Information Circular
Number 5

UNIVERSITY OF WISCONSIN
WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY
George F. Hanson, State Geologist

A PRELIMINARY STUDY OF THE DISTRIBUTION OF SALINE WATER IN THE BEDROCK AQUIFERS OF EASTERN WISCONSIN

By

Roy W. Ryling

U. S. Geological Survey

Prepared by
United States Geological Survey
in cooperation with the
Wisconsin Geological and Natural History Survey

Madison, Wisconsin
1961

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A PRELIMINARY STUDY OF THE DISTRIBUTION OF SALINE WATER IN THE BEDROCK AQUIFERS OF EASTERN WISCONSIN

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INTRODUCTION

The occurrence of saline water in the bedrock aquifers of eastern Wisconsin has been known for many years. Because of the ready availability of fresh water from other sources, little has been known of the extent of the saline-water area. Saline ground water is a potential source of contamination to wells if it moves into fresh-water zones.

The purpose of this study was to delimit the areas of saline ground water to determine the general extent of this quality of water problem in eastern Wisconsin.

The term "saline water" is used in this report for water containing either sulfate, chloride, or dissolved solids in quantities exceeding the recommended maximums of those constituents established by the U. S. Public Health Service (1946) for drinking water - more than 250 ppm (parts per million) sulfate or chloride, or more than 1,000 ppm total dissolved solids. The term has been used by the U. S. Geological Survey (Krieger and others, 1957) to designate water that is generally considered unsuitable for human consumption. No attempt has been made in this report to relate the concentration of sulfate, chloride, or total dissolved solids to use of water. Saline water above the stated maximums may be adequate for many industrial and public supply uses.

The study is part of a cooperative program of the U. S. Geological Survey and the Wisconsin Geological and Natural History Survey to determine the ground-water resources of the State and was planned in cooperation with George F. Hanson, State Geologist. It was made under the immediate supervision of C. L. R. Holt, Jr., District Geologist, Ground Water Branch, U. S. Geological Survey. T. G. Newport of the U. S. Geological Survey collected water samples for chemical analysis.

The area of investigation includes 18 counties and the parts of 3 others, and extends from Kenosha and Walworth Counties in the south to Door and Marinette Counties in the north. The report describes the geology of the water-bearing rocks; shows by means of maps the areas in which the bedrock aquifers yield water containing excessive sulfate, chloride, and dissolved solids; and shows on a series of geologic sections the stratigraphic distribution of waters of inferior quality.

Previous work on the distribution of saline water in eastern Wisconsin was done by Weidman and Schultz (1915) and Drescher (1956). Weidman and Schultz list chemical analyses of ground water and show the location of wells that yield water containing more than 1,000 ppm dissolved solids. In the report by Drescher, the generalized extent of the area underlain by saline water in eastern Wisconsin is shown on a map based on data available at the time of study.

The chemical analyses of water samples and the well and test-hole logs upon which this report is based, were obtained from published data and from the files of the U. S. Geological Survey, the Wisconsin Geological and Natural History Survey, the Wisconsin State Board of Health, and the State Laboratory of Hygiene. These data are presented in three water-quality maps and in three geologic sections.

GEOLOGY

Structure and stratigraphy

A ground-water study in an area involves a study of the geology, because the rocks that constitute the water-bearing units, or aquifers, are the natural environment of ground water. Aquifers form reservoirs for the accumulation and storage of ground water and conduits for its movement.

In eastern Wisconsin, the consolidated rocks, consisting mainly of sandstone, dolomite, shale, and possibly some limestone, all of Paleozoic age, dip eastward from a structural high in the north-central part of the State. The Wisconsin arch, as this high is known, is the principal outcrop area of Precambrian rocks that form the basement complex in the study area. The consolidated rocks, of which the older are exposed toward the center of the arch, are largely covered by unconsolidated deposits of Pleistocene and Recent age.

The rocks of Ordovician and Silurian ages form a succession of layers that are relatively uniform in thickness and large in extent. Exceptions to this are the Prairie du Chien group and the St. Peter sandstone where it overlies the Prairie du Chien. Rocks of the Upper Cambrian series thicken to the east. A structural contour map showing the configuration of the upper surface of the Ordovician Maquoketa shale (Hanson, 1960) indicates the general structural features of the underlying water-bearing dolomite and sandstone units. The map shows three prominent east trending concave upward folds (synclines) and four convex upward folds (anticlines) in a rock unit that otherwise dips relatively uniformly eastward. The synclines center in east-central Manitowoc County, southeastern Sheboygan County and east-central Milwaukee County. The syncline in Manitowoc County extends northeastward into southeastern Kewaunee County.

The aquifers that supply ground water in eastern Wisconsin are, from oldest to youngest, undifferentiated sandstones of Late Cambrian age; the Prairie du Chien group, the St. Peter sandstone, the Platteville-Galena unit of Ordovician age; the Niagara dolomite of Silurian age; and the surface deposits consisting predominantly of glacial rock material of Pleistocene age. See table 1.

The discussion of the distribution of saline water does not include the Pleistocene deposits, because these deposits, almost exclusively, yield fresh water to wells. No wells are known to obtain water from the Precambrian rocks within the area of study, and no chemical analyses are available of water from wells in the Thiensville and Milwaukee formations of Devonian age.

In this report the Waubakee dolomite of Silurian age has not been differentiated from the Niagara dolomite of Silurian age. The Decorah formation of Ordovician age is included with the Platteville-Galena unit of Ordovician age. Formations that have not been differentiated are treated as a unit in this report.

Rock characteristics

The Cambrian rock units are, in ascending order, the Mount Simon sandstone, the Eau Claire sandstone, and the Galesville sandstone of the Dresbach group, the Franconia sandstone, and the Trempealeau formation. They consist of fine- to coarse-grained sandstone, dolomitic in places, and some shale and dolomite beds. The Eau Claire and Franconia sandstones commonly are shaly. These formations are treated as a unit in this report.

The Prairie du Chien group of Ordovician age is a dolomite, which is sandy in places; it varies considerably in thickness and lateral continuity, mainly because the group was extensively eroded before the deposition of the St. Peter sandstone of Middle Ordovician age.

The St. Peter sandstone is fine-to medium-grained, white to light gray to pink, dolomitic in places and crossbedded. Red shale occurs locally near its base.

The stratigraphic position of the Prairie du Chien relative to the underlying Cambrian rocks and the overlying St. Peter sandstone is illustrated in figures 4 and 5. Where the Prairie du Chien is missing, the St. Peter sandstone overlies the Upper Cambrian series. The passage of water through dolomite of the Prairie du Chien is described by Weidman and Schultz (1915, p. 33) as being *** greatly aided by systems of joints and fissures, both transverse and oblique to the bedding planes.

The Platteville formation, Decorah formation, and Galena dolomite of Ordovician age have not been mapped separately in the geologic sections and are treated as a rock unit, referred to herein as the Platteville-Galena unit. The unit is predominantly a light-gray dolomite.

Table 1.--Stratigraphic units in eastern Wisconsin and their water-bearing characteristics

System	Stratigraphic unit	Description	Water-bearing characteristics
Quaternary	Recent deposits	Sand, silt, peat, organic mud, marl, and gravel.	Sandy zones yield small to moderate amounts of water to wells.
	Pleistocene deposits	Glacial drift, mostly till, clay, silt, sand, gravel, and boulders.	Sand and gravel beds yield water to wells. Important aquifer in buried valleys.
Mississippian		Black carbonaceous shale.	Small areal extent. Not used as aquifer.
Devonian	Milwaukee formation Thiensville formation	Shale, dolomite, and possibly some limestone; some beds are bituminous.	Yields some water to domestic wells from crevices.
Silurian	Waubakee dolomite Niagara dolomite	Dolomite, thin-bedded to massive; some coral reefs. Some chert. Crevices and solution channels abundant but inconsistent.	Important aquifer but variable in yield to wells. Yields water to wells from crevices and solution channels.
Ordovician	Maquoketa shale	Shale and dolomitic shale. Some beds of dolomite as much as 40 feet thick.	Usually not an aquifer. Generally cased off in wells.
	Galena dolomite Decorah formation Platteville formation	Dolomite. Some shale. Sandy at base.	Yields small amounts of water to wells from joints, bedding planes, and sandy zones - principally in areas where not overlain by Maquoketa shale.
	St. Peter sandstone	Sandstone, fine- to medium-grained, dolomitic in places. Red shale near base in places.	Yields small to large amounts of water to wells, depending upon permeability and thickness.
	Prairie du Chien group	Dolomite. Sandy and shaly zones in places. Some chert.	Yields small amounts of water to wells.
Cambrian	Upper Cambrian series: Trempealeau formation Franconia sandstone Dresbach group: Galesville sandstone Eau Claire sandstone Mount Simon sandstone	Sandstone, fine- to coarse-grained, dolomitic. Some shale and dolomite beds. Eau Claire and Franconia commonly shaly.	Important aquifer. Yields small to large amounts of water to wells, depending upon permeability and thickness. Each formation may be an aquifer but the series usually considered in aggregate.
Precambrian	Undifferentiated	Crystalline rocks, such as granite and quartzite.	Usually not an aquifer.

The Maquoketa shale of Ordovician age, which overlies the Platteville-Galena unit, consists predominantly of blue-gray shale and gray dolomite. This unit yields little or no water to wells and is not considered an aquifer.

The Niagara dolomite of Silurian age overlies the Maquoketa shale; it directly underlies the glacial drift in the eastern two-thirds of the area of investigation - from Door County in the north to Kenosha County in the south. It consists of light-gray dolomite. Wells penetrating to aquifers of Ordovician and Cambrian age commonly are left uncased opposite the Niagara dolomite.

Occurrence and movement of ground water

Ground water in eastern Wisconsin is derived from rain or snow. Part of the precipitation runs off in streams, part is returned to the atmosphere by evaporation and transpiration of plants, and part enters the soil. Of the precipitation that enters the soil, a small part reaches the zone of saturation, in which all the openings of the rocks are filled with water.

Ground water moves under the influence of gravity from areas of recharge to areas of discharge. In rocks that are poorly permeable, such as very fine-grained sandstone, silt, clay, or shale, molecular attraction retards the movement of water so that it may move toward a well more slowly than it can be withdrawn by even a small pump. In more permeable rocks, such as coarse sand and gravel and cavernous limestone or dolomite, water moves with comparative freedom, although the movement generally is extremely slow compared to the flow of a stream. Such rocks are capable of yielding large quantities of water to wells.

The direction of ground-water movement is determined by local and regional hydraulic gradients, which depend upon rock permeabilities, geologic structure, ground-water recharge and discharge, and topography. In eastern Wisconsin the general direction of ground-water movement is eastward. This regional trend of movement has been modified in places, particularly in the Milwaukee-Waukesha area, by large-scale withdrawals of ground water which have resulted in lowered water levels. The general direction of ground-water movement within the area of water-level decline is toward the localities of maximum decline.

Heavy pumping from an aquifer that contains saline water can cause movement of the saline water toward the area of pumping, and serious damage to water supplies may result.

SALINE-WATER DISTRIBUTION

In the following section, the distribution of saline water is discussed in terms of geographic extent and also with respect to the geologic units in which saline water is found. Maps are presented showing the distribution of bodies of saline water (as defined on p. 1) and concentrations of sulfate, chloride, and dissolved solids in parts per million. Three geologic sections show the structure and stratigraphy and also indicate in a general way the stratigraphic units yielding saline water.

Geographic distribution

The discussion of the geographic or areal distribution of sulfate, chloride, and dissolved-solids content of water from the bedrock aquifers is based largely upon the information presented on the quality-of-water maps. These maps show generalized information and are not intended to be precise. Nor are they to be interpreted as indicating water-quality zones within a single aquifer. The maps are drawn on the basis of the analyses of water samples from bedrock wells commonly deriving water from two or three aquifers. Water from these wells is therefore a blend of the waters from the several aquifers.

To avoid disregarding what may be an important occurrence of saline water in an area of sparse data, high concentrations of sulfate and dissolved solids in southeastern Marinette County were shown on the map, although these concentrations are indicated by the chemical analysis of water from only one well. Where data are lacking over an extensive area within the region studied, the quality of water was not mapped; for example, in the northern part of Door County.

The area investigated in eastern Wisconsin includes about 9,060 square miles, of which approximately 8,360 square miles have sufficient data to permit very generalized mapping of the distribution of sulfate, chloride, and dissolved-solids contents. The mapping was based on chemical analyses of water from 154 wells. The geographic distribution of the zones that correspond to the several ranges in concentration of the three constituents are indicated by different map symbols. Consecutive range zones are indicated only where supporting data are available. In Winnebago County, for example, the range in concentration from 0 to 100 ppm sulfate is adjacent to one of more than 250 ppm (fig. 1).

Sulfate

The geographic distribution of sulfate in water from the bedrock aquifers of eastern Wisconsin is shown in figure 1. To indicate differences in distribution, the sulfate content is presented in figure 1 in four ranges of concentration. Sulfate concentrations generally increase to the east. A conspicuous exception is an area of high sulfate water in the Lake Winnebago area.

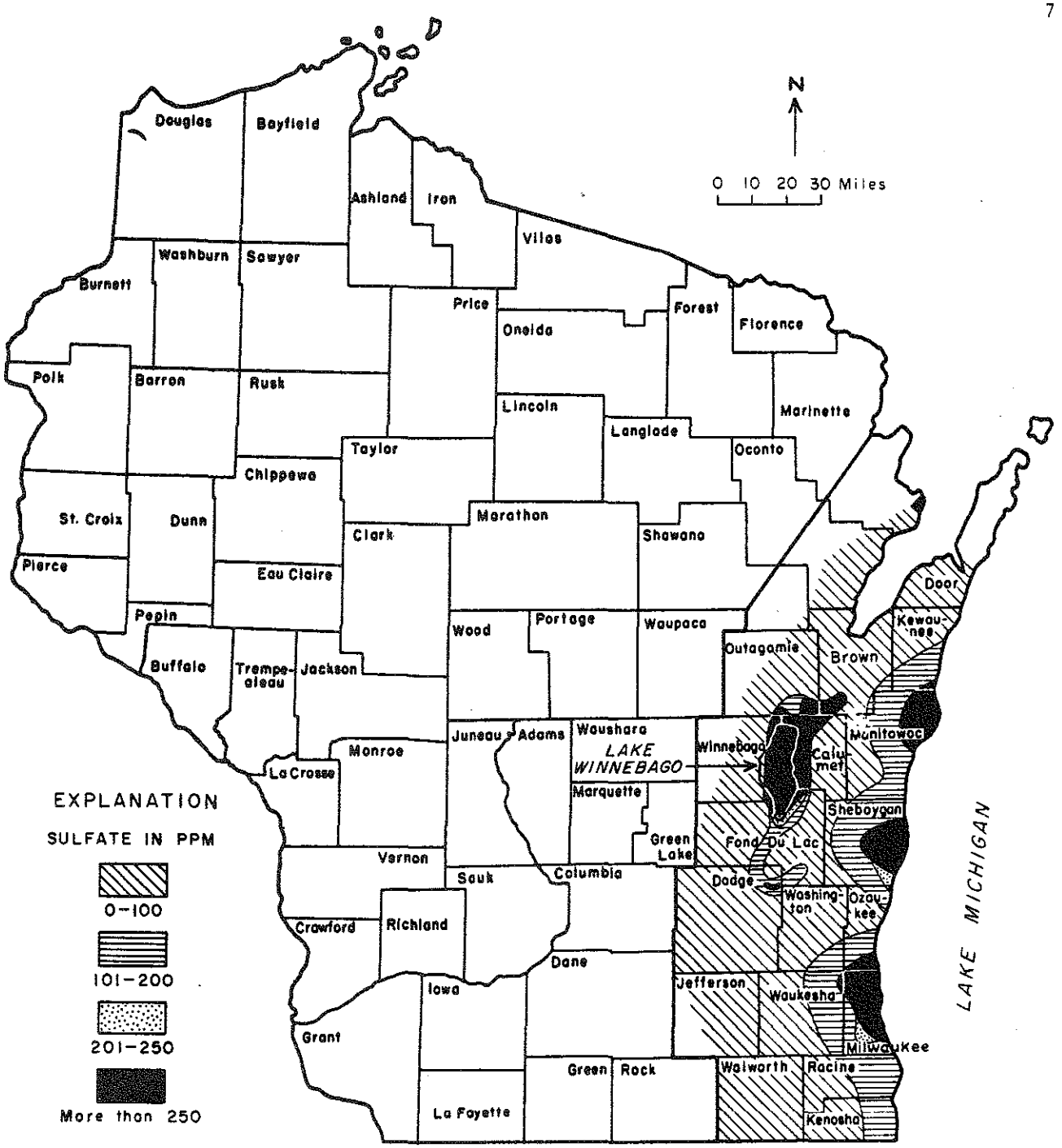

Figure 1.--Map showing the geographic distribution of sulfate content of water from the bedrock aquifers of eastern Wisconsin.

Sulfate in ground water in quantities exceeding 250 ppm occurs in 6 mappable areas. Three of these areas are along the eastern edge of the area of investigation, centering in northeastern Manitowoc County, central Sheboygan County and eastern and northern Milwaukee County. A fourth area covers western Calumet County and parts of Brown, Outagamie, Winnebago and Fond du Lac Counties. Two apparently small areas are in northeastern Dodge County and southeastern Marinette County.

The saline water in northeastern Manitowoc County contains as much as 1,790 ppm sulfate. The water samples are from wells tapping the Niagara dolomite. The analysis of a water sample "from the 1,640 feet level" (Weidman and Schultz, 1915) in a test well drilled in 1914 indicates that the St. Peter sandstone and the Upper Cambrian series probably contain saline water in this area.

In east-central Sheboygan County the sulfate content of water from the Niagara dolomite is generally more than 250 ppm and is as much as 762 ppm. The St. Peter sandstone and the Prairie du Chien group in this area yield composite water having a sulfate content as much as 2,050 ppm. A well tapping the St. Peter sandstone yielded water with 1,850 ppm sulfate.

In eastern and northern Milwaukee County and parts of Ozaukee and Waukesha Counties, the sulfate content of water in the Niagara dolomite may be as much as 508 ppm. In northeastern Milwaukee County, a well tapping the Niagara dolomite, the Platteville-Galena unit, and the St. Peter sandstone yields water containing 2,250 ppm sulfate. However, in much of east-central Milwaukee County sulfate ranges from more than 250 ppm to less than 400 ppm. The water, although of inferior quality with respect to sulfate, is suitable for almost all uses.

The distribution of high-sulfate waters in Manitowoc, Sheboygan, and Milwaukee Counties corresponds generally to locations of synclines discussed on page 2.

Sulfate concentrations in the Lake Winnebago area are as much as 922 ppm in Calumet, 919 ppm in Brown, 815 ppm in Outagamie, 954 ppm in Winnebago, and 390 ppm in Fond du Lac Counties. The wells in this area generally tap the Platteville-Galena unit, the St. Peter sandstone, the Prairie du Chien group, and the Upper Cambrian series.

An area of relatively high sulfate content extends from the southern end of the Lake Winnebago area into Dodge County, where the sulfate content of water from the Niagara dolomite is as much as 2,900 ppm.

In southeastern Marinette County, the sulfate content is 687 ppm in water from a well, which may be uncased, in the Upper Cambrian series. The extent of this area of high sulfate water is not known.

The table below shows the areal extent of each of the four ranges of sulfate concentration. Ground water containing more than 250 ppm sulfate occurs in 10.6 percent of the mapped area.

	Range in sulfate concentration (in ppm)			
	0-100	101-200	201-250	More than 250
Areal extent, in square miles	5,933	1,489	50	890
Areal extent, in percent of total area mapped	71.0	17.8	.6	10.6

Chloride

The geographic distribution of chloride in the bedrock aquifers of eastern Wisconsin is shown in figure 2. The differences in concentration of chloride are presented in the same ranges used in mapping sulfate distribution in figure 1.

Chloride occurs in excessive amounts in water from wells in the bedrock aquifers in east-central Sheboygan County, northeastern Milwaukee County and northeastern Dodge County.

In east-central Sheboygan County, the Niagara dolomite yields water containing as much as 355 ppm chloride to wells. The chloride content of water from wells tapping the St. Peter sandstone and in the Prairie du Chien group is as much as 4,310 ppm.

In northeastern Milwaukee County, two wells seven-tenths mile apart tapping the Niagara dolomite, the Platteville-Galena unit, and the St. Peter sandstone yield water of very different chloride content, namely, 1,890 and 175 ppm.

In a small area of northeastern Dodge County, the chloride concentration of water in the Niagara dolomite is 438 ppm.

The table below shows the areal extent of each of four ranges in chloride concentration. Chloride concentrations exceeding 250 ppm occur in only about 0.4 percent of the area mapped.

	Range in chloride concentration (in ppm)			
	0-100	101-200	201-250	More than 250
Areal extent, in square miles	8,185	137	7	33
Areal extent, in percent of total area mapped	97.9	1.6	.1	.4

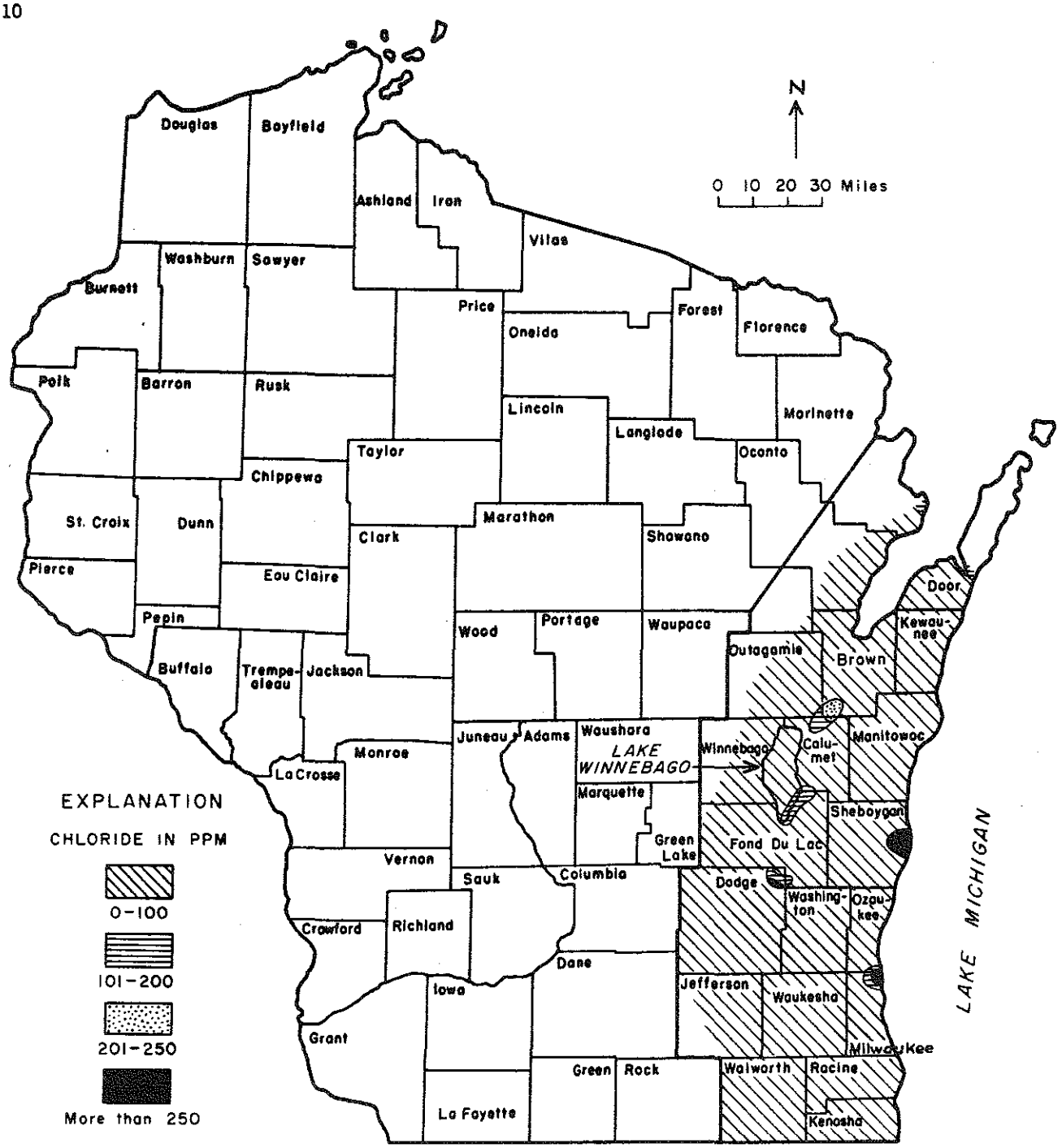

Figure 2.--Map showing the geographic distribution of chloride content of water from the bedrock aquifers of eastern Wisconsin.

Dissolved solids

The geographic distribution of dissolved-solids content of water from the bedrock aquifers of eastern Wisconsin is shown in figure 3. To indicate differences in distribution, the dissolved-solids content is shown for four ranges.

In general, the distribution of dissolved solids content of the ground water corresponds closely to that of sulfate.

In northeastern Manitowoc County, dissolved-solids concentrations are as much as 3,550 ppm in water from the Niagara dolomite. Water from the St. Peter sandstone and the Upper Cambrian series is as much as 3,260 ppm.

In east-central Sheboygan County, the maximum dissolved-solids content is 1,840 ppm in water from the Niagara dolomite. The analysis of a composite sample of water from a well tapping the St. Peter sandstone and the Prairie du Chien group indicates 10,440 ppm of dissolved solids.

In northeastern Milwaukee County, the two wells tapping the Niagara dolomite, the Platteville-Galena unit, and the St. Peter sandstone yield composite samples containing 2,440 to 6,690 ppm dissolved solids.

In the Lake Winnebago area, concentrations of dissolved solids are as much as 1,980 ppm in Calumet, 1,890 ppm in Brown, 1,460 ppm in Outagamie, 1,791 ppm in Winnebago, and 1,060 ppm in Fond du Lac Counties. The wells in this area generally tap the Platteville-Galena unit, the St. Peter sandstone, the Prairie du Chien group, and the Upper Cambrian series.

An area of relatively high dissolved-solids content extends from the southern end of the Lake Winnebago area into Dodge County, where water from the Niagara dolomite contains as much as 5,730 ppm dissolved solids.

In southeastern Marinette County, the dissolved-solids content of water from a well tapping the Upper Cambrian series is 1,220 ppm. The extent of this area of high concentration of dissolved solids is not known.

The table below shows the areal extent of each of four ranges of dissolved-solids concentration. Ground water that is saline with respect to dissolved solids occurs in 9.1 percent of the area mapped.

	Range in dissolved solids (in ppm)			
	0-250	251-500	501-1,000	More than 1,000
Areal extent, in square miles	76	5,366	2,174	746
Area extent, in percent of total area mapped	.9	64.0	26.0	9.1

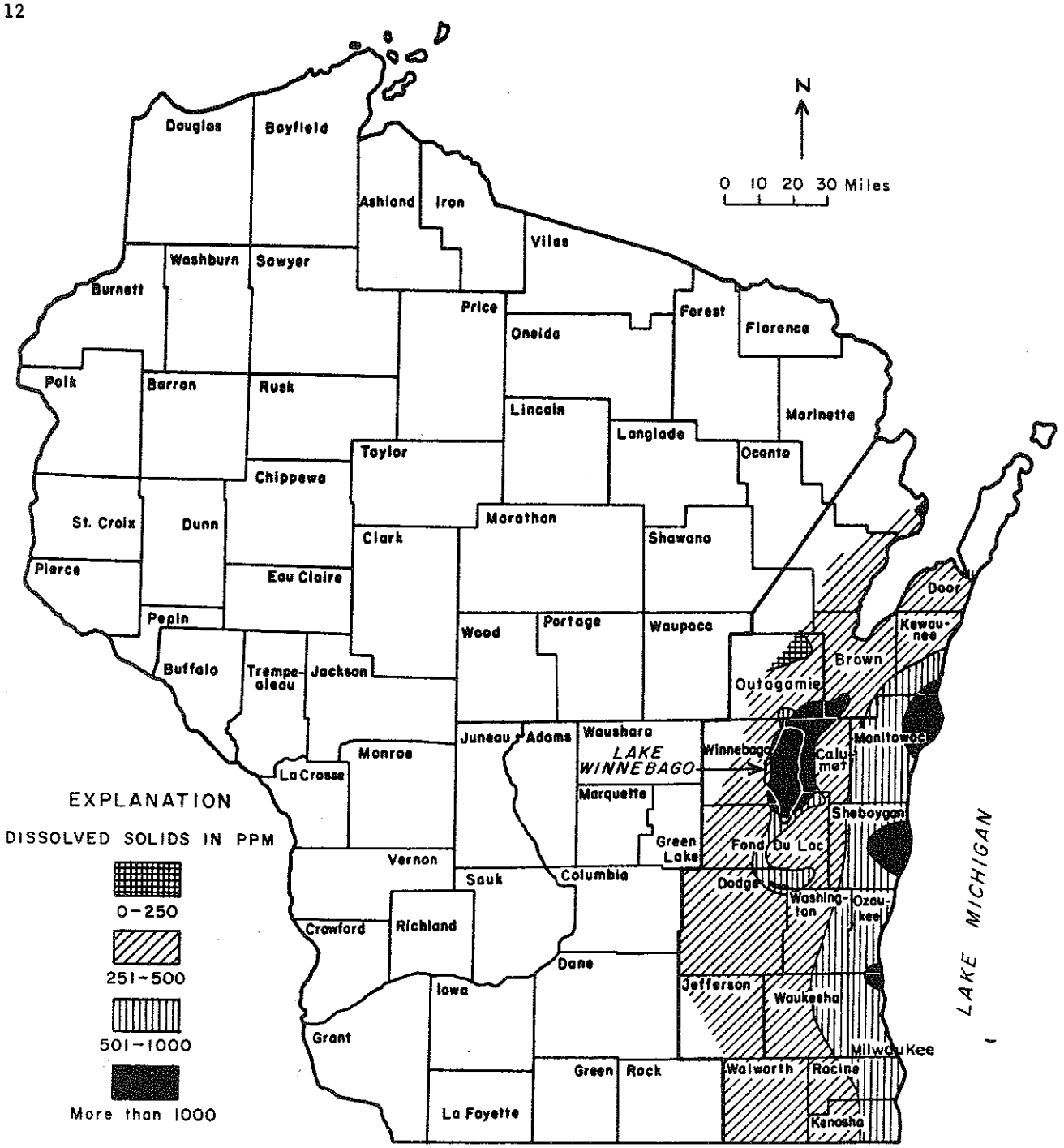

Figure 3.--Map showing the geographic distribution of dissolved-solids content of water from the bedrock aquifers of eastern Wisconsin.

Stratigraphic distribution

The discussion of the stratigraphic distribution of sulfate, chloride, and dissolved solids in the ground water is based largely upon the information presented on geologic sections A-A', B-B', and C-C' in figures 4, 5, and 6. The locations of these sections were chosen to show geologic and hydrochemical relationships in areas of saline water.

The sequence of the different rock units in the geologic sections are based on log descriptions and stratigraphic correlations by the Wisconsin Geological and Natural History Survey. The logs are numbered to correspond with the system of reference involving the use of an abbreviated county name (Ca, Calumet; FL, Fond du Lac; Je, Jefferson; Ml, Milwaukee; Mn, Manitowoc; Ou, Outagamie; Sb, Sheboygan; and Wk, Waukesha) in combination with a serial number indicating a specific well in the county.

The analytical data and well logs shown in the sections most commonly pertain to the same well. For a well tapping one aquifer, these analyses are shown on the section adjacent to the uncased part of the well. When a well taps two or three aquifers, the analyses are shown adjacent to the lowest uncased part of the well.

The land surface and the thickness and upper and lower surfaces of the Pleistocene deposits are indicated only at the well sites. The contact between the Precambrian rocks and the Upper Cambrian series is based largely upon data obtained from a map showing the configuration of the Precambrian surface (Thwaites, 1957).

The maximum concentrations of sulfate, chloride, and dissolved solids in water from the bedrock aquifers in the saline-water areas of eastern Wisconsin are listed in table 2.

Outagamie County to Manitowoc County

The wells shown on the geologic section A-A' (fig. 4) that extends from southwestern Outagamie County to east-central Manitowoc County tap one or more aquifers. Of the 8 wells in this section, 5 tap 2 or 3 aquifers. The chemical analyses of water from the five wells represent the composition of mixed waters from the several aquifers.

The regional changes in the mineralization of ground water show increasing concentrations of sulfate, chloride, and dissolved solids from well Ou 33 to well Mn 8. Although no analyses of the water obtained from the St. Peter sandstones and the Upper Cambrian series in well Mn 8 are available, the well log mentions specifically salt water in the "sandstones", which can only mean the St. Peter sandstone and the sandstones of the Upper Cambrian series.

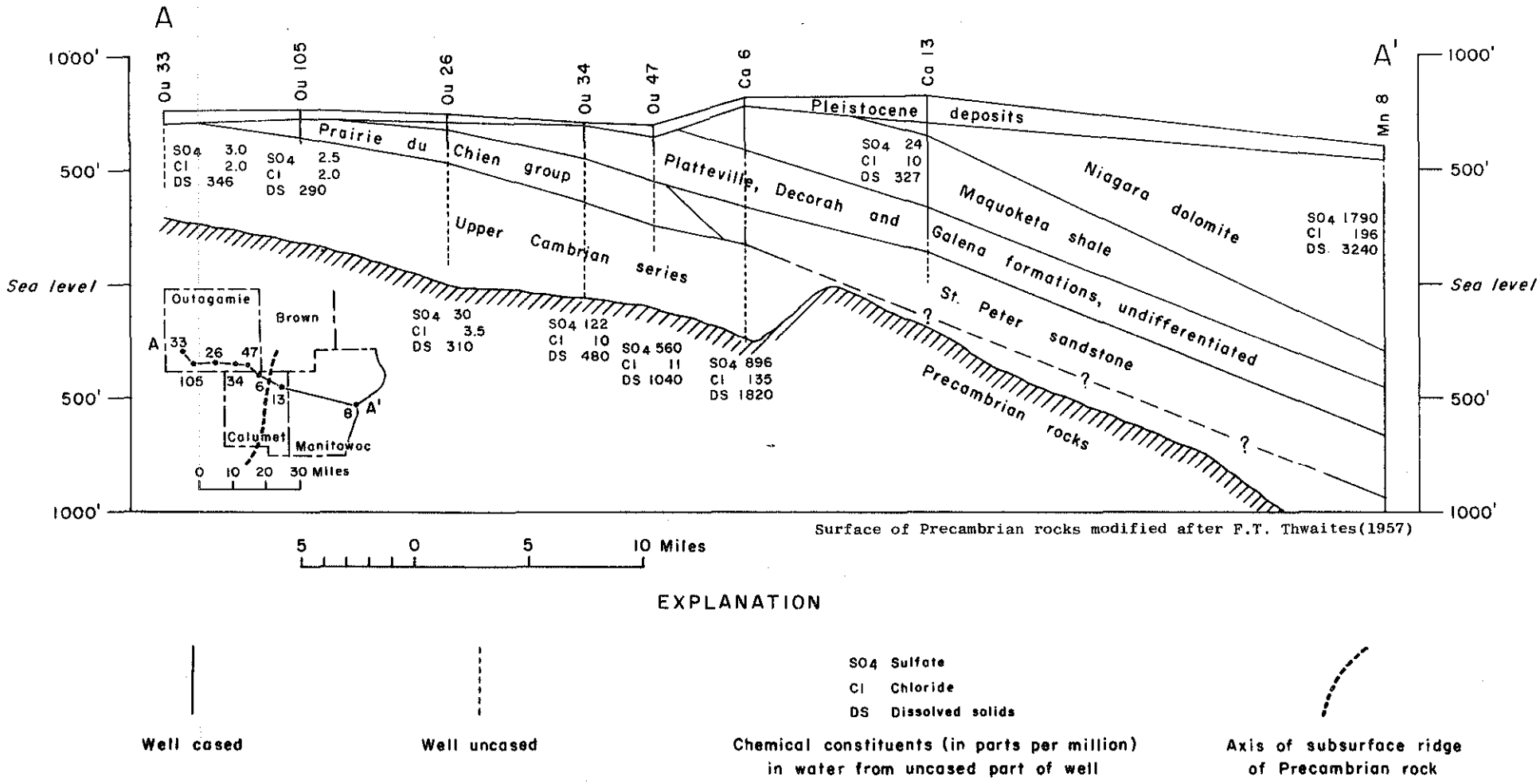

Figure 4.--Geologic section A-A' in eastern Wisconsin showing the stratigraphic distribution of sulfate, chloride, and dissolved-solids content of water from the bedrock aquifers.

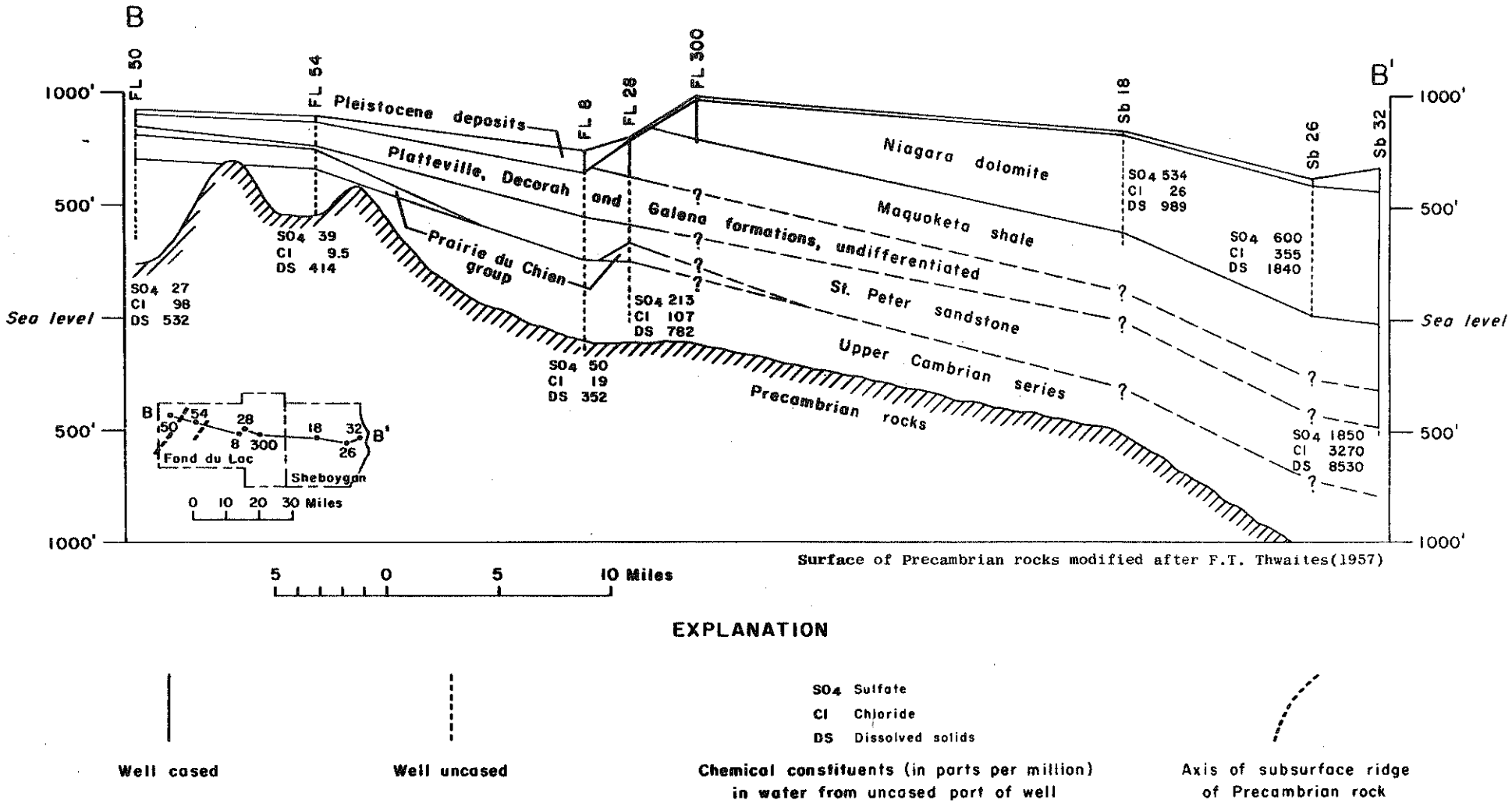

Figure 5.--Geologic section B-B' in eastern Wisconsin showing the stratigraphic distribution of sulfate, chloride, and dissolved-solids content of water from the bedrock aquifers.

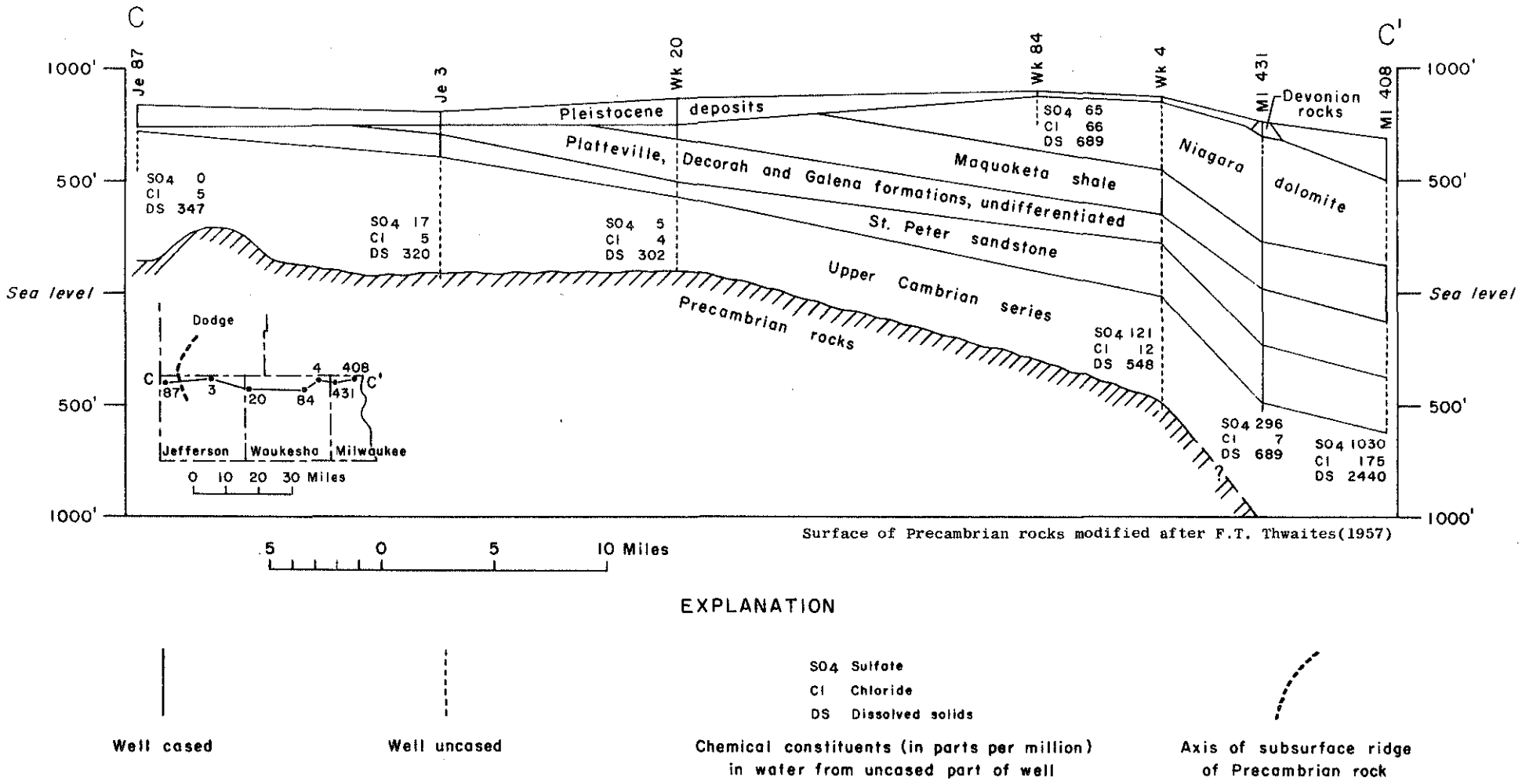

Figure 6.--Geologic section C-C' in eastern Wisconsin showing the stratigraphic distribution of sulfate, chloride, and dissolved-solids content of water from the bedrock aquifers.

Table 2.--Maximum concentrations of sulfate, chloride, and dissolved solids in water from the bedrock aquifers in the saline-water areas of eastern Wisconsin.

Saline-water area	Maximum concentrations					
	Sulfate		Chloride		Dissolved solids	
	Parts per million	Aquifer(s)	Parts per million	Aquifer(s)	Parts per million	Aquifer(s)
Northeastern Manitowoc County	1,790	Niagara dolomite	196	Niagara dolomite	3,550	Niagara dolomite
East-central Sheboygan County	2,050	St. Peter sandstone and Prairie du Chien group	4,310	St. Peter sandstone and Prairie du Chien group	10,440	St. Peter sandstone and Prairie du Chien group
Northern Milwaukee County	2,250	Niagara dolomite, Platteville-Galena unit, St. Peter sandstone	1,890	Niagara dolomite, Platteville-Galena unit, St. Peter sandstone	6,690	Niagara dolomite, Platteville-Galena unit, St. Peter sandstone
Lake Winnebago area	954	Platteville-Galena unit, St. Peter sandstone, Prairie du Chien group, Upper Cambrian series	250	St. Peter sandstone(?) and Upper Cambrian series(?)	1,980	Platteville-Galena unit(?), St. Peter sandstone(?), Upper Cambrian series(?)
Northeastern Dodge County	2,900	Niagara dolomite	438	Niagara dolomite	5,730	Niagara dolomite
Southeastern Marinette County	687	Upper Cambrian series	131	Upper Cambrian series	1,220	Upper Cambrian series

The concentrations of chemical constituents increased rather rapidly from well Ou 33 to well Ca 6. Sulfate and chloride increased from 3.0 to 896 ppm and from 2.0 to 135 ppm, respectively. Dissolved-solids content increased from 346 to 1,820 ppm. Although these changes in concentration occurred over about 26 miles, the largest increase occurred over about 7 miles, from well Ou 34 to Ca 6. This area of relatively high mineralization is immediately west of a subsurface ridge of Precambrian rock that trends northeastward (Thwaites, 1957).

The relatively rapid increase in the concentrations of sulfate, chloride, and dissolved solids is probably related to the partial stratigraphic trap formed by this ridge of poorly permeable rock that extends upward about 300 feet into the relatively permeable rocks of the Upper Cambrian series. Water of high mineral content is denser than less highly mineralized water and may tend to accumulate at depth within the aquifer, particularly where the ground-water movement within the aquifer is markedly retarded. Immediately updip from the subsurface ridge would be an area of entrapment, because the ground-water movement around this ridge would leave an area of nearly stagnant water adjacent to the updip side of the ridge. However, the data available are inadequate to determine the causes of the saline-water distribution. The explanation given is the most likely of several that can be presented.

Along the line of geologic section A-A', no analyses are available of water from the Upper Cambrian series, the St. Peter sandstone, or the Platteville-Galena unit. The Niagara dolomite yields saline water in parts of northeastern Manitowoc County. The chemical analyses of water from two wells tapping the upper part of the Niagara dolomite indicate that the dissolved-solids content ranged from 2,540 to 3,240 ppm (Weidman and Schultz, 1915). The analysis of water of higher concentration is indicated at the site of well Mn 8, which is used as a geologic control in section A-A'.

Fond du Lac County to Sheboygan County

In section B-B', from northwestern Fond du Lac County to east-central Sheboygan County (fig. 5), mineralization of ground water increases markedly eastward. At the western end of the section, well FL 50 yielded water with a concentration of sulfate, chloride, and dissolved solids of 27, 98, and 532 ppm, respectively; whereas well Sb 32 at the eastern end of this section yielded water of 1,850, 3,270, and 8,530 ppm, respectively.

Two prominent ridges of Precambrian rock that trend northeastward are shown in the western part of the section. These ridges are of small lateral extent. The concentrations of dissolved solids were greater in wells FL 50 and FL 54, which are updip from the ridges, than at well FL 8, which is 20 miles east of well FL 50 and about 10 miles downdip from the easternmost ridge.

Water from well FL 28 showed a relatively high concentration of saline constituents. This higher concentration may be due to southward movement of saline water from the Lake Winnebago area or to poor circulation in the aquifer in this area.

The Niagara dolomite yielded water of relatively poor quality to wells Sb 18 and Sb 26 in central and eastern Sheboygan County. The concentration of sulfate ranged from 534 to 600 ppm, whereas that of chloride and dissolved solids ranged from 26 to 989 ppm and 355 to 1,840 ppm, respectively. The differences in the concentrations of sulfate, chloride, and dissolved solids in water from well Sb 18 to well Sb 26 indicates an eastward increase in mineral content within this rock unit.

Well Sb 32 tapped the St. Peter sandstone and yielded saline water with a sulfate, chloride, and dissolved-solids content of 1,850, 3,270, and 8,530 ppm, respectively.

Jefferson County to Milwaukee County

In geologic section C-C' (fig. 6) which extends from northwestern Jefferson County to northeastern Milwaukee County, a low subsurface ridge of Precambrian rock does not form a significant partial barrier to the regional direction of ground-water movement. The small changes in the chemical quality of the water as it moves through the aquifers from well Je 87 to well Wk 4, would represent possibly the general conditions in the corresponding areas of sections A-A' and B-B' had there been no significant ridges of Precambrian rock.

The mineralization of ground water increases eastward, and more rapidly as the wells penetrate to greater depths. This regional trend applies also to the cross sections previously discussed, although the trend may be somewhat obscured by the effects of the partial stratigraphic traps. This regional change in the concentrations of mineral matter in ground water may be explained by the decreasing permeabilities of the several aquifers down the dip and the resultant decrease in ground water circulation. Moreover, the mineralization of ground water may increase with the increased distance of ground-water movement within the aquifer system and with the depth of occurrence due to the geothermal gradient. The Maquoketa shale is a confining bed, which prevents the flushing of the underlying aquifers by local recharge.

The Upper Cambrian series yields fresh water to wells Je 87 and Je 3. The composite water samples from Wk 20 and Wk 4 also were fresh. Well Ml 408 yields saline water; the sulfate, chloride, and dissolved-solids contents were 1,030, 175, and 2,440 ppm, respectively. This well taps the Niagara dolomite, the Platteville-Galena unit, and the St. Peter sandstone.

The Niagara dolomite yields fresh water to well Wk 84 and water that is slightly high in sulfate content to well Ml 431. Because of differences in hydraulic heads the highly mineralized water in the Niagara dolomite locally may be due to contamination by the upward movement of saline water through abandoned test wells from the deeply buried water-bearing sandstones into the Niagara dolomite. The wells may tap the dolomite, or if cased opposite this aquifer, the casing may be open because of corrosion.

SUMMARY AND CONCLUSIONS

The bedrock aquifers that are sources of water supply in eastern Wisconsin are, from oldest to youngest, the undifferentiated sandstones of Late Cambrian age; the Prairie du Chien group, St. Peter sandstone, and the Platteville-Galena unit of Ordovician age; and the Niagara dolomite of Silurian age.

Sulfate occurs in ground water in quantities exceeding 250 ppm in 6 areas in eastern Wisconsin. Three of these are along the eastern edge of the area of investigation, centering in northeastern Manitowoc County (1,790 ppm maximum recorded), central Sheboygan County (2,050 ppm maximum), and eastern and northern Milwaukee County (2,250 ppm maximum). A fourth area covers much of western Calumet County and parts of Brown, Outagamie, Winnebago and Fond du Lac Counties (954 ppm maximum). Two small areas are in northeastern Dodge County (2,900 ppm maximum) and southeastern Marinette County (687 ppm maximum). Ground water containing more than 250 ppm sulfate occurs in about 10.6 percent of the mapped area. The regional pattern of distribution shows increasing concentrations of sulfate eastward.

Chloride occurs in ground water in quantities exceeding 250 ppm in three areas in eastern Wisconsin - east-central Sheboygan County (with 4,310 ppm maximum recorded), northern Milwaukee County (1,890 ppm maximum) and northeastern Dodge County (438 ppm maximum). Chloride concentrations exceeding 250 ppm occur in only about 0.4 percent of the area mapped.

Concentrations of dissolved solids exceeding 1,000 ppm occur in the same general areas as those of excessive sulfate. In the area centering in northern Manitowoc County, the maximum recorded concentration of dissolved solids is 3,550 ppm. In central Sheboygan County and northern Milwaukee County, the maximum concentrations are 10,440 and 6,690 ppm, respectively. In western Calumet County and parts of Brown, Outagamie, Winnebago, and Fond du Lac Counties, the maximum concentration of dissolved solids is 1,980 ppm. In northeastern Dodge and southeastern Marinette Counties, water analyses indicate maximum concentrations of 5,730 and 1,220 ppm, respectively. Ground water that contains concentrations of dissolved solids exceeding 1,000 ppm occurs in 9.1 percent of the area mapped. The regional pattern of distribution shows increasing concentrations of dissolved solids eastward.

The locations of the three areas of saline ground water in Manitowoc, Sheboygan, and Milwaukee Counties generally coincide with probable structural lows in the water-bearing bedrock units of Late Cambrian and Ordovician age.

Along the geologic section from Outagamie County to Manitowoc County, the concentrations of sulfate, chloride, and dissolved solids increase rapidly immediately updip from a ridge of Precambrian rock that extends upward several hundred feet into the Upper Cambrian series. Further updip and immediately downdip from this ridge, the ground water is fresh. This high, therefore, appears to form a partial barrier to the eastward movement of ground water. The Niagara dolomite and the Upper Cambrian series yield saline water to wells in eastern Manitowoc County. Wells uncased opposite the Platteville-Galena unit, the St. Peter sandstone, and the Upper Cambrian series yield saline water to wells immediately updip from the west of the ridge of Precambrian rock.

Two subsurface ridges of Precambrian rock that have considerable relief but are of small lateral extent extend from Fond du Lac County to Sheboygan County. Concentrations of dissolved solids are higher updip from and within the ridge area than they are 10 miles downdip from the easternmost ridge. The Niagara dolomite yields water of relatively poor quality to wells in central and eastern Sheboygan County. The St. Peter sandstone contains saline water in eastern Sheboygan County.

From Jefferson County to Milwaukee County there are no significant partial stratigraphic barriers to the regional direction of ground-water movement. The changes in the chemical quality of the water as it moves downdip through the aquifers possibly would represent the general conditions in the previously discussed areas had there been no high ridges of Precambrian rock. In eastern Waukesha and northwestern Milwaukee Counties, the Niagara dolomite yields predominently fresh water to wells. In northeastern Milwaukee County, a well tapping the Niagara dolomite, the Platteville-Galena unit, and the St. Peter sandstone yields saline water.

Although there is an abundant supply of ground water in eastern Wisconsin, saline water in certain parts of the several bedrock aquifers is a potential source of contamination of the supply. Only in very general terms do the available data delimit the geographic and stratigraphic distribution of saline ground water. To improve the understanding of its distribution and to study its direction and rate of movement into fresh water areas, a plan of investigation should comprise the following:

1. Continue collecting well records and chemical analyses of water from bedrock aquifers, with preference for water samples from wells tapping a single aquifer in and adjacent to areas tentatively mapped as having saline ground water.

2. Establish observation wells in and adjacent to selected areas of saline ground water to determine change of chemical quality of water with time and the direction of ground-water movement.

3. Correlate distribution of saline water with geologic and hydrochemical factors to define the causes of the occurrence of saline water in eastern Wisconsin.

4. Suggest that water-well engineers and drillers collect water samples for chemical analysis from each of the several aquifers during drilling operations in or near the saline-water areas shown in this report.

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