Area, Kenosha Co., Wis.	1	-do.-	87	----	.70	----	----	----	-do.-	
Pecatonica gas storage project, Winnebago Co., Ill.	----	-do.-	----	58	----	1.5	----	----	Van Den Berg (1975)	Laboratory determination of K from drill cores. Rock type reported as sandstone.
Leaf River gas storage project, Ogle Co, Ill.	1	Eau Claire Formation (uppermost 30 ft of Proviso Siltstone Member)	----	----	----	----	----	----	Witherspoon and Neuman (1967)	137-day pumping test in Galesville Sandstone. Observation well open 30 ft below top of Eau Claire. K' $1.9x10^{-7}$ ft/d.
Troy Grove gas storage project, La Salle Co, Ill.	1	Eau Claire Formation (lowermost 60 ft of Proviso Siltstone Member)	----	----	----	----	----	----	Witherspoon and others (1962)	3-day pumping test in sandstone layer in Eau Claire. Observation well open 60 ft above top of sandstone. K' estimated to be <$8.8x10^{-8}$ ft/d.

approximately to the top of a local confining unit within the Mount Simon Sandstone. It is a zone as much as 300 to 500 ft thick that contains much interbedded red shale. A prominent 10- to 60-ft-thick shale zone in extreme northwestern Indiana, referred to as the "B Cap" (Becker and others, 1978), probably corresponds to part of the local confining unit.

Hydraulic properties of the Mount Simon aquifer have been measured at several locations in the northern Midwest (table 6), but the values generally are representative of only a few hundred feet of the upper part of the aquifer. Hydraulic conductivities from packer or pumping tests range from 0.38 to 21 ft/d; the median is 4.8 ft/d. Published values of hydraulic conductivity from laboratory permeability determinations on drill cores of the Mount Simon range from 0.027 to more than 4.9 ft/d, with a median of 0.27 ft/d. The cores in Illinois and Indiana are from test holes for underground gas-storage projects and industrial-disposal wells in the Illinois basin and its northern perimeter. Hydraulic conductivities determined on the cores are low, with a maximum of 1.2 ft/d and a median of 0.12 ft/d.

The following hydraulic conductivity values were used in the three-dimensional ground-water flow models:

1. Northern Midwest regional model (Mandle and Kontis, in press)—3.0 to 8.6 ft/d.
2. Northeastern Illinois-southeastern Wisconsin (H.L. Young and A.J. MacKenzie, U.S. Geological Survey, written commun., 1988)—0.5 to 5.2 ft/d.
3. Twin Cities area (Guswa and others, 1982)—9.4 to 38 ft/d.

GROUND-WATER FLOW SYSTEM

Ground-water recharge, movement, and discharge are components of the hydrologic cycle that are important to understanding the flow regime of the Cambrian-Ordovician aquifer system. In the

TABLE 6.—*Hydraulic characteristics of the Mount Simon aquifer*

[ORSANCO: Ohio River Valley Water Sanitation Commission; ----, not available; Do. (do.), ditto]

Well or site location	No. of wells or tests	Geologic unit (nomenclature of this report)	Transmissivity, *T* (ft^2/d): Value or range	Transmissivity, *T* (ft^2/d): Average	Horizontal hydraulic conductivity, *K* (ft/d): Value or range	Horizontal hydraulic conductivity, *K* (ft/d): Average	Storage coefficient, *S* (dimensionless): Value or range	Storage coefficient, *S* (dimensionless): Average	Reference or source	Remarks
Southeastern Minnesota	----	Mount Simon and Hinckley Sandstones and Fond du lac Formation	270-9,400	----	----	2.0-23	$1.0x10^{-6}$-$1.0x10^{-2}$	----	Kanivetsky and Walton (1979)	Range of values, including estimates from specific capacities.
Minneapolis-St. Paul area, Minn.	4	Mount Simon and Hinckley Sandstones	1,600-3,100	2,600	----	----	$6.6x10^{-5}$-$8.3x10^{-3}$	$2.8x10^{-3}$	Norvitch and others (1973)	
Southeastern Minnesota	207	Mount Simon Sandstone	----	----	0.033->4.9	3.2 (median)	----	----	-do.-	Laboratory determination of *K* from drill cores.
Do.	54	Hinckley Sandstone and Fond du Lac Formation	----	----	.000-3.7	0.48 (median)	----	----	-do.-	Do.
USGS test well, Reno, Houston Co., Minn.	1	Mount Simon Sandstone	----	----	6.3	----	----	----	USGS packer test, 1981	
USGS test well, Stoddard, Vernon Co., Wis.	1	-do.-	3,600	----	9.2	----	----	----	-do.-	388-ft-thick interval.
Do.	1	-do.-	2,600	----	21	----	----	----	-do.-	Lowermost 123 ft.
USGS test well, Red Mound School, Vernon Co., Wis.	1	-do.-	3,300	----	7.1	----	----	----	-do.-	466-ft-thick interval.
Do.	1	-do.-	1,900	----	12	----	----	----	-do.-	Lowermost 161 ft.
USGS test well, Bagley, Grant Co., Wis.	1	-do.-	7,900	----	12	----	----	----	-do.-	634-ft-thick interval.
Do.	1	-do.-	3,700	----	17	----	----	----	-do.-	Lowermost 214 ft.
Dousman, village well 2, Waukesha Co., Wis.	1	-do.-	870	----	2.7	----	----	----	USGS packer test, 1983	320-ft-thick interval.
Do.	1	-do.-	630	----	2.9	----	----	----	-do.-	Lowermost 220 ft.
Eagle, village well 2, Waukesha Co., Wis.	1	-do.-	880	----	2.8	----	----	----	USGS packer test, 1980	317-ft-thick interval.
Mukwonago, village well 2, Waukesha Co., Wis.	1	-do.-	1,000	----	2.2	----	----	----	USGS packer test, 1982	472-ft-thick interval.
Bong Recreation Area, Kenosha Co., Wis.	1	-do.-	1,700	----	2.0	----	----	----	USGS packer test, 1983	879-ft-thick interval.
Do.	1	-do.-	630	----	5.1	----	----	----	-do.-	Uppermost 124 ft.
Do.	1	-do.-	740	----	1.3	----	----	----	-do.-	Lowermost 549 ft.
Greenfield High School, Milwaukee Co., Wis.	1	-do.-	2,200	----	7.5	----	----	----	-do.-	295-ft-thick interval.
Do.	1	-do.-	1,300	----	11	----	----	----	-do.-	Uppermost 119 ft.

TABLE 6.—*Hydraulic characteristics of the Mount Simon aquifer*—Continued

[ORSANCO: Ohio River Valley Water Sanitation Commission; ----, not available; Do. (do.), ditto]

Well or site location	No. of wells or tests	Geologic unit (nomenclature of this report)	Transmissivity, *T* (ft^2/d)		Horizontal hydraulic conductivity, *K* (ft/d)		Storage coefficient, *S* (dimensionless)		Reference or source	Remarks
			Value or range	Average	Value or range	Average	Value or range	Average		
USGS test well, Green Island, Jackson Co., Iowa	1	-do.-	350	----	.38	----	----	----	USGS packer test, 1981	926-ft-thick interval.
Limback well, Galena, Jo Daviess Co., Ill.	1	Eau Claire Formation (Elmhurst Sandstone Member), Mount Simon Sandstone	2,400	----	4.8	----	----	----	USGS packer test, 1980	508-ft-thick interval.
Rockford, city well 4, Winnebago Co., Ill.	1	-do.-	2,600	----	4.4	----	----	----	-do.-	582-ft-thick interval.
Do.	1	Mount Simon Sandstone	750	----	2.8	----	----	----	-do.-	Lowermost 266 ft.
USGS test well, Zion, Lake Co., Ill.	1	Eau Claire Formation (Elmhurst Sandstone Member), Mount Simon Sandstone	840	----	1.5	----	----	----	-do.-	560-ft-thick interval.
Troy Grove gas storage project, La Salle Co., Ill.	----	-do.-	----	----	----	0.41	----	----	Buschbach and Bond (1967)	Laboratory determination of *K* from drill cores.
Ancona gas storage project, Livingston and La Salle Cos., Ill.	----	Mount Simon Sandstone	----	----	----	.31	----	----	-do.-	Do.
Pontiac gas storage project, Livingston Co., Ill.	----	-do.-	----	----	----	.068	----	----	Van Den Berg (1975)	Do.
Herscher gas storage project, Kankakee Co., Ill.	----	Eau Claire Formation (Elmhurst Sandstone Member), Mount Simon Sandstone	----	----	----	.51	----	----	Buschbach and Bond (1967)	Do.
Herscher NW gas storage project, Kankakee Co., Ill.	----	-do.-	----	----	----	.22	----	----	-do.-	Do.
Crescent City gas storage project, Iroquois Co., Ill.	----	Mount Simon Sandstone	----	----	----	.027	----	----	Bergstrom (1968)	Do.
Lake Bloomington gas storage project, McLean Co., Ill.	----	-do.-	----	----	----	.12	----	----	Van Den Berg (1975)	Do.
Lexington gas storage project, McLean Co., Ill.	----	-do.-	----	----	----	.11	----	----	ORSANCO (1976)	Do.
Hudson gas storage project, McLean Co., Ill.	----	-do.-	----	----	----	0.12	----	----	Van Den Berg (1975)	Do.

TABLE 6.—*Hydraulic characteristics of the Mount Simon aquifer*—Continued

[ORSANCO: Ohio River Valley Water Sanitation Commission; ----, not available; Do. (do.), ditto]

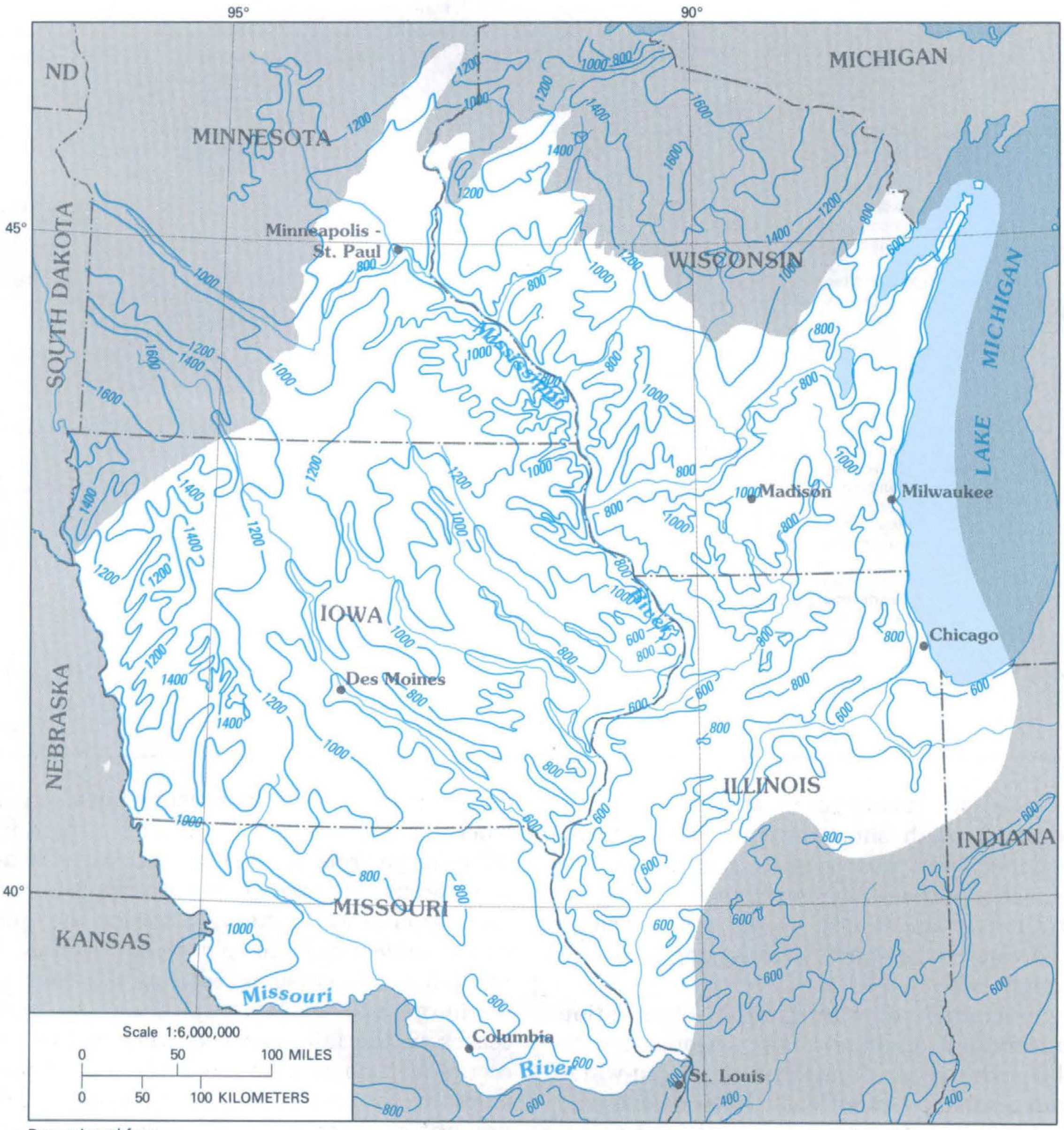
Well or site location	No. of wells or tests	Geologic unit (nomenclature of this report)	Transmissivity, *T* (ft^2/d)		Horizontal hydraulic conductivity, *K* (ft/d)		Storage coefficient, *S* (dimensionless)		Reference or source	Remarks
			Value or range	Average	Value or range	Average	Value or range	Average		
Mahomet gas storage project, Champaign Co., Ill.	----	-do.-	----	----	----	.041	----	----	Buschbach and Bond (1967)	Do.
Jones and Laughlin Steel Corporation disposal well, Putnam Co., Ill.	----	Eau Claire Formation (Elmhurst Sandstone Member), Mount Simon Sandstone	----	----	0.014-1.4	.088	----	----	Heidari and Cartwright (1981), ORSANCO (1976)	Do.
U.S. Steel waste disposal well 1, Lake Co., Ind.	----	Mount Simon Sandstone	----	----	----	1.2	----	----	ORSANCO (1976)	Do.
Inland Steel waste disposal well 1, Lake Co., Ind.	----	-do.-	----	----	----	.82	----	----	-do.-	Do.
Midwest waste disposal well 1, Porter Co., Ind.	----	Eau Claire Formation (Elmhurst Sandstone Member), Mount Simon Sandstone	----	----	----	.12	----	----	-do.-	Do.
Bethlehem Steel waste disposal well 1C, Porter Co., Ind.	----	Mount Simon Sandstone	----	----	.055-.27	----	----	----	Becker and others (1978)	Do.
Bethlehem Steel waste disposal well 2C, Porter Co., Ind.	----	-do.-	----	----	.027-.27	----	----	----	-do.-	Do.

northern Midwest, recharge to the water table occurs mainly through short-term events, such as spring snowmelt and heavy spring and summer rains, whereas ground-water discharge occurs almost continuously as steady seepage to streams and other surface-water bodies, as springflow, and by evapotranspiration.

Long-term water-level records from observation wells in unconfined aquifers show seasonal trends that correlate with general patterns of ground-water recharge and discharge. In at least the northern one-half of the study area, the ground freezes in the winter, preventing recharge by infiltration. However, discharge to streams continues, causing the water table to decline. Snow accumulates until it melts in the spring, when the meltwater can infiltrate through the thawed ground. When the snow melts prior to thawing of the ground, recharge is limited and surface runoff increases. Recharge increases when the ground thaws and allows rapid infiltration of recharge from snowmelt, and when heavy spring rains occur. This period of recharge generally replenishes ground-water storage. During the summer, the water table rises sharply from recharge by heavy rains but otherwise recedes as a result of natural discharge and evapotranspiration. As plant growth ceases in the fall, some recovery of the water table occurs prior to resumption of the winter period of decline of the water table. Extreme conditions of drought or greatly above-normal precipitation cause departures from this generalized pattern.

The preceding paragraph pertains to the effects of recharge and discharge to or from unconfined aquifers, which generally consist of the unconsolidated glacial drift and alluvial deposits that directly underlie most of the land surface in the northern Midwest. These surficial deposits are in direct hydraulic connection with the underlying bedrock aquifers and provide the source of recharge to these aquifers.

Recharge to bedrock aquifers occurs by direct infiltration in the outcrop or subcrop area, as well as by leakage through confining units. Vertical flow to the bedrock aquifers is controlled by the least permeable zone within the surficial deposits or bedrock through which the water passes. The flow rate is directly proportional to the vertical hydraulic conductivity and to the hydraulic gradient across the low-permeability zone, and is inversely proportional to the thickness of the zone.



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

EXPLANATION

—800— WATER-TABLE CONTOUR — Shows altitude of the water table, 1980. Contour interval 200 feet. Datum is sea level

FIGURE 19.—Generalized water table and major surface-water drainage network in the northern Midwest.

Some aquifers in the northern Midwest contain saline water; thus, the direction and magnitude of ground-water flow depend on the density of the water as well as the hydraulic head. This condition dominates ground-water flow in the aquifer system in much of western and southern Iowa and northern Missouri and to the south and east of the study area in Illinois, Indiana, and Michigan.

The concept of multiple flow systems of different areal and subsurface extent (Toth, 1962; Freeze and Witherspoon, 1967) applies to ground-water flow in the northern Midwest. The flow systems, which are driven by the hydraulic head at the water table (fig. 19), range from local to intermediate to regional in scope. These conceptual flow systems are illustrated in figure 20 as generalized predevelopment flow paths along an east-west hydrogeologic section across southern Wisconsin. The water table is used for the top of the section.

The flow paths are highly diagrammatic and should not be construed as representative of exact conditions. The paths are based on the premise that the section is parallel to the direction of most ground-water flow. This generally is true in the eastern half of the section but is not in the western half. Thus, the flow paths shown in the west are idealized, especially in the deep intermediate and regional flow systems.

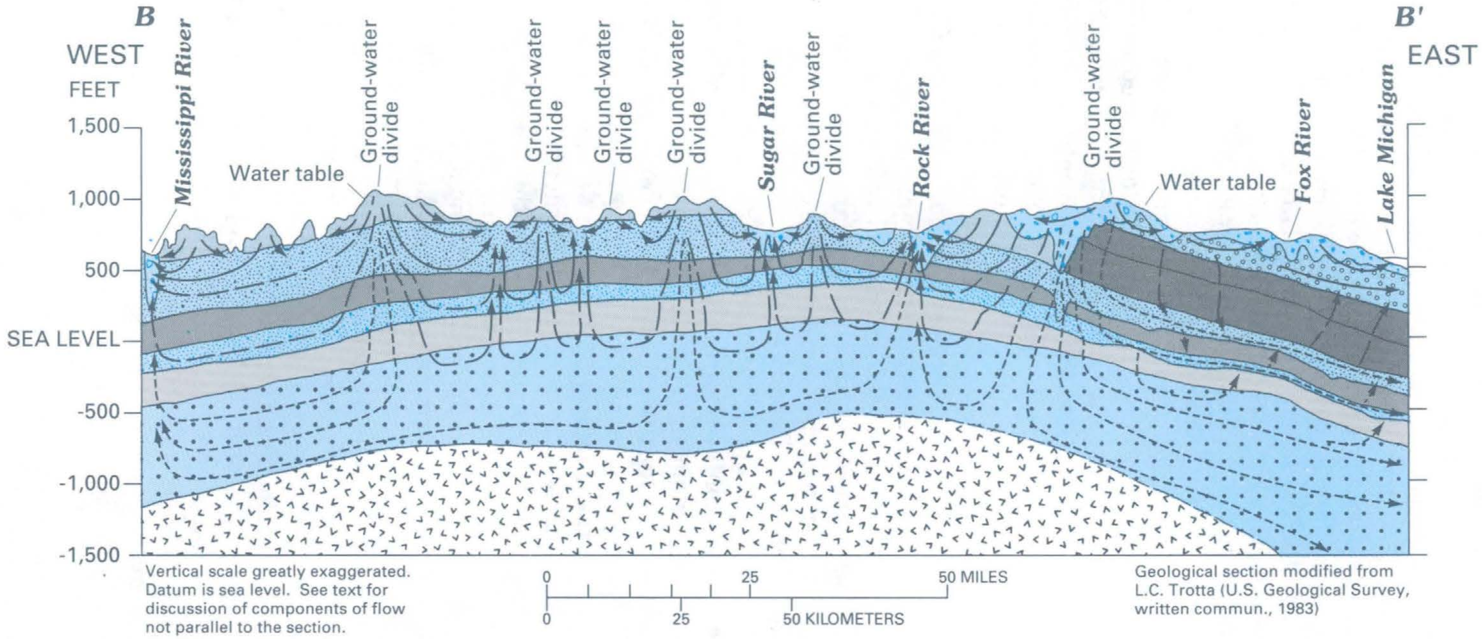
The water table is in shallow, unconfined aquifers in the northern Midwest and is closely related to the relief of the land surface. The generalized water table shown in figure 19 does not reflect local areas of decline that have resulted from concentrated pumping of water-table aquifers. The water table is highest in northwestern Iowa, southwestern Minnesota, and northern Wisconsin, areas just upgradient from the general erosional limit of the Cambrian rocks. High areas of the water table occur in dissected uplands elsewhere in the study area. Relatively shallow, local flow systems (mostly less than a few miles in length) dominate the water-table regime and account for a large part of the overall volume of ground-water recharge and discharge in the study area. Much of this flow does not pass through the bedrock aquifers but is discharged from glacial drift into surface-water bodies or is lost by evapotranspiration. These local flow systems also are dominant in the uppermost bedrock in areas where glacial drift is thin or absent—mainly, the Driftless Area of western Wisconsin, extreme northwestern Illinois, and the adjacent uplands along the Mississippi River in Minnesota and Iowa.

Although the depth to the water table commonly is less than 50 ft in most of the study area, depths may be 200 to 300 ft beneath the highest ridges in the Driftless Area. Shallower, perched ground water is present where low-permeability beds restrict downward percolation.

The same general pattern of recharge in upland areas and lateral flow of ground water to lower areas of discharge occurs in the bedrock; however, flow is mainly deeper, slower, and occurs over much longer distances. Downward flow to deeper aquifers in recharge areas is primarily vertical and is restricted by intervening confining units. Head diminishes along the downward flow path. This decline in head was observed in several packer tests during the study (table 7, fig. 21) in areas of direct recharge from glacial drift to the Cambrian-Ordovician aquifer system. In upland areas of western Wisconsin and southeastern Minnesota, the heads measured in the St. Peter-Prairie du Chien-Jordan aquifer were 200 to 245 ft higher than in the deeper Ironton-Galesville aquifer. In the recharge area west of Milwaukee (wells 12–14), the head in the Mount Simon aquifer was 95 to 135 ft lower than in the shallower Galena-Platteville unit in these wells. Some of the difference probably is due to regional pumping from the aquifer system in the Chicago-Milwaukee area.

The converse is true in discharge areas and in the deeper confined aquifers where the head gradient is upward. Results of the packer tests (table 7) show only slight differences in head between aquifers in the confined parts of the Cambrian-Ordovician aquifer system in eastern Wisconsin, northeastern Illinois, and northwestern Indiana (wells 11, 15–19). However, this is an area with many multiaquifer wells in the Cambrian-Ordovician aquifer system in which interaquifer flow and drawdown from heavy pumping would tend to equalize the head between the aquifers. The upward hydraulic gradient in the Mount Simon aquifer at Zion, Illinois, is a remnant of the predevelopment artesian head within the Cambrian-Ordovician aquifer system near the western shore of Lake Michigan. The head of 386 ft above sea level was measured within the uppermost 560 ft of the Mount Simon aquifer. Additional data from deep piezometers installed at this site showed the head to be 425 ft above sea level at a point 892 ft below the top of the aquifer (Nicholas and others, 1987). This head is 50 ft higher than in the Ironton-Galesville aquifer, showing the regional trend of upward flow from the deeper aquifers.

Maps of the predevelopment potentiometric surfaces of the Silurian-Devonian, St. Peter-Prairie du Chien-Jordan, and Mount Simon aquifers (figs. 22–24) indicate the general patterns of regional ground-water flow. These surfaces, based on the earliest recorded heads in the aquifers, depict the approximate steady-



EXPLANATION

HYDROGEOLOGIC UNITS

- Drift aquifer
- Silurian-Devonian aquifer
- Maquoketa confining unit — Consists of Maquoketa Shale, Galena Dolomite, and the Decorah, Platteville, and Glenwood Formations where overlain by the Maquoketa Shale
- Galena Dolomite and Decorah, Platteville, and Glenwood Formations — Included in model water-table layer
- St. Peter-Prairie du Chien-Jordan aquifer
- St. Lawrence-Franconia confining unit
- Ironton-Galesville aquifer
- Eau Claire confining unit
- Mount Simon aquifer
- Precambrian crystalline rocks (confining unit)

—— CONTACT — Dashed where approximate

GENERALIZED GROUND-WATER FLOW PATH

- Local flow system
- Intermediate flow system
- Regional flow system

B–B' LINE OF SECTION SHOWN IN PLATE 1

FIGURE 20.—Generalized hydrogeologic section across southern Wisconsin illustrating typical predevelopment flow systems in the northern Midwest.

TABLE 7.—*Hydraulic-head data for aquifers in the Cambrian-Ordovician aquifer system*

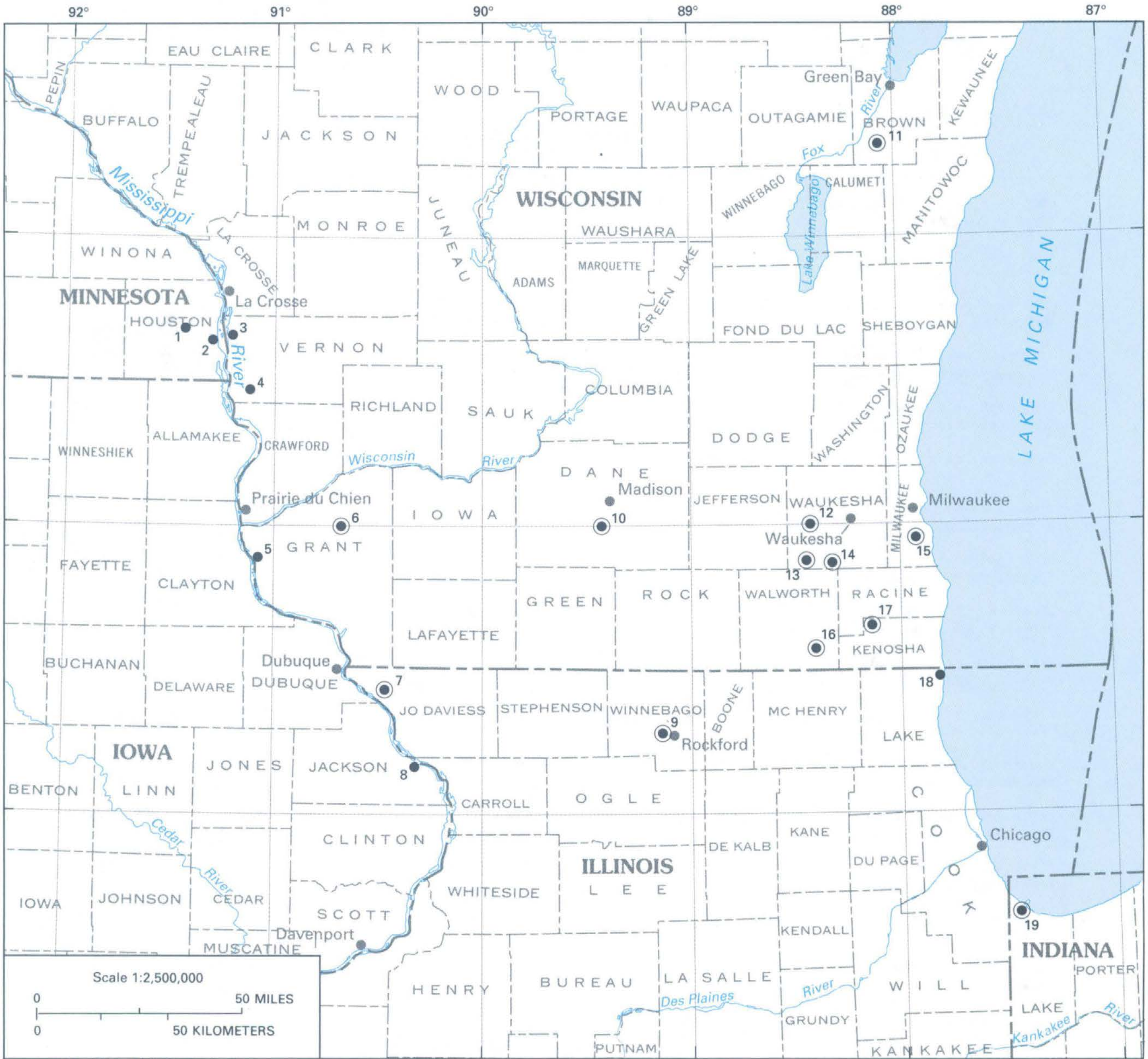
[Data from measurements during aquifer tests (May 1980 to September 1983) using inflatable packers. NP, not present; --, not available; do., ditto]

Map no. in fig. 21	Well name and location	Land surface (ft above sea level)	Location in the hydrologic flow system	Hydraulic head (ft above sea level) Mount Simon aquifer	Head difference between successive aquifer layers (ft)[1]	Hydraulic head (ft above sea level) Ironton-Galesville aquifer	Head difference between successive aquifer layers (ft)[1]	Hydraulic head (ft above sea level) St. Peter-Prairie du Chien-Jordan aquifer	Head difference between successive aquifer layers (ft)[1]	Hydraulic head (ft above sea level) Galena-Platteville unit
1	USGS test wells, Caledonia, Houston Co., Minn.[3]	1,210	Recharge area	686	77-	763	200-	963	--	NP
2	USGS test wells, Reno, Houston Co., Minn.	1,140	-do.-	652	8+	644	211-	855	--	NP
3	USGS test well, Stoddard, Vernon Co., Wis.	650	Discharge area	669	--	NP	--	NP	--	NP
4	USGS test well, Red Mound School, Vernon Co., Wis.	1,120	Recharge area	689	12+	677	245-	922	--	NP
5	USGS test well, Bagley, Grant Co., Wis.	635	Discharge area	692	20+	672	46+	626	--	NP
6	Fennimore, city well 4, Grant Co., Wis.[4]	1,185	Recharge area	--	--	746	208-	954	--	--
7	Limback well, Galena, Jo Daviess Co., Ill.	610	-do.-	639	1-	640	32+	608	>4-	>612 [2]
8	USGS test well, Green Island, Jackson Co., Iowa	610	-do.-	630	--	--	--	--	--	594
9	Rockford, city well 4, Winnebago Co., Ill.	730	Recharge area	646	10-	656	15-	671	0	671
10	Fitchburg, city well 1, Dane Co., Wis.	1,015	-do.-	--	--	924	20-	944	--	NP
11	Greenleaf, village well 1, Brown Co., Wis.	748	Confined	--	--	578	3-	581	0	581
12	Dousman, village well 2, Waukesha Co., Wis.[4]	895	Recharge area	729	58-	787	63-	850	14-	864
13	Eagle, village well 2, Waukesha Co., Wis.	925	-do.-	682	33-	715	93-	808	11+	797
14	Mukwonago, village well 2, Waukesha Co., Wis.[4]	841	-do.-	580	28-	608	49-	657	18-	675
15	Greenfield High School, Milwaukee Co., Wis.	793	Confined	431	1-	NP	--	432	0	432
16	Lake Geneva, village well 1, Walworth Co., Wisconsin	860	-do.-	--	--	--	--	659	4-	663
17	Bong Recreation Area, Kenosha Co., Wis.	802	-do.-	492	5-	497	1-	498	4+	494
18	USGS test well, Zion, Lake Co., Ill.	586	-do.-	386	11+	375	1-	376	3+	373
19	C and E Power Systems, East Chicago, Lake Co., Ind.	595	-do.-	--	--	195	5-	200	5+	195

[1] + indicates upward and - indicates downward hydraulic gradient.
[2] Total head not measureable due to leak around casing of flowing well.
[3] No packer tests, heads from piezometers in each aquifer.
[4] Test by Wisconsin District personnel.

state conditions of head and flow prior to the beginning of large-scale drilling of deep wells into the Cambrian-Ordovician aquifer system in the late 1800's. Head changes caused by pumping these wells are discussed in the following section, "Withdrawal of Ground Water and Its Effects."

Several factors complicate the preparation of maps of predevelopment potentiometric surfaces for the study area. Although many of the earliest deep wells were described in reports of the first geological surveys in each State, measured heads commonly were not reported. Some accounts gave



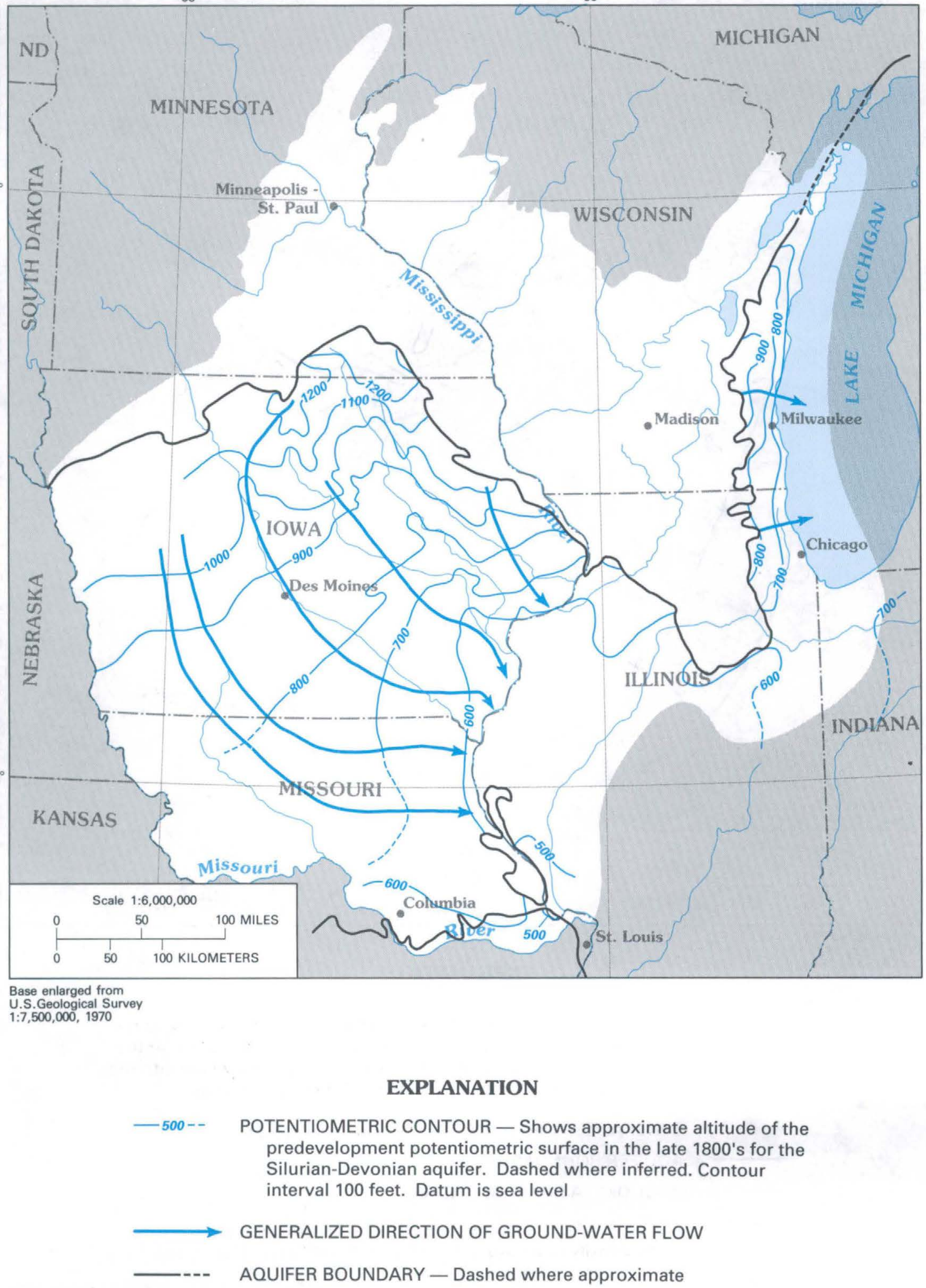
Base modified from U.S. Geological Survey National Atlas 1:2,000,000, 1970

EXPLANATION

WELL FINISHED IN THE CAMBRIAN-ORDOVICIAN AQUIFER SYSTEM IN WHICH PACKER TESTS WERE PERFORMED — Numbers are identification numbers in table 7

- •4 U.S. Geological Survey test well drilled for the Northern Midwest RASA (Note: no packer tests in well 1)
- ◉10 Other well

FIGURE 21.—Locations of test wells drilled for the study and of existing wells used for packer tests.



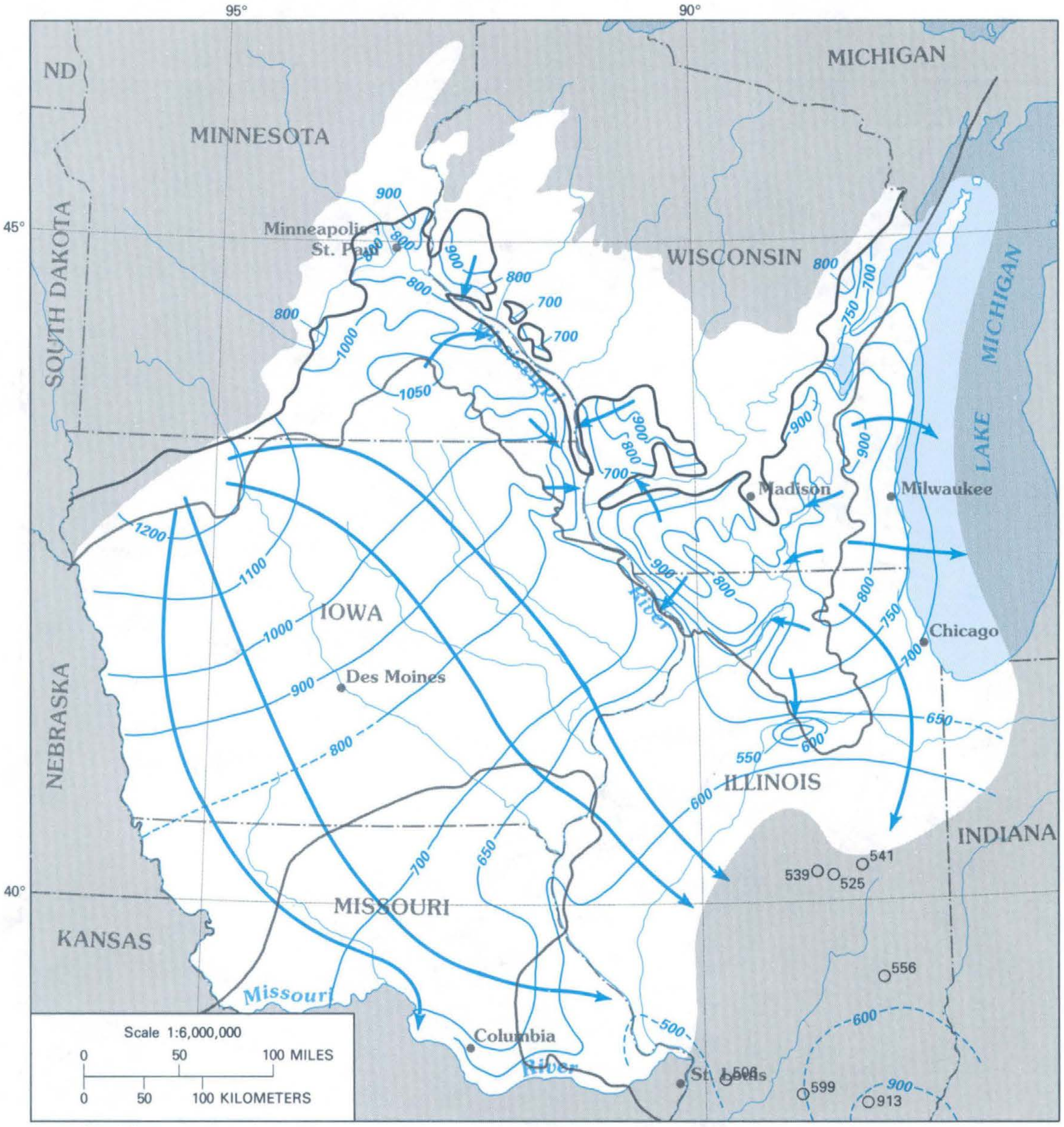
EXPLANATION

500 - - POTENTIOMETRIC CONTOUR — Shows approximate altitude of the predevelopment potentiometric surface in the late 1800's for the Silurian-Devonian aquifer. Dashed where inferred. Contour interval 100 feet. Datum is sea level

→ GENERALIZED DIRECTION OF GROUND-WATER FLOW

— - - - AQUIFER BOUNDARY — Dashed where approximate

FIGURE 22.—Approximate predevelopment potentiometric surface for the Silurian-Devonian aquifer. Modified from Mandle and Kontis (in press).



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

EXPLANATION

— 500 - - POTENTIOMETRIC CONTOUR — Shows approximate altitude of the predevelopment potentiometric surface in the late 1800's for the St. Peter-Prairie du Chien-Jordan aquifer. Dashed where inferred. Contour interval, in feet, is variable. Datum is sea level

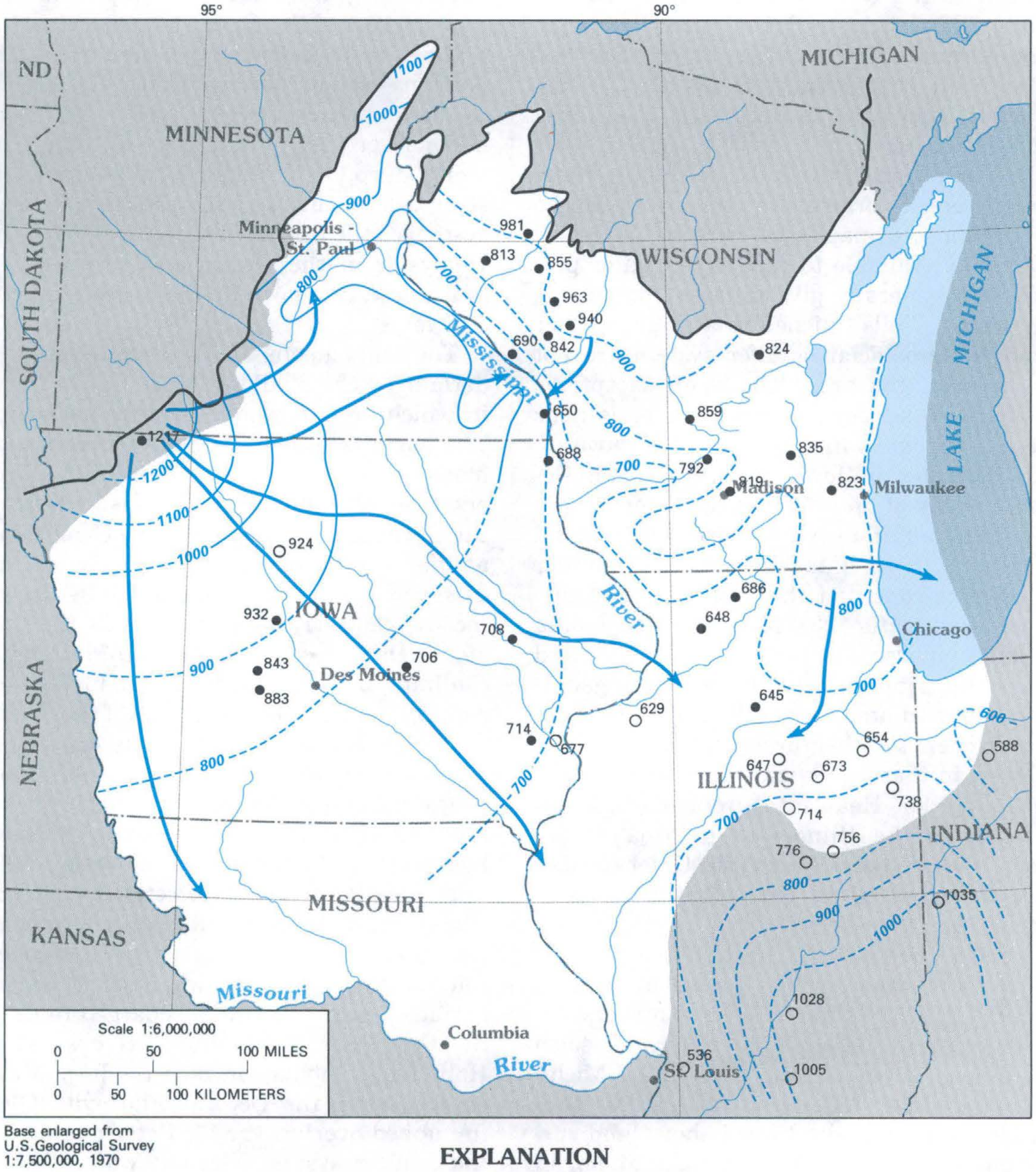
→ GENERALIZED DIRECTION OF GROUND-WATER FLOW

AQUIFER BOUNDARY

MAQUOKETA SHALE BOUNDARY

○ 506 WELL LOCATION — Number is water-level measurement corrected for density to equivalent freshwater head, in feet (Bond, 1972). Datum is sea level

FIGURE 23.—Approximate predevelopment potentiometric surface for the St. Peter-Prairie du Chien-Jordan aquifer. Modified from Mandle and Kontis (in press).



EXPLANATION

—700--- POTENTIOMETRIC CONTOUR — Shows approximate altitude of the predevelopment potentiometric surface in the late 1800's for the Mount Simon aquifer. Dashed where inferred. Contour interval 100 feet. Datum is sea level

GENERALIZED DIRECTION OF GROUND-WATER FLOW

AQUIFER BOUNDARY

LOCATION OF WELL WITH HYDRAULIC HEAD MEASUREMENT — Number is altitude, in feet above sea level

●706 Freshwater head measurement

○924 Measurement corrected for water density to obtain equivalent freshwater head

FIGURE 24.—Approximate predevelopment potentiometric surface for the Mount Simon aquifer. Modified from Mandle and Kontis (in press).

more emphasis to the geologic units penetrated and others mainly addressed the flowing artesian wells. Also, casing information was seldom reported, so the exact aquifer unit or combination of units represented by a reported head is uncertain. Previously compiled predevelopment or "early" head maps for parts of the Cambrian-Ordovician aquifer system, from various sources, formed the framework of the regional potentiometric maps. The personal interpretation of the data available to each investigator produced maps that generally give different portrayals of the early heads. Wells finished in a single aquifer of the Cambrian-Ordovician aquifer system are not common in most of the area. The main exceptions are in areas where an aquifer crops out or is near the surface and for wells in the St. Peter-Prairie du Chien-Jordan aquifer in Iowa and Minnesota. Because of the scarcity of data for the St. Peter-Prairie du Chien-Jordan aquifer in northern Illinois and eastern Wisconsin, head data for some multiaquifer wells were used to construct the potentiometric surface for that aquifer (fig. 23). Measured head data are particularly sparse for the Mount Simon and Ironton-Galesville aquifers because the units generally are deeply buried and most wells drilled to these units are also open to other overlying strata; thus, the water levels in these wells are a composite of the heads in each aquifer. Head measurements in zones of saline water in the Illinois basin area in the Mount Simon and St. Peter-Prairie du Chien-Jordan aquifers are corrected to an equivalent freshwater head (Bond, 1972).

The first deep wells drilled into confined parts of the Cambrian-Ordovician aquifer system in the late 1800's produced artesian flow in several topographically low areas in the Mississippi River, Missouri River, and Illinois River valleys, near Lake Michigan, and around Lake Winnebago in northeastern Wisconsin. The areas of highest head above land surface were along the western shore of Lake Michigan from Sheboygan County, Wisconsin, to Lake County, Illinois, and along the Mississippi River where it forms the Iowa-Wisconsin line and in the extreme southeastern corner of Iowa. Original heads of more than 100 ft above land surface were recorded at Sheboygan, Milwaukee, and Kenosha, Wisconsin, and at Dubuque, Iowa (Weidman and Schultz, 1915).

The potentiometric surface of each aquifer in its outcrop or subcrop area is closely related to the water table, showing some of the detailed and irregular configuration of the water table, but there is little similarity where the aquifer is confined. Rather, the potentiometric surfaces of the confined aquifers depict broad, regional patterns of uniform hydraulic gradient. Predevelopment ground-water flow in most of the Cambrian-Ordovician aquifer system was away from the recharge areas, either within patterns of flow over intermediate distances toward regional discharge areas (see fig. 20), such as the major river valleys and Lake Michigan, or down dip along deep, long, regional flow paths toward the structural basins. Ground water in intermediate flow systems still discharges upward to the major river valleys from the Cambrian-Ordovician aquifer system below, as shown by the heads in wells 5 through 8 in table 7.

The Minneapolis-St. Paul metropolitan area is underlain by the shallow Twin Cities structural basin, in which ground water is under artesian conditions. The basin is a subfeature of the Hollandale embayment (pl. 1) and the Minnesota and Mississippi Rivers. The artesian conditions result from recharge in the elevated outcrop areas of the Cambrian-Ordovician aquifer system on the perimeter of the basin. Deep dissection of the bedrock surface by the river valleys incised geologic units as deep as the Jordan Sandstone; thus, the local Decorah-Platteville-Glenwood confining bed (fig. 18) is absent in the valleys, interrupting the confined conditions of the St. Peter-Prairie du Chien-Jordan aquifer in the center of the basin. The predevelopment heads in the deeper Ironton-Galesville and Mount Simon-Hinckley aquifers, which are least affected by the dissection, caused an upward hydraulic gradient and ground-water discharge to the upper aquifers and, indirectly, to the river valleys (Delin and Woodward, 1984). Predevelopment flow in the Cambrian-Ordovician aquifer system elsewhere in southeastern Minnesota was strongly controlled by the surface topography and discharged to the Minnesota, St. Croix, or Mississippi Rivers, except in the Hollandale embayment near the Iowa-Minnesota line. In that area, the Decorah-Platteville-Glenwood confining bed overlies the St. Peter aquifer and confines the aquifer system. Ground water flowed from the perimeter of the embayment toward its center and then to the south into northeastern Iowa, where it discharged to the Mississippi River valley.

The longest flow paths in the Cambrian-Ordovician aquifer system extended southeastward from the recharge area of northwestern Iowa to the Illinois basin or to the Mississippi River and Missouri River valleys near their confluence, a distance of as much as 400 mi (fig. 23). Ground water in the aquifer system in northeastern Iowa is primarily unconfined and flows to the Mississippi River. Early accounts of artesian wells in Iowa (Norton, 1897; Norton and others, 1912) stated the mistaken belief that the source of artesian ground water in Iowa was the outcrop areas of the Cambrian and Ordovician rocks of southern Minnesota and central Wisconsin, which these authors even used to explain the observed southeastward flow direction across Iowa as a result of the heads in southern Minnesota and central Wisconsin and those in the obviously high area of northwestern Iowa.

Head and ground-water flow in the structural basins are probably unchanged from the predevelopment conditions. The basins contain brines that strongly restrict the regional movement of freshwater into the basins, thus forcing the confined water to discharge upward through overlying rocks. Flow rates are very small because of the low vertical hydraulic conductivity of the Maquoketa Shale and the large thickness of Devonian, Mississippian, and Pennsylvanian rocks. Therefore, horizontal flow in the aquifers within the basins may be controlled more by the vertical leakage coefficient of the overlying rocks than by the hydraulic conductivity of the aquifers. The hydraulic head is gradually dissipated by upward leakage and friction losses along flow paths in the basins until, as Bond (1972) indicates, the vertical head gradient may not be adequate to cause upward flow across shale layers in the center of the basin except through fractures.

WITHDRAWAL OF GROUND WATER AND ITS EFFECTS

An abundant ground-water resource has been an important part of the economic development of the northern Midwest for more than a century. Although shallow wells and springs served the rural and small community needs of the early settlers, a more abundant and reliable pure water supply became necessary as the population increased. This need was met by drilling deep wells, whose large yields aided industrial and municipal growth. The drilling of deep wells may have begun prior to 1860, but the earliest documented deep well seems to be one drilled to a depth of 711 ft in the Galena-Platteville unit at Chicago in 1864 (Shufeldt, 1865).[1] Drilling of deep wells proliferated throughout the area by the 1880's and 1890's, especially where flowing artesian wells could be obtained. Some flowing wells were connected directly to small distribution systems and to the water systems in homes of wealthy citizens with their own deep wells.

Unwarranted beneficial properties, including medicinal uses, were often attributed to ground water from deep or artesian wells and springs. The water was bottled and sold under the labels of artesian, spring, or mineral waters at many locations, an industry that is still productive. A particular water was distinctive and made marketable by characteristic tastes from dissolved hydrogen sulfide or iron; by high dissolved-solids concentration, generally due to sodium, chloride, and (or) sulfate; and by laxative properties from high concentrations of magnesium and sulfate.

The supply from these wells initially was considered inexhaustible, and many wells were allowed to flow unregulated as "fountains" in gardens and parks. Overdraft and interference between closely spaced wells caused heads in deep wells to decline, and many no longer flowed by the early 1900's. Norton (1897) described an unusual installation at Keokuk, Iowa, of four wells drilled to depths of 2,000 to 2,230 ft during a short period beginning in 1889. The wells were located on a bluff 160 ft above the Mississippi River and had original heads 30 ft above the surface. They flowed into a small lake, spilling over the bluff's edge to power two dynamos 130 ft below, which furnished electricity for city lighting. The combined flow of the wells was 2,000 gal/min (gallons per minute) initially but diminished to 1,500 gal/min in 1894 and 900 gal/min in 1896. The deepest well ceased flowing sometime before 1905, and the level of the lake was reported to be slowly declining in 1908 (Norton and others, 1912). Inadequate depths of casing and corrosion of iron casing in wells commonly allowed discharge into upper aquifers with lower head, adding to the general decline in head.

Discharge and withdrawal of ground water from the Cambrian-Ordovician aquifer system has increased more or less steadily to the present time, in direct relation to the general growth in population and economic and industrial development, especially in the population centers. This growth is illustrated by graphs of the historical pumpage from the aquifer system in the Chicago and Twin Cities areas (fig. 25). Major centers of pumping from the aquifer system are shown in figure 26 as county totals that exceeded an average of 1 Mgal/d (million gallons per day) in 1979–80. Pumpage was almost 180 Mgal/d from each of the Chicago and Twin Cities metropolitan areas outlined in figure 25 (Kirk and others, 1982; Horn, 1984). Pumpage exceeded 10 Mgal/d in only a few other areas: 43,

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[1]This is a very colorful account that describes both the drilling of the well and the "shows" of petroleum, beginning near the surface in the Silurian dolomite, that increased to "considerable quantities" below the Maquoketa Shale. Flowing water from the well was said to drive a water wheel to power drilling of other wells on the site. The account is embellished in spiritualistic claims and attributes the knowledge of "water and oil underneath this ground" to a spiritualist medium as early as 1863. It imaginatively promised "a cheap, inexpensive, perennial river***forever" that would be the basis for economic prosperity and educational opportunity for the poor. An essay titled "Of the origin of petroleum, its uses and applications" follows the article on the Chicago well.

18, 12, and 11 Mgal/d, respectively, in Dane, Waukesha, Jefferson, and Fond du Lac Counties, Wisconsin, and 22 and 14 Mgal/d in La Salle and Winnebago Counties, Illinois. Total pumpage from the Cambrian-Ordovician aquifer system in the study area averaged 684 Mgal/d in the period 1976–80 (Mandle and Kontis, in press).

AREAL UTILIZATION OF AQUIFERS

The particular aquifer or combination of aquifers used to obtain large water supplies in different areas of the northern Midwest depends primarily on the productivity of the aquifer. However, water quality and depth of the aquifer also are important factors.

In the Chicago area, most wells in the Cambrian-Ordovician aquifer system are cased to the base of the Maquoketa Shale and left uncased in most of the remainder of the Cambrian-Ordovician rocks that are penetrated. Some older wells were constructed with no casing or poorly sealed casing in the Silurian-Devonian aquifer, and some were left open to the Mount Simon aquifer. Thus, yields of most deep wells are a composite of the yields of more than one aquifer.

Suter and others (1959) estimated that the 76 Mgal/d pumped from "deep wells"[2] in northeastern Illinois in 1958 was derived proportionally from the Illinois aquifer units as then defined (fig. 18) as follows: 20.5 Mgal/d (27 percent) from the Silurian aquifer, 42.8 Mgal/d (56 percent) from the Cambrian-Ordovician aquifer, and 12.8 Mgal/d (17 percent) from the Elmhurst-Mount Simon aquifer. These proportions were used by the Illinois State Water Survey for many years to classify total deep-well pumpage by contributing aquifer. Although records of new wells drilled after 1958 show that no wells were constructed open to the Silurian aquifer (Ackermann, 1976), many older wells may have been abandoned without complete plugging of the borehole, and corrosion of casings allows leakage from the Silurian aquifer. However, Ackermann (1976) presented evidence to show that the volumetric contributions from the Silurian and Elmhurst-Mount

[2] The term "deep wells" refers to wells drilled into the Cambrian-Ordovician aquifer system, an unspecified number of which are also open to the Silurian-Devonian aquifer.

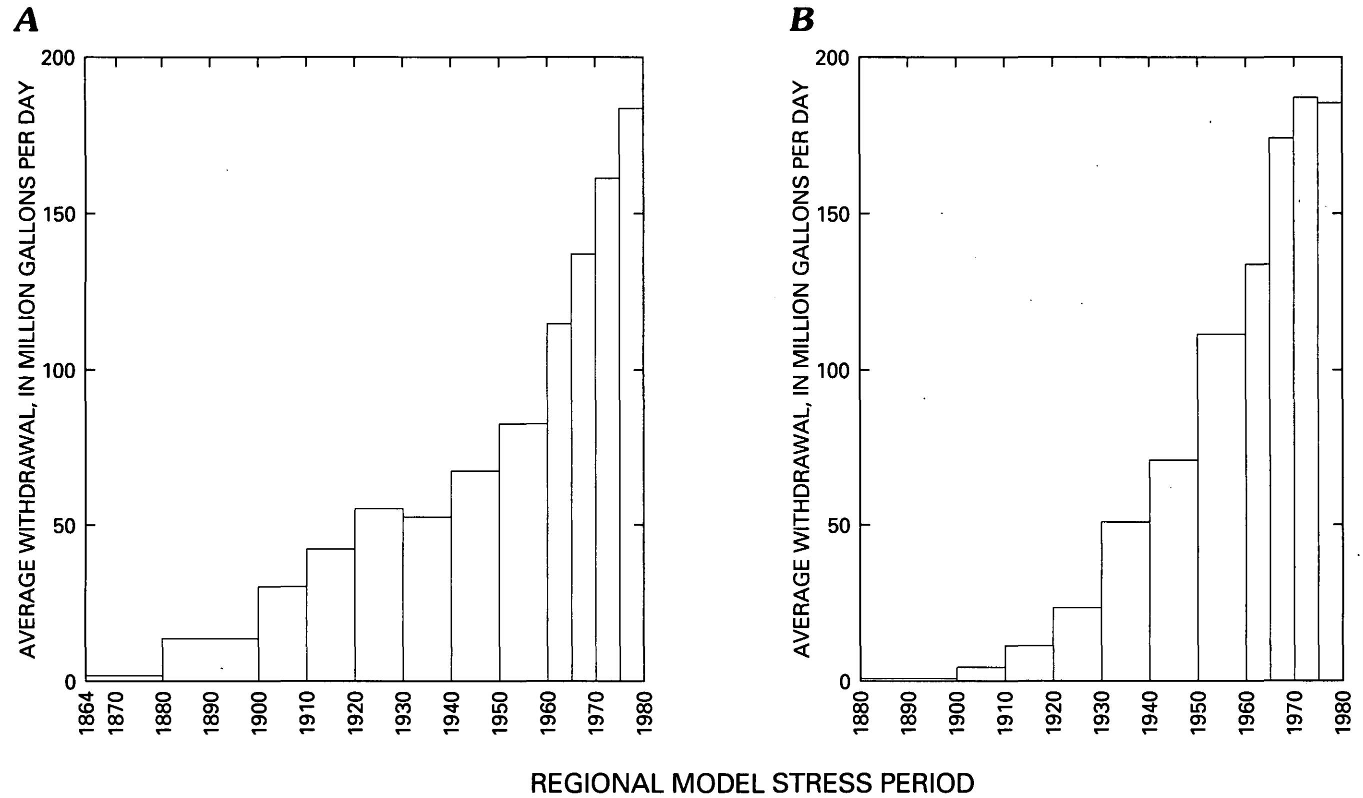


FIGURE 25.—Average historical ground-water withdrawal rates from the Cambrian-Ordovician aquifer system in the Chicago and Twin Cities areas. *A*, Eight-county Chicago area (see fig. 26). Data from files of Illinois State Water Survey, compiled for Northern Midwest Regional Aquifer-System Analysis. *B*, Seven-county Twin Cities area (see fig. 26). Data from Horn (1983).

Base modified from U.S. Geological Survey National Atlas 1:7,500,000

Sources of data: Illinois, Kirk and others (1982); Iowa, R. C. Buchmiller (U.S. Geological Survey, written commun., 1986); Minnesota, Horn (1983); Missouri, Imes (1985); Wisconsin, U.S. Geological Survey, Wisconsin State Water-Use Data System

EXPLANATION

2.8 AVERAGE PUMPAGE, IN MILLION GALLONS PER DAY — Number is average total pumpage from the Cambrian–Ordovician aquifer system in those counties with 1 million gallons per day, or more

METROPOLITAN AREAS OF FIGURE 25

FIGURE 26.—Major areas of ground-water withdrawal from the Cambrian-Ordovician aquifer system, 1979–80.

Simon aquifers had not increased in proportion to their 1958 percentages, but rather were relatively constant at rates of 20 to 30 Mgal/d for the Silurian and 14 Mgal/d for the Elmhurst-Mount Simon. Visocky (1982) states that the Elmhurst-Mount Simon has been plugged off in many wells because of increasing salinity of the water, and that by 1975 the combined contributions from the Silurian and Elmhurst-Mount Simon aquifers may have declined to 14 percent of total deep-well pumpage. However, the proportion from each source was not estimated by Visocky.

Walton and Csallany (1962) estimated the specific capacity of four intervals of the Cambrian-Ordovician aquifer system in six representative multiaquifer wells in the Chicago area in order to estimate the proportionate contribution to wells from each interval. Their specific-capacity estimates indicate the proportionate yield of each interval from the Cambrian-Ordovician aquifer system would be: (1) Galena Dolomite through St. Peter Sandstone—12 percent, (2) Prairie du Chien Group through Franconia Formation—28 percent, (3) Ironton and Galesville Sandstones—32 percent, and (4) Eau Claire Formation and Mount Simon Sandstone—27 percent. This distribution is significantly different from the estimates made by Suter and others (1959) for the local Cambrian-Ordovician aquifer: 15 percent from the St. Peter, 80 percent from the Ironton-Galesville, and essentially no contribution from the Prairie du Chien through the Franconia.

Local equivalents of the regional St. Peter-Prairie du Chien-Jordan aquifer are the main source of ground water in the remainder of northern Illinois, especially in the west. The Ancell aquifer and the Galena-Platteville unit (see fig. 18) are at or near the surface in those areas and are confined by the Maquoketa Shale in only a few places. Very large well yields usually are not needed; thus, these shallow bedrock aquifers generally provide an adequate source of ground water.

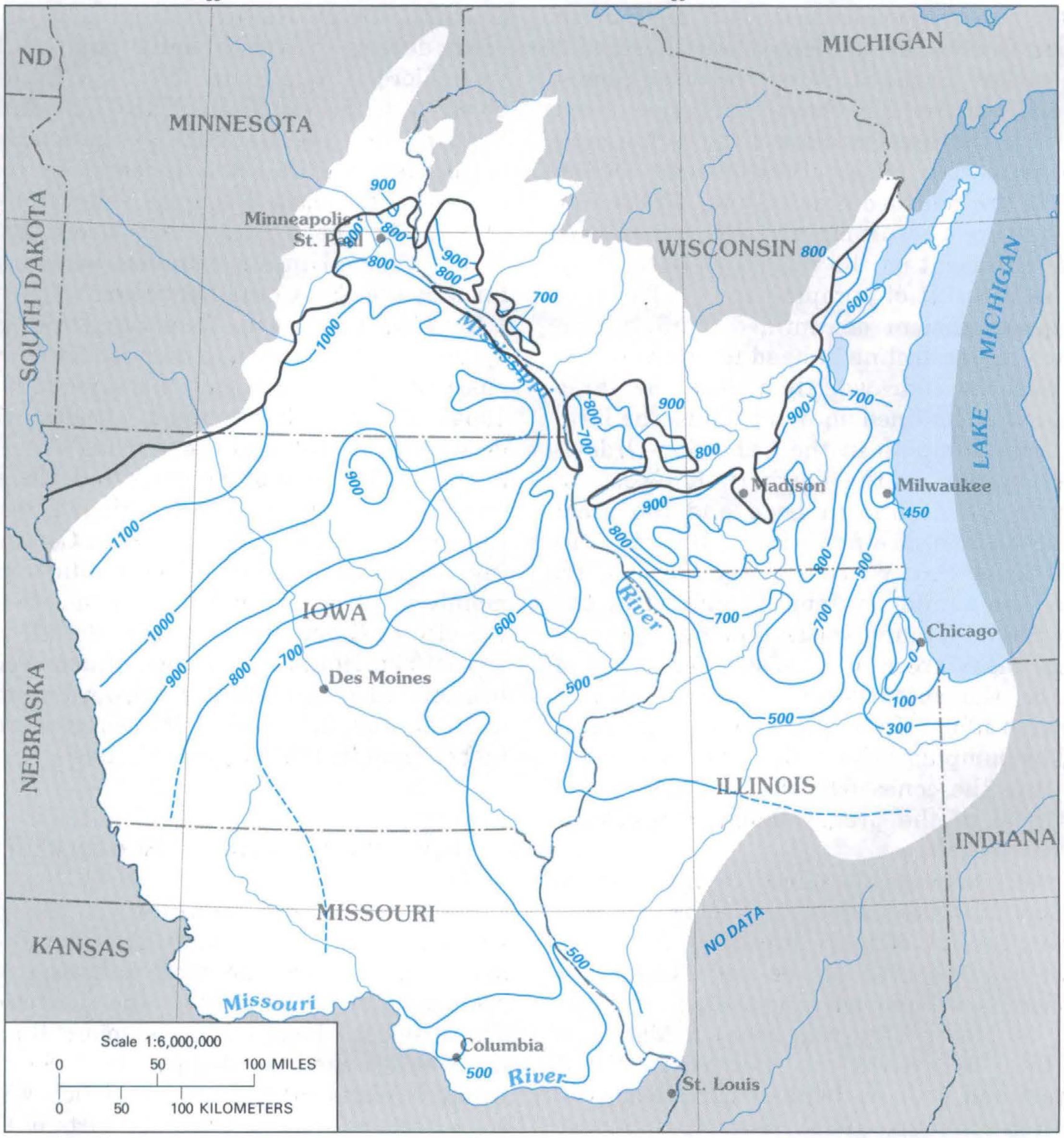
The Mount Simon aquifer is open to few wells in the Chicago area because, as is discussed in the later section "Ground-Water Quality," it contains mostly saline water. Salinity increases to the concentration of brines with increased depth in the aquifer and toward the Illinois and Michigan basins. The deep location of the Mount Simon and the salinity of its water make the aquifer unsuitable as a water supply. However, it is used for underground storage of natural gas in several projects within and on the perimeter of the Illinois basin, as far north as northwestern La Salle County, Illinois (70 mi south of the center of the Illinois-Wisconsin State line), and for injection of industrial liquid wastes in a few wells, primarily in northwestern Indiana (Ackermann and others, 1974; Ohio River Valley Water Sanitation Commission, 1976). Because of its saline water, the Mount Simon aquifer is not used as a water supply in northwestern Indiana.

Major withdrawals of ground water from the Cambrian-Ordovician aquifer system in Wisconsin (fig. 26) are from the Mount Simon and Ironton-Galesville aquifers in Dane, Waukesha, Jefferson, Fond du Lac, Brown, and Dodge Counties. Because the aquifer system consists mainly of permeable sandstone and is not deeply buried in Wisconsin, it provides moderate to large water supplies throughout most of its extent. The primary exceptions are along its northern perimeter on the Wisconsin arch, where it is thin as a result of erosion, and near Lake Michigan from northern Milwaukee County northward to southern Brown County and westward around Lake Winnebago, where it contains highly mineralized water (Ryling, 1961; Franz, 1985).

The Cambrian-Ordovician aquifer system in Iowa is buried progressively deeper, and its water becomes more mineralized to the south and southwest; therefore, wells generally are drilled only as deep as necessary to obtain a desired supply. Large yields usually are obtained from the Jordan aquifer (fig. 18), and wells commonly are not drilled to deeper aquifers, except in the unconfined area of northeastern Iowa. The St. Peter Sandstone commonly is left open in wells that are finished in the Jordan and contributes a small part of the yield of these wells.

The Prairie du Chien-Jordan aquifer (fig. 18) contributes more than 80 percent of the pumpage from the aquifer system in the Twin Cities area and is the most important bedrock aquifer in Minnesota. Next in importance is the Mount Simon-Hinckley aquifer, which contributes about 11 percent of the pumpage from the aquifer system in the Twin Cities area.

Pumpage from the Cambrian-Ordovician aquifer system in northern Missouri is limited to a small area in the southeastern part of the area (fig. 26) where the water is not highly mineralized. Of 14.1 Mgal/d pumped in 1980 from a 10-county area, mainly for public supply and irrigation, 12.6 Mgal/d were from Audrain, Boone, Callaway, and St. Charles Counties (Imes, 1985). The most productive parts of the aquifer system in this area are the Roubidoux Formation and Gasconade, Eminence, and Potosi Dolomites (fig. 18), equivalent stratigraphically to the Prairie du Chien Group and Jordan Sandstone and hydraulically to regional aquifer layer 3.



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

EXPLANATION

—500--- POTENTIOMETRIC CONTOUR — Shows approximate altitude of the 1980 potentiometric surface for the St. Peter-Prairie du Chien-Jordan aquifer. Dashed where inferred. Contour interval, in feet, is variable. Datum is sea level

——— AQUIFER BOUNDARY

FIGURE 27.—Generalized potentiometric surface for the St. Peter-Prairie du Chien-Jordan aquifer, 1980. Modified from Mandle and Kontis (in press).

CHANGES IN HYDRAULIC HEAD DUE TO DEVELOPMENT

Compared with predevelopment conditions (fig. 23), the 1980 potentiometric surfaces of aquifers in the Cambrian-Ordovician aquifer system (illustrated here by the surface for the St. Peter-Prairie du Chien-Jordan aquifer in fig. 27) show little effect from ground-water withdrawal in most of the recharge or unconfined areas, but major areas of head decline are evident in the confined areas. These differences in head decline are a result mainly of the function of the storage coefficient on the release of water from an aquifer as a result of pumping stress. The very small storage coefficient of confined aquifers produces a much larger decline in head for a given rate of ground-water withdrawal than does the large specific yield of unconfined aquifers. Thus, the largest effects from pumping in the Cambrian-Ordovician aquifer system in the northern Midwest, in terms of both the decline in head and the areal extent of the decline, are at Chicago, Illinois, Milwaukee and Green Bay, Wisconsin, and Mason City, Iowa, where the aquifer system is confined by the Maquoketa Shale. Ground-water flow has been altered within these areas of head decline (cones of depression on the potentiometric surface). Water moving downgradient from the recharge areas is intercepted by pumping wells in the cones, and water is induced into the cones from the opposite direction, a reversal of the predevelopment hydraulic gradient.

The difference between the effects of drawdown in confined and unconfined aquifers is shown by the following comparisons of total drawdown from predevelopment conditions at Mason City, Iowa, and Madison, Wisconsin. Pumpage from the confined Jordan aquifer at Mason City was about 8 Mgal/d in 1980, and total drawdown was more than 200 ft (M.R. Burkart and R.C. Buchmiller, U.S. Geological Survey, written commun., 1988). However, pumpage from unconfined Cambrian sandstones at Madison was about 40 Mgal/d, and yet total drawdown was only about 60 ft. The cone of depression at Madison induces recharge through deeply incised bedrock valleys and affects only a local area around the city (McLeod, 1975), whereas the deeper cone at Mason City is part of a large area with head declines of more than 50 ft that covers two-thirds of Iowa (Horick and Steinhilber, 1978).

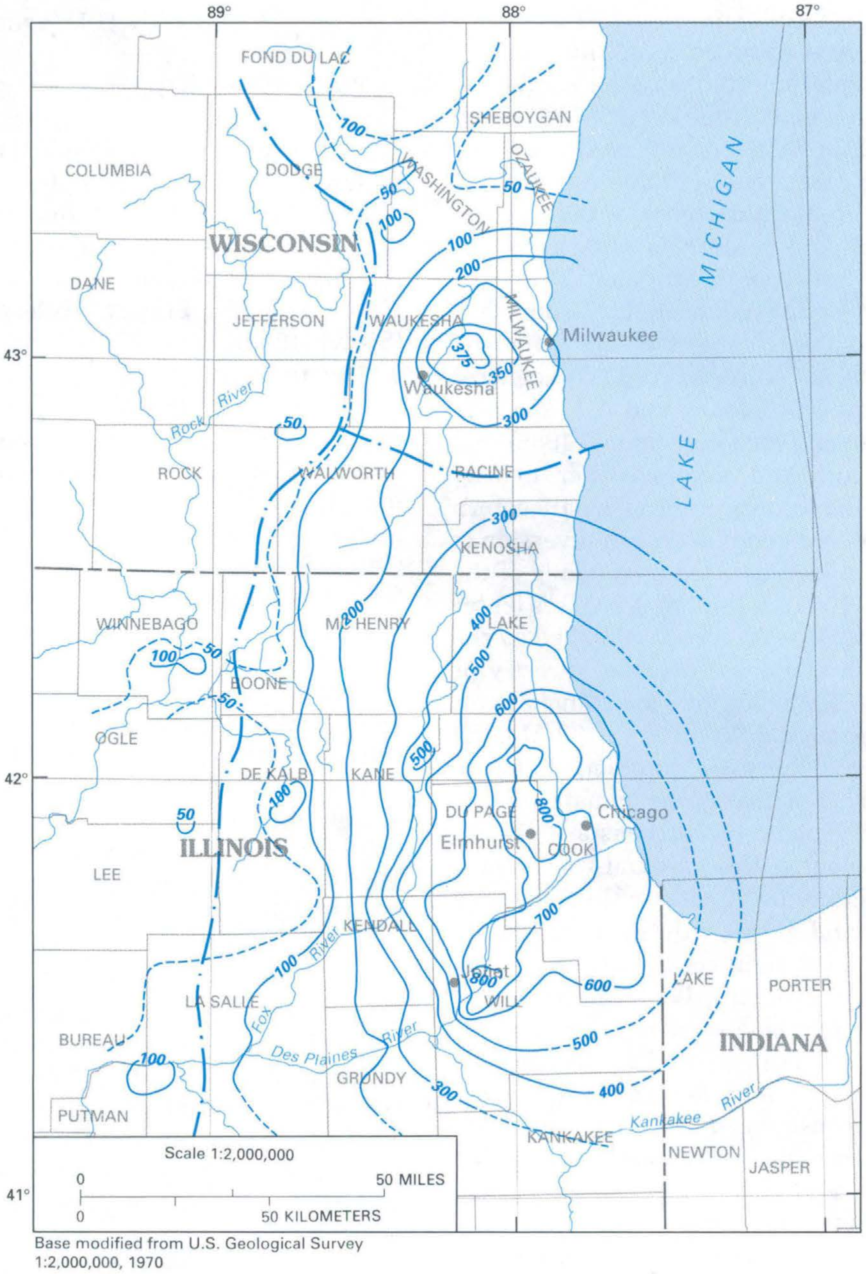
Although the historical trends and rates of pumping from the Cambrian-Ordovician aquifers in the Chicago and Twin Cities areas (fig. 25) are similar, the amount and extent of historical drawdown are not. The decline of the composite head in the aquifer system below the Maquoketa confining unit was more than 900 ft at Chicago from 1864 to 1980 (Visocky, 1982). However, from 1890 to 1980, the head decline in the heavily pumped Prairie du Chien-Jordan aquifer in the Twin Cities was only about 90 ft (Schoenberg, 1984). This relatively small head decline results from a combination of high transmissivity and the incomplete confinement caused by the incised bedrock valleys previously described. The head decline was about 200 ft in the Mount Simon-Hinckley aquifer, which is well confined by the Eau Claire Formation.

By 1957, head in the Cambrian-Ordovician aquifer system in Green Bay had declined as much as 440 ft since development began there in 1886 (Knowles, 1964). The city discontinued withdrawals from its deep wells in 1957 and began using water from Lake Michigan. The rate of pumping from the aquifer system declined from 13.1 to 5.3 Mgal/d, resulting in a recovery of almost 300 ft by 1960. Continued pumping of industrial and other public-supply wells, mainly south of Green Bay, has caused the head in the city of Green Bay to slowly decline about 40 ft since 1960. However, the cone of depression in 1980 has shifted a few miles southward from the 1957 location, and the head at its center is about 100 ft higher than in 1957 (Krohelski, 1986).

DEVELOPMENT IN THE CHICAGO-MILWAUKEE AREA

The large head declines in the Cambrian-Ordovician aquifer system in the Chicago-Milwaukee area (fig. 28) are the most impressive effects of ground-water withdrawal in the northern Midwest. The historical head decline of more than 900 ft in the Chicago area is evidenced by 1980 nonpumping water levels of more than 200 ft below sea level in some area wells in the deepest parts of the regional cone of depression near Joliet in northwestern Will County and Elmhurst in northwestern Cook County (Sasman and others, 1982). In addition to the 180 Mgal/d pumped from the Cambrian-Ordovician aquifer system in the eight-county Chicago area in 1980, about 33 Mgal/d were pumped from seven counties in southeastern Wisconsin.

Maximum head decline in the Milwaukee area by 1980 was more than 375 ft, centered in eastern Waukesha County. In 1950, a separate cone of depression was centered on Waukesha, Wisconsin, 13 mi west of the center of the main cone in central Milwaukee County (Foley and others, 1953).



EXPLANATION

200 ---- LINE OF EQUAL HEAD DECLINE, 1864–1980 — Dashed where approximate. Interval, in feet, is variable

—·— MAJOR POTENTIOMETRIC DIVIDE

FIGURE 28.—Decline in head for the composite Cambrian-Ordovician aquifer system in the Chicago-Milwaukee area, 1864–1980. Modified from H.L. Young and A.J. MacKenzie (U.S. Geological Survey, written commun., 1988).

However, by 1980 the Milwaukee cone had expanded westward to include eastern Waukesha County and the Waukesha cone (fig. 28), corresponding to a westward shift of the locus of pumping. The total rate of withdrawal in southeastern Wisconsin changed little from 1971 to 1980, even with population increases, because of water conservation and recycling measures by industrial and domestic users. The mutual interference of the Chicago and Milwaukee pumping centers is shown by the coalescence of their cones of depression. The east-west potentiometric divide between the cones has been displaced northward about 6 mi from the Racine-Kenosha County line in 1961 to central Racine County in 1980 (H.L. Young and A.J. MacKenzie, U.S. Geological Survey, written commun., 1988).

The city of Chicago and several other nearby municipalities in a five-county area of northeastern Illinois obtain their water supplies from a diversion of water from Lake Michigan, as fixed by a ruling of the U.S. Supreme Court (1967). A limit of 3,200 ft^3/s (cubic feet per second) (2,070 Mgal/d) was established as the amount of water that could be diverted, directly or indirectly, from Lake Michigan into the Illinois River waterway. Of this amount, 1,700 ft^3/s (1,100 Mgal/d) is direct withdrawal for "domestic" (municipal and industrial) purposes. This source is inadequate to supply the entire water demand of northeastern Illinois and must be supplemented from ground-water sources. The Cambrian-Ordovician aquifer system provided 59 percent of the ground water withdrawn in 1980 in the previously mentioned eight-county area of northeastern Illinois (Kirk and others, 1982). Management of the Lake Michigan diversion is administered by the Illinois Department of Transportation, Division of Water Resources (1980), which is directed to "make any allocations to new users of Lake Michigan water with the goal of reducing withdrawals from the Cambrian-Ordovician aquifer." This requirement is the basis for a ground-water management policy that aims to reduce the demand on the Cambrian-Ordovician aquifer system by optimization of other ground-water resources and by requiring recipients of new allocations to abandon any deep wells they have within five years. Completion of major parts of the Metropolitan Sanitary District of Greater Chicago Tunnel and Reservoir Plan (TARP) will decrease the amount of the Lake Michigan diversion that is now required for stream dilution to meet water-quality standards, which will allow more of the diversion to be allocated to public-supply and industrial uses (Macaitis and others, 1977).

GROUND-WATER QUALITY

By D.I. SIEGEL

This section describes, in general, the regional chemical quality and physical characteristics of ground water in the Cambrian-Ordovician aquifer system in the northern Midwest. Additional description of the ground-water quality of the aquifer system, including trace-metal distribution, isotopic composition, and geochemical evolution, is given in U.S. Geological Survey Professional Paper 1405–D (Siegel, 1989).

The interpretation of water quality in this section includes a synthesis of basic data from more than 3,000 analyses of water quality in the study area. These analyses represent the water quality mainly of three regional aquifers (fig. 18)—the Mount Simon aquifer, the St. Peter-Prairie du Chien-Jordan aquifer, and the combined drift and Cretaceous aquifers—and were obtained from the U.S. Geological Survey's data base WATSTORE (Water Data Storage and Retrieval System), from published reports by State and Federal agencies, and from samples collected during this project. Water chemistry of local parts of the Cambrian-Ordovician aquifer system is described in some detail in the following reports: in Minnesota by Winter (1974), Norvitch and others (1973), and Maderak (1965); in Wisconsin by Kammerer (1981, 1984), Holt and Skinner (1973), and Ryling (1961); in Iowa by Horick and Steinhilber (1978); in Missouri by Feder (1979) and Gann and others (1971, 1973); and in Illinois by Larson (1963), Gibb and O'Hearn (1980), and Visocky and others (1985). Description and analyses of brines in the Cambrian-Ordovician aquifer system are available in Meents and others (1952), Graf and others (1965, 1966), Bond (1972), and the files of the Illinois, Indiana, and Michigan Geological Surveys and of the Illinois State Water Survey.

Mean concentrations are used where multiple analyses are available from the same well. In general, analyses are not used that do not balance electrochemically within 5 percent. Some partial analyses of brines include data only for dissolved solids and chloride but are 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 as approximate. Locations of sample sites for analyses used in this report are given in figure 29. Because of the

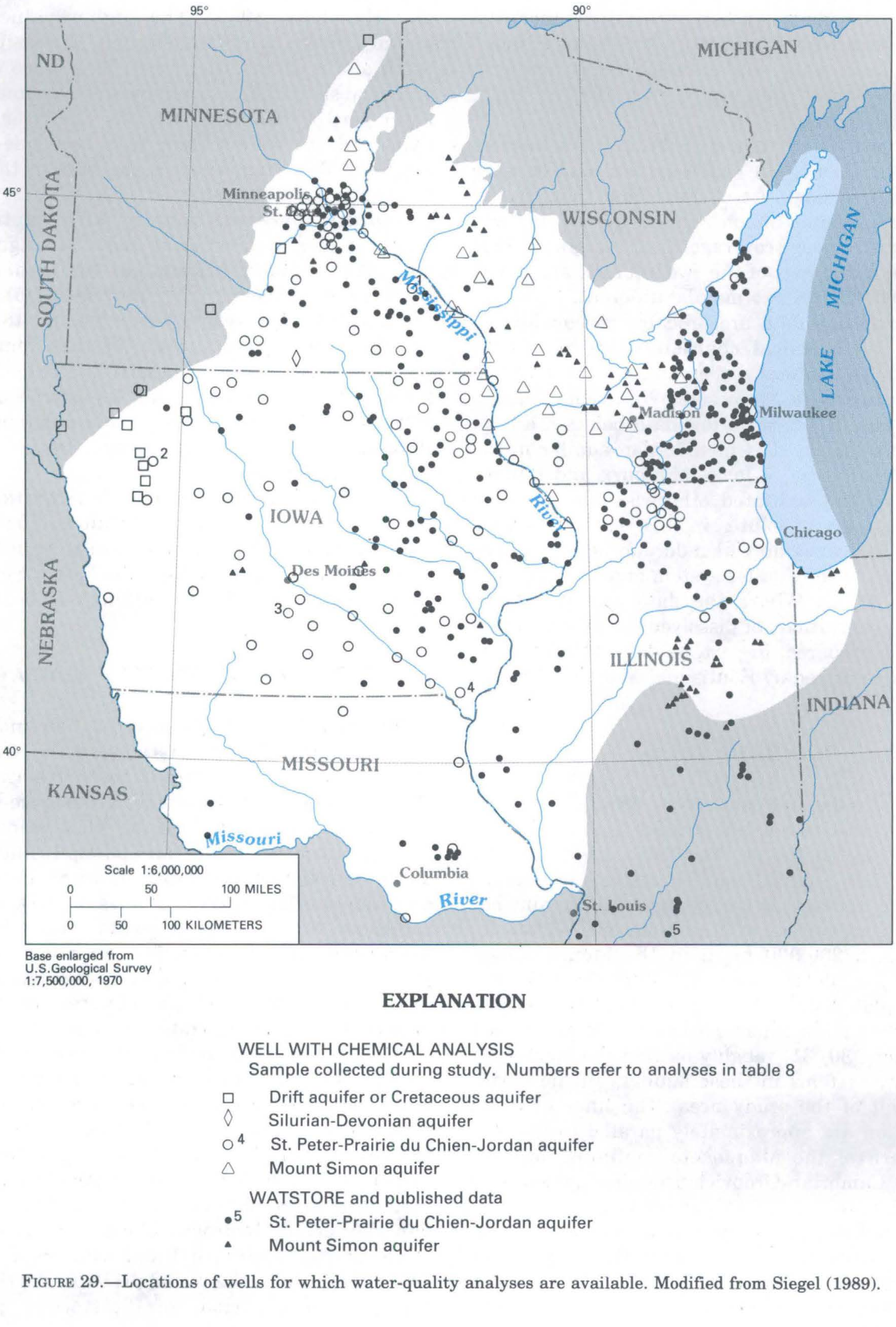


FIGURE 29.—Locations of wells for which water-quality analyses are available. Modified from Siegel (1989).

high density of data for the Silurian-Devonian, Cretaceous, and drift aquifers within their recharge areas in Wisconsin, Minnesota, Iowa, and Illinois, the locations of only new data for these aquifers, collected as part of this study from 1980 to 1983, are shown in figure 29.

Maps showing the areal distribution of solutes in the St. Peter-Prairie du Chien-Jordan aquifer were derived from a composite of data from that aquifer and from the Mount Simon aquifer, for which there is significant regional coverage. It is recognized that because the lithologies of the two aquifers are different, their chemistry also may be different. However, maps of composite data are probably reasonable because (1) the chemical characteristics of ground water in these aquifers are essentially the same in the outcrop areas in Minnesota, Wisconsin, Illinois, and Iowa, and (2) all but a few data points are from the St. Peter-Prairie du Chien-Jordan aquifer in the major confined areas in Iowa, Missouri, and Illinois. Therefore, unless indicated otherwise, the maps of areal distribution of solutes in this report represent the St. Peter-Prairie du Chien-Jordan aquifer in the confined part of the aquifer system and both aquifers in outcrop areas. Where the data are numerous, maps of concentrations of dissolved solids and specific ions were prepared, in part, by data-interpretation techniques described by Kontis and Mandle (1980).

DISSOLVED SOLIDS

The dissolved-solids content of ground water in the Cambrian-Ordovician aquifer system in the northern Midwest has a range as extreme as any found in other regional aquifer systems. Dissolved solids range from less than 200 mg/L (milligrams per liter) in recharge areas in Minnesota and Wisconsin, to more than 200,000 mg/L in the Mount Simon aquifer in the Illinois basin (fig. 30). The 500-mg/L lines of equal dissolved-solids concentration in the St. Peter-Prairie du Chien-Jordan and Mount Simon aquifers (figs. 30, 31) roughly outline the occurrence of local-flow systems in these aquifers in the northern one-half of the study area. The lines of equal concentration are approximately parallel to the outcrop pattern of the Maquoketa confining unit between the Cambrian-Ordovician aquifer system and the overlying units in Illinois and Wisconsin.

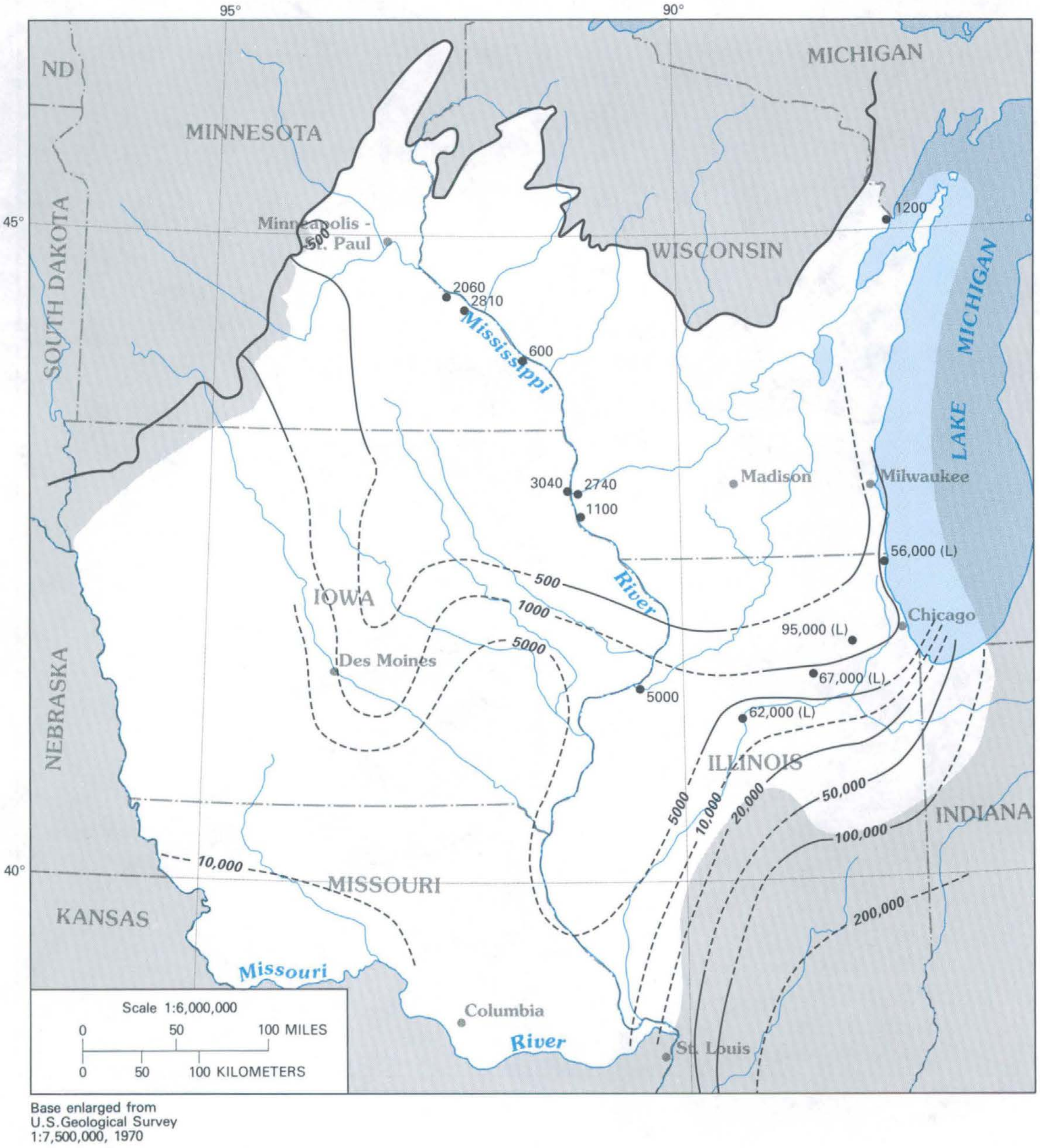
Dissolved solids generally increase in the direction of the hydraulic gradient because the longer flow paths increase the residence time of water in the aquifer, which results in a longer period of interaction with soluble minerals (Chebotarev, 1955; Back and Hanshaw, 1965). The higher values in the Mount Simon aquifer along the Mississippi River north of the Quad Cities area (fig. 30) are indicative of a very slow rate of ground-water movement in the lower part of the aquifer system. The river valley in that area receives discharge from both sides, leaving a zone of flow stagnation at the base of the aquifer system beneath the valley.

Salinity increases rapidly with depth in the Mount Simon aquifer near Lake Michigan (Suter and others, 1959; Ackermann and others, 1974; Nicholas and others, 1987). Barnes (1985) describes the interface of a wedge of saline water that underlies freshwater near the top of the Mount Simon aquifer in northeastern Illinois. The saline water is known to be at or above the top of the aquifer in extreme northwestern Indiana and adjacent parts of Illinois, but the interface is deeper in the aquifer to the west and northwest.

Locally high dissolved-solids concentrations in the St. Peter-Prairie du Chien-Jordan aquifer north of Milwaukee (fig. 31) possibly are a result of high rates of upward leakage from the Mount Simon aquifer where the Eau Claire confining unit is absent.

EFFECTS OF PLEISTOCENE GLACIATION

The distribution of dissolved solids and of other water-quality characteristics for the Cambrian-Ordovician aquifer system in the northern Midwest shows some residual effects from the large-scale continental glaciations during the Pleistocene. For example, in central Iowa, the 500-mg/L line of equal dissolved-solids concentration in the St. Peter-Prairie du Chien-Jordan aquifer outlines an area, which extends to the south-southwest (fig. 31), where dissolved-solids concentrations are much lower than in nearby parts of the aquifer system. In both Iowa and northern Missouri, the direction of increasing dissolved-solids concentration is generally toward the southwest, perpendicular to the direction of present-day ground-water flow. Because this ground water with low-dissolved-solids concentration also is isotopically depleted in $\delta^{18}O$ (standard expression of the ratio of the less abundant oxygen-18 ion with respect to the more common oxygen-16 ion) and δD (standard expression of the ratio of the less abundant deuterium (hydrogen-2) ion with respect to the more common hydrogen-1 ion) with respect to modern precipitation, the water probably represents recharge during periods of Pleistocene glaciation



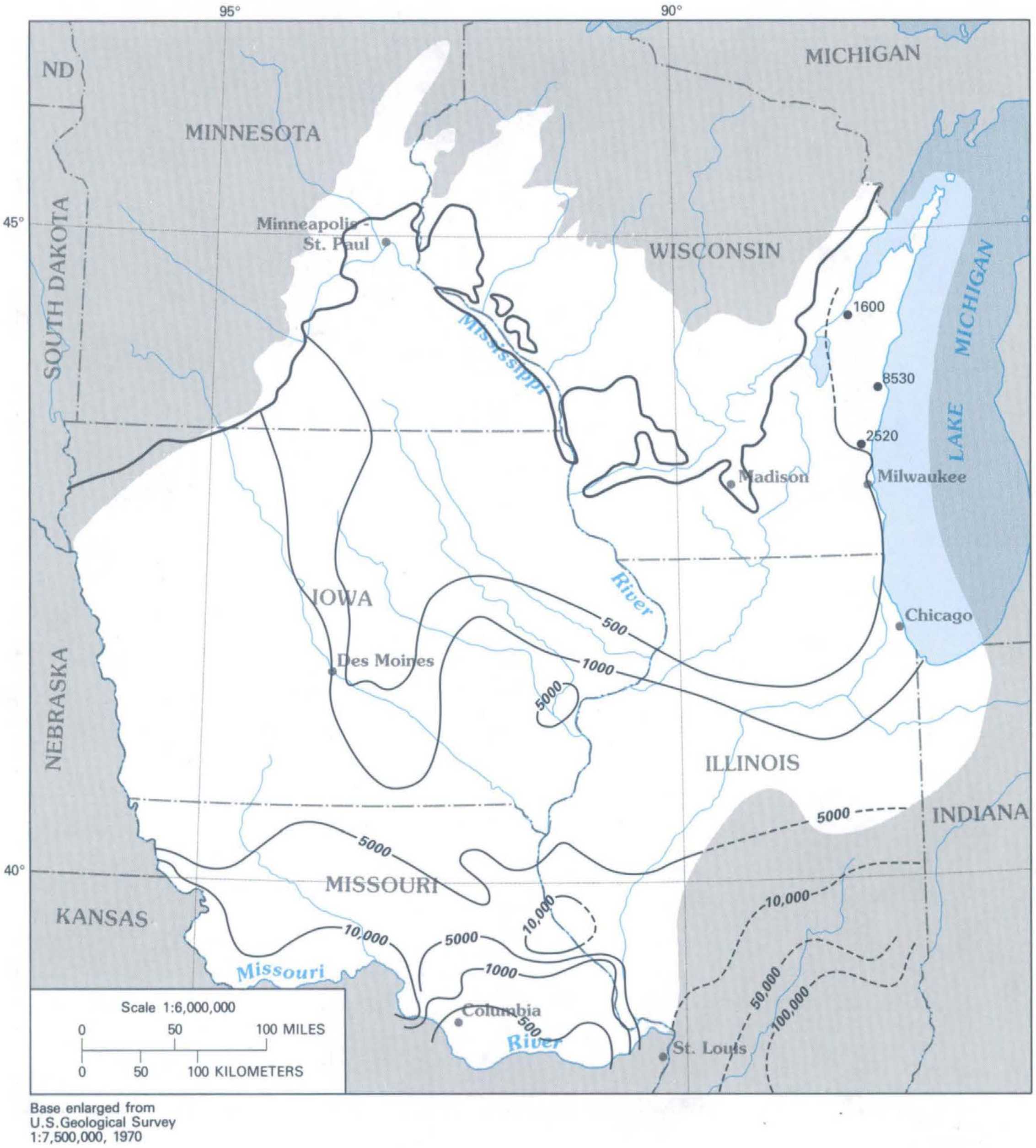
EXPLANATION

—500--- LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION — Dashed where approximate or inferred. Interval, in milligrams per liter, is variable

——— AQUIFER BOUNDARY

•3040 WELL YIELDING WATER WITH DISSOLVED-SOLIDS CONCENTRATION THAT EXCEEDS THE CONCENTRATIONS ON WHICH THE LINES ARE BASED — Number is dissolved-solids concentration, in milligrams per liter. (L) indicates water sample from lower part of the aquifer

FIGURE 30.—Dissolved-solids distribution in the Mount Simon aquifer.



EXPLANATION

—500--- LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION — Dashed where approximate or inferred. Interval, in milligrams per liter, is variable

——— AQUIFER BOUNDARY

•2520 WELL YIELDING WATER WITH DISSOLVED-SOLIDS CONCENTRATION THAT EXCEEDS THE CONCENTRATIONS ON WHICH THE LINES ARE BASED — Number is dissolved-solids concentration, in milligrams per liter

FIGURE 31.—Dissolved-solids distribution in the St. Peter-Prairie du Chien-Jordan aquifer. Distribution in northeastern Missouri and southern Illinois adapted from Imes (1985) and Meents and others (1952), respectively.

(Siegel, 1989). $\delta^{18}O$ ranges from less than −17 to more than −9 per mil (per thousand) and δD ranges from less than −130 to more than −60 per mil from north-central to northeastern Iowa. These values indicate that the source of the ground water was precipitation in a colder climate, similar to the present climate hundreds of miles north of the study area. The recharge probably was from subglacial meltwater from the Des Moines lobe of Wisconsin glaciation in north-central Iowa (D.I. Siegel, Syracuse University, written commun., 1988). The water is thought to have been emplaced by very high hydraulic gradients caused by the pressure of the overlying load of glacial ice (Siegel, 1989).

Although analyses of water quality from the Mount Simon aquifer in central Iowa are scarce, an area of dilute water is inferred in the general vicinity of the dilute water in the St. Peter-Prairie du Chien-Jordan aquifer (fig. 30). Because the Mount Simon aquifer also was covered numerous times by glacial ice, it is likely that it also contains a similar area of dilute water. This can be verified only by additional chemical quality-of-water data from future drilling into the Mount Simon aquifer.

In another area of the aquifer system, glaciation resulted in enrichment, rather than in dilution, of dissolved solids in ground water. Near the Lake Michigan shore in eastern Wisconsin and northeastern Illinois, dissolved-solids concentration increases from west to east (fig. 31). Dissolved solids normally increase along the direction of flow in regional flow systems; however, the area of higher dissolved solids in eastern Wisconsin and northeastern Illinois is close to the present recharge area. This increase in dissolved solids is caused largely by increases in both calcium and sulfate concentrations. There are few natural sources of sulfate in the matrix of the St. Peter-Prairie du Chien-Jordan aquifer or the overlying aquifers; thus, another source must be identified. Positive $\delta^{34}S$ values (standard expression of the ratio of the less abundant sulfur-34 ion with respect to the more abundant sulfur-32 ion) of sulfur in sulfate in the water indicate that the sulfur has an evaporitic origin (Siegel, 1989). This enrichment of $\delta^{34}S$ and the distribution of dissolved solids suggest the displacement of brines updip in the aquifer from the Michigan basin when isostatic loading by glacial ice caused the direction of the hydraulic gradients to be from east to west, the reverse of the present gradient (Gilkeson and others, 1981; Perry and others, 1982; Siegel and Franz, 1984; Franz and Siegel, 1984; Franz, 1985; Siegel, 1989).

MAJOR SOLUTES

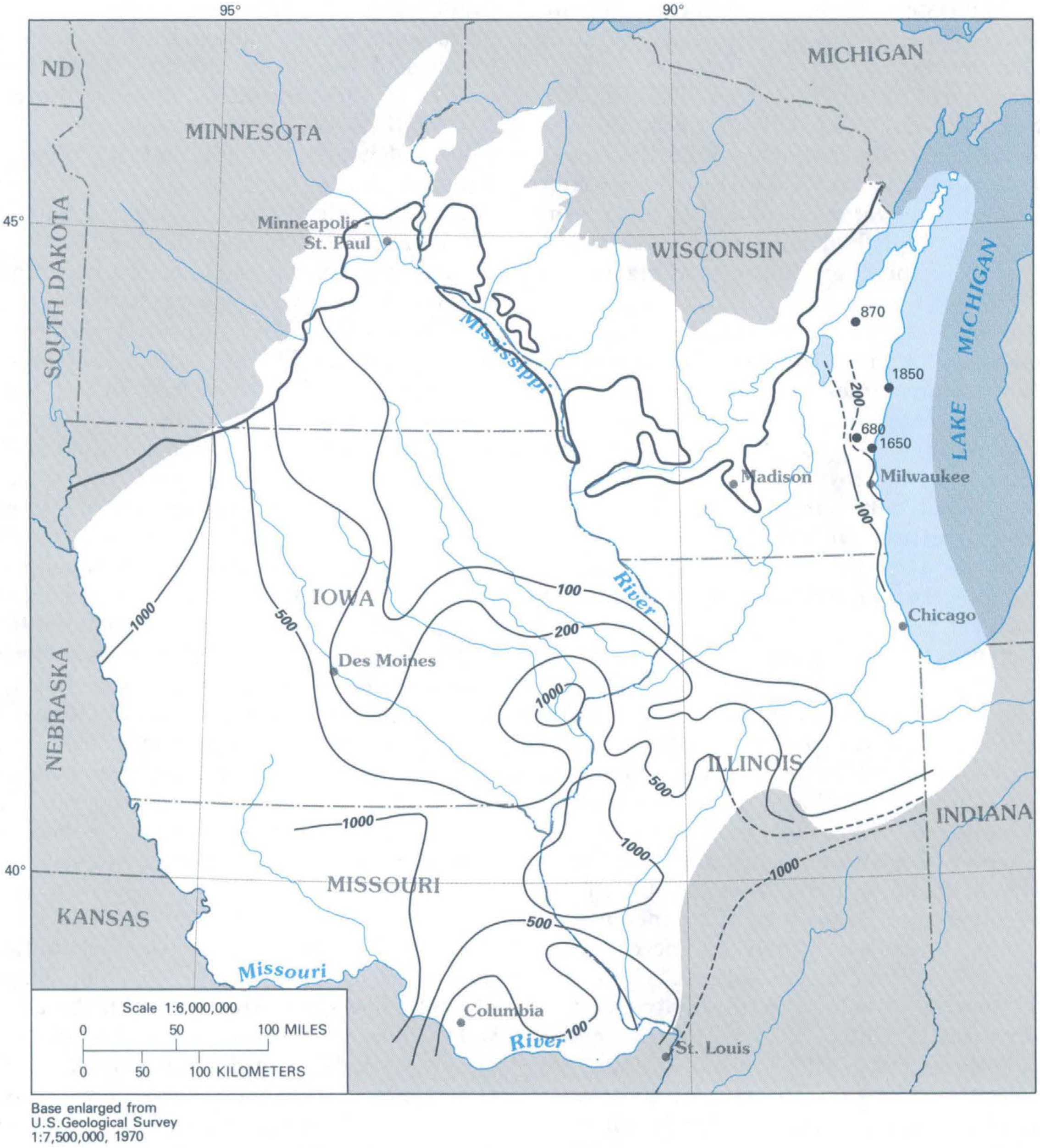
The major cations in the ground water of the Cambrian-Ordovician aquifer system are calcium, magnesium, and sodium, and the dominant anions are bicarbonate, sulfate, and chloride. The patterns of distribution of the concentrations of sulfate, chloride, and sodium closely resemble that of dissolved solids, although the gradients of their concentrations are dissimilar.

For example, sulfate concentrations in the St. Peter-Prairie du Chien-Jordan aquifer (fig. 32) range from less than 100 mg/L in the recharge areas in Minnesota and Wisconsin to more than 1,000 mg/L in northwestern Missouri, northwestern Iowa, and parts of central Illinois. Unlike the three orders of magnitude range of dissolved solids, the range in concentration of sulfate is about one order of magnitude. The pattern of distribution of sulfate shown by Siegel (1989) correlates with the area of dilute ground water in Iowa and an area of $\delta^{34}S$ enrichment in eastern Wisconsin. This indicates that the occurrence or lack of sulfate concentrations greater than 100 mg/L can be used, just as dissolved solids can be used to indicate paleohydrogeologic conditions.

The distribution pattern of chloride, commonly considered to be a relatively "nonreactive" constituent, also shows an area of low concentration in central Iowa (fig. 33). This area of low chloride concentration is not as distinct as the areas of low dissolved-solids and low sulfate concentrations because the concentrations of chloride in the ground water prior to the emplacement of the dilute water from Pleistocene glaciation were probably smaller. The distribution of sodium is similar.

Calcium and magnesium collectively cause the majority of water hardness. The distribution of hardness in the St. Peter-Prairie du Chien-Jordan aquifer (fig. 34) shows no correlation with the area of dilute water in central Iowa, unlike the distributions of dissolved solids, chloride, and sulfate.

Hardness throughout central Iowa is equal to or less than 500 mg/L (as $CaCO_3$). This probably is because the ground water has redissolved carbonate minerals to reach equilibrium after the emplacement of glacial meltwater (Siegel, 1989). However, noncarbonate hardness, probably caused by the emplacement in the aquifer of calcium-rich water from the Michigan basin, increases total hardness in eastern Wisconsin to more than 1,000 mg/L. Noncarbonate hardness is thousands of milligrams per liter in northwestern Missouri and southeastern Illinois because of the high salinity in the Forest City and Illinois basins. Almost all of the water in the aquifer is classified as hard or very hard (more than 120 mg/L as $CaCo_3$).



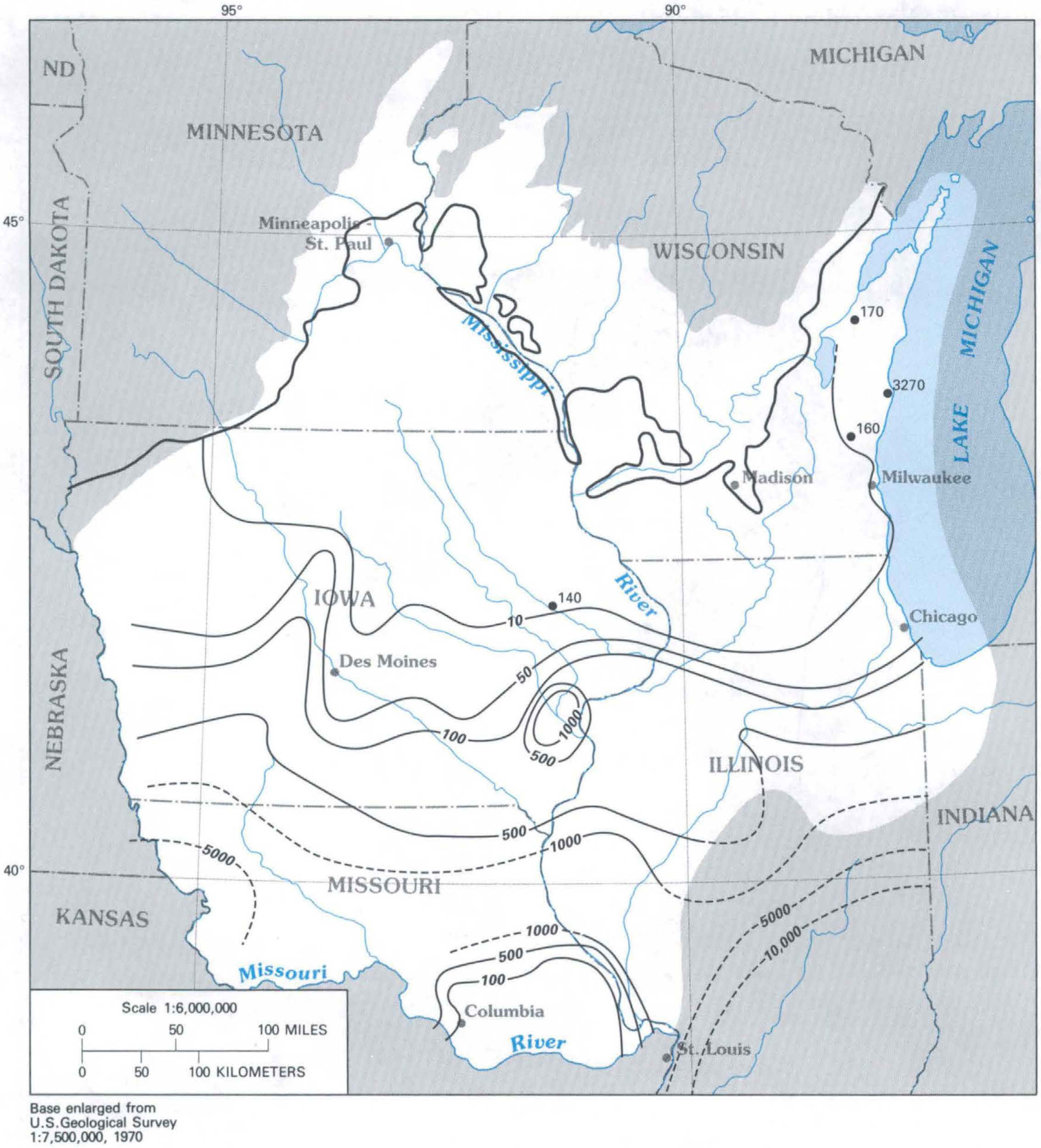
EXPLANATION

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

——— AQUIFER BOUNDARY

•1850 WELL YIELDING WATER WITH SULFATE CONCENTRATION THAT EXCEEDS THE CONCENTRATIONS ON WHICH THE LINES ARE BASED — Number is sulfate concentration, in milligrams per liter

FIGURE 32.—Sulfate distribution in the St. Peter-Prairie du Chien-Jordan aquifer. Modified from Siegel (1989).



EXPLANATION

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

——— AQUIFER BOUNDARY

•3270 WELL YIELDING WATER WITH CHLORIDE CONCENTRATION THAT EXCEEDS THE CONCENTRATIONS ON WHICH THE LINES ARE BASED — Number is chloride concentration, in milligrams per liter

FIGURE 33.—Chloride distribution in the St. Peter-Prairie du Chien-Jordan aquifer. From Siegel (1989).

HYDROCHEMICAL CLASSIFICATION

Water quality in the Cambrian-Ordovician aquifer system was classified according to dominant solutes using the classification system of Back (1966) to define hydrochemical facies (fig. 35).

Ground water in recharge areas is of the Ca-Mg-HCO_3 type, except in northwestern Iowa and

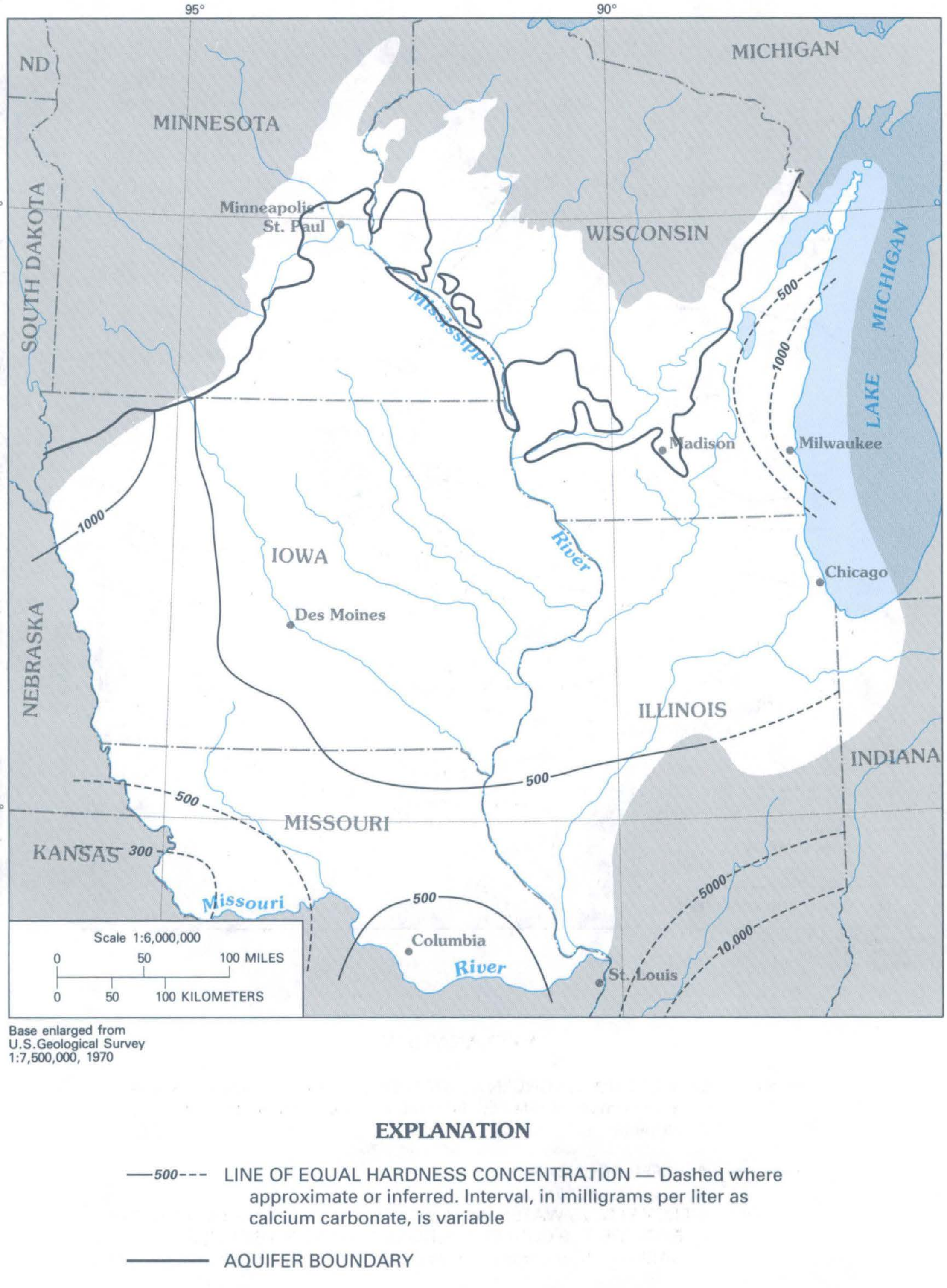


FIGURE 34.—Hardness distribution in the St. Peter-Prairie du Chien-Jordan aquifer.

southwestern Minnesota, where the aquifer is overlain by Cretaceous rocks that contain disseminated pyrite and mixed-layer clay minerals. Oxidation of the pyrite and ion exchange on the clays has produced a water of the Ca-Na-SO_4-HCO_3 type. Along the present major flow paths, from northwestern Iowa to central Illinois, water quality changes sequentially from Ca-Na-SO_4-HCO_3 to Na-Ca-SO_4-

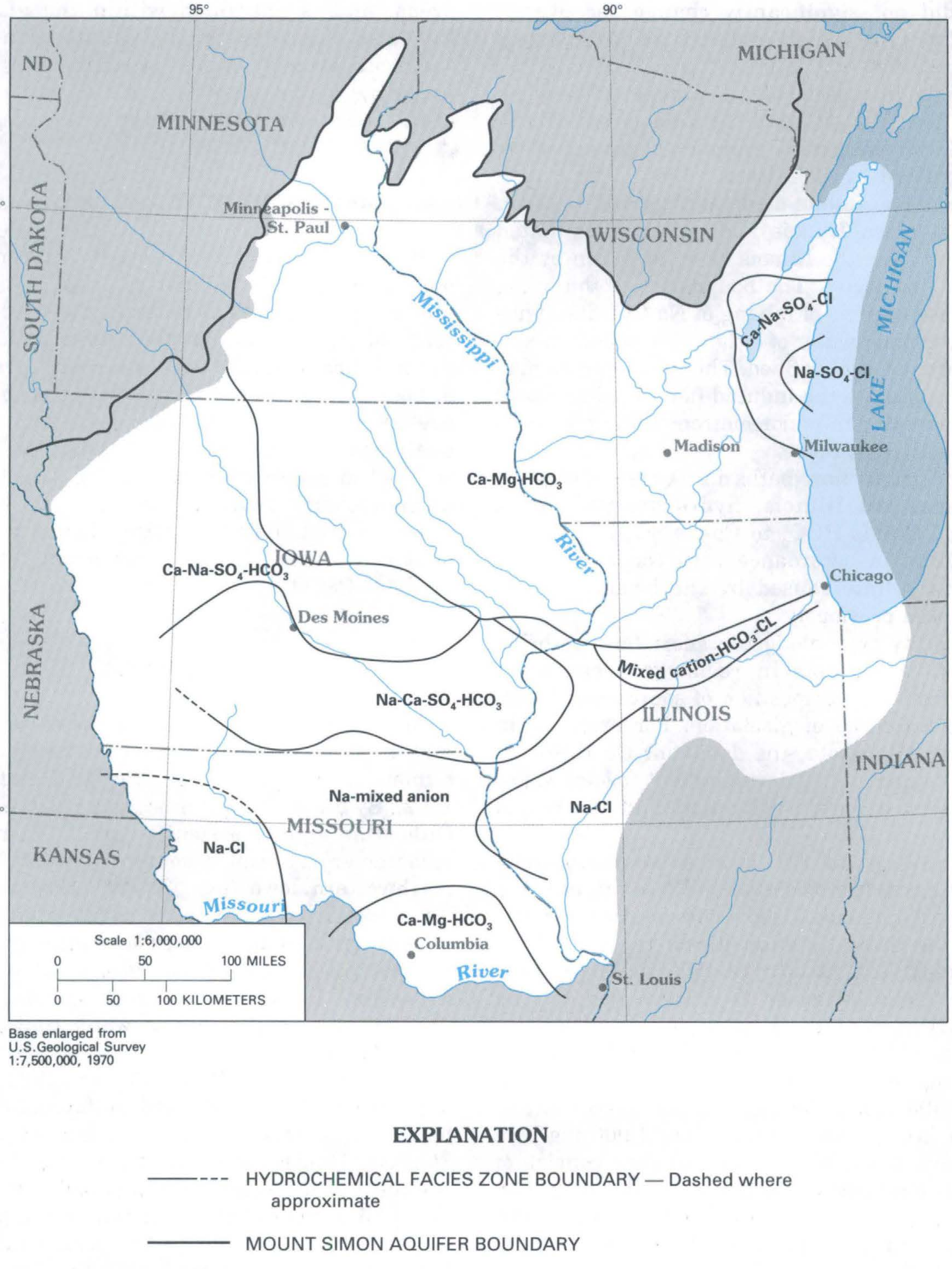


FIGURE 35.—Hydrochemical facies of ground water in the Mount Simon and St. Peter-Prairie du Chien-Jordan aquifer. From Siegel (1989).

HCO_3, Na-mixed anion, and Na-Cl types. These changes in water quality along the direction of present flow occur even within the area of dilute recharge from Pleistocene glaciation, indicating that the dilution process and subsequent chemical reactions between the water and the aquifer minerals did not significantly change the overall water-quality type, which probably was established prior to glaciation.

The trend of increased chloride concentration along the major flow paths toward the Illinois basin is in accordance with the general evolution of ground-water quality discussed by Chebotarev (1955). The transition zone between sulfate-dominated ground water in Iowa and western Illinois and chloride-dominated ground water near the Illinois basin is shown by the Na-mixed anion facies. The boundaries of this zone, which represent areas of mixing of Na-Cl brines with more dilute ground water of either bicarbonate or sulfate type, are not well defined. The mixing areas may change in relation to the induced flow of saline water caused by pumping in major metropolitan areas such as Chicago and Milwaukee.

Along the major flow paths in eastern Wisconsin and northeastern Illinois, hydrochemical facies change from Ca-Mg-HCO_3 to Ca-Na-SO_4-Cl and Na-SO_4-Cl waters, in accordance with the increase in calcium and sulfate caused by the brine emplacement discussed previously.

Water-quality type along the short flow paths in the local flow systems in recharge areas more directly reflects the composition of source rocks than it does the influence of glaciation. For example, in southeastern Minnesota, the dominant Ca-Mg-HCO_3 water type is unchanged downgradient toward major discharge areas along the Minnesota and Mississippi Rivers.

Water quality in the Cretaceous and drift aquifers is much less variable and less mineralized than in the Cambrian-Ordovician aquifer system. However, the direct relationship of these aquifers to the underlying Cambrian-Ordovician aquifer system in recharge areas is emphasized by the close similarities in their quality of water. Dissolved-solids content of water in the Cretaceous and drift aquifers in recharge areas ranges from less than 500 mg/L throughout the north-central part of the study area to more than 1,000 mg/L in northwestern Iowa, where the aquifers consist of pyritiferous Cretaceous rocks and glacial drift (fig. 36). Hydrochemical facies in the Cretaceous and drift aquifers in these areas are the same as those in the underlying Cambrian-Ordovician aquifer system. Ca-Mg-HCO_3 water is predominant in the north-central part of the study area; however, Ca-Na-SO_4-HCO_3 water occurs in southwestern Minnesota and northwestern Iowa (fig. 37). The sulfate is from the oxidation of pyrite whose source is the Dakota Formation, which overlies the Cambrian-Ordovician aquifer system in some areas, and is entrained within the glacial drift. Pyrite as the source of the sulfate is indicated by the isotopic composition of sulfur in the sulfate (negative values of $\delta^{34}S$) and the undersaturation of the water with respect to gypsum (Siegel, 1989).

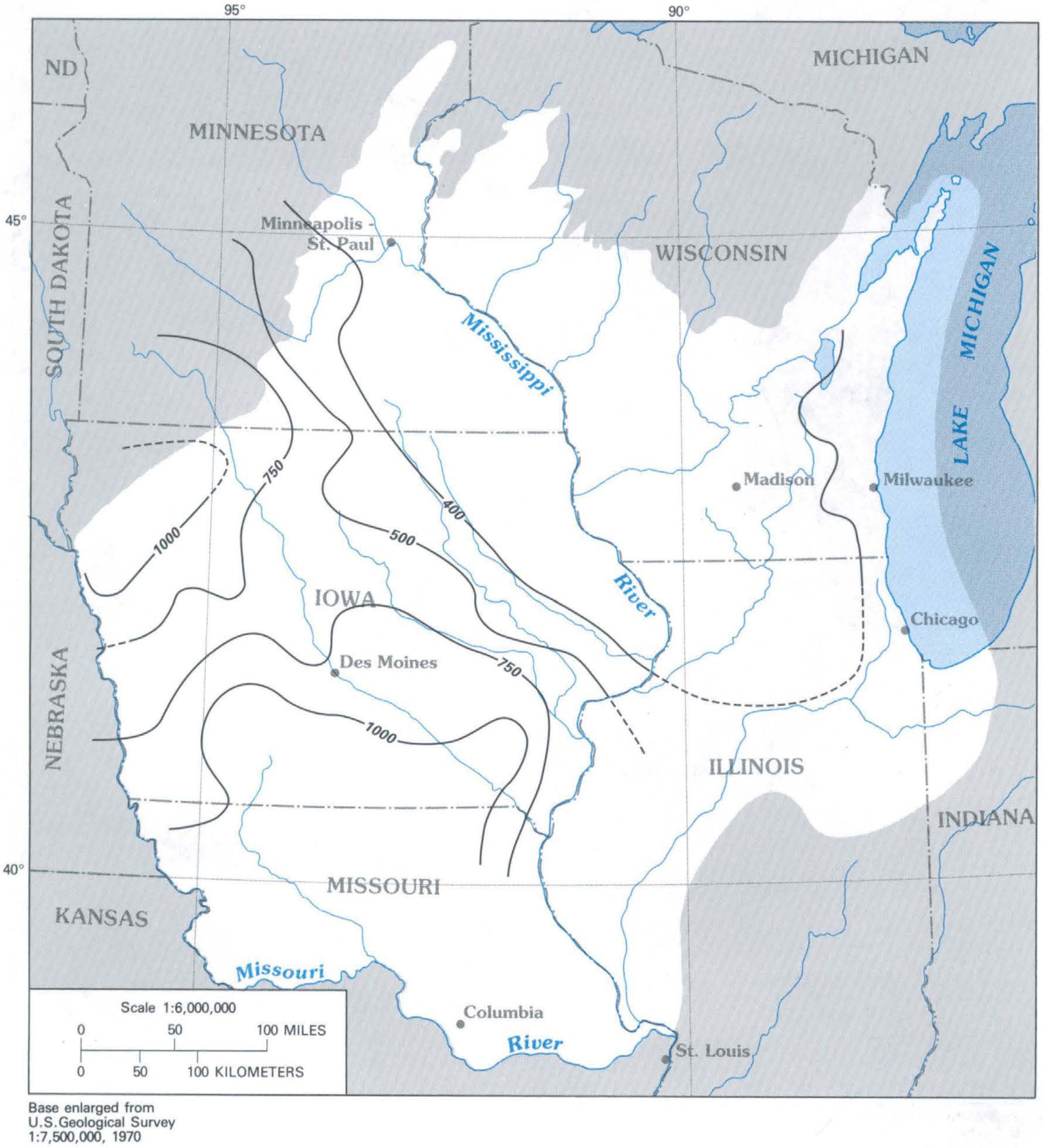
REPRESENTATIVE WATER QUALITY

Because of the large range of concentration of most solutes in the aquifer system, five representative analyses of ground water in the unconfined and confined parts of the aquifer system and within the major hydrochemical facies zones are given in table 8. Locations of the sampling points are shown in figure 29. Dissolved-solids concentrations in these analyses range from a low of 310 mg/L in water from the well in southeastern Minnesota (which is located in the recharge area) to more than 100,000 mg/L in a deep formation water in the Illinois basin. Hardness is variable, ranging from about 300 to 7,000 mg/L (as $CaCO_3$).

POTABILITY

In general, all water with a dissolved-solids content of more than 500 mg/L is not recommended for human consumption (U.S. Public Health Service, 1962). By use of this criterion, water in the Cambrian-Ordovician aquifer system is potable in most of the recharge area, except in southwestern Minnesota and northwestern Iowa (figs. 30, 31). However, because less mineralized water is not available in some areas of southern Iowa and eastern Wisconsin, ground water with concentrations of dissolved solids as high as 2,000 mg/L from the confined aquifer system is used as drinking water. Also, use of water containing more than 250 mg/L of sulfate or chloride is not recommended (U.S. Public Health Service, 1962). Considering the dissolved-solids and sulfate concentrations together as criteria for potability, ground water in the St. Peter-Prairie du Chien-Jordan aquifer in about one-third of the study area is potable, with an additional 15 percent of the area marginally potable (fig. 38). Dissolved-solids and sulfate concentrations in the Mount Simon aquifer are high over a larger but less well-defined area. This aquifer is not used significantly in western and southern Iowa, in northern Missouri, in Illinois south and southwest of Chicago, in northern Indiana, and in eastern Wisconsin north of Milwaukee.

Concentrations of some constituents, normally found in trace amounts, exceed commonly accepted limits or normal background levels in some areas in the Cambrian-Ordovician aquifer system. In particular, barium concentrations in eastern Wisconsin and northeastern Illinois exceed 1 mg/L where sulfate concentrations are depressed by sulfate reduction (fig. 38) (Gilkeson and others, 1981; Perry and others, 1982; Franz and Siegel, 1984). Radium activity in much of the confined part of the aquifer system in

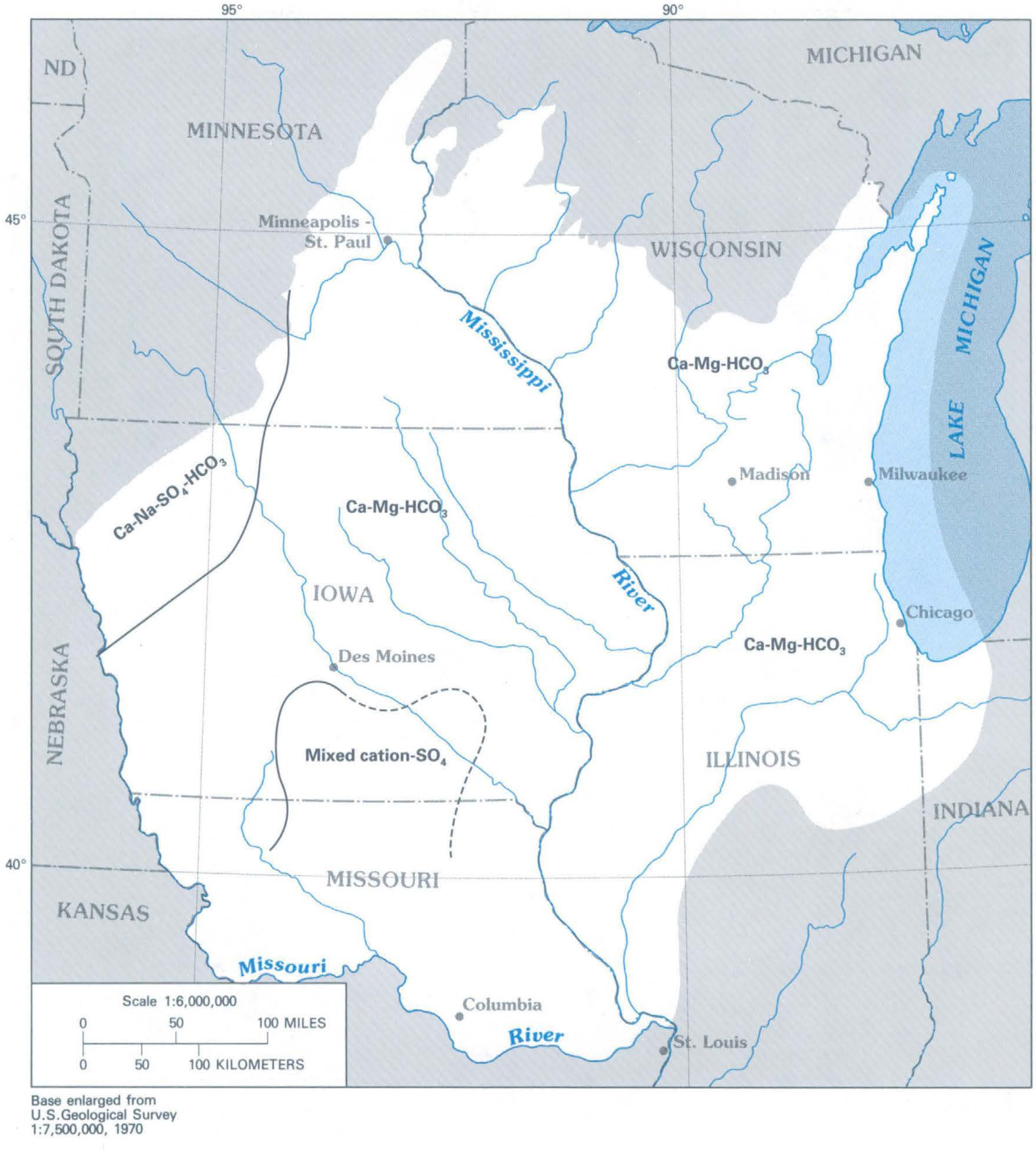


EXPLANATION

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

FIGURE 36.—Dissolved-solids distribution in the Cretaceous and drift aquifers.

eastern Wisconsin, northeastern Illinois, and central Iowa exceeds the current primary drinking-water standard of 5 picocuries per liter (U.S. Environmental Protection Agency, 1986) and has been a source of concern to State and local government (Lucas and Ilcewicz, 1958; Brown and Morris, 1959; Krause, 1959, 1960; Larson and Weatherford, 1960; Lucas, 1960, 1985; Morris and Klinsky, 1962; Emrich and Lucas, 1963; Kristoff and others, 1975; Horick and Steinhilber, 1978; Cochran and Hahne, 1979; Gilkeson and Cowart, 1982; Gilkeson and others, 1983). The source of the radium is not certain but



EXPLANATION

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

FIGURE 37.—Hydrochemical facies of ground water in the Cretaceous and drift aquifers. From Siegel (1989).

TABLE 8.—*Representative analyses of water quality in the St. Peter-Prairie du Chien-Jordan aquifer*

[Results in milligrams per liter, except as indicated. "*" indicates field values. Analyses 1 to 4 by U.S. Geological Survey. Analysis 5 from Meents and others (1952). Location of wells shown in fig. 29]

Analysis number	1	2	3	4	5
Well identification	Plainview #1 (Wabasha County, Minnesota)	Storm Lake #4 (Buena Vista County, Iowa)	Indianola #11 (Warren County, Iowa)	Donnellson #5 (Lee County, Iowa)	B-450 (sec. 20, T. 2 N., R. 2 E., Marion County, Illinois)
Hydrochemical facies	Ca-Mg-HCO_3	Ca-Na-SO_4-HCO_3	Na-Ca-SO_4-HCO_3	Na-mixed anion	Na-Cl
Date	Feb. 12, 1980	Sept. 4, 1980	June 10, 1981	Aug. 5, 1980	----
pH (standard units)	7.4	7.2 *	7.7 *	7.6 *	6.4
Specific conductance (µS/cm at 25 °C)	580	2,320 *	1,040 *	2,450 *	----
Calcium	72	279	55	62	6,862
Magnesium	27	64	22	28	1,513
Sodium	9.1	170	140	490	39,555
Potassium	.8	43	17	17	----
Bicarbonate	296	329 *	305 *	312 *	58
Sulfate	18	1,100	240	400	1,393
Chloride	24	30	30	370	76,582
Hardness (as $CaCO_3$)	290	970	230	270	6,953
Silica	17	8.3	12	9.5	32
Dissolved solids, sum of constituents	310	1,860	670	1,540	127,050

probably is related to the occurrence of uranium and thorium in the matrix of sandstones.

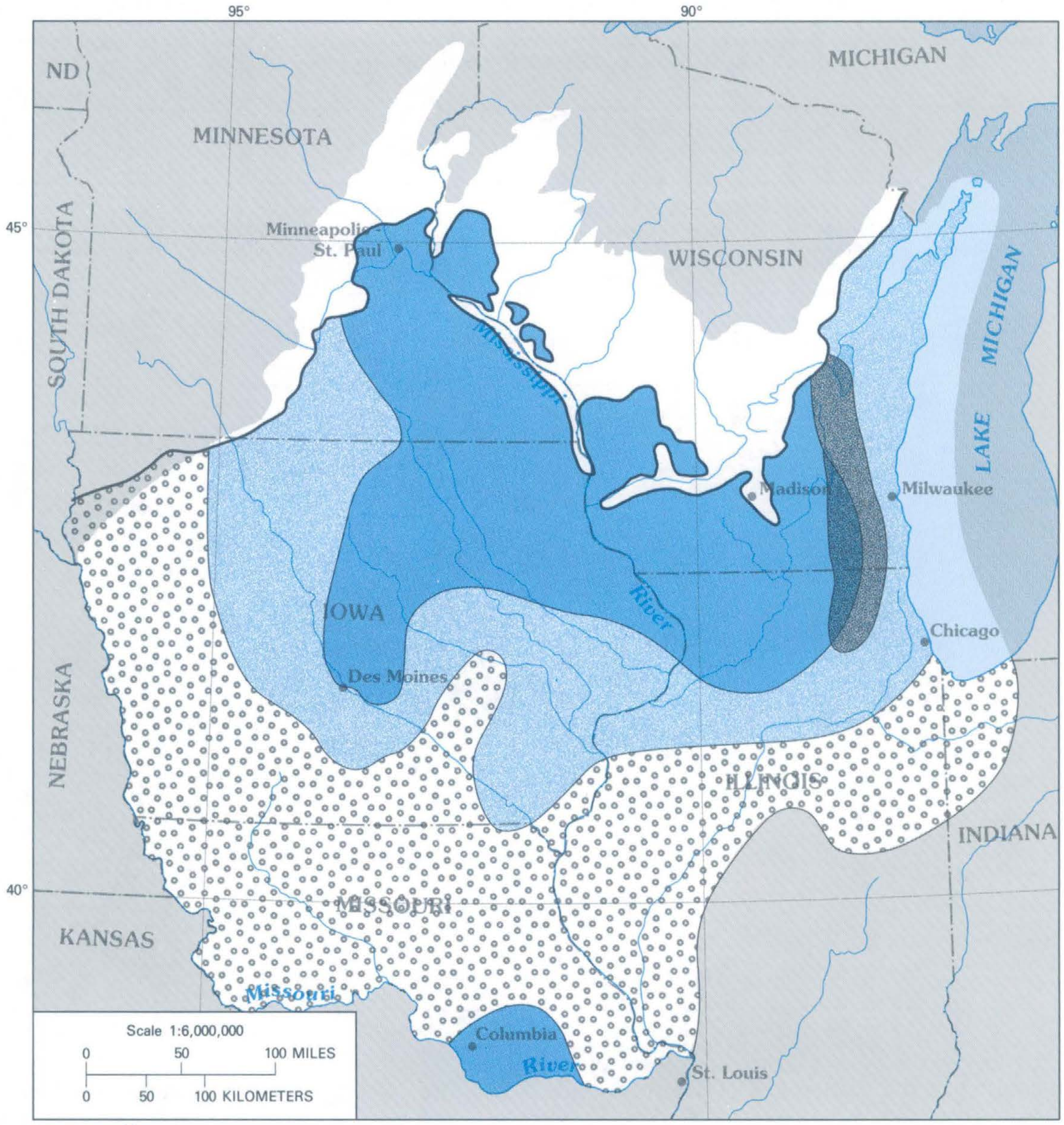
High concentrations of iron and hydrogen sulfide also degrade ground water in some localized areas.

SUMMARY

Much of the sequence of sedimentary rocks that overlie the Precambrian basement in the northern Midwest consists of marine sandstone and carbonate rocks of Cambrian and Ordovician age, which together form the major regional aquifer system of the area. The Cambrian-Ordovician aquifer system is essentially continuous and contains very productive aquifers throughout an area of about 161,000 mi^2 in southeastern Minnesota, Wisconsin, Iowa, northern Missouri, northern Illinois, and northwestern Indiana. Many metropolitan areas depend on the aquifer system for municipal and industrial water supplies.

The present topography of the northern Midwest generally is the result of Pleistocene continental glaciers that deposited a veneer of glacial drift on the eroded bedrock surface as recently as about 10,000 years B.P. The topography is formed by a variety of depositional and erosional features in the drift, which averages 50 to 100 ft in thickness but is as much as several hundred feet thick in end moraines and buried bedrock valleys. Drift is commonly less than 50 ft thick on some upland areas and is entirely absent in the Driftless Area of southwestern Wisconsin and adjacent areas.

Consolidated sedimentary rocks beneath the drift range in age from Precambrian to Cretaceous, cropping out from oldest to youngest in generally



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

EXPLANATION

AREA OF POTABLE WATER

AREA OF MARGINALLY POTABLE WATER

AREA WHERE RADIUM CONCENTRATIONS COMMONLY EXCEED 10 PICOCURIES PER LITER

AREA WHERE BARIUM CONCENTRATIONS MAY EXCEED 1 MILLIGRAM PER LITER

AQUIFER BOUNDARY

FIGURE 38.—Potability of ground water in the St. Peter-Prairie du Chien-Jordan aquifer.

concentric, arcuate patterns away from the Transcontinental and Wisconsin arches, topographically high areas of the Precambrian basement in northern Minnesota and Wisconsin, respectively. The oldest rocks also crop out, or are near the surface, near the Missouri and Mississippi Rivers in eastern and southern Missouri, dipping away from the Ozark uplift—a high on the Precambrian surface in southeastern Missouri. Thickness of the sedimentary rocks likewise increases away from the arches and toward flanking structural basins: the Forest City basin in southwestern Iowa, the Illinois basin in southeastern Illinois, and the Michigan basin centered on the Michigan Lower Peninsula. Maximum thicknesses of about 14,000 and more than 15,000 ft occur in the Illinois and Michigan basins, respectively.

Rocks in the northern Midwest are broadly divisible regionally into five aquifers, each underlain by a less permeable confining unit. The uppermost aquifer generally contains the water table and consists mainly of the drift aquifer, which is primarily unconsolidated glacial drift. A small area of Cretaceous shale and sandstone in western Iowa also is included in the uppermost regional aquifer for this study. Specifically, the Dakota Formation, which is a major artesian aquifer in North and South Dakota, also is an important aquifer in northwestern Iowa.

The entire sequence of rocks ranging in age from Pennsylvanian through Late Devonian form the uppermost regional confining unit, consisting primarily of shales and carbonate rocks. The unit contains some local aquifers with small to moderate yields, but on the whole, relative to the Cambrian-Ordovician aquifer system, it has low permeability and can be considered a regional confining unit. These rocks form the bedrock surface in most of the southern and western parts of the area, increasing in thickness from an erosional edge to more than 3,000 ft in the Illinois and Michigan basins. However, the unit is absent in Minnesota, Wisconsin, northeastern Iowa, northern Illinois, and northwestern Indiana.

Rocks of Middle Devonian through Silurian age are mainly dolomite and limestone and are termed the Silurian-Devonian aquifer. This aquifer immediately overlies the Cambrian-Ordovician aquifer system, except where the Silurian is absent on the Wisconsin arch. Permeability of the aquifer is highly variable and depends primarily on the extent and degree of intersection of fractures and joints in the rock, and on the subsequent solutional enlargement of these openings by weathering action and ground-water movement. This secondary permeability is greatest in the outcrop or subcrop areas of the aquifer in eastern Wisconsin, northeastern Illinois, and northeastern Iowa. Except for the outcrop area, the aquifer is overlain and confined by the younger rocks of the Pennsylvanian-Mississippian-Devonian confining unit. The Silurian-Devonian aquifer thickens from its erosional edge to more than 1,000 ft in the Illinois and Michigan basins but generally is 200 to 500 ft thick in its outcrop areas.

The remaining sedimentary rocks older than Silurian (mostly Cambrian and Ordovician in age) are the main subject of this study. The Cambrian-Ordovician aquifer system consists of three successive pairs of alternating aquifers and overlying confining units. The hydrogeologic units are named for their dominant stratigraphic components in the northern part of the study area but consist of appropriate stratigraphic and hydrologic equivalents in the southern part. The components of the Cambrian-Ordovician aquifer system (from youngest to oldest) as defined for this study are as follows:

1. Maquoketa confining unit—This unit provides the primary confinement to the aquifer system. The Maquoketa Shale is its main component, but where the Maquoketa overlies dolomite and shale of the Galena Dolomite and the Decorah, Platteville, and Glenwood Formations, these units also are an important part of the confining unit. Where the Maquoketa Shale is absent, these formations are more likely to have a higher permeability because of weathering and are moderately productive aquifers in some places. In southeastern Minnesota, the Maquoketa Formation is mainly limestone and is included with limestone of the overlying Devonian Cedar Valley Formation and the underlying dolomitic limestones of the Dubuque and Galena Formations to form the local upper carbonate aquifer. The Maquoketa confining unit increases in thickness from the north to the south and east. It commonly is 400 to 600 ft thick in eastern Iowa, eastern Wisconsin, and in northeastern Illinois.

2. St. Peter-Prairie du Chien-Jordan aquifer—All or parts of this unit are important sources of ground water, especially in the western part of the study area in Iowa and Minnesota. The local Jordan aquifer in those States generally consists of the Jordan Sandstone and the hydraulically connected dolomite of the overlying Prairie du Chien Group. High productivity of the Jordan aquifer depends on the degree of development of secondary permeability in the overlying dolomite because of

fractures and solutional enlargement by weathering. The aquifer is well confined in most of Iowa but is dissected and only partially confined in extreme northeastern Iowa and much of southeastern Minnesota. The aquifer underlies the ridges of the Driftless Area and adjacent parts of Minnesota where, because the water table is very deep, the upper part of the aquifer is unsaturated. The aquifer is not as important in the eastern part of the study area because the Jordan is not present and the Prairie du Chien is thin or absent due to pre-St. Peter Sandstone erosion in much of southern Wisconsin and northern Illinois. In northern Missouri, the aquifer consists of the St. Peter and underlying carbonate equivalents of the Prairie du Chien and Jordan: the Roubidoux Formation and the Gasconade and Eminence Dolomites. The Roubidoux and Gasconade contain some sandstone that makes them productive aquifers. The aquifer increases in thickness away from the northern erosional area to more than 1,500 and 1,000 ft, respectively, in the Illinois and Michigan basins.

3. St. Lawrence-Franconia confining unit—The two formations that compose this unit generally are very silty and shaly, fine grained, poorly sorted, dolomitic sandstones. Although they contribute water locally to some multiaquifer wells, their anisotropy and low permeability cause them to be important as a regional confining unit. These formations grade laterally southward and eastward into the Potosi and Derby-Doerun Dolomites and the Davis Formation (a shaly, silty dolomite) in Missouri, Illinois, and Indiana. The thickness of the unit generally is about 100 to 200 ft in the northern, freshwater part of the aquifer system but is less than 100 ft thick in most of Wisconsin.

4. Ironton-Galesville aquifer—This aquifer is the most productive part of the Cambrian-Ordovician aquifer system in the east-central part of the study area in Illinois and Wisconsin. It consists of the moderately sorted, quartzose Ironton and Galesville Sandstones and generally is 50 to 150 ft thick. In eastern Wisconsin north of Milwaukee, these sandstones are difficult to distinguish from those of the underlying Eau Claire and Mount Simon Sandstones; thus the aquifer is poorly defined there. The aquifer terminates as the sandstones grade into carbonate rocks of the Davis Formation to the south and southwest in central Iowa, Missouri, southern Illinois, and north-central Indiana.

5. Eau Claire confining unit—This is an important confining unit throughout much of the study area south of its northern erosional limit. Its confining property depends on the dominance of shale, siltstone, and dolomite over sandstone; the latter generally increases toward the north. Dolomite content increases southward and westward, where the Eau Claire Formation is replaced laterally by the Bonneterre Formation in northwestern Missouri and western Iowa. In northern Illinois, the confining unit consists of the two uppermost members of the Eau Claire Formation, as the latter is defined by the Illinois State Geological Survey. From 50 to 125 ft of fine-grained sediment is usually evident from borehole gamma logs and descriptive geologic logs from well cuttings in extreme northern Illinois, southern Wisconsin, and southeastern Minnesota. Overall thickness of the confining unit increases steadily from its northern outcrop area to about 200 to 300 ft in central Iowa and northern Illinois and to more than 750 ft in the Illinois basin.

6. Mount Simon aquifer—This is the most extensive aquifer in the northern Midwest by virtue of its basal position on the Precambrian surface. It consists mainly of the Mount Simon Sandstone in the north and its equivalent, the Lamotte Sandstone, in northern Missouri. However, the underlying Precambrian Hinckley Sandstone is included in Minnesota, and the overlying Elmhurst Sandstone Member of the Eau Claire Formation is included in northern Illinois. The aquifer materials are dominantly poorly to moderately sorted sandstone that has variable amounts of fine-grained sediment, including zones of lenticular shale beds, especially near the top of the Mount Simon. The overall permeability of the aquifer is lower than that of the other aquifers in the Cambrian-Ordovician aquifer system.

The Mount Simon aquifer crops out in large areas of northern Wisconsin and eastern Minnesota and generally dips smoothly to the south and east toward the structural basins. It is thickest (more than 2,000 ft) along the northern perimeter of the Illinois basin in north-central Illinois and along the Midcontinent Rift System in central and north-central Iowa. The top is more than 12,000 ft below sea level at the centers of the Illinois and Michigan basins.

The great thickness of the Mount Simon aquifer in Illinois and extreme eastern Wisconsin is not, and generally cannot, be utilized because (1) adequate yields generally are obtained from multiaquifer wells that are finished in the overlying aquifers of the Cambrian-Ordovician aquifer system and that do not penetrate the Mount Simon aquifer or penetrate it for only a few hundred feet; and (2) water is saline in the lower part of the Mount Simon aquifer near Lake Michigan and is progressively more saline in the entire aquifer toward the Illinois and Michigan basins, where brines occur. The aquifer is not used extensively in Iowa because of its great depth and saline-water content in the western and southern parts of the State.

The dense crystalline rocks of the Precambrian basement beneath the Cambrian-Ordovician aquifer system are a very effective confining unit whose upper surface marks the lower limit of the Cambrian-Ordovician aquifer system.

Ground-water movement in the northern Midwest can be described in general terms of local to intermediate to regional flow systems. Local flow systems are mainly unconfined, and regional flow systems are generally confined, but intermediate flow systems may be either unconfined or confined.

The direction of ground-water flow in unconfined areas has remained unchanged from predevelopment conditions, but the direction in confined areas has been reversed where ground-water withdrawals have been large.

Local flow systems usually are less than a few miles in length from recharge areas to discharge areas and represent most of the flow within the water-table aquifers, which is a large part of the overall volume of ground-water recharge and discharge in the northern Midwest. Most of this flow does not enter the bedrock aquifers, or penetrates only to shallow depths, and is discharged from glacial drift into surface-water bodies or is lost by evapotranspiration. Where the glacial drift is thin or absent, notably in the Driftless Area of southwestern Wisconsin and adjacent uplands along the Mississippi River, local flow systems also occur in the uppermost bedrock. The depth to the water table commonly is less than 50 ft in most of the area, but the water table is 200 to 300 ft deep beneath the highest ridges in the Driftless Area. Shallower, perched ground water is present under the ridges where rocks with low permeability restrict downward percolation of water through the thick unsaturated zone.

Ground-water movement in most of the rest of the bedrock occurs in intermediate or regional flow systems, where flow is deeper, slower, and traverses much longer distances from areas of recharge to areas of discharge. The major areas of recharge to regional flow in the Cambrian-Ordovician aquifer system are in the unconfined, interbasin highlands in northwestern Iowa; in southeastern Minnesota; in western, southern, and eastern Wisconsin; and in northern Illinois. Downward flow of ground water in recharge areas is restricted, in general, by any rock unit with low vertical hydraulic conductivity and, in particular, by intervening confining units. Hydraulic head in the recharge area decreases with increasing depth. Although the flow rates are small, significant recharge also occurs as downward leakage from the water table through the Maquoketa confining unit where the altitude of the water table is higher than the heads in underlying aquifers of the Cambrian-Ordovician aquifer system.

Ground water in most of the Cambrian-Ordovician aquifer system is confined and, prior to development, moved from the recharge areas over intermediate distances toward regional discharge areas (such as the major river valleys and Lake Michigan) or down dip along deep, long, regional flow paths toward the structural basins. The longest flow paths originated in the recharge area of northwestern Iowa and extended southeastward as much as 400 mi to the Illinois basin or to the Mississippi River and Missouri River valleys near their confluence. Other major directions of confined flow were eastward from eastern Wisconsin to the Michigan basin and southward from northeastern Illinois to the Illinois basin. Packer tests during the project showed only slight differences between the heads in aquifer layers in the confined parts of the aquifer system in eastern Wisconsin, northeastern Illinois, and northwestern Indiana. These heads are probably equalized because of interaquifer flow through the large number of multiaquifer wells and because of regional drawdown from heavy pumping of the Cambrian-Ordovician aquifer system.

Regional ground-water discharge from the Cambrian-Ordovician aquifer system occurs mainly as slow, upward leakage from the confined aquifers as the water moves toward the structural basins. Very saline water on the basin margins and brines deep within the basins restrict regional flow of ground water into the basins, thus forcing the confined water to discharge upward through overlying rocks. Hydraulic head is gradually dissipated by this upward leakage and by friction losses along the flow paths into the basins until the head may become too small to cause upward flow from deep within the basins. Ground water in intermediate flow systems discharges upward to the major river valleys, such as to the Mississippi River valley in the Twin Cities artesian basin.

Pumpage from the Cambrian-Ordovician aquifer system increased more or less steadily to about 680 Mgal/d by 1980, commensurate with the general growth in population (especially in the population centers) and with economic and industrial development. The largest concentrations of pumpage are in the Chicago and Twin Cities metropolitan areas, about 180 Mgal/d in each area in 1980. Elsewhere, pumpage in local centers exceeded 10 Mgal/d in only a few areas.

Hydraulic heads of aquifers in the Cambrian-Ordovician aquifer system in 1980, as compared with predevelopment heads, show little effect from ground-water withdrawal in most of the recharge or unconfined areas, but major head declines (cones of depression in the potentiometric surface) are evident in the confined areas. The largest effects, in terms of the total decline in head and the areal extent of the decline, are at Chicago, Illinois, Milwaukee and Green Bay, Wisconsin, and Mason City, Iowa, where the aquifer system is confined by the Maquoketa confining unit. Formation of these cones of depression has reversed the direction of ground-water flow in large areas around these centers of pumping.

The head decline of more than 900 ft in the Chicago area is the most impressive effect of ground-water withdrawal in the northern Midwest. Nonpumping water levels in some wells in the Chicago area near the center of the cone of depression were more than 200 ft below sea level in 1980. The maximum head decline in the Milwaukee area was more than 375 ft in 1980.

The city of Chicago and several nearby communities obtain their water supplies from a diversion of water from Lake Michigan that is limited by the U.S. Supreme Court. This source furnishes most of the water supply for northeastern Illinois, but the ground-water resource is a necessary supplementary source of supply. As part of its management of this diversion, the Illinois Division of Water Resources has a policy of reducing demand on the Cambrian-Ordovician aquifer system by optimizing the use of all other ground-water resources before an allotment from the diversion is granted, and by requiring new recipients to abandon any deep wells they have within five years to reduce the head decline in the aquifer system.

Ground water in the Cambrian-Ordovician aquifer system in the northern Midwest is characterized by an extreme range of mineralization, but its quality in much of the study area is good for most purposes. The major cations are calcium, magnesium, and sodium, and the major anions are bicarbonate, sulfate, and chloride. The distribution of sulfate, chloride, and sodium concentrations is closely related to the distribution of dissolved solids but with dissimilar areal concentration gradients. Interpretation of the present distribution of major solutes in terms of hydrochemical facies and of other water-quality characteristics, such as stable isotopic ratios, gives an indication of some residual effects of continental glaciation during the Pleistocene on ground-water quality in the northern Midwest.

Dissolved-solids concentration is low (generally less than 1,000 mg/L) in the recharge areas in Wisconsin, southern Minnesota, northeastern Iowa, and north-central Illinois where the aquifer system crops out or subcrops beneath glacial drift. The water in these areas is the Ca-Mg-HCO_3 type, derived from and identical to that in the overlying glacial drift. However, the concentration of dissolved solids increases in the direction of ground-water movement and with increased depth and thickness of the aquifers, especially where they are confined by the Maquoketa confining unit. Transition to higher dissolved solids in the confined areas commonly is accompanied by substantial increases in sulfate concentration.

In northwestern Iowa and southwestern Minnesota, the water in the Cretaceous aquifer and the Cambrian-Ordovician aquifer system is a Ca-Na-SO_4-HCO_3 type, derived from oxidation of pyrite in the Cretaceous Dakota Formation.

The water is increasingly saline toward the deep structural basins, where Na-Cl brines with dissolved solids of more than 200,000 mg/L are present. These changes in dominant ions may be the result of ion exchange of calcium and magnesium for sodium in clay minerals or the result of membrane filtration that could cause calcite precipitation coincident with increases in sodium and chloride. Saline water is present in the Mount Simon aquifer near Lake Michigan in eastern Wisconsin and northeastern Illinois and is present in successively younger rocks to the east and south as they dip toward the structural basins. The situation is similar in Iowa, where the salinity increases to the southwest and south, generally down dip. However, the direction of the increase in mineralization in Iowa is perpendicular to the general direction of ground-water flow, which is to the southeast.

Analysis of the isotopic composition of the ground water strongly indicates that the source of much of the ground water in the confined part of the aquifer system in Iowa probably was recharge from glacial meltwater. That water is isotopically depleted in $\delta^{18}O$ and δD with respect to modern precipitation—an indication that its source was precipitation in a much colder climate than the present. A major example is in an area of low-dissolved-solids ground water in the Jordan aquifer in central Iowa. Dissolved-solids concentrations there are 500 mg/L or less but are more than 1,000 mg/L in water in adjacent areas. The depletion of $\delta^{18}O$ and δD and increased concentrations of lithium, radium-226, and bromide also correlate with the area of low dissolved solids. The water in this area probably is a result of subglacial meltwater recharge from the Des Moines lobe of Wisconsin glaciation in north-central Iowa, emplaced by very high hydrostatic head caused by the overlying load of glacial ice.

Loading by Pleistocene ice sheets is also believed to be a cause of the saline water in the aquifer system near Lake Michigan. Increased dissolved solids there result from higher concentrations of calcium and sulfate. The isotopic content of sulfur in the sulfate indicates that the sulfur has an evaporitic origin. A source of evaporitic sulfur is available in the Michigan basin but not in the Cambrian and Ordovician formations west of Lake Michigan. Isostatic loading by glacial ice over the Michigan basin probably reversed the hydraulic gradients, causing saline water in the Michigan basin to discharge westward through the present recharge areas.

Natural water-quality problems in the Cambrian-Ordovician aquifer system are related primarily to increases in dissolved solids, which limit its usefulness for municipal and domestic purposes in much of the confined aquifer system in central and southern Illinois, Indiana, southern and western Iowa, and northern Missouri. In addition to a recommended limit of not more than 500 mg/L of dissolved solids, sulfate and chloride are individually recommended to be less than 250 mg/L (U.S. Public Health Service, 1962). Waters that exceed these limits are sometimes used where other sources are not available. Radium activity exceeds the current primary drinking-water standard of 5 picocuries per liter (U.S. Environmental Protection Agency, 1986) in much of the confined aquifer system in eastern Wisconsin, northeastern Illinois, and central Iowa. Excessive concentrations of iron and hydrogen sulfide are somewhat common, and hardness is almost always excessive.

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