Geology and Ground-Water Resources of Fond du Lac County, Wisconsin

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1604

Prepared in cooperation with the Geological and Natural History Survey, University of Wisconsin, and the city of Fond du Lac

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By THOMAS G. NEWPORT

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Special reference is given to the area of the city of Fond du Lac. Prepared in cooperation with the Geological and Natural History Survey, University of Wisconsin, and the city of Fond du Lac

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1962

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

The U.S. Geological Survey Library catalog card for this publication appears on page 52.

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C.

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GEOLOGY AND GROUND-WATER RESOURCES OF FOND DU LAC COUNTY, WISCONSIN

By Thomas G. Newport

ABSTRACT

The principal water-bearing rocks underlying Fond du Lac County, Wis., are sandstones of Cambrian and Ordovician age and dolomite of Silurian age. Other aquifers include dolomite of Ordovician age and sand and gravel of Quaternary age. Crystalline rocks of Precambrian age, which underlie all the water-bearing formations, form a practically impermeable basement complex and yield little or no water to wells.

Ground water is the source of all public and most private and industrial water supplies in the county. The municipalities and industries obtain water chiefly from wells that penetrate the sandstones of Cambrian and Ordovician age. The Platteville formation and Galena dolomite of Ordovician age and the Niagara dolomite of Silurian age supply water to most domestic and stock wells and to a few industrial wells. Several buried valleys in the bedrock surface contain water-bearing deposits of sand and gravel.

The source of the ground water in Fond du Lac County is local precipitation. Recharge to the water-bearing beds occurs in most of the county but is greatest where the bedrock formations are near the surface. Ground water is discharged by seeps and springs, by evaporation and transpiration, and by wells.

Ground-water levels in wells fluctuate in response to recharge and to natural discharge and pumping. In areas not affected by pumping, water levels generally decline through the summer months because of natural discharge and lack of recharge, recover slightly in the fall after the first killing frost, decline during the winter, and recover in the spring when recharge is greatest. In areas of heavy pumping, the water levels are lowest in late summer and highest in late winter. Water levels in wells in the Fond du Lac area were about 5 to 50 feet above the land surface in 1885, but they had declined to as low as 185 feet below the land surface by 1957.

Coefficients of transmissibility and storage of the sandstones of Cambrian and Ordovician age were determined by making controlled aquifer tests at Fond du Lac. The coefficients were verified by comparing computed water-level declines with actual declines. The computed values were within about 30 percent of the actual values, a reasonable agreement for coefficients of this type.

Probable declines of water levels by 1966 were computed, using the same coefficients of transmissibility and storage. If the distribution of wells and the rate of pumping remain the same in 1957–66 as they were in 1956, the water levels will decline about 5 feet more by 1966. If, however, the distribution of pumped wells remains the same but the pumping by the city of Fond du Lac increases at a uniform rate from the 3 mgd (million gallons per day) pumped in 1956 to 5 mgd in 1966, the water levels in 1966 will be at least 60 feet below

those of 1956. Dispersal of wells to the northwest toward the recharge area would reduce the water-level declines.

The results of pumping tests of test holes tapping the Niagara dolomite indicate that wells producing at least 200 gpm (gallons per minute) could be developed east of the Niagara escarpment.

The ground water in Fond du Lac County is, in general, a hard calcium and magnesium bicarbonate water, which contains excessive iron in some areas.

INTRODUCTION

Water levels in deep artesian wells in the Fond du Lac area, Wisconsin, have been declining gradually for many years. The continuing decline caused concern among ground-water users in the area, and it became apparent that a comprehensive investigation of the ground-water resources of Fond du Lac County would be essential to the orderly planning of future water supplies.

In 1946 the U.S. Geological Survey, in cooperation with the Wisconsin Geological and Natural History Survey, University of Wisconsin, began a program of ground-water studies in Wisconsin. The investigation of the geology and ground-water resources of Fond du Lac County, begun in September 1953 and completed in February 1959, was a part of this statewide program. The city of Fond du Lac contributed funds to the Wisconsin Geological and Natural History Survey for cooperation between that agency and the U.S. Geological Survey to defray part of the cost of the investigation.

PURPOSE AND SCOPE OF INVESTIGATION

The purpose of this investigation was to determine the thickness, character, and areal extent of the water-bearing beds underlying Fond du Lac County with special reference to the Fond du Lac area; to determine the capacity of the beds to absorb, store, transmit, and discharge water; and to determine the chemical character of the ground water. A detailed study was made of the geology and ground-water resources of the sandstones of Cambrian and Ordovician age and the Niagara dolomite of Silurian age in the vicinity of Fond du Lac, and reconnaissance studies were made of all the water-bearing beds throughout the county.

The investigation was planned cooperatively with George F. Hanson, State Geologist. It was conducted under the immediate supervision of W. J. Drescher, district engineer, and C. L. R. Holt, Jr., district geologist, who succeeded Mr. Drescher in 1957.

DESCRIPTION OF THE AREA

LOCATION AND POPULATION

Fond du Lac County is in east-central Wisconsin at the southern end of Lake Winnebago. It is bounded on the north by Winnebago and Calumet Counties, on the east by Calumet and Sheboygan Counties, on the south by Washington and Dodge Counties, and on the west by Green Lake County. The distance across the county is 36 miles from east to west and 18 to 27 miles from north to south. The county has an area of approximately 760 square miles.

In 1950, the population of Fond du Lac County was 67,829, of which 29,936 (44 percent) resided in the city of Fond du Lac.

ECONOMIC DEVELOPMENT

The economy of the county is chiefly agricultural. Dairying is of major importance and sweet corn, peas, oats, and barley are grown extensively. There are several canning factories and many small milk-processing and cheese plants in the county. Repair shops for two railroads are located at North Fond du Lac. In 1958, there were approximately 15 industrial plants in the city of Fond du Lac.

TOPOGRAPHY AND DRAINAGE

The most pronounced topographic feature in the county is a west-facing escarpment of Niagara dolomite (pl. 2). It extends from south of Pipe to Eden, thence southwestward to Oakfield and south to the Dodge County line. The top of the escarpment ranges from about 50 to 150 feet above the general level of the area to the west.

The area east of the escarpment is higher and more rolling than the area to the west. The so-called Kettle Moraine area in the southeastern part of the country is rolling to hilly. To the north, the surface is gently rolling and is characterized by numerous hills, or drumlins, and by a few relatively flat areas.

A large flat plain, 3 to 8 miles wide, lies immediately west of the escarpment and extends southward from Lake Winnebago to a few miles north of the Dodge County line. West of this plain the surface is gently rolling.

Most of the streams that drain the county originate within its boundaries. The area east of the escarpment is drained by the Manitowoc, Sheboygan, and Milwaukee Rivers and their tributaries into Lake Michigan. The flat plain in the central part of the county is drained by the East Branch of the Fond du Lac River and De Neveu Creek and their tributaries into Lake Winnebago. The West Branch of the Fond du Lac River and Anderson Creek drain the north-central part of the county, also into Lake Winnebago. The extreme northwestern part of the county is drained by Silver Creek and the west-central part by Grand River. Both streams flow into the Fox River in Winnebago County and thence into Lake Winebago. The headwaters of the Rock River drain the southwestern and south-central parts of the county southward to the Mississippi River.

CLIMATE

The climate of Fond du Lac County is characterized by mild summers and cold winters. The average annual temperature recorded at Fond du Lac is 46.6°F. Temperature extremes range from a high of 106°F, recorded in 1916, to a low of −41°F, recorded in January 1951.

The average monthly precipitation at Eldorado, Fond du Lac, and Ripon are shown in figure 1; the annual precipitation at these stations for the periods of record are shown in figure 2. About 50 percent of the precipitation falls from May to August during the principal growing season.

PREVIOUS INVESTIGATIONS

The general features of the geology and the occurrence of ground water in Fond du Lac County are described in reports by Chamberlin (1877), Weidman and Schultz (1915), and Alden (1918). In 1950 Spicer made an electrical-resistivity survey to determine the depths to the Precambrian basement complex in the Ripon–Fond du Lac area, and in 1954 Woollard and Hanson made a seismic investigation to determine the thickness of the glacial deposits in the Campbellsport area.

NUMBERING SYSTEM

The wells, test holes, and springs are numbered in the order that they were visited during the field investigation. The letters that precede the numbers designate the counties as follows: FL, Fond dù Lac; Dg, Dodge; GL, Green Lake; Wi, Winnebago. Because of space limitations, the prefixes are omitted

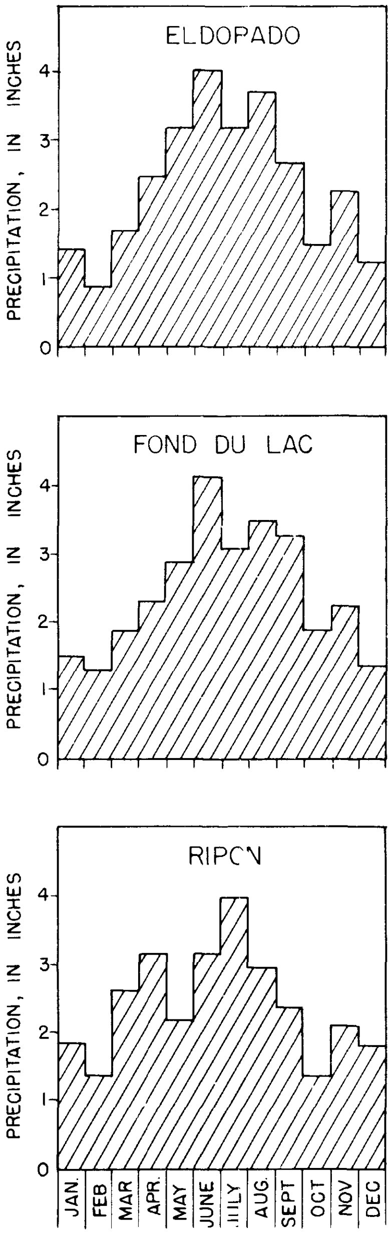

FIGURE 1.—Average mo~thly precipitation at Eldorado, For~d du Lac, and Ripon, in Fond du Lac County, Wis. From records of U.S. Weather Bureau.

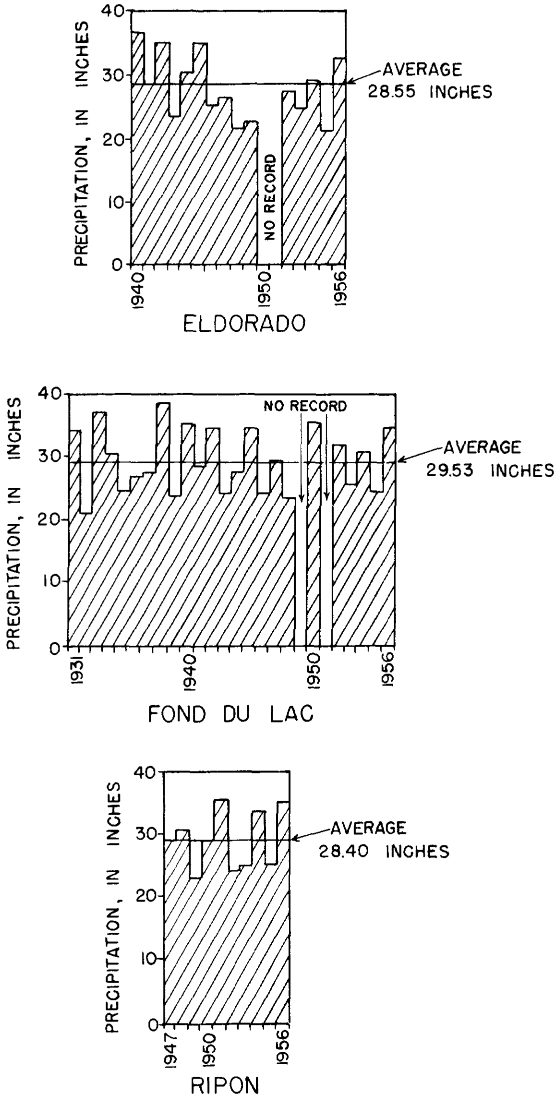

FIGURE 2.—Annual precipitation at Eldorado, Fond du Lac, and Ripon, in Fond du Lac County, Wis. From records of U.S. Weather Bureau.

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from several of the illustrations. The location of the wells, test holes, and springs is shown on plate 1.

ACKNOWLEDGMENTS

The writer wishes to thank the many persons who have contributed information and assistance during the field investigation and preparation of this report. Acknowledgment is made to the municipal employees, particularly the former superintendent, Mr. E. J. Braun, and the present superintendent, Mr. H. D. Elmer, of the Fond du Lac Water Department, for supplying data on water levels, pumpage, and locations of wells; to well drillers, well owners, and consulting engineers for furnishing well logs, records of water levels, pumpage, and other data; and to the Wisconsin State Laboratory of Hygiene for making chemical analyses of the water samples collected during this investigation. Thanks are also expressed to Mr. G. F. Hanson, State Geologist, for his review of this report; to Mr. F. T. Thwaites, retired professor of geology at the University of Wisconsin, to Mr. J. B. Steuerwald, State Geological and Natural History Survey, for preparing the sample logs of wells and supplying geologic data; and to Mr. O. J. Muegge, State Sanitary Engineer, for supplying well records from the files of the State Board of Health.

GEOLOGIC FORMATIONS AND THEIR WATER-BEARING PROPERTIES

The map showing the bedrock geology of Fond du Lac County (pl. 2) was modified from the "Geologic Map of Wisconsin" (Bean, 1949) using sample logs (logs compiled by Wisconsin Geological and Natural History Survey from examination of well samples) of wells and test holes and field observations.

The rocks underlying Fond du Lac County range in age from Precambrian to Quaternary and are of sedimentary, metamorphic, and igneous origin. A generalized description of the rock units and their water-bearing characteristics is given below. The sample logs of wells FL 22, FL 31, FL 33, FL 50, FL 59, FL 125, and test hole FL 300 are given in table 1. The bedrock formations dip gently to the east and southeast (pl. 3).

Lithology and water-bearing characteristics of rock units underlying Fond du Lac County, Wis.

System	Rock unit	Maximum thickness[1] (feet)	Lithology	Water-bearing characteristics
Quaternary	Recent alluvium	10	Clay, peat, silt, sand, and gravel.	Not important as an aquifer.
	Unconformity			
	Pleistocene deposits	222+	Unstratified till and stratified clay, sand, and gravel.	Yields water from sand and gravel. Important aquifer where sufficiently thick and adequately recharged.
	Unconformity			
Silurian	Niagara dolomite	325	Dolomite, medium-gray to white. Generally massive. Some coral reefs. Fractures abundant but variably distributed.	Important aquifer. Yields water from solutionally enlarged openings along fractures and bedding planes.
	Unconformity			
Ordovician	Neda formation	20	Shale, hematitic, oolitic, some dolomite.	Not important as an aquifer.
	Maquoketa shale	365	Shale, medium-bluish-gray, dolomitic, interstratified with thin beds of light-gray and medium-gray dolomite.	Not important as an aquifer. Generally cased off in wells.
	Galena dolomite and Platteville formation	265	Dolomite, light-gray to medium-bluish-gray, massive.	Unit yields small to moderate quantities of water, principally in areas where not overlain by Maquoketa shale.
	St. Peter sandstone	260	Sandstone, fine- to medium-grained, white to light-gray, dolomitic in some places. Red shale may occur near base.	Yields small to moderate quantities of water.
	Unconformity			
	Prairie du Chien group	240	Dolomite, cherty, thin-bedded to massive. Some layers of chert, shale, and sandstone.	Yields small quantities of water.
Cambrian	Trempealeau formation Franconia sandstone Galesville sandstone of Dresbach group Eau Claire sandstone of Dresbach group	515	Sandstone, very fine to coarse grained, dolomitic, silty. Some layers of shale, siltstone, and dolomite.	Important aquifer. Yields small to large quantities of water depending upon permeability and thickness.
	Unconformity			
Precambrian rocks		Unknown	Crystalline rocks, such as quartzite, granite, schist, and gneiss.	Not an aquifer.

[1] Based on well logs.

TABLE 1.—*Sample logs of selected wells and test holes in Fond du Lac County, Wis.*

	Thickness (feet)	Depth (feet)
FL 22, NW¼NW¼ sec. 36, T. 15 N., R. 14 E. Surface altitude, 990 feet.		
Quaternary system:		
Pleistocene deposits:		
Clay, gray, some boulders	15	15
Ordovician system:		
Galena dolomite and Platteville formation:		
Dolomite, gray	185	200
Dolomite, gray, sandy	15	215
Prairie du Chien group:		
Dolomite, gray	65	280
Dolomite, gray, cherty	10	290
Dolomite, gray	45	335
Shale, green, very dolomitic	5	340
Cambrian system:		
Trempealeau formation:		
Shale, red, dolomitic	5	345
Siltstone, pink, sandy, dolomitic	45	390
Siltstone, dark-red, dolomitic, glauconitic	25	415
Franconia sandstone:		
Sandstone, pink, fine-grained, slightly silty	155	570
Galesville sandstone:		
Sandstone, gray, silty, fine- to medium-grained	210	780
Siltstone, pink, sandy	20	800
Sandstone, pink, fine- to medium-grained	25	825
Conglomerate, quartzite pebbles	20	845
Siltstone, pink; some shale, red	10	855
Precambrian:		
Quartzite, pink	28	883
FL 31, NW¼SE¼ sec. 10, T. 15 N., R. 17 E. Surface altitude 754 feet.		
Quaternary system:		
Pleistocene deposits:		
Clay, red, dolomitic	35	35
Clay, gray, dolomitic	70	105
Ordovician system:		
Galena dolomite and Platteville formation:		
Dolomite, gray	185	290
Sandstone, gray, dolomitic, fine- to medium-grained	10	300
St. Peter sandstone:		
Sandstone, gray to pink, fine- to medium-grained	130	430
Shale, red	40	470
Cambrian system:		
Trempealeau formation:		
Sandstone, gray to pink	20	490
Dolomite, gray	5	495
Franconia sandstone:		
Sandstone, gray, dolomitic, very fine-grained	25	520
Siltstone, pink, dolomitic	45	565
Sandstone, gray, dolomitic	10	575
Galesville sandstone:		
Sandstone, gray, very fine- to fine-grained	165	740
Precambrian:		
Quartzite, gray	5	745

TABLE 1.—*Sample logs of selected wells and test holes in Fond du Lac County, Wis.*—Continued

	Thickness (feet)	Depth (feet)
FL 33, SW¼NW¼ sec. 15, T. 15 N., R. 17 E. Surface altitude, 760 feet.		
No samples	65	65
Ordovician system:		
Galena dolomite and Platteville formation:		
Dolomite, gray	175	240
Sandstone, gray, dolomitic, medium- to coarse-grained	5	245
Dolomite, gray	10	255
Sandstone, gray, dolomitic, very fine-grained	15	270
St. Peter sandstone:		
Sandstone, gray to white, fine- to medium-grained	75	345
Conglomerate	5	350
Shale, red	10	360
Conglomerate	10	370
Prairie du Chien group:		
Dolomite, gray, sandy at base	40	410
Sandstone, gray, coarse-grained	5	415
Precambrian:		
Quartzite, gray and pink; some slate	10	425
FL 50, SE¼NW¼ sec. 22, T. 16 N., R. 14 E. Surface altitude, 929 feet.		
No samples	25	25
Ordovician system:		
Galena dolomite and Platteville formation:		
Dolomite, gray	40	65
St. Peter sandstone:		
Sandstone, gray, fine- to medium-grained	45	110
Shale, red	5	115
Prairie du Chien group:		
Dolomite, gray	20	135
Sandstone, gray, fine- to medium-grained	10	145
Dolomite, gray, chert at top	75	220
Cambrian system:		
Trempealeau formation:		
Sandstone, pink, dolomitic, fine- to medium-grained	20	240
Siltstone, gray, dolomitic	40	280
Franconia sandstone:		
Sandstone, pink, dolomitic, glauconitic, fine-grained	30	310
Siltstone, gray, dolomitic	5	315
Sandstone, gray, dolomitic, fine- to medium-grained	65	380
Shale, red, dolomitic, glauconitic	15	395
Sandstone, pink, fine- to medium-grained	25	420
Galesville sandstone:		
Sandstone, gray, fine- to medium-grained	75	495

TABLE 1.—*Sample logs of selected wells and test holes in Fond du Lac County, Wis.*—Continued

	Thickness (feet)	Depth (feet)
FL 59, NE¼SE¼ sec. 11, T. 15 N., R. 17 E. Surface altitude, 757 feet.		
Quaternary system:		
Pleistocene deposits:		
Clay, red, dolomitic	15	15
Clay, gray, dolomitic, boulder	90	105
Ordovician system:		
Galena dolomite and Platteville formation:		
Dolomite, gray	225	330
Sandstone, gray, dolomitic, fine- to coarse-grained	15	345
St. Peter sandstone:		
Sandstone, gray, fine- to medium-grained	110	455
Shale, red, dolomitic	50	505
Cambrian system:		
Trempealeau formation:		
Siltstone, gray to pink, dolomitic	35	540
Franconia sandstone:		
Sandstone, pink, dolomitic, very fine to fine grained	55	595
Sandstone. gray, dolomitic, fine- to medium-grained	25	620
Galesville sandstone:		
Sandstone, gray, fine- to medium-grained	190	810
Sandstone, red, fine to very coarse grained	15	825
Precambrian:		
Quartzite, pink	10	835
FL 125, NE¼NE¼ sec. 13, T. 13 N., R. 18 E. Surface altitude, 1038 feet.		
No samples	20	20
Silurian system:		
Niagara dolomite:		
Dolomite, gray	312	332
Ordovician system:		
Neda formation:		
Shale, hematitic, oolitic, dolomitic, hard	3	335
Shale, dark-reddish-brown, hematitic, slightly dolomitic	15	350
Maquoketa shale:		
Shale, gray, dolomitic	30	380
Dolomite, gray	10	390
Shale, gray, dolomitic	50	440
Dolomite, gray	20	460
Shale, gray, dolomitic	20	480
Dolomite, gray	5	485
Shale, gray, dolomitic	133	618
Galena dolomite and Platteville formation:		
Dolomite, gray	217	835
Sandstone, gray, dolomitic, fine- to coarse-grained	20	855
St. Peter sandstone:		
Sandstone, gray, fine-grained	10	865
Siltstone, gray, very dolomitic	5	870
Sandstone, gray, fine- to medium-grained	80	950

TABLE 1.—*Sample logs of selected wells and test holes in Fond du Lac County, Wis.*—Continued

	Thickness (feet)	Depth (feet)
FL 125, NE¼NE¼ sec. 13, T. 13 N., R. 18 E. Surface altitude, 1038 feet—Continued		
Cambrian system:		
Trempealeau formation:		
Dolomite, gray	55	1, 005
Franconia sandstone:		
Siltstone, greenish-gray, very dolomitic	10	1, 015
Sandstone, gray, dolomitic, fine- to coarse-grained	25	1, 040
Siltstone, gray, very dolomitic	10	1, 050
Sandstone, gray, very dolomitic, fine-grained	20	1, 070
Sandstone, white, medium- to coarse-grained	5	1, 075
Sandstone, gray, dolomitic, very fine to medium grained	25	1, 100
Galesville sandstone:		
Sandstone, white, fine- to medium-grained	75	1, 175
Eau Claire sandstone:		
Sandstone, gray, very dolomitic	40	1, 215
Shale, gray, dolomitic	10	1, 225
Sandstone, fine- to medium-grained	75	1, 300
Test hole FL 300, NW¼SW¼ sec. 11, T. 15 N., R. 18 E. Surface altitude, 994 feet.		
Quaternary system:		
Pleistocene deposits:		
Clay, dark-gray	10	10
Gravel, light-gray, sandy	5	15
Silurian system:		
Niagara dolomite:		
Dolomite, light-gray	30	45
Dolomite, light-gray; some chert	50	95
Dolomite, light-gray	10	105
Dolomite, light-gray; some chert	30	135
Dolomite, light-gray, cherty	40	175
Dolomite, light-gray	15	190
Ordovician system:		
Maquoketa shale:		
Shale, light-gray, dolomitic	5	195
Dolomite, light-gray, pyritic	5	200
Shale, light-gray, dolomitic	10	210

PRECAMBRIAN ROCKS

Crystalline rocks of Precambrian age such as quartzite, granite, schist, and gneiss, which are estimated to be several thousand feet thick, underlie with a major unconformity the sedimentary rocks of Cambrian, Ordovician, Silurian, and Quaternary ages. One of the units of crystalline rock, the Utley metarhyolite, is exposed in Green Lake County approximately 1.5 miles southwest of Fairwater, but none are exposed in Fond du Lac County.

Although the surface of the crystalline rocks has a regional slope of about 20 to 30 feet per mile toward the east and south, the surface in Fond du Lac County is uneven, with slopes ranging from a few feet to several hundred feet per mile. This surface has a relief of at least 1,100 feet in Fond du Lac County (pl. 3, section *C–C'*).

In the southwestern part of the city of Fond du Lac quartzite was found in wells FL 30, FL 33, FL 34, and FL 35 at depths of 400–440 feet or about 315–360 feet above mean sea level. The sample log of well FL 33 is given in table 1. Less than a mile northeast of these wells, quartzite was found in well FL 31 at a depth of 740 feet or at approximately 10 feet above mean sea level (table 1). The city's wells north and northeast of well FL 31 tapped quartzite at elevations below mean sea level. Quartzite was found at a depth of 555 feet or 200–225 feet above mean sea level in test holes FL 37, and FL 38, 1 mile north and 1¾ miles east of well FL 30 respectively. Based on the limited data from wells, it is believed that the structural high in the crystalline rocks near the southern part of the city of Fond du Lac (pl. 3, section *B–B'*) is steep-sided to the north.

Another structural high in the crystalline rocks is centered approximately 10 miles west of Fond du Lac and 2 miles south of Rosendale. Quartzite was found in well FL 212 at a depth of 65 feet or 870 feet above mean sea level, and at a depth of 102–140 feet or about 800–835 feet above mean sea level in wells FL 74, FL 210, and FL 211. Well FL 55 in Rosendale tapped quartzite at a depth of 420 feet or approximately 500 feet above mean sea level.

During the spring of 1957, 21 electrical-resistivity profiles were made in the area between well FL 212 and Fond du Lac by H. C. Spicer and G. J. Edwards, of the U.S. Geological Survey, to determine the depth to the surface of the crystalline rock. The analysis of the resistivity data by Spicer (1950), and an analysis made independently by Woollard (Woollard and Hanson, 1954), suggested an eastward-trending structural high in the surface of the crystalline rocks south of Rosendale. The results of the resistivity studies were inconclusive, however, and test drilling will be necessary to determine accurately the configuration of the crystalline-rock surface.

The rocks of Precambrian age do not yield water and form a practically impermeable basement complex below the sedimentary rocks.

CAMBRIAN SYSTEM

Sandstones of Cambrian age unconformably overlie the crystalline rocks of Precambrian age, and are in turn overlain by younger formations. The sandstones filled in the depressions and covered most of the high areas on the Precambrian surface. The rocks of Cambrian age penetrated by wells in Fond du Lac County are, in ascending order, the Eau Claire sandstone, the Galesville sandstone, the Franconia sandstone, and the Trempealeau formation. The Galesville sandstone, Eau Clarie sandstone, and Mount Simon sandstone are formations of Dresbach group. The name Dresbach has long had formational status in U.S. Geological Survey nomenclature as the Dresbach sandstone, and it is here redesignated a group. Trowbridge and Atwater (1934) proposed the name Galesville member for beds then called Dresbach sandstone by the U.S. Geological Survey; the name Galesville is here assigned formational status as the Galesville sandstone. Although the Eau Claire sandstone was found in only one well and the Mount Simon sandstone has been absent in wells in Fond du Lac County, they are known to be present to the south and to the east.

The thickness of the rocks of Cambrian age, which ranges from 0 to 515 feet, differs greatly throughout the county because of the irregular upper surface of the Precambrian rocks. The rocks of Cambrian age are thin or absent in the areas where mounds or ridges occur in the crystalline rocks (FL 33 and FL 300, table 1, and pl. 3, sections *B–B′* and *C–C′*.

DRESBACH GROUP

EAU CLAIRE SANDSTONE

The Eau Claire sandstone is a fine- to medium-grained dolomitic sandstone that is well consolidated and does not cave into uncased wells. It is generally light gray, but may be white to moderate pink.

The Eau Claire sandstone was identified only in well FL 125 at Campbellsport, where the top of the formation was 1,175 feet below the land surface (pl. 3, section *A–A′*). The well was drilled through 125 feet of the Eau Claire but did not penetrate it completely (table 1).

GALESVILLE SANDSTONE

The Galesville sandstone consists mostly of fine- to medium-grained sandstone. It it chiefly light gray but includes a few zones that are pale pink. Some of the beds are well cemented with silica or dolomite and are difficult to drill. A few thin beds of siltstone, generally less than 5 feet thick, are present. Detailed descriptions of Galesville sandsone are given in logs of wells FL 22, FL 31, FL 50, FL 59, and FL 125 (table 1).

The Galesville sandstone underlies all of Fond du Lac County, except in those areas underlain by structural highs in the Precambrian rocks, where it was not deposited. The sandstone was completely penetrated by wells at Fairwater, Brandon, Fond du Lac, Rosendale, Campbellsport, and Waupun. The greatest thickness penetrated was 285 feet in well FL 22 at Brandon (table 1 and pl. 3, section *A–A′*).

The Galesville sandstone is believed to be the most productive water-bearing formation in the Fond du Lac area. Its permeability is variable, especially in a vertical direction, because of changes in the sorting of the sand and the presence of layers of dolomite and siltstone.

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FRANCONIA SANDSTONE

The Franconia sandstone is a fine- to medium-grained sandstone that is silty and dolomitic. Thin beds of siltstone and dolomite, generally less than 10 feet thick, occur within the formation. The color of the Franconia is predominantly light gray, but white, moderate pink, and moderate red also occur. The sandstone is cemented by dolomite but is not difficult to drill. Detailed descriptions of Franconia sandstone are given in logs of wells FL 22, FL 31, FL 50, FL 59, and FL 125 (table 1).

The known thickness of the Franconia sandstone ranges from 0, in areas underlain by structural highs in the Precambrian rocks, to 185 feet, in well FL 15 at Ripon; however, the entire thickness of the formation was not penetrated in well FL 15. Where the Franconia sandstone is not present, it was not deposited or was removed by erosion before deposition of the Trempealeau formation.

The Franconia sandstone is believed to rank next to the Galesville sandstone in importance as a source of water to wells in the Fond du Lac area. The permeability of the sandstone is variable, especially in a vertical direction, because of changes in the sorting of the sand and the presence of thin beds of dolomite and siltstone.

TREMPEALEAU FORMATION

The Trempealeau formation is the uppermost unit of the Cambrian system in the Fond du Lac area. Although the formation does not crop out in Fond du Lac County, it is covered by only about 20 feet of glacial drift in the valley of Silver Creek about a mile west of Ripon in Green Lake County.

The Trempealeau formation consists of light-gray very fine to medium grained dolomitic sandstone and moderate-pink or moderate-red siltstone. Detailed description of the Trempealeau formation are given in logs of wells FL 22, FL 31, FL 50, FL 59, and FL 125 (table 1). The known thickness of the formation in the county ranges from 0, in well 51 at Ripon, to 105 feet, in well FL 10 at Fond du Lac. The Trempealeau was probably removed by erosion in the vicinity of well FL 51.

The Trempealeau formation probably has a low permeability because the unit consists chiefly of very fine grained sandstone interbedded with siltstone. It is believed to yield only relatively small quantities of water to wells.

ORDOVICIAN SYSTEM

The rock units of the Ordovician system, in ascending order, are the Prairie du Chien group, St. Peter sandstone, Platteville formation and Galena dolomite, Maquoketa shale, and Neda formation. These formations successively overlie the rocks of Cambrian age and are exposed locally, with the exception of the Neda formation, in the county (pl. 2). They are overlain by deposits of Pleistocene age in most of the western part of the county and by the Niagara dolomite in the eastern part. The rocks of the Prairie du Chien group, the St. Peter sandstone, and the Platteville formation and Galena dolomite are believed to be hydraulically connected with each other and with the underlying rocks of Cambrian age.

PRAIRIE DU CHIEN GROUP

The Prairie du Chien group consists of cherty dolomite and thin beds of shale. The dolomite is light gray to white, hard, and dense. It contains nodules of gray to white chert and a few thin beds of sandstone. A few exposures of the Prairie du Chien group occur near Ripon (pl. 2). Detailed descriptions of the Prairie du Chien group are given in logs of well FL 22, FL 33, and FL 50 (table 1).

The rocks of the Prairie du Chien group range greatly in thickness within relatively short distances because their upper surface is very irregular. In several areas, the rocks of this group were completely removed prior to the deposition of the St. Peter sandstone. For example, the Prairie du Chien group was absent in well FL 51 at Ripon, but in well FL 18, 1½ miles southeast of FL 51, it was 160 feet thick. In Fond du Lac County the Prairie du Chien is thickest (240 feet) in well FL 16, about 2 miles southwest of Campbellsport.

The rocks of the Prairie du Chien group have a low permeability but yield small quantities of water to wells from openings along fractures and bedding planes.

ST. PETER SANDSTONE

The St. Peter sandstone consists of fine- to medium-grained consolidated sandstone that is dolomitic in some places. It is chiefly white to light gray, and contains small lenses of reddish slightly dolomitic shale near the base of the formation. Although the sandstone does not generally cave into uncased wells, drillers report that where shale is penetrated in the St. Peter sandstone it must be cased off to prevent caving. The upper part of the St. Peter sandstone is exposed in several road cuts near Ripon (pl. 2). Detailed descriptions of the St. Peter sandstone are given in logs of wells FL 31, FL 33, FL 50 FL 59, and FL 125 (table 1).

The St. Peter sandstone was deposited on the eroded surface of the rocks of the Prairie du Chien group and thus has an irregular lower surface. The upper surface, however, is relatively even. Where the Prairie du Chien group is uncommonly thick, the St. Peter sandstone generally is thin or is missing. Similarly, where the rocks of the Prairie du Chien group are thin or missing the St. Peter sandstone is thick. In those areas where the St. Peter is missing, the Platteville formation rests directly upon the rocks of the Prairie du Chien group, and where the Prairie du Chien is missing the St. Peter sandstone is in contact with the rocks of Cambrian age. In Fond du Lac County the maximum thickness of the St. Peter sandstone penetrated in the subsurface was 260 feet in test hole FL 52 at Ripon.

Most of the wells in Fond du Lac County that obtain water from the St. Peter sandstone also obtain part of their supply from overlying and underlying formations. Well FL 135 at Ripon is open opposite the Platteville formation and Galena dolomite as well as the St. Peter sandstone, but it is believed to obtain most of its water supply from the sandstone. This well was reported pumped at 200 gpm for 24 hours with a drawdown in water level of 31 feet, indicating a specific capacity of 6.4 gpm per foot of drawdown.

PLATTEVILLE FORMATION AND GALENA DOLOMITE

The Platteville formation and Galena dolomite have not been differentiated in the subsurface in the Fond du Lac area, and are considered as a unit in this report.

The Platteville formation and Galena dolomite consist of light-gray to medium-bluish-gray dolomite. The beds in the Galena dolomite are thicker than in the Platteville. The contact between the Platteville formation and the underlying St. Peter sandstone is exposed in a road cut near Ripon in the NE¼ sec. 19, T. 16 N., R. 14 E. (fig. 3). Detailed descriptions of the Platteville formation and Galena dolomite are given in logs of wells FL 22, FL 31, FL 33, FL 50, FL 59, and FL 125 (table 1).

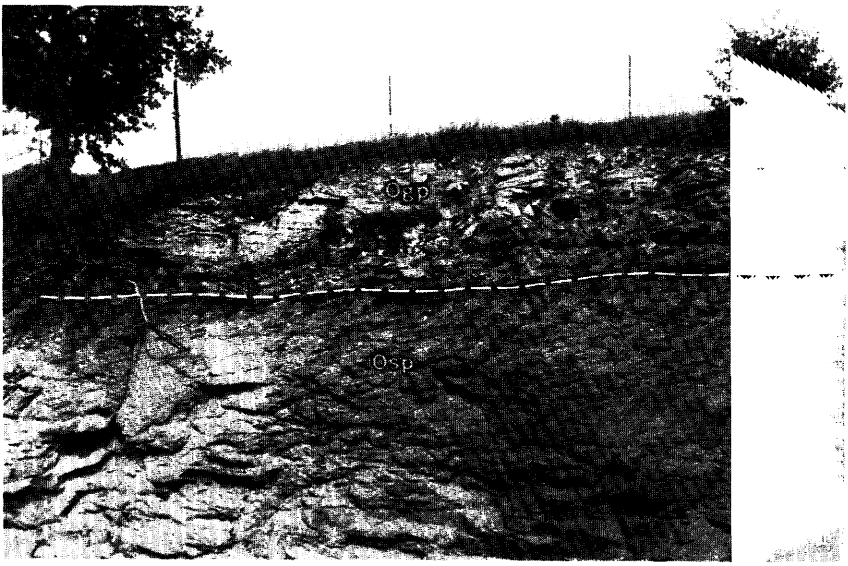


FIGURE 3.—Contact of Platteville formation and St. Peter sandstone in road cut near Ripon in NE¼ sec. 19, T. 16 N., R. 14 E.

The Platteville formation and Galena dolomite underlie Fond du Lac County except in a small area in the northwestern corner of the county near Ripon and in the valley of Grand River near Fairwater, where they have been removed by erosion. The unit is thickest (265 feet) in well FL 310 at Campbellsport. The most common thickness is about 200 feet.

Ground water in the dolomite occurs in solutionally enlarged openings along fractures and bedding planes. Drillers report that domestic and stock wells completed in the dolomite generally yield from about 2 to 15 gpm. However, most of these wells do not penetrate the full thickness of this unit. Well FL 41 at Fond du Lac was reported pumped at a rate of 40 gpm for 10 hours and had a drawdown in water level of 31 feet, indicating a specific capacity of 1.3 gpm per foot of drawdown.

MAQUOKETA SHALE

The Maquoketa shale is a medium-bluish-gray soft dolomitic shale interstratified with thin beds of light-gray and medium-gray dolomite. It must be cased off in wells to prevent caving.

The formation is absent in the western part of the county, is concealed by glacial drift and slumped fragments of Niagara dolomite in a narrow belt (½ to 3 miles wide) along the western edge of the Niagara escarpment, and underlies the Niagara dolomite east of the escarpment. The shale is well exposed in a quarry of the Oakfield Brick Co. near Oakfield (fig. 4). Detailed descriptions of the Maquoketa shale are given in logs of wells FL 125 and FL 300 (table 1).

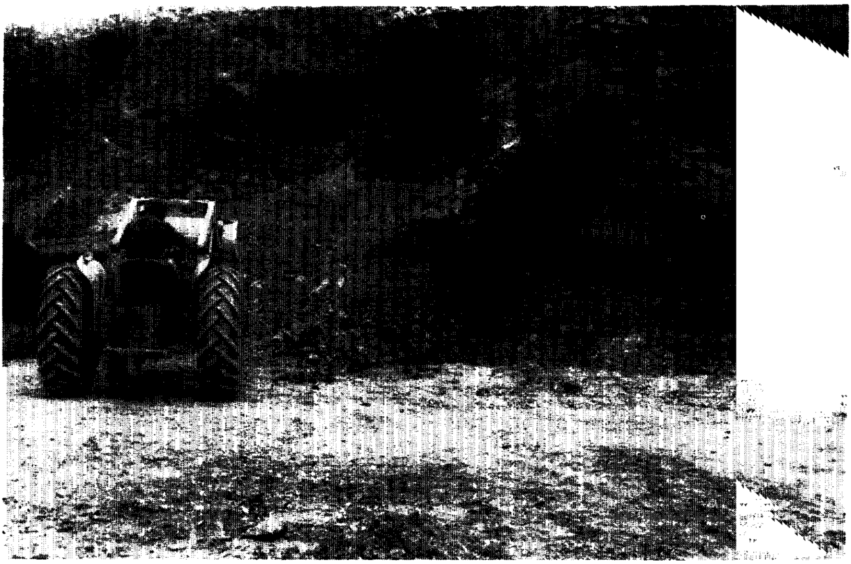


FIGURE 4.—Outcrop of Maquoketa shale in a quarry near Oakfield, Wis.

The Maquoketa shale yields very small quantities of water to wells in some parts of Wisconsin. Records are not available, however, of any well in Fond du Lac County that obtains water from this formation. Along the Niagara escarpment, many seeps and springs issue from the Niagara dolomite at or near the contact between the dolomite and the Maquoketa shale. The shale underlies and forms a relatively impermeable base for the water-bearing Niagara dolomite. The greatest thickness of Maquoketa shale penetrated was 365 feet in well FL 130 at Mount Calvary (pl. 3, section *C–C'*).

NEDA FORMATION

The Neda formation is composed of lenticular beds of oolitic, dolomitic, hematitic, red shale. It was penetrated by wells only at Campbellsport in the southeastern part of Fond du Lac County, where it had a maximum thickness of 18 feet (well FL 125, table 1) but it is not exposed in the county. This formation is not important as an aquifer in Fond du Lac County because it is limited in areal extent, is thin, and probably has a low permeability.

SILURIAN SYSTEM

NIAGARA DOLOMITE

The Niagara dolomite of Silurian age unconformably overlies the Maquoketa shale and dips gently eastward. It is medium gray to white and contains some coral reefs. Detailed descriptions of the Niagara dolomite are given in logs of wells FL 125 and FL 300 (table 1). The beds are generally massive and are intersected by joints. Although fracturing is greatest in the upper part of the dolomite, drillers and well owners have reported large openings throughout the entire thickness of the formation. The distribution of the fracturing is variable and a regional pattern is not discernible.

The Niagara dolomite is present in the eastern part of the county, east of the Niagara escarpment (pl. 2). It crops out along the escarpment and at a few places to the east (pl. 2), but in most of the area is covered by a varied thickness of Pleistocene deposits. The Niagara dolomite is best exposed south of Fond du Lac in quarries of the Fond du Lac Stone Co. and the Marblehead Lime Co. A small reef structure in the dolomite is exposed in the quarry of the Fond du Lac Stone Co. in the SE¼NW¼ sec. 10, T. 14 N., R. 17 E. (fig. 5).

In general, the Niagara dolomite is thinnest along the Niagara escarpment and is thickest along the eastern boundary of the county. The known thickness of the dolomite ranges from 1 foot in well FL 178 near Peebles to 324 feet in well FL 130 at Mount Calvary (pl. 3, section *C–C'*).

Ground water in the Niagara dolomite occurs in openings along fractures and bedding planes, many of which have been enlarged by the solvent action of circulating ground water. The yields of wells

FIGURE 5.—A small reef structure in the Niagara dolomite in the quarry of the Fond du Lac Stone Co. in the SE¼NW¼ sec. 10, T. 14 N., R. 17 E.

tapping the dolomite generally range from about 5 to more than 400 gpm. The large yields are obtained from wells that intersect zones of relatively high permeability.

The water in the dolomite may occur under either water-table or artesian conditions. Most of the flowing artesian wells are more than 100 feet in depth. Water from test hole FL 302, 7 miles east of Fond du Lac, drilled to a depth of 210 feet, flowed 142 gpm and had a pressure head of more than 19 feet above land surface. The total pressure could not be measured because part of the pressure was dissipated when some of the water flowed outside the casing and upward through the glacial drift. In June 1956 this well was pumped at a rate of 400 gpm and had a specific capacity of about 6 gpm per foot of drawdown.

QUATERNARY SYSTEM

Unconsolidated deposits of Quaternary age overlie the consolidated rocks in most of Fond du Lac County. These deposits, largely of glacial origin and of Pleistocene age, consist of stratified clay, sand, and gravel, and unstratified till, which is an unsorted mixture of glacial sediments. All sediments deposited by or from glacial ice or in water derived from the melting of the ice are termed "drift." Drift of the Cary and Valders substages of the Wisconsin stage of glaciation form prominent topographic features. These features have been mapped and are described in detail by Alden (1918).

The Pleistocene deposits are thickest in preglacial valleys which carried melt water from ice sheets. It is believed these deposits may be as much as 300 feet thick in eastern Fond du Lac County. The Pleistocene deposits are reported at least 222 feet thick (their entire thickness was not penetrated) in well FL 190, northeast of Calvary, in the northeastern part of the county. The thickness of sand and gravel in well FL 190 was reported to be 140 feet.

The stratified and well-sorted sediments are very permeable and, where sufficiently thick and adequately recharged, may supply large quantities of water to wells. The water-bearing beds of sand and gravel in eastern Fond du Lac County are saturated to levels near the land surface and are readily recharged. Large supplies of water might be developed locally by penetrating and adequately developing the full thickness of these deposits.

Deposits of clay, silt, sand, and gravel of Recent age underlie flood plains in the valleys of the larger streams. Recent deposits of clay, peat, and silt occur in some of the valleys between the hills of till. The Recent sediments in the county have a maximum thickness of about 10 feet, and because they are thin and limited in areal extent yield only small amounts of water to wells.

GROUND WATER

SOURCE AND OCCURRENCE

The source of all ground water in Fond du Lac County is precipitation in the form of rain and snow. A part of the precipitation flows into streams and lakes as direct runoff, a part returns to the atmosphere through evaporation and transpiration, and a part seeps downward through the soil and rocks to the zone of saturation to become ground water. The top of the zone of saturation is called the water table, and its position is shown by the level at which water stands in nonartesian wells. All openings in the zone of saturation are filled with water, and it is water in the zone of saturation that can be obtained by wells and that flows from springs.

Ground water occupies pores, fractures, and bedding-plane openings in the rocks. The size, shape, and distribution of the openings in the rocks vary considerably from place to place, and they control the storage and movement of water. The amount of water that can be stored in a rock depends on the porosity of the rock. The porosity of a rock is its property of containing interstices or open spaces and is the ratio, expressed as a percentage, of the open space in a rock to its total volume.

The permeability of a rock is a measure of its capacity to transmit water under a hydraulic gradient. Permeability may be expressed as a coefficient that denotes the rate in gallons per day at which water will move through a cross section of the rock (1 foot square, under a hydraulic gradient of 1 foot per foot loss in head of 1 foot for each foot of travel of the water, whatever the direction of movement).

Clay and shale generally have high porosity but low permeability because their pore spaces, though numerous, are very small. A sand or gravel may have a lower porosity than clay or shale but have a high permeability because the interconnected open spaces are large. Permeable rock zones through which ground water moves freely enough to supply wells are called aquifers.

ARTESIAN CONDITIONS

Water in an aquifer under artesian pressure is restricted in direction of movement by relatively impermeable overlying and underlying rocks. Recharge seeps into the aquifer where it is at or near the land surface and moves down gradient to become confined under pressure between relatively impermeable rocks. Ground water moves from areas of high pressure to areas of low pressure.

When a well penetrates a confined aquifer downdip from its intake area, hydrostatic pressure causes the water to rise above the bottom of the confining layer. The imaginary surface to which water will rise in tightly cased artesian wells is called the piezometric surface of the confined water. An artesian well will flow if the piezometric surface is above the land surface.

The rocks underlying Fond du Lac County consist of alternating strata of relatively permeable rock, principally sandstone, and relatively impermeable rock, chiefly dolomite, shale, or clay. Water in the permeable beds is generally under artesian pressure.

The sandstones of Cambrian age and the St. Peter sandstone of Ordovician age are the most productive water-bearing units in the county. The sandstones are hydraulically connected, and water moves from one sandstone layer to another whenever there is a difference in head. East of the Niagara escarpment, the Maquoketa shale forms a relatively impermeable seal above the sandstones and maintains artesian pressure. In the area west of the Niagara escarpment, the Platteville formation and Galena dolomite are less permeable than the underlying sandstones and locally maintain the artesian pressure in the sandstones.

Water in the Platteville formation and Galena dolomite is under artesian pressure except in the areas of outcrop and in areas where they are overlain by relatively thin drift. Even in these areas, the water in the lower part of this unit is generally under artesian pressure because the upper beds of dolomite are dense and leakage probably occurs from the underlying sandstones.

Water in the Niagara dolomite is under artesian pressure except locally in the areas of outcrop and in those areas where the dolomite is overlain by relatively thin deposits of peat or drift. In general, the water in the lower part of the formation is confined under artesian pressure.

Artesian conditions occur locally in the Pleistocene deposits where sand and gravel deposits are confined between silt and clay.

WATER-TABLE CONDITIONS

The water table is the upper surface of the zone of saturation except where that surface is formed by a bed of relatively impermeable material which confines the water under artesian pressure. Unconfined water in the zone of saturation moves slowly through the rocks in a direction determined by the slope of the water table. The water table is not a level or stationary surface; variations from place to place and time to time in its shape and altitude occur as a result of such factors as variation in the permeability and structure of the rocks, variations in the rate of withdrawal of water from wells and by springs, and variations in precipitation which affect the rate of recharge.

Water in the rocks of the Prairie du Chien group, the St. Peter sandstone, the Platteville formation and Galena dolomite, and the Niagara dolomite is under water-table conditions in areas where these formations crop out or where they are covered by only a thin mantle of Quaternary deposits. Water in the deposits of Quaternary age also is under water-table conditions.

RECHARGE OF GROUND WATER

The ground-water reservoirs in Fond du Lac County are recharged chiefly by the direct downward percolation of precipitation through the unsaturated zone to the water table. A small amount of recharge water also may be infiltrated from streams and depression ponds. Upon reaching the zone of saturation the water becomes a part of the ground-water reservoir and moves down the slope of the water table or the piezometric surface.

Recharge to the bedrock formations occurs in most of the county but is greatest in areas where these units are near the surface. The sandstones of Cambrian and Ordovician ages that supply water to the Fond du Lac city wells are recharged over an area of about 250 square miles. This recharge area extends westward from the Niagara escarpment to the ground-water divides (pl. 4) in the western and southwestern parts of the county. Water enters the sandstones of Cambrian and Ordovician ages through the overlying consolidated rocks and glacial drift and moves down the slope of the hydraulic gradient principally toward the city of Fond du Lac.

If as much as 10 percent, or about 3 inches, of the annual precipitation (probably a conservative estimate) reaches the water table in the 250-square-mile recharge area, the recharge would be about 36 mgd. In 1956, withdrawals in the vicinity of the city of Fond du Lac were about 3 mgd.

The configuration of the piezometric surface (pl. 4) indicates that the sandstones of Cambrian and Ordovician ages are not being recharged in substantial amount from Lake Winnebago. The clay and marl bottom of the lake restricts water from moving downward and recharging the underlying formations. The surface of Lake Winnebago is approximately 100 feet above the piezometric surface.

The Niagara dolomite is recharged in most of the area east of the Niagara escarpment. Water enters the dolomite where it crops out or through overlying deposits of Pleistocene age. A ground-water divide lies east of the Niagara escarpment (pl. 5).

DISCHARGE OF GROUND WATER

Ground water may be discharged naturally by flow through seeps and springs and by evaporation and transpiration, and artificially by wells.

The springs in Fond du Lac County are gravity springs; that is, water does not issue under artesian pressure but is caused by the water table intersecting the land surface. The water of a gravity spring percolates from permeable material or flows from an opening in a rock formation, under the action of gravity, as a surface stream flows down its channel (Meinzer, 1923b, p. 51). The gravity springs in Fond du Lac County are divided into (a) depression springs, where water flows to the surface from permeable material simply because the surface intersects the water table and (b) contact springs, where water flows to the surface from permeable material overlying less permeable or impermeable material that retards or prevents downward percolation of the groud water and thus deflects it to the surface.

Many small contact springs and seeps occur along the Niagara escarpment in the eastern and southern parts of the county. The water issues from the Niagara dolomite near the contact of the dolomite with the underlying Maquoketa shale. A few depression springs occur along Rock River and Silver Creek and their tributaries in the western part of the county, and along the margins of water-table lakes in the eastern part. The depression springs along Rock River and Silver Creek issue chiefly from the Platteville formation and Galena dolomite; those along the margins of the water-table lakes issue from sand and gravel deposits of Pleistocene age.

Although most springs in the county flow less than 1 gpm, a few discharge as much as 60 gpm. A few springs have been improved and the water is used for domestic or stock supply. The water from most of the springs, however, is lost by transpiration, evaporation, and infiltration into the ground downslope from the springs.

In Fond du Lac County, the discharge of ground water by evaporation and transpiration is greatest in areas where the water table is shallow, such as marshes and undrained depression ponds.

Ground water from wells is used for nearly all domestic, stock, public supply, and industrial supplies in Fond du Lac County. The combined ground-water withdrawals from all wells in the county is estimated to have averaged about 10 mgd in 1957.

MOVEMENT OF GROUND WATER

The movement of ground water is controlled by discharge, recharge, topography, and the structure and permeability of the rocks, and is altered artificially by local pumping and by discharge to or recharge from manmade reservoirs. The direction of movement of ground water in Fond du Lac County is shown by the piezometric maps (pls. 4 and 5). These maps, constructed from water-level measurements made in wells, show, by contour lines, the configuration of the piezometric surface. Water flows down the slope of the hydraulic gradient from points of higher altitude to points of lower altitude, roughly at right angles to the contour lines.

The piezometric map in the area west of the Niagara escarpment (pl. 4) does not represent the piezometric surface of any one geologic unit as it was compiled from water-level measurements made in wells tapping the rocks of Cambrian age, the Prairie du Chien group, the St. Peter sandstone, the Platteville formation and Galena dolomite, or a combination of these units. The rock units, however, are believed to be hydraulically connected and can be considered a single aquifer.

Movement of the ground water is dominantly eastward toward Fond du Lac from two ground-water divides in the western and southwestern parts of the country (pl. 4). One of these divides trends southwestward across the western part of the county. West of this divide movement of ground water is principally westward toward Ripon and Fairwater. A second ground-water divide trends eastward from near Fairwater to Lagoda and thence southward to the Fond du Lac County–Dodge County boundary. In this area movement of ground water is generally southward toward Waupun. The two ground-water divides roughly parallel topographic divides.

A deep cone of depression, caused by pumping large quantities of water for municipal and industrial use, underlies the city of Fond du Lac (pl. 4). In the area affected by the Fond du Lac pumping, the general eastward direction of movement of water is interrupted and water moves toward the center of the cone of depression from all sides.

The map showing the piezometric surface in the area east of the Niagara escarpment (pl. 5) is based chiefly on water-level measurements in shallow wells that penetrate only the upper part of the dolomite. A ground-water divide approximately parallels the Niagara escarpment and is 1 to 5 miles to the east. Its location varies seasonally and with long-term changes in recharge and discharge. East of the ground-water divide, movement of ground water is dominantly eastward. West of the divide, ground water moves towards the Niagara escarpment where it is discharged as spring flow or seepage.

The movement of ground water from one water-bearing bed to another is governed largely by the difference in pressure head of the water in the beds and by the permeability of the intervening material. The movement probably is large in areas where two permeable beds are in direct contact, such as in the western part of Fond du Lac County where the Galena and Platteville unit lie directly upon the St. Peter sandstone and the head in the Galena and Platteville is appreciably higher than in the St. Peter. Movement from one permeable bed to another in places where they are separated by a confining layer of low permeability probably is small, but, nevertheless, the ground water does move through a confining layer, albeit slowly, if there is a difference in pressure head of the water in the two aquifers.

The continuous movement of water between the various rock units in Fond du Lac County does not represent net addition to or depletion of the total ground-water supply. However, the piezometric maps (pls. 4 and 5) show that ground water moves out of the county to the east, south, and west.

WATER LEVELS AND THEIR SIGNIFICANCE

An essential part of a study of the ground-water resources of any area is the collection of data on water levels over as long a period as possible. The purpose of collecting information on water levels is to determine short-term changes and long-range trends in ground-water levels in wells, and to relate this information to changes in storage in the ground-water reservoirs. Detailed records of water levels in a few wells in the Fond du Lac area have been collected since 1948. Records in less detail are available for a longer period.

The water table and the piezometric surfaces of artesian aquifers in Fond du Lac County are not stationary, but rise or decline depending upon the amount of recharge to or discharge from the ground-water reservoirs. When recharge exceeds discharge water levels in wells rise, and when discharge exceeds recharge water levels decline. Because recharge is greater during some seasons of the year than during other seasons, water levels are said to fluctuate. In areas not affected by pumping, water levels generally rise in the spring, owing to thawing of the frost which permits recharge from melting snow and rainfall; gradually decline during the growing season when the natural discharge exceeds the recharge; often rise in the fall after vegetation has been killed by the frost; and decline during the winter when frost in the soil prevents recharge. In areas affected by pumping, the decline in water levels may be accentuated during periods of above-normal temperature when the demand for water is great. Such periods commonly correspond to periods of reduced recharge.

The first deep wells at Fond du Lac were drilled in 1885 into sandstones of Cambrian age and they flowed naturally. Weidman and Schultz (1915, p. 333) reported that the static water levels were 25 to 50 feet above the level of Lake Winnebago prior to 1885. As the demands for water for municipal and industrial use increased during later years, additional deep wells were drilled and natural flow ceased. Prior to 1945, the municipal wells were concentrated within an area of half a square mile in the vicinity of the municipal pumping plant. The wells that have been drilled since 1945 are spaced half a mile or more apart.

The increasing withdrawal of ground water at Fond du Lac, chiefly for municipal use, has created a gradually expanding and deepening cone of depression in the piezometric surface. By 1951, the nonpumping (static) water levels in wells near the center of pumping had declined to as much as 125 feet below land surface; and by 1957, to as much as 175 feet below land surface. The maximum decline in artesian pressure has been about 200 feet since the first deep wells were drilled in 1885. The extent of the cone of depression in the Fond du Lac area in 1956 is shown on plate 4.

The fluctuation of water levels in four typical wells in Fond du Lac County and the precipitation at Fond du Lac are shown in figure 6. The hydrographs of well FL 14 at Waupun, well FL 81 near Ladoga, and well FL 89 near Marytown show seasonal fluctuations in water levels that correspond to seasonal changes in recharge. Water levels in these wells declined through the summer of 1954 and rose rapidly in the early fall when precipitation was above average. In 1955 the levels declined throughout most of the year because the precipitation was below average. In 1956 the hydrographs show the normal spring rise in water levels caused by snowmelt and precipitation. The water level in well FL 29, 2 miles east of Fond du Lac, declined approximately 15 feet during 1953–56 as a result of pumping in the Fond du Lac area.

Hydrographs of eight wells in Fond du Lac are shown in figures 7 through 14. The water level in well FL 8 (city well 10), approximately a half mile northeast of the center of pumping, while fluctuating seasonally, declined only about 5 feet from 1951 to 1955 (fig. 7), but in 1955, the water level rapidly declined about 40 feet to the top of the pump bowls owing to an increase in the rate of pumping. In 1956 and 1957 the rate of pumping was reduced to maintain the pumping level at the top of the pump bowls. The hydrograph of well FL 9 (city well 11) near the center of pumping, shows no net decline in water level in 1951 and 1952 (fig. 8). From 1952 to 1957, however, the water level declined about 60 feet owing to the increased

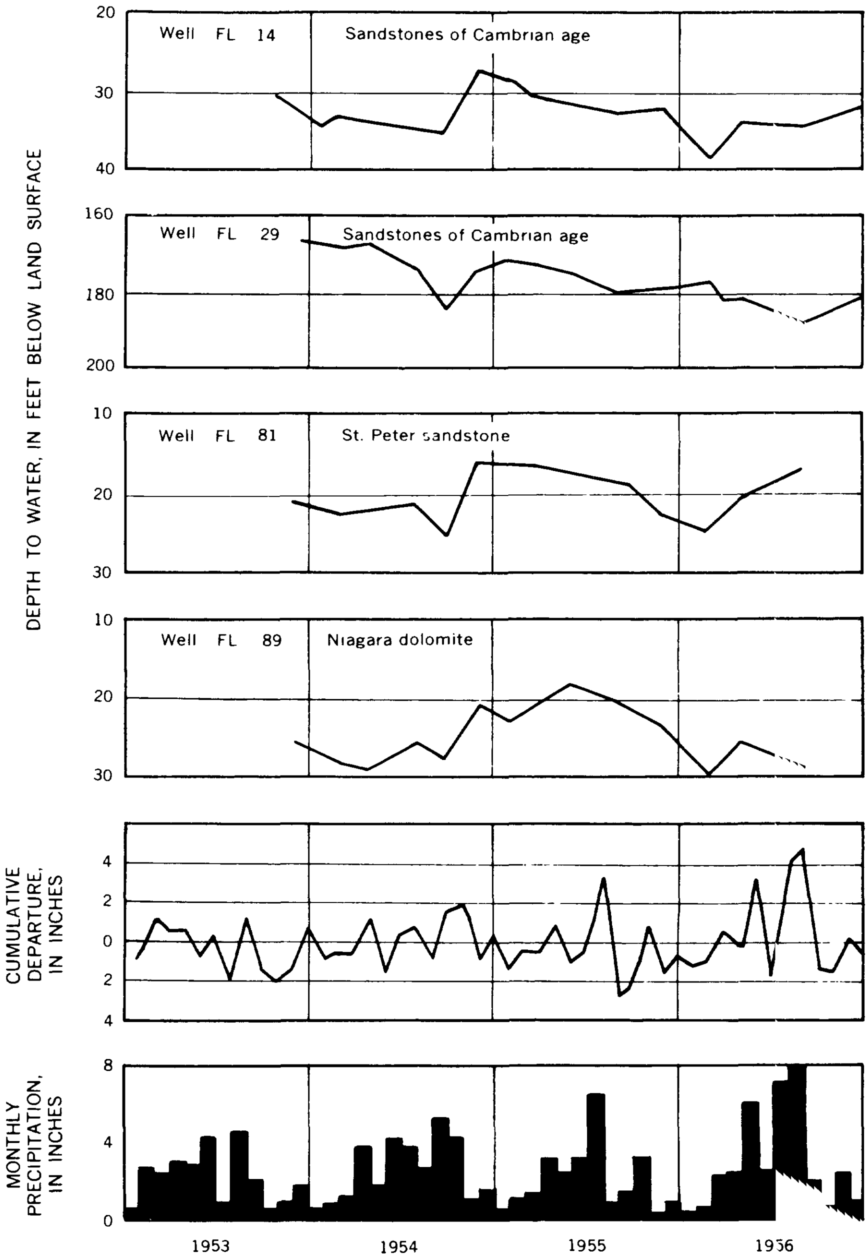


FIGURE 6.—Fluctuations of water levels in four wells in Fond du Lac County, Wis., and monthly precipitation and cumulative departure from average monthly precipitation at Fond du Lac.

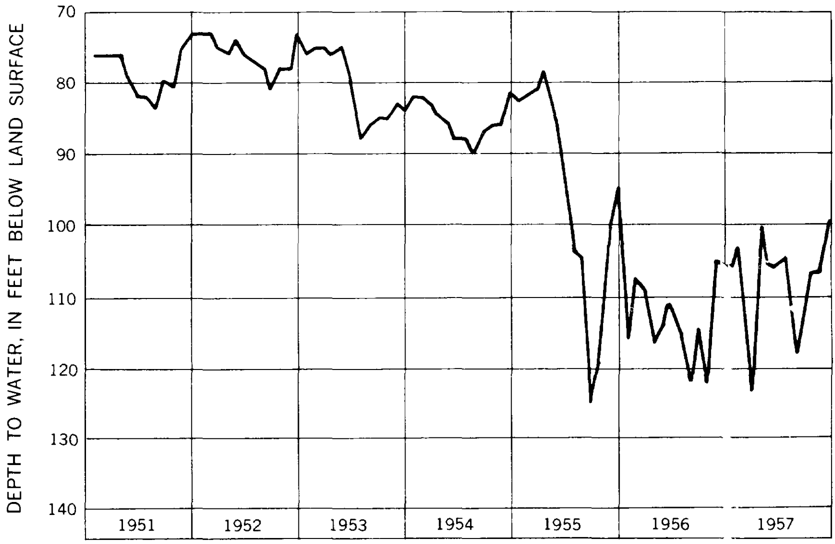


FIGURE 7.—Hydrograph showing fluctuations of water level in well FL 8, Fond du Lac city well 10.

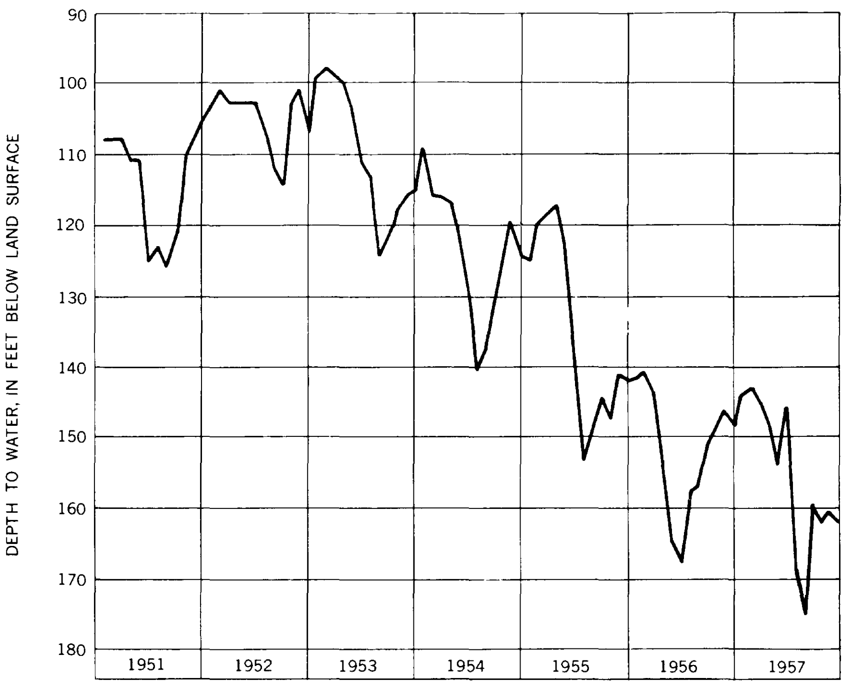


FIGURE 8.—Hydrograph showing fluctuations of water level in well FL 9, Fond du Lac city well 11.

rate of pumping. The water level in well FL 24 (city well 15), also near the center of pumping, declined about 20 feet from 195? to 1957 (fig. 9). The smaller decline in water levels in well FL 24 than in well FL 9 was caused by a gradual reduction in the pumping rate of well FL 24 from 700 gpm in 1953 to 450 gpm in 1957. The hydrograph of well FL 31 (city well 12), also near the center of pumping, shows that the water level declined approximately 40 feet from 1951 to 1956 (fig. 10). Most of the decline in water level occurred in 1955 and was caused by increasing the rate of discharge after the pump had been lowered. The hydrograph of well FL 32 (city well 13), about a mile north of the center of pumping, shows a decline of about 30 feet from 1951 to 1957 (fig. 11). The rate of pumping gradually declined from 700 gpm in 1951 to 550 gpm in 1957. The hydrograph of well FL 59 (city well 14), about a mile east of the center of pumping, shows a decline of approximately 45 feet from 1953 to 1956, but little or no decline in 1956 and 1957 (fig. 12). The change in trend of the water level in 1956 and 1957 was due to a reduction in the rate of pumping. The hydrographs of well FL 20 (fig. 13), about a mile northwest of the center of pumping, and well FL 21 (fig. 14), in North Fond du Lac, show that the water levels rose from 1950 to 1953. Precipitation was above average and the temperature was below average during the summer months, which

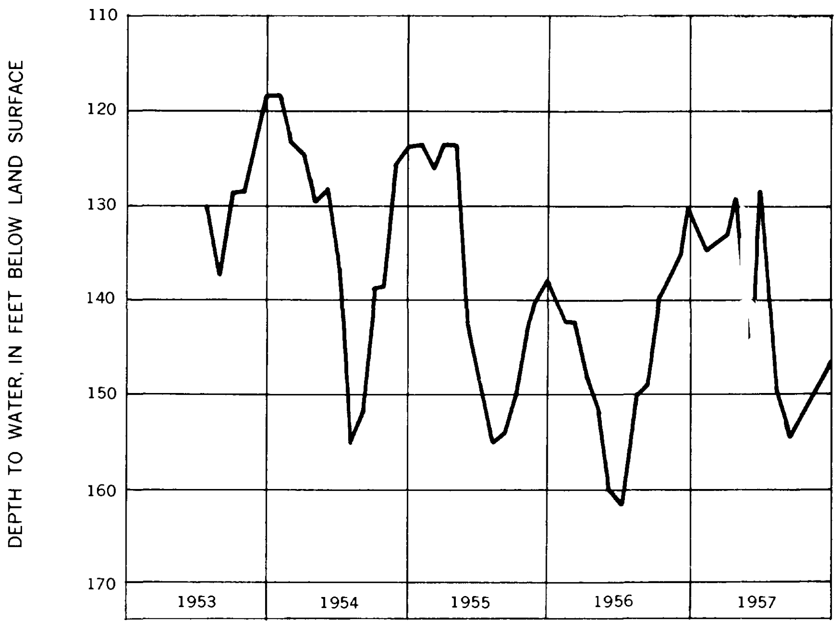


FIGURE 9.—Hydrograph showing fluctuations of water level in well FL 24, Fond du Lac city well 15.

resulted in a decrease in pumping of water for cooling purposes and for sprinkling. From 1953 to 1956, water levels gradually declined in response to an increase in pumping. Water levels rose in the latter part of 1956 and fluctuated only slightly in 1957, owing to a slight reduction in pumping.

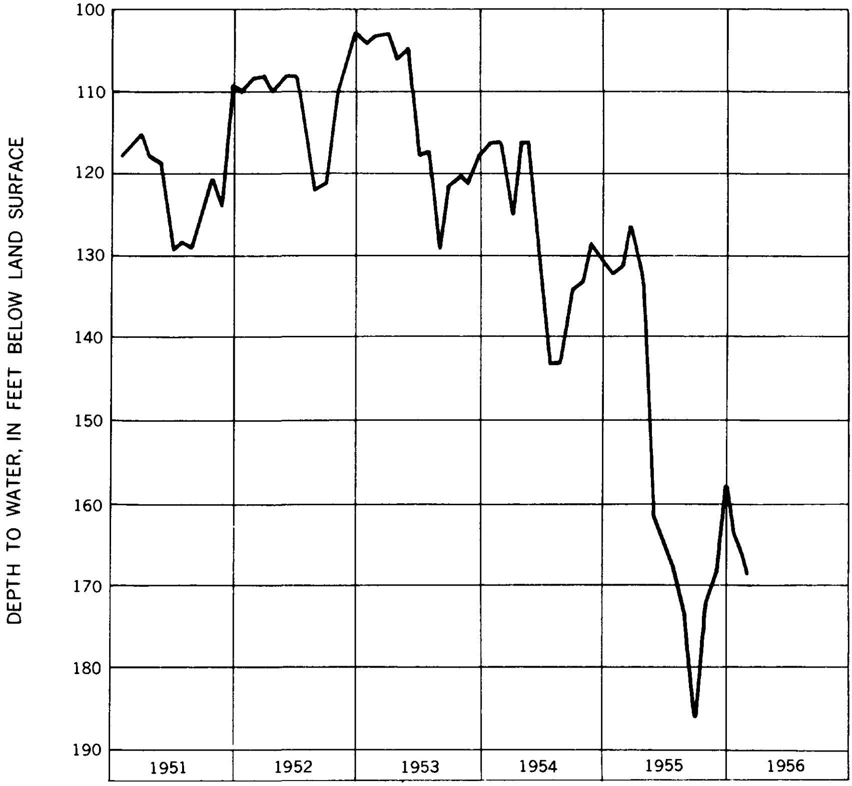


FIGURE 10.—Hydrograph showing fluctuations of water level in well FL 31, Fond du Lac city well 12.

The hydrograph of well FL 19 (fig. 15), 13 miles northeast of Fond du Lac, shows a steady 13-foot decline in water level from 1948 through 1957.

AQUIFER TESTS

Aquifer tests of the sandstones of Cambrian and Ordovician ages were made in May 1954 at Fond du Lac and in May 1955 at Ripon. Aquifer tests of the Niagara dolomite were made in 1956 in an area east of Fond du Lac. The purpose of the tests was to determine the hydraulic characteristics—the coefficients of transmissibility and storage—of the aquifers. The coefficients in turn are used in predicting the rate and the amount of lowering of water levels to be expected at various rates of pumping.

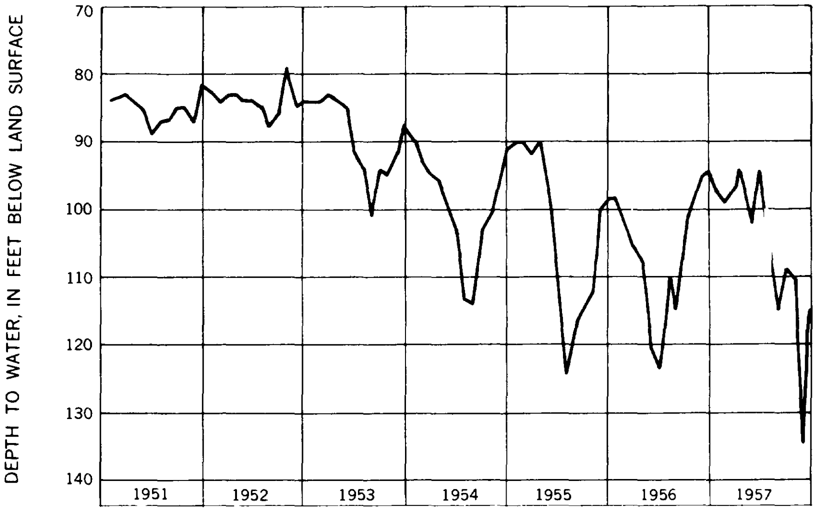


FIGURE 11.—Hydrograph showing fluctuations of water level in well FL 32, Fond du Lac city well 13.

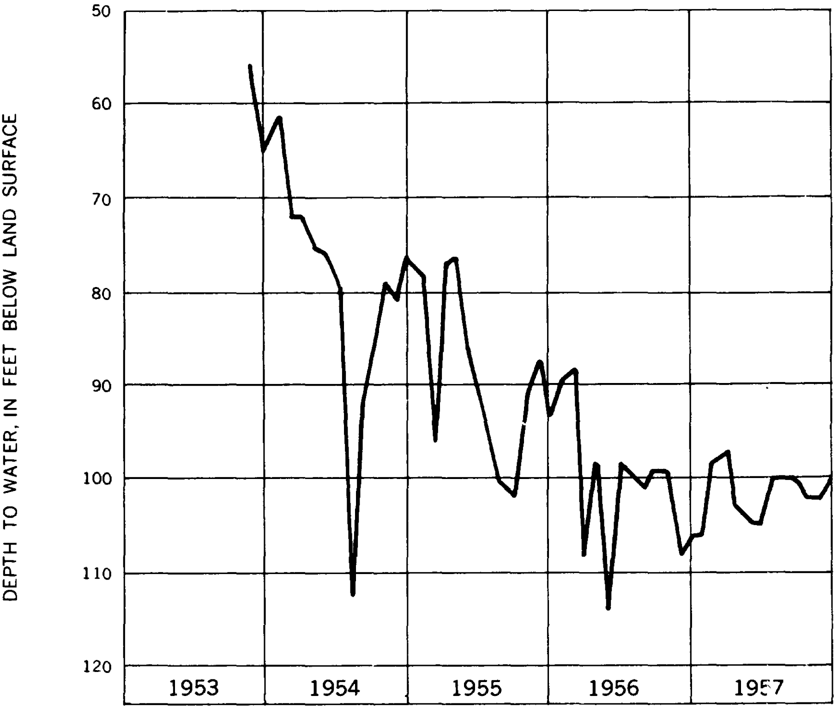


FIGURE 12.—Hydrograph showing fluctuations of water level in well FL 59, Fond du Lac city well 14.

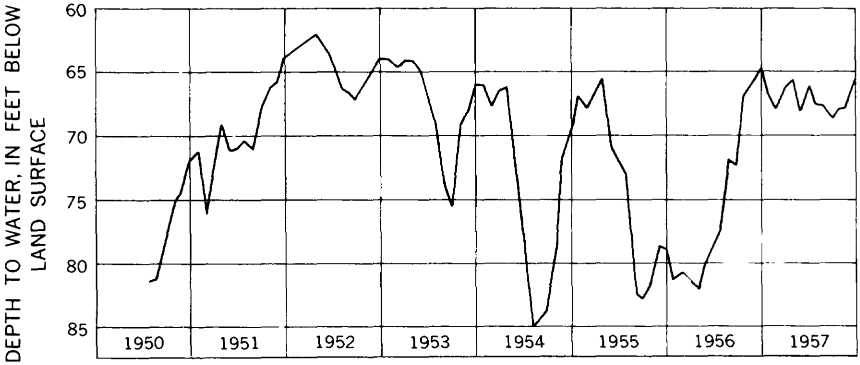


FIGURE 13.—Hydrograph showing fluctuations of water level in well FL 20 in northwestern Fond du Lac.

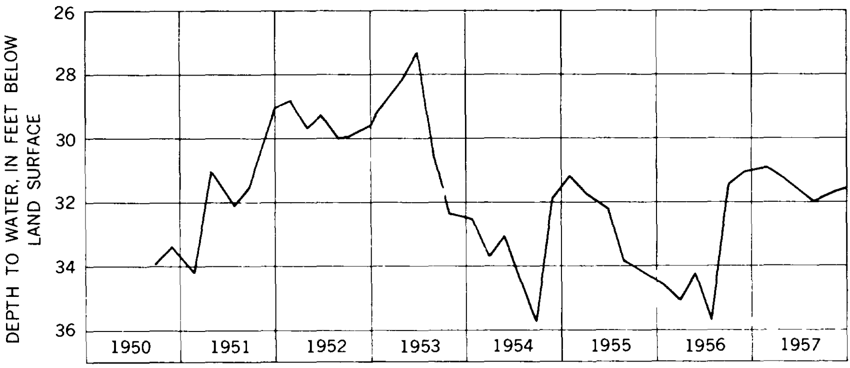


FIGURE 14.—Hydrograph showing fluctuations of water level in well FL 21 in North Fond du Lac.

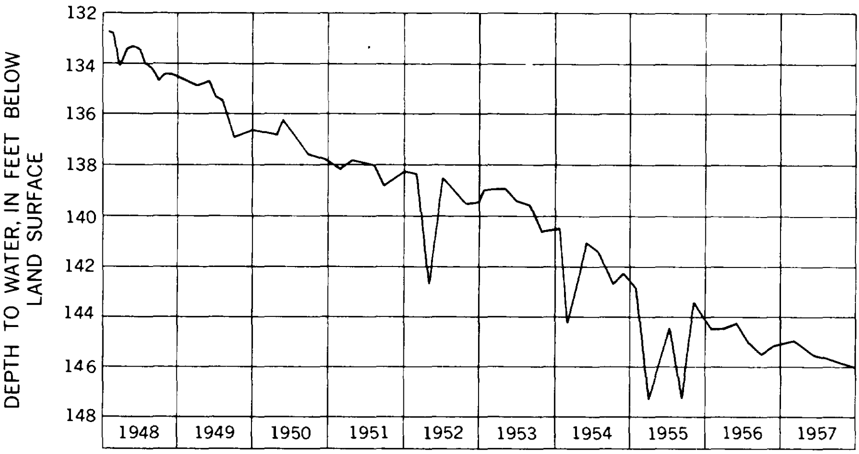


FIGURE 15.—Hydrograph showing fluctuations of water level in well FL 19, 13 miles northeast of Fond du Lac.

The coefficient of transmissibility is expressed as the rate of flow of water, at the prevailing water temperature, in gallons per day, through a vertical strip of the aquifer 1 foot wide and extending the full saturated height of the aquifer, under a hydraulic gradient of 100 percent (1 foot per foot). The coefficient of storage of an aquifer is defined as the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface.

Each test consisted of starting or stopping the pump in a well and measuring the amount and rate of change in water level in the pumped well and in each of several observation wells. The discharge from the pumped well was measured by recording meters in the discharge line or by the change in volume of water in storage reservoirs. Measurements of depth to water were made with a steel tape or by an air line and pressure gage except in wells **FL 10** and **FL 12**, which were equipped with recording gages.

SANDSTONES OF CAMBRIAN AND ORDOVICIAN AGES AT FOND DU LAC

ANALYSES OF DATA

The aquifer tests were analyzed by the nonequilibrium formula, first developed by Theis (1935). The nonequilibrium formula is

$$s=\frac{114.6Q}{T}W(u)$$

where $W(u)=\int_u^\infty \frac{e^{-u}du}{u}=-0.5772-\log_e u+u-\frac{u^2}{2\cdot 2!}+\frac{u^3}{3\cdot 3!}-\frac{u^4}{4\cdot 4!}\cdot$

and $u=\frac{1.87r^2S}{Tt}$;

- s=drawdown, in feet, at any point of observation in the vicinity of a well discharging at a constant rate;
- Q=discharge, in gallons per minute;
- T=coefficient of transmissibility, gallons per day per foot;
- r=distance, in feet, from discharging well to the point of observation;
- S=coefficient of storage, expressed as a decimal fraction;
- t=time in days since pumping started.

The nonequilibrium formula assumes that the aquifer is infinite in areal extent, that it is homogenous and isotropic (transmits water in all directions with equal facility), that its coefficients of transmissibility and storage are constant, that it is confined between impermeable beds, that the discharging well penetrates the entire thickness of the aquifer, and that the discharged water is released from storage instantaneously with decline in head. None of these conditions is fully met in nature, and considerable judgment is necessary to decide the extent to which it can be assumed that they apply in any particular area.

A summary of the values of the coefficients of transmissibility and storage determined from the aquifer tests at Fond du Lac is given in table 2. The coefficients of transmissibility and storage averaged 25,000 gpd per foot and 0.0002, respectively. The locations of the wells used for the aquifer tests are shown in figure 16.

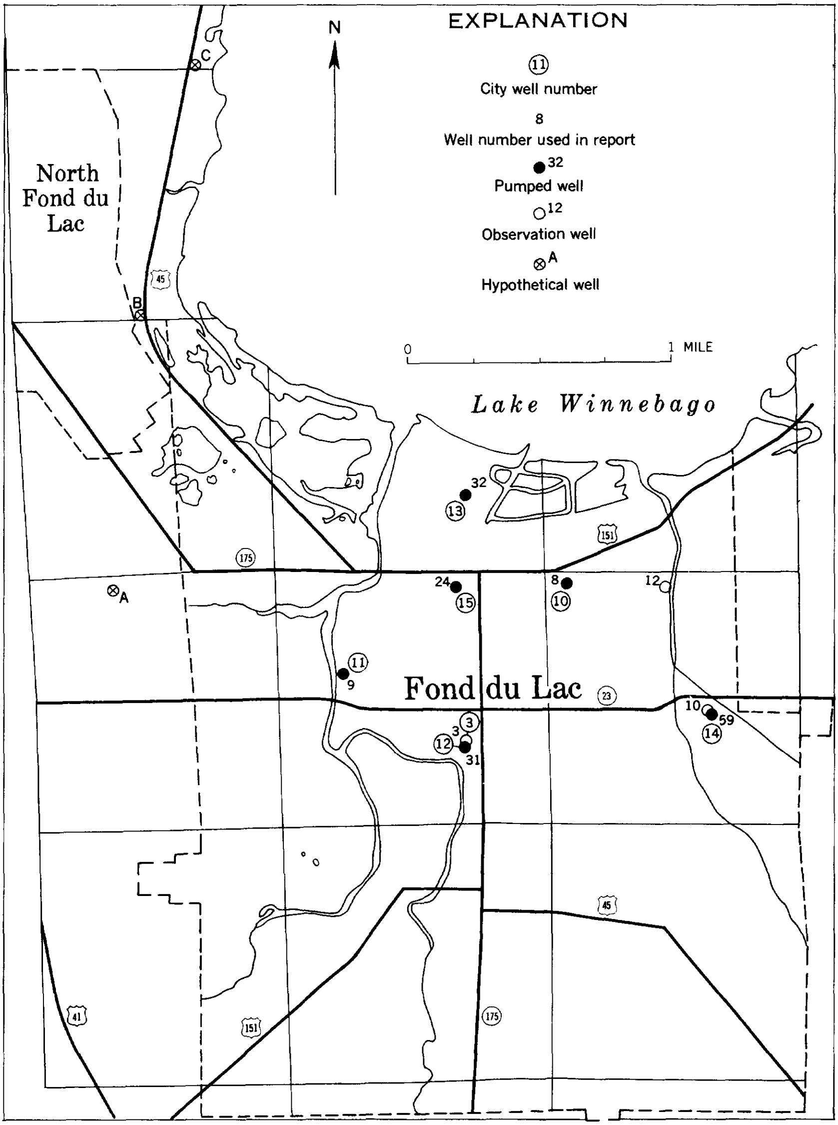


FIGURE 16.—Map of the Fond du Lac area showing location of wells for aquifer tests.

TABLE 2.—*Summary of coefficients of transmissibility and storage of sandstones of Cambrian and Ordovician ages computed from aquifer tests at Fond du Lac*

Well	Coefficient of transmissibility		Coefficient of storage	
	Number of tests	Average	Number of tests	Average
FL 3	2	24, 400	2	0 0001
FL 8	5	27, 200		
FL 9	2	36, 800		
FL 10	1	6, 600	1	. 0002
FL 12	2	26, 000	2	. 0001
FL 24	8	31, 800	4	. 0002
FL 31	4	54, 600	2	. 00035
FL 32	4	16, 800	1	. 0001
FL 59	2	5, 400		
Average		25, 000		0 0002

APPLICATION OF COEFFICIENTS TO PAST RECORDS

It is desirable to verify the values of the coefficients of transmissibility and storage computed from short-term aquifer tests by applying the coefficients to an analysis of available long-term records of pumpage and water levels.

The decline in water level in well FL 31 from 1885, when large ground-water withdrawals began in the area, to the end of 1956 was computed by applying the nonequilibrium formula to the pumpage data shown in figure 17. For example: The average rate of pumping for 1885 to 1914 was 0.75 mgd. This rate was used to calculate the first increment of decline from 1885 through 1956, a period of 72 years. A rate of 0.9 mgd (the increase in the average rate from 0.75 to 1.65 mgd) was used to compute the second increment of decline from 1914 to 1956. Six increments of pumping were used to compute the total decline. The sum of the computed increments of decline, less the effect of recharge, should be equal to the actual decline in water levels since 1885.

The effective recharge area is the area in which water enters the rocks of Cambrian and Ordovician ages from the surface or from overlying rocks and from which the water moves eastward in the direction of the hydraulic gradient toward the Fond du Lac area. The ground-water divides (pl. 4) delineate the western extent of the recharge area. They are approximately parallel to the contours on the piezometric surface west of the area of withdrawal. In the western part of the recharge area, little or no fluctuation of water levels takes place except that typical of water-table wells.

The effects of recharge were computed using the method of images (Ferris, 1948). That is, the effect of recharge on the drawdown

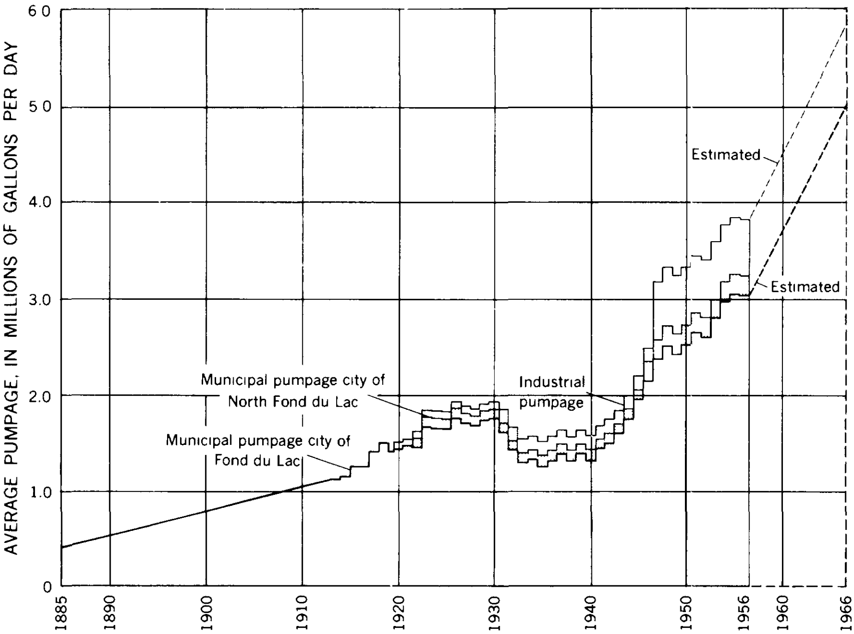


FIGURE 17.—Pumpage from deep wells in the Fond du Lac area, 1885–1956. Municipal pumpage for Fond du Lac was metered from July 1912 through December 1956; all other pumpage was estimated.

produced by a pumping well is the same as though the aquifer were infinite and a like recharging well or source were located on a line perpendicular to and an equal distance on the opposite side of the recharge boundary. The same increments of pumping applied to compute the declines were used in determining the effects of recharge. The hypothetical net computed decline in water level in well FL 31 for 1885 through 1925 was 64 feet and for 1885 through 1956 was 91 feet. The altitude of the water level at the site of well FL 31 was 762 feet in 1885; it was 695 feet in October 1925 and 630 feet in December 1956. Thus, the actual decline in water level in well FL 31 was 67 feet from 1885 to 1925 and 132 feet from 1885 to 1956. The actual decline in water level at well FL 31 was larger than the computed decline by about 5 percent from 1885 to 1925 and about 50 percent from 1885 to 1956.

The difference in the actual and computed declines for the two periods of withdrawals are reasonable, considering the deficiencies in hydrologic and geologic data. It is believed that the average coefficients determined for the Fond du Lac area are approximately correct and may be applied with reasonable accuracy to estimate short-period changes in water levels that will result from any given condition of pumping.

The thinning of the sandstone over the structural high in the crystalline rocks in the southern part of the Fond du Lac area (pl. 3, section B–B′) would result in a decrease in the transmissibility of the sandstone in that area. Although this decrease in transmissibility was not considered in computing the decline in water level, it may account for part of the difference in the computed and actual decline.

The aquifer tests indicated a lower transmissibility of the sandstones in the vicinity of wells FL 10 and FL 59 (table 2). Sample logs of these wells indicate that the sandstones are finer grained than the sandstones to the west. During the deposition of the sandstones, the crystalline-rock "highs" may have created barriers to the movement of water and resulted in the deposition of finer grained sand and silt locally. In the area north and east of these barriers test drilling is needed to determine the extent of the local change in character of the sandstone.

APPLICATION OF COEFFICIENTS TO FUTURE CONDITIONS

The lowering in water levels that will occur at distances of 100 to 20,000 feet from a well pumped continuously at 1 mgd for 1 month, 6 months, 1 year, 5 years, 10 years, and 20 years are shown in figure 18. The graph is based on the average coefficients of transmissibility and storage determined for the Fond du Lac area and on the assumption that the aquifer is infinite and all the pumped water is withdrawn from storage (no recharge). Estimates of the decline in water level at any well can be made by adding together the drawdown effects

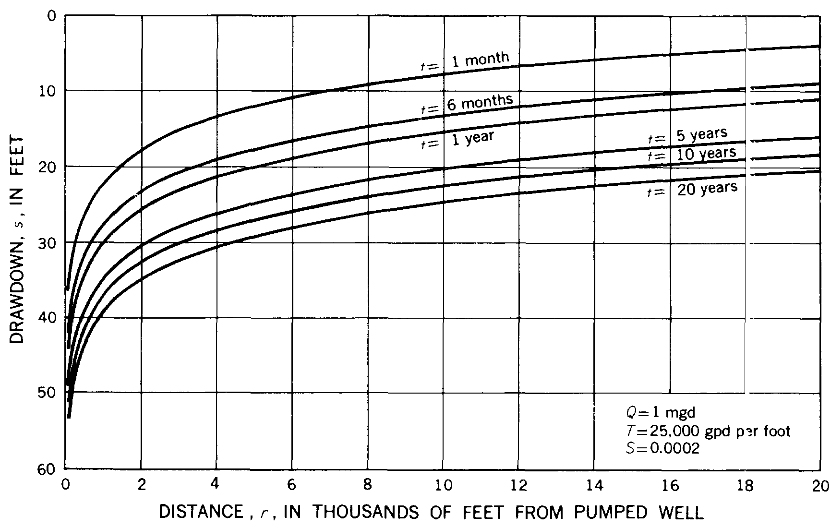


FIGURE 18.—Theoretical drawdown in an infinite aquifer, based on coefficients of transmissibility and storage determined for sandstones of Cambrian and Ordovician ages at Fond du Lac, Wis.

caused by surrounding pumped wells. These estimates will be larger than the probable actual decline in water level, as the effects of recharge were not considered in preparing figure 18.

In order to estimate future declines in water levels in the Fond du Lac area, it is necessary to estimate future ground-water withdrawals. It is estimated the municipal pumpage by Fond du Lac will increase at a nearly uniform rate from the 3 mgd pumped in 1956 to about 5 mgd in 1966, and that the distribution and amount of the withdrawals for other uses will remain about the same as in 1956 (fig. 17).

If the distribution and amount of pumpage in the area in 1957–66 should remain the same as in 1956, the water level in well FL 31 could be expected to decline about 5 feet more by 1966. If, however, the distribution of pumped wells remains the same but the pumping by Fond du Lac increases at a uniform rate to 5 mgd in 1966, the decline in water level in well FL 31 should be about 60 feet below the level of 1956. Static levels in other wells in the area would decline a like or lesser amount, according to the nearness of the wells to the center of the cone of depression. Pumping levels should decline by approximately the same amount as the static levels if the present rates of pumping from individual wells are maintained.

In order to show the advantage of adequate spacing of wells, it is assumed that the present rate of pumping from existing wells will continue and that the increased withdrawals will be supplied by hypothetical wells at points A, B, and C as shown on figure 16. These hypothetical wells were arbitrarily located for purposes of illustration only; if wells were to be drilled near these sites geologic, economic, and other factors should be considered. Assuming that hypothetical wells A, B, and C were pumped at 460 gpm each, the combined rate of pumping would be about 2 mgd. If the wells were put into use at 2½-year intervals, adding well A in July 1959, well B in January 1961, and well C in July 1963, the water level in well FL 31 by 1966 would be about 30 feet below the 1956 level, instead of the 60 feet that would occur if the additional water had been pumped from the existing wells. The static levels in wells A, B, and C would have declined about 65 feet by 1966. By that year the pumping of the three hypothetical wells would have caused a decline of about 35 feet below the level of 1956 in the North Fond du Lac municipal wells.

NIAGARA DOLOMITE

In 1956 the city of Fond du Lac drilled three test holes to determine if sufficient water were available from the Niagara dolomite for a supplemental water supply. Test holes FL 300, FL 302, and FL 303 were drilled approximately 3 miles east of the Niagara escarpment (fig. 19) and 5½ miles east of Fond du Lac.

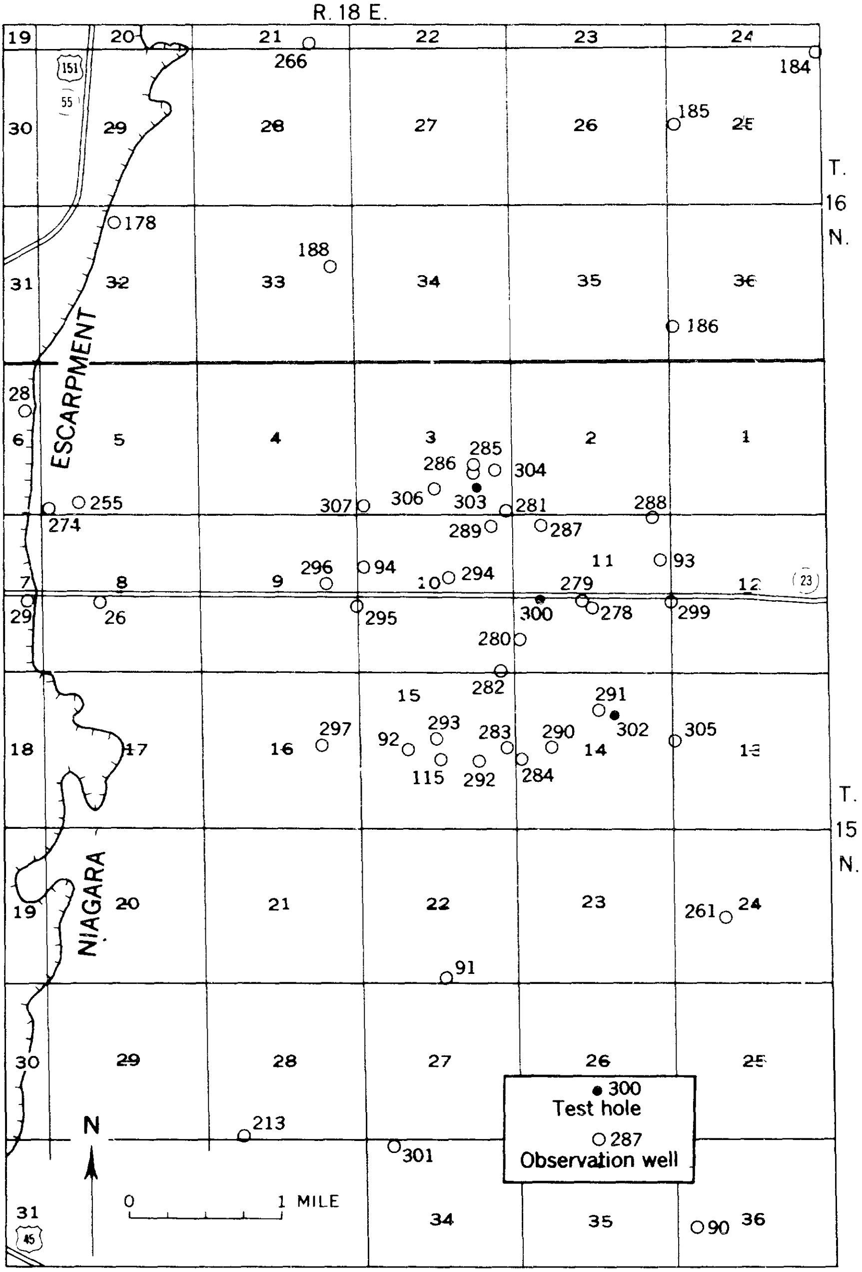


FIGURE 19.—Map of Niagara dolomite test area showing location of wells and test holes for aquifer tests.

Test hole FL 300 was pumped on April 24–26, 1956, for 2 hours at 50 gpm, 2 hours at 100 gpm, 2 hours at 150 gpm, and about 39 hours at 200 gpm. The water level declined 47.5 feet during the period of pumping. The water level in well FL 299, 4,600 feet east of well FL 300, declined 4.5 feet; the water level in well FL 280, 1,600 feet southwest, declined 1.5 feet; and the water level in well FL 283, 5,200 feet southwest, declined 0.1 foot. Measurable declines did not occur in wells FL 281 (3,000 feet northwest of well FL 300), FL 290 (5,000 feet south), FL 292 (5,800 feet southwest), and FL 293 (6,000 feet southwest). The well in which the largest decline was measured is east of the test hole, which direction corresponds to the local orientation of major joints in the Niagara dolomite.

Test hole FL 302, 4,600 feet southeast of test hole FL 300, was completed in May 1956 at a depth of 210 feet. At this depth an opening was found and water began to flow at a rate of 150 gpm. The test hole was pumped for successive 2-hour intervals at rates of 200, 275, and 350 gpm. The pumping rate was then increased to 400 gpm and the test continued for 24 hours more. By the end of the period of pumping the water level had declined to 39 feet below land surface, about 65 feet below the estimated static water level. The water level in well FL 283, 3,800 feet west of test hole FL 302, declined 42 feet; the water level in well FL 284, 3,500 feet west, declined 31 feet; and the water level in well FL 293, 6,100 feet west, declined 8 feet. After pumping stopped, the water level in test hole FL 302 recovered to 19 feet above the land surface, and water began to flow from cracks in the ground at a distance of several feet from the well. To prevent possible caving around the well, the valve was opened to allow the water to flow.

Test hole FL 303, 4,300 feet northwest of test hole FL 300, was drilled in July 1956. The water level in this test hole declined 32 feet during 24 hours of pumping at 100 gpm. The water level declined about 1 foot in test hole FL 300, 4,300 feet southeast of test hole FL 303, and in well FL 304, 950 feet northeast of FL 303.

Ground water of economic importance in the Niagara dolomite is confined to solutionally enlarged openings along fractures and bedding planes. Wells that fail to intersect such openings yield only small amounts of water.

The pumping of test holes FL 300 and FL 302 showed the controlling effect that the local east-west orientation of joints has on the movement of ground water. Water levels in wells east and west of the test holes were affected more than were the water levels in wells to the north and south.

The results of the pumping tests on the test holes in the Niagara dolomite indicate that wells producing at least 200 gpm could be developed in the area east of the Niagara escarpment. Because of the variability of the joints and fractures in the dolomite, test holes should be drilled through the full thickness of the Niagara prior to any large-scale development.

The Niagara dolomite in the test area is recharged by local precipitation. Recharge takes place most readily where the dolomite is near the land surface.

The extent of marshes in the area in 1910 is shown in figure 20. Subsequently the area was drained by ditches, and the extent of the marshes in 1955 is shown in figure 21. The draining is reported to have lowered the water table 5 to 15 feet and has decreased the potential amount of water available to recharge the dolomite.

Additional work is needed to determine the recharge to and discharge from the Niagara dolomite.

SPECIFIC CAPACITY OF WELLS

The relation between the discharge and the resultant drawdown in water level in a pumped well is known as the specific capacity and is generally expressed in gallons per minute per foot of drawdown. For example, if a well is pumped at a rate of 1,000 gpm and the water level is thereby lowered 200 feet, the specific capacity of the well is 5 gpm per foot of drawdown. In a like manner, if the specific capacity of a well is 5 gpm per foot of drawdown, there is an implication that, within certain limits, the discharge of the well will be increased 5 gpm for every foot of increased drawdown.

The specific capacity of a well depends both on the coefficients of transmissibility and storage and on the construction and development of the well. Specific capacities computed for the wells pumped during the aquifer tests at Fond du Lac and Ripon and in the Niagara dolomite and reported by well owners or well drillers for wells in other areas of the county are presented in table 3.

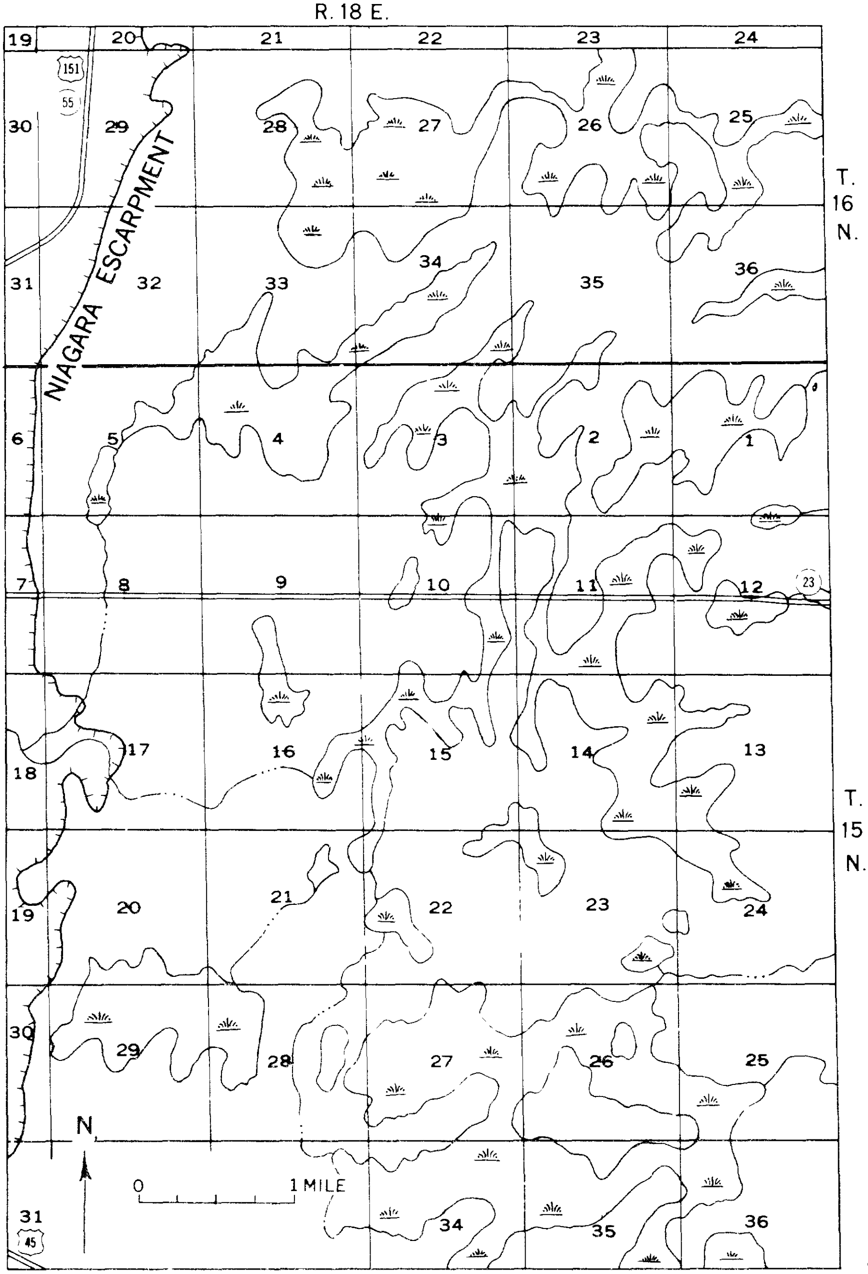


FIGURE 20.—Map of Niagara dolomite test area showing extent of marshes in 1910.

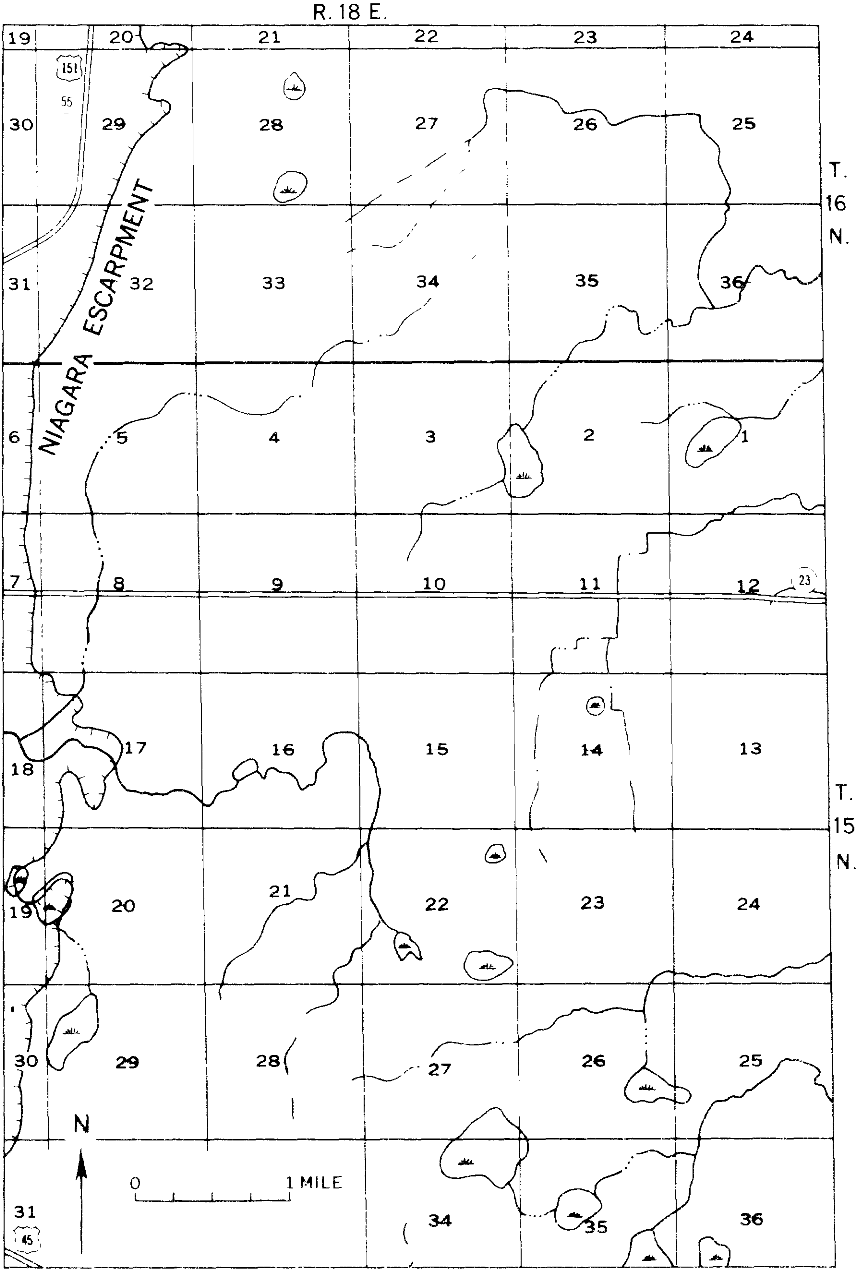


FIGURE 21 — Map of Niagara dolomite test area showing extent of marshes in 1955.

TABLE 3.—*Specific capacity of wells in Fond du Lac County, Wis.*

[Geologic source of water: Cu, sandstones of Cambrian age; Ogp, Galena dolomite and Platteville formation; Osp, St. Peter sandstone; Sn, Niagara dolomite]

Well	Geologic source of water	Drawdown (feet)	Discharge (gpm)	Specific capacity (gpm per foot)
1	Osp, Cu	13	363	28
2	Osp, Cu	72	279	4
3	Osp, Cu	34	945	28
4	Osp, Cu	18	363	20
5	Osp, Cu	68	774	11
*6	Osp, Cu	72	300	4
7	Osp, Cu	31	594	19
*8	Osp, Cu	92	472	5
*9	Osp, Cu	62	922	15
22	Cu	41	267	7
*24	Osp, Cu	73	516	7
28	Osp, Cu	83	100	1
30	Osp	124	411	3
*31	Osp, Cu	44	508	12
32	Osp, Cu	92	625	7
34	Osp	39	165	4
40	Cu	41	90	2
41	Ogp	31	40	1
42	Osp	16	100	6
43	Cu	89	500	6
*48	Osp	62	550	9
49	Osp	35	300	9
*50	Cu	64	340	5
*51	Osp, Cu	102	635	6
54	Cu	16	430	27
55	Osp, Cu	122	1, 280	10
56	Cu	91	235	3
58	Cu	20	473	24
*59	Osp, Cu	143	385	3
*117	Osp	74	340	5
135	Osp	31	200	6
*300	Sn	48	200	4
*302	Sn	65	400	6
*303	Sn	32	100	3
308	Osp	5	60	12
309	Osp	90	300	3
310	Osp	191	325	2

*Data from aquifer test.

UTILIZATION OF WATER

Of the wells and springs inventoried, 169 supplied water for domestic and stock use, 78 for public use, and 34 for industrial use. The inventory included most of the industrial and public-supply wells, selected domestic and stock wells, and a few of the springs. The combined average daily pumpage from all wells in Fond du Lac County in 1957 is estimated at 10 million gallons.

DOMESTIC AND STOCK SUPPLIES

Most of the domestic and stock wells listed are 6 inches or less in diameter, and they range in depth from 6 to 702 feet. The domestic wells are generally equipped with jet, cylinder, or submersible pumps operated by electric motors and connected to pressure systems. The stock wells are generally equipped with cylinder pumps operated by hand, wind, or electric motors. The yields of individual wells are small, generally less than 10 gpm.

PUBLIC SUPPLIES

The cities of Brandon, Campbellsport, Fond du Lac, North Fond du Lac, Oakfield, Ripon, and Waupun have municipal water supplies obtained from wells. The municipal pumpage in 1957 ranged from about 16 million gallons at Oakfield to 1,163 million gallons at Fond du Lac (table 4).

TABLE 4.—*Municipal pumpage of ground water in Fond du Lac County, Wis., 1957*

[Data from Wisconsin State Board of Health, Section on Sanitary Engineering]

City	Number of wells	Pumpage, in thousands of gallons					
		Minimum daily amount	Date	Maximum daily amount	Date	Average daily	Total
Brandon	1	32	1- 6	170	8- 5	47	17,000
Campbellsport	2	30	10-22	210	8- 3	134	49,000
Fond du Lac	6	2,353	4-21	4,430	8-22	3,186	1,163,000
North Fond du Lac	2	76	1-31	177	6-31	130	47,000
Oakfield	1	7	10-25	297	7-30	43	16,000
Ripon	3	349	12- 1	1,256	9-15	714	260,000
Waupun	2	262	9-22	883	7-24	426	155,000
Total	17					4,680	1,707,000

The water supply for Brandon (population 728) is obtained from well FL 22, which is 883 feet in depth and taps water in sandstone of Cambrian age. The well was reportedly pumped at 267 gpm with a drawdown in water level of 41 feet in 1956. In 1957, the daily pumpage ranged from 32 to 170 thousand gallons and averaged 47 thousand gallons.

The water for Campbellsport (population 1,254) is supplied by wells FL 125 and FL 310. Well FL 125, tapping sandstone of Cambrian age, is 1,300 feet in depth. Well FL 310, tapping the St. Peter sandstone, is 875 feet in depth, and in 1957 it was reportedly pumped at 325 gpm with a drawdown in water level of 191 feet. In 1957 the combined daily pumpage from both wells ranged from 30 to 210 thousand gallons and averaged 134 thousand gallons.

The water supply for Fond du Lac (population 29,936) comes from 6 wells (wells FL 8, 9, 24, 31, 32, and 59) that penetrate the full thickness of the standstones of Cambrian age and range in depth from 760 to 885 feet. The wells are reportedly pumped at rates ranging from about 350 to 950 gpm; their yield-drawdown characteristics are given in table 3. In 1957 the total pumpage ranged from about 2.4 to 4.4 mgd and averaged 3.2 mgd.

The water for North Fond du Lac (population 2,291) is supplied by wells FL 43 and FL 309. Well FL 43, tapping sandstone of Cambrian age, is 655 feet in depth and is reportedly pumped at 500 gpm. Well FL 309, 367 feet deep, obtains water from the St. Peter sandstone and in 1956 was reportedly pumped at 300 gpm with a drawdown in water level of 89.5 feet. In 1957 the daily pumpage ranged from 76 to 177 thousand gallons and averaged 130 thousand gallons.

The water supply for Oakfield (population 697) comes from well FL 47, which is 439 feet deep and obtains water from the St. Peter sandstone. The daily pumpage in 1957 ranged from 7 to 297 thousand gallons and averaged 43 thousand gallons.

Ripon (population 5,619) is supplied water by wells FL 15, FL 48, and FL 51. The wells range in depth from 185 to 490 feet and obtain water from sandstones of Cambrian and Ordovician ages. During an aquifer test in 1955, well FL 48 was pumped at 550 gpm and had a drawdown in water level of 62 feet, and well FL 51 was pumped at 635 gpm and had a drawdown of 102 feet. In 1957 the daily pumpage ranged from 349 to 1,256 thousand gallons and averaged 714 thousand gallons.

Waupun (population 1,998) is supplied by wells FL 14 and FL 23, 965 and 755 feet deep, which obtain water from the sandstones of Cambrian age. Well FL 14 was reported to yield 680 gpm. The daily pumpage in 1957 ranged from 262 to 883 thousand gallons and averaged 426 thousand gallons.

There are 39 schools in the rural areas of Fond du Lac County, all of which obtain their water supply from wells. Two of the wells draw from deposits of Pleistocene age, 8 from the Niagara dolomite, 23 from the Galena dolomite and Platteville formation, and 6 from the St. Peter sandstone. The yields of individual wells are small, as only small amounts of water are required.

INDUSTRIAL SUPPLIES

The water used for industrial purposes in Fond du Lac County is ground water from public water supplies or from privately owned industrial wells. The largest industrial use of water is in the processing of dairy products and the processing and canning of food. There are 8 large and 18 small milk-processing plants and 6 canning plants in the county. It is estimated that the industrial use of ground water in Fond du Lac County in 1957 averaged about 3 mgd.

CHEMICAL CHARACTER OF WATER

Chemical analyses were made of samples of ground water from 52 selected wells and test holes and 2 springs in Fond du Lac County. The location of the wells, test holes and springs sampled is shown on plate 1. The analyses show the dissolved mineral content of the water but not the bacterial or sanitary quality.

As rain falls through the atmosphere it dissolves small amounts of gases and mineral matter. Upon reaching the ground it begins to dissolve minerals from the soil and rocks through which it moves. The amount and kind of dissolved mineral matter contained in ground water differ greatly from place to place as a result of many factors; such as, the type of organic material in the soil, the kind and amount of soluble mineral matter present in the rocks through and over which the water moves, the length of time the water is in contact with soil or rocks, and the temperature and pressure of the water. Some rocks contain readily soluble salts, and water in contact with them will become highly mineralized. Other rocks consist of relatively insoluble minerals, and water in contact with them tend to dissolve only small amounts of mineral matter. Calcium, present in nearly all ground water, is dissolved from limestone, gypsum, dolomite, and other rocks containing calcium. Other constituents commonly found in ground water include sodium, potassium, magnesium, iron, manganese, bicarbonate, sulfate, chloride, fluoride, nitrate, and silica.

The chemical character of water may restrict its use for municipal, industrial, and domestic supply, or for irrigation. The standards of water quality for a particular purpose are not easily defined; however, the chemical character of water for municipal supplies is commonly judged by standards promulgated by the U.S. Public Health Service (1946) for water used by common carriers in interstate commerce. According to these standards, iron and manganese together should not exceed 0.3 ppm (part per million); magnesium, 125 ppm; chloride, 250 ppm; and sulfate, 250 ppm. Dissolved solids preferably should not exceed 500 ppm; although if water of such quality is not available, a dissolved solids content of as much as 1,000 ppm may be permitted. The average individual, however, can become adjusted to drinking water considerable higher in content of most of the constituents listed than the values specified in these standards.

Hardness is of primary importance and is generally recognized in water by its soap consuming properties or by deposits of insoluble salts formed when the water is heated or evaporated. Calcium and magnesium cause most of the hardness of natural waters. Other constituents also cause hardness, but they are generally present in such small quantities in most natural waters as to have little effect on hardness. Specific limits cannot be set for hardness, but water having a hardness of less than 60 ppm is generally considered soft. Water having a hardness of 61 to 120 ppm is rated as moderately hard, but is usable for most purposes. Water whose hardness is 121 to 200 ppm is considered hard and softening is necessary for industries using soap. Water having a hardness of more than 200 ppm is considered very hard and generally requires softening before being satisfactory for most uses.

The hardness of the 54 samples of water collected in Fond du Lac County ranged from 55 to 598 ppm and averaged about 330 ppm. The water from most of the wells sampled is very hard; only 5 samples had a hardness of less than 200 ppm.

Iron is derived from practically all rocks and soils and is a common constituent in most natural waters. When iron or manganese is present in water in excess of 0.3 ppm, it will stain fabrics, utensils, and fixtures. If sufficient iron or manganese is present to give a disagreeable taste to water and to cause staining it can be removed by aeration and filtration. The iron content of the 54 samples of water ranged from 0 to 4.4 ppm and averaged about 1 ppm. Ten of the samples contained no iron, 7 contained 0.1 ppm of iron, 2 contained 0.2 ppm, 6 contained 0.3 ppm, 10 contained 0.4 to 1.0 ppm, and 19 contained more than 1.0 ppm.

Fluoride in drinking water in excess of 1.5 ppm may cause mottled enamel on children's teeth if the water is used during the period of calcification of the teeth—that is, roughly during the first 6 to 8 years of life (Dean and others, 1942). The fluoride content of the 54 samples of water collected in Fond du Lac County ranged from less than 0.1 to 1.4 ppm and averaged 0.3 ppm.

The ground water in Fond du Lac County is very hard and in some areas it contains excessive iron, but otherwise it is satisfactory for most uses. The dissolved solids content of the 54 samples of water collected ranged from 256 to 1,060 ppm and averaged 455 ppm.

CONCLUSIONS AND RECOMMENDATIONS

Much of Fond du Lac County is underlain by thick sandstone beds of Cambrian and Ordovician ages. These supply most of the water now withdrawn by industrial and public-supply wells. The water in the sandstones is under artesian pressure, although the pressure head has declined in the vicinity of the city of Fond du Lac. Consolidated rocks of the Prairie du Chien group, the St. Peter sandstone, the Platteville formation and Galena dolomite, and the Niagara dolomite and unconsolidated deposits of Pleistocene age supply adequate water to most domestic and farm wells.

Recharge occurs throughout most of the county but is greatest in areas where the bedrock formations are near the surface. Essentially all recharge is derived from local precipitation. It is estimated that the sandstones of Cambrian and Ordovician ages from which water is pumped by the city of Fond du Lac are recharged over an area of about 250 square miles.

If the distribution of wells and the rate of pumping, about 3.8 mgd, in the Fond du Lac area remain the same as they were in 1956, the water-level decline from 1956 to 1966 will be about 5 feet. If, however, the distribution of pumped wells remains the same but the amount of municipal pumpage by Fond du Lac increases at a uniform rate from 3 mgd in 1956 to 5 mgd in 1966, the water levels in 1966 will be at least 60 feet below the levels of 1956. Dispersal of wells so as to enlarge the area of withdrawal would lessen interference between wells and thereby reduce the decline of water levels in wells near the center of the cone of depression. Dispersal of wells to the northwest, toward the recharge area, would be more effective in reducing water-level decline than dispersal in any other direction. The thinning of the sandstone over the structural high in the crystalline rocks in the southern part of Fond du Lac makes locating of wells to the south and southwest less practical. Test holes should be drilled to determine the thickness of the aquifer and the availability of ground water in any specific locality where large-capacity wells are desired.

The results of pumping tests of wells in the Niagara dolomite indicate that wells producing at least 200 gpm could be developed in the area east of the Niagara escarpment. Because of the variability of water-bearing openings in the dolomite, test holes should be drilled prior to any large-scale development. Additional studies are needed to determine the quantity of water that may be available from the Niagara dolomite. The springs and streams issuing from the Niagara escarpment should be studied with regard to amount of flow, quality, source, and temperature.

It is recommended that water-level measurements in wells tapping sandstones of Cambrian and Ordovician ages and the Niagara dolomite in Fond du Lac County be continued. These measurements are necessary to determine water-level trends and the declines of water level that will result from additional development. Data or pumpage should continue to be collected and correlated with changes in water levels.

The results of studies to January 1957 lead to the general conclusion that ample ground water is available to meet foreseeable future needs in Fond du Lac County, provided that pumped wells are dispersed sufficiently that excessive local declines in water level can be avoided. Whether such dispersal is economically feasible in comparison with other means for obtaining water to meet future increased needs is an economic question that is beyond the scope of this investigation.

REFERENCES

Alden, W. C., 1918, The Quaternary geology of southeastern Wisconsin: U.S. Geol. Survey Prof. Paper 106, 356 p.

Bean, E. F., 1949, Geologic map of Wisconsin: Wisconsin Geol. and Nat. History Survey.

Birge, E. A., and Juday, Chancey, 1914, The inland lakes of Wisconsin: Wisconsin Geol. and Nat. History Survey Bull. 27, p. 96–98.

Chamberlin, T. C., 1877, Geology of eastern Wisconsin, *in* Geology of Wisconsin: Wisconsin Geol. and Nat. History Survey, v. 2, pt. 2, p. 93–405.

Darton, N. H., 1905, Preliminary list of deep borings in the United States: U.S. Geol. Survey Water-Supply Paper 149, 175 p.

Dean, H. T., Arnold, F. A., Elvove, Elias, Johnston, D. C., and Short, E. M., 1942, Domestic water and dental caries: U.S. Public Health Repts., v. 57, no. 32, p. 1176–1177.

Drescher, W. J., 1956, Ground water in Wisconsin: Wisconsin Geol. Survey Inf. Circ. 3, 36 p.

Ferris, J. G., 1948, Ground-water hydraulics as a geophysical aid: Michigan Dept. Conserv., Geol. Survey Div. Tech. Rept. 1, 12 p.

Kirchoffer, W. G., 1905, The sources of water supply in Wisconsin: Wisconsin Univ. Bull. 106, Eng. Ser., v. 3, no. 2, p. 163–249.

Martin, Lawrence, 1932, The physical geography of Wisconsin: Wisconsin Geol. and Nat. History Survey Bull. 36, 446 p.

Meinzer, O. E., 1923a. The occurrence of ground water in the United States, with a discussion of principles: U.S. Geol. Survey Water-Supply Paper 489, 321 p.

——— 1923b, Outline of ground-water hydrology, with definitions: U.S. Geol. Survey Water-Supply Paper 494, 71 p.

——— ed., 1942, Hydrology, pt. 9 of Physics of the earth; New York, McGraw-Hill Book Co., Inc., p. 385–477.

Spicer, H. C., 1950, Investigation of bedrock depths by electrical-resistivity methods in the Ripon-Fond du Lac area, Wisconsin: U.S. Geol. Survey Circ. 69, 37 p.

Theis, C. V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans. p. 519–524.

Thwaites, F. T., 1923, The Paleozoic rocks found in deep wells in Wisconsin and northern Illinois: Jour. Geology, v. 31, p. 529–555.

——— 1940, Buried pre-Cambrian of Wisconsin: Wisconsin Acad. Sci., Arts, and Letters Trans., v. 32, p. 233–242.

Trowbridge, A. C. and Atwater, G. I., 1934, Stratigraphic problems in the upper Mississippi valley: Geol. Soc. America Bull. v. 45, p. 21–80.

United States Public Health Service, 1946, Drinking water standards: Public Health Repts., v. 61, no. 11, p. 371–384, Repr. 2697.

Weidman, Samuel, and Schultz, A. R., 1915, The underground and surface water supplies of Wisconsin: Wisconsin Geol. and Nat. History Survey Bull. 35, p. 330–343.

Whitson, A. R., and others, 1914, Soil survey of Fond du Lac County, Wisconsin: Wisconsin Geol. and Nat. History Survey Bull. 37, Soil Ser. no. 7, 85 p.

Wisconsin State Board of Health, Bureau of Sanitary Engineering, 1935, Public water supplies of Wisconsin: Madison, Wis., 31 p.

Wisconsin State Department of Agriculture, 1952, Fond du Lac County agriculture: County Agr. Statistics Ser., 62 p.

Woollard, G. P., and Hanson, G. F., 1954, Geophysical methods applied to geologic problems in Wisconsin: Wisconsin Geol. Survey Bull. 78, Sci. Ser. no. 15, p. 68–78.

Newport, Thomas Gwynn, 1922–

Geology and ground-water resources of Fond du Lac County, Wisconsin. Washington, U.S. Govt. Print. Off., 1962.

iv, 51 p. illus., maps (part col., part in pocket) diagrs., tables. 25 cm. (U.S. Geological Survey. Water-supply paper 1604)

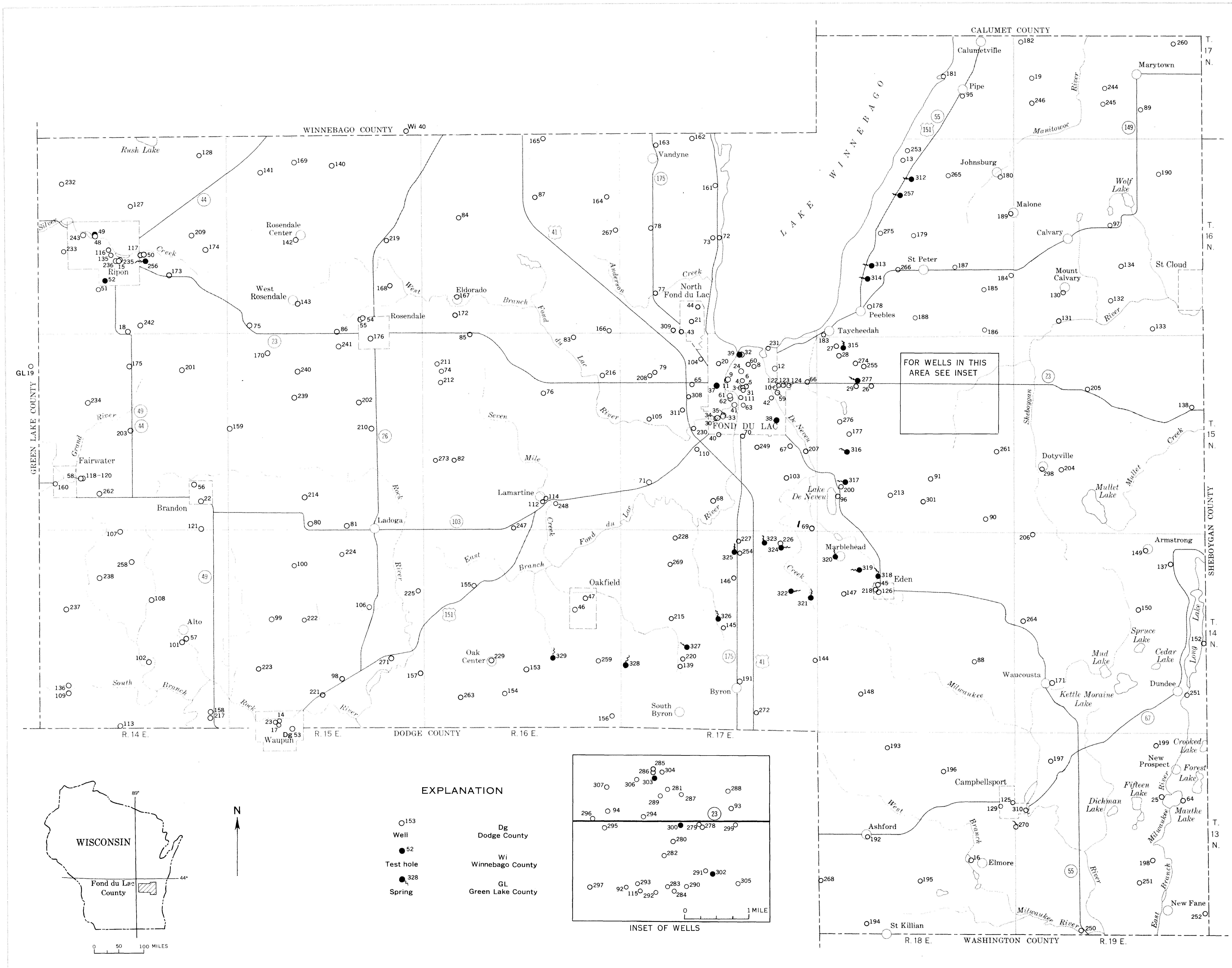
Prepared in cooperation with the Geological and Natural History Survey, University of Wisconsin, and the city of Fond du Lac.

Bibliography: p. 50–51.

1.Geology—Wisconsin—Fond du Lac Co. 2.Water, Underground—Wisconsin—Fond du Lac Co. 3.Water-supply—Wisconsin—Fond du Lac Co. I.Wisconsin. Geological and Natural History Survey. II.Title: Fond du Lac County, Wisconsin.

(Series)

U.S. GOVERNMENT PRINTING OFFICE: 1962 O—604855

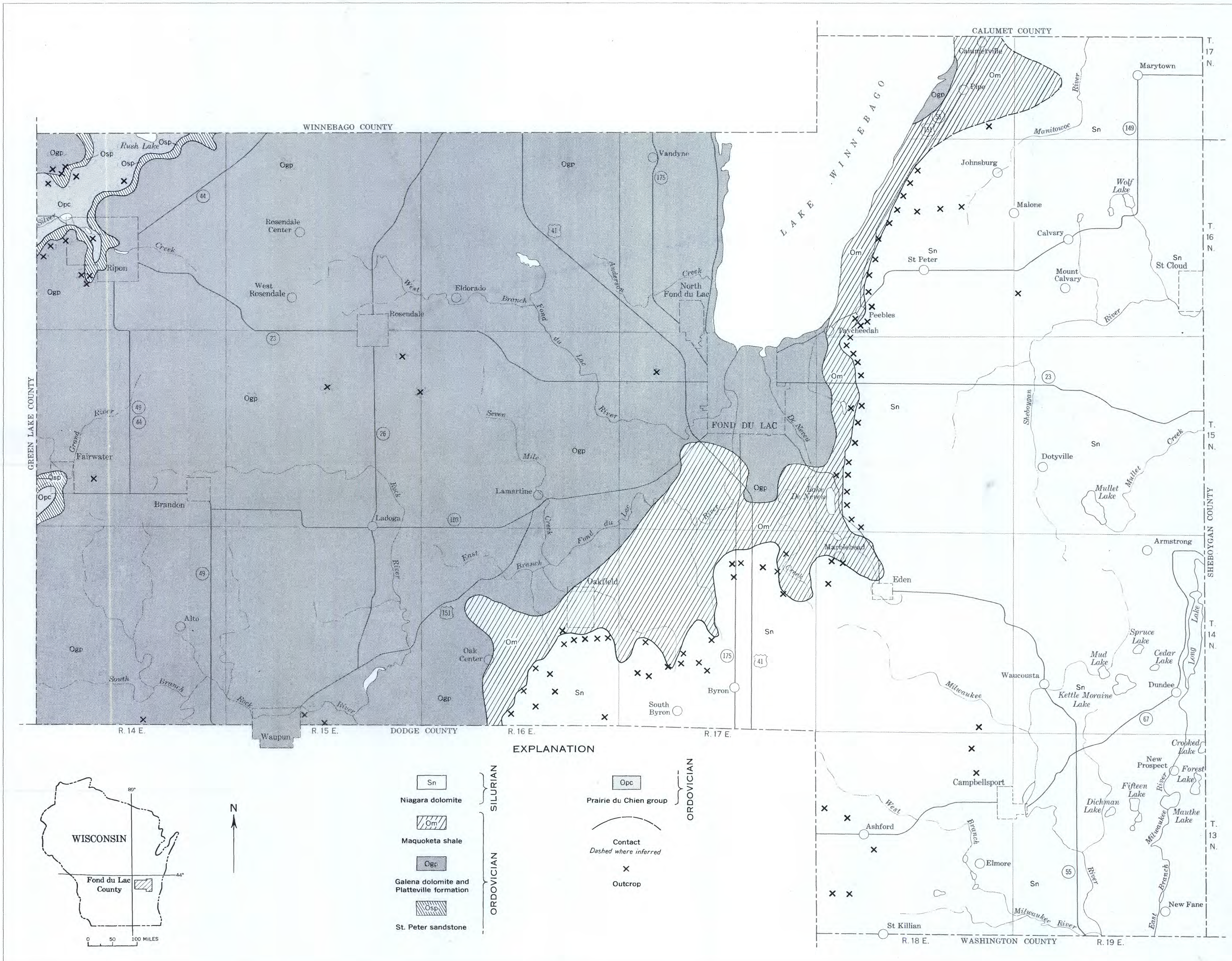


Base compiled from maps of the State Highway Commission of Wisconsin and field notes

MAP OF FOND DU LAC COUNTY, WISCONSIN, SHOWING LOCATION OF WELLS, TEST HOLES, AND SPRINGS

1 0 5 MILES

DATUM IS MEAN SEA LEVEL



Base compiled from maps of the State Highway Commission of Wisconsin and field notes

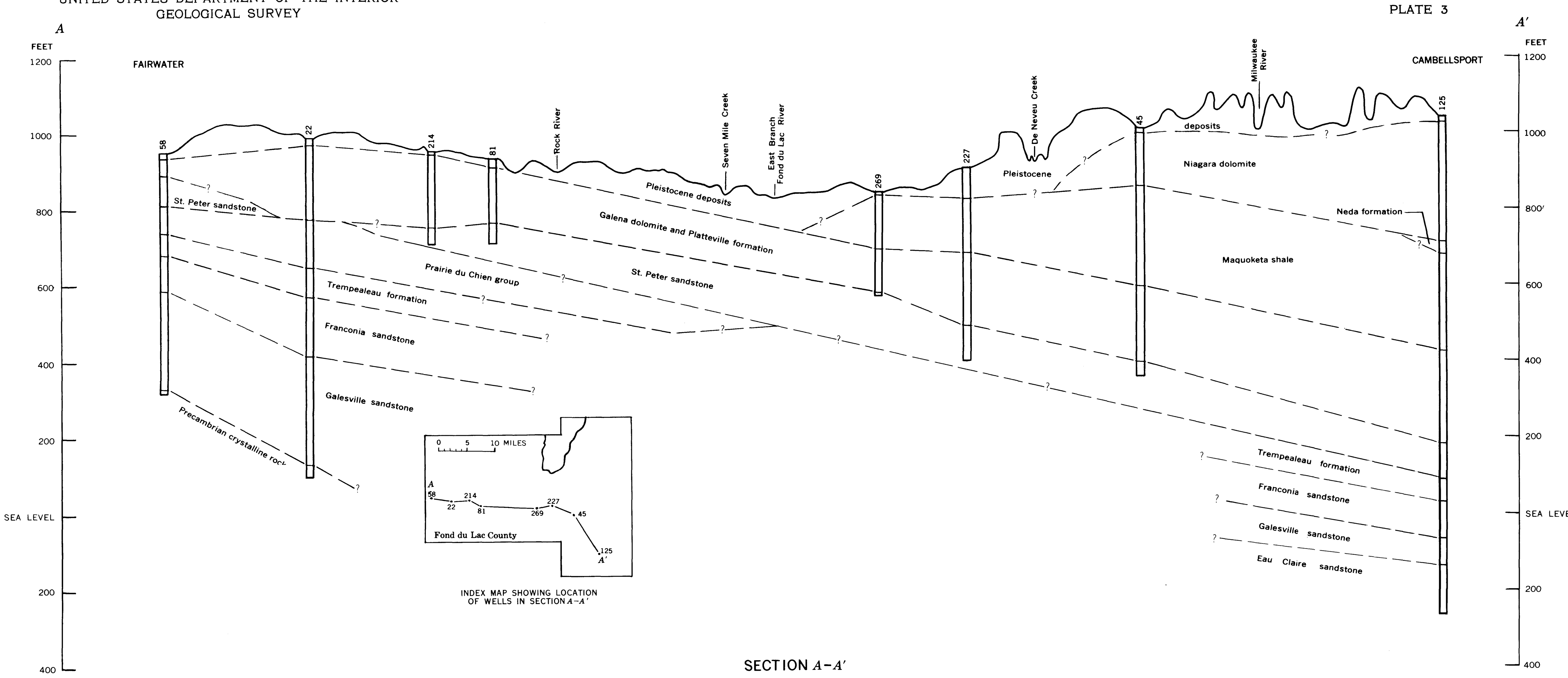
INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D. C.—10461

Modified from Geologic Map of Wisconsin, E. F. Bean (1949)

MAP OF FOND DU LAC COUNTY, WISCONSIN, SHOWING BEDROCK GEOLOGY

1 0 5 MILES

DATUM IS MEAN SEA LEVEL



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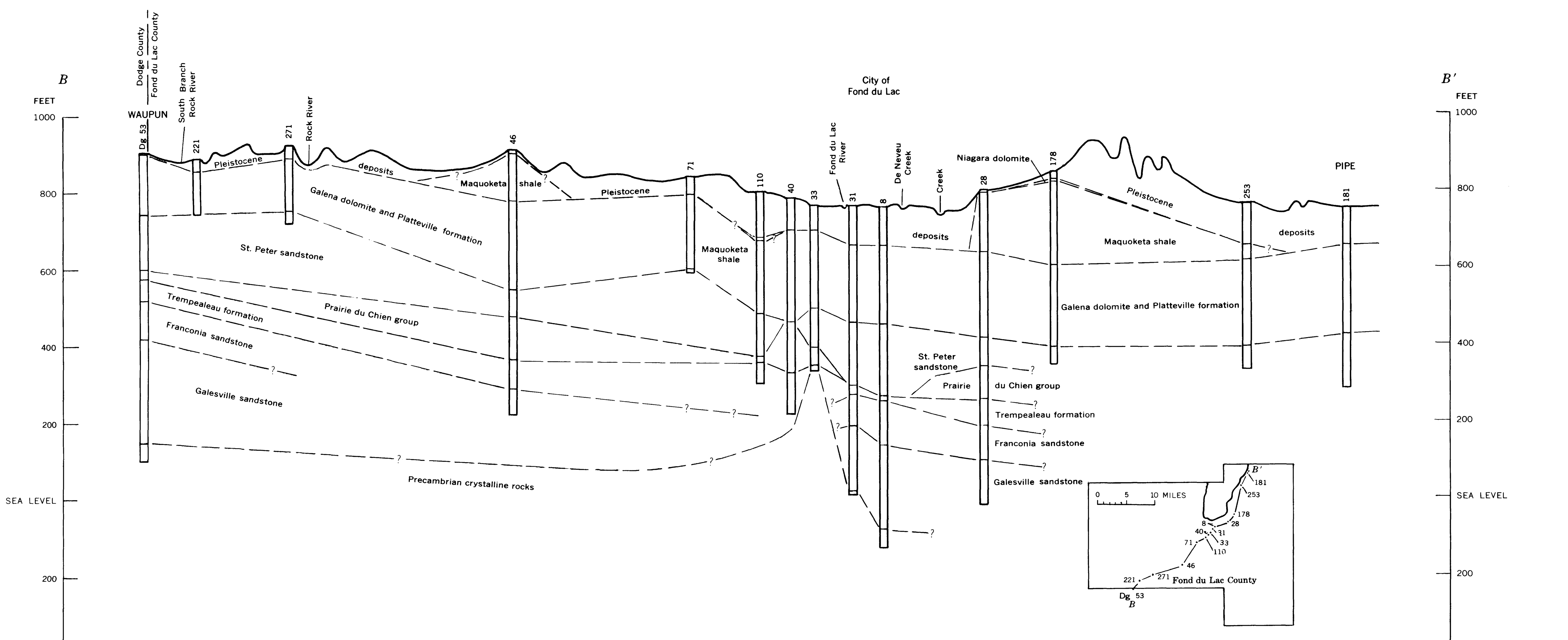

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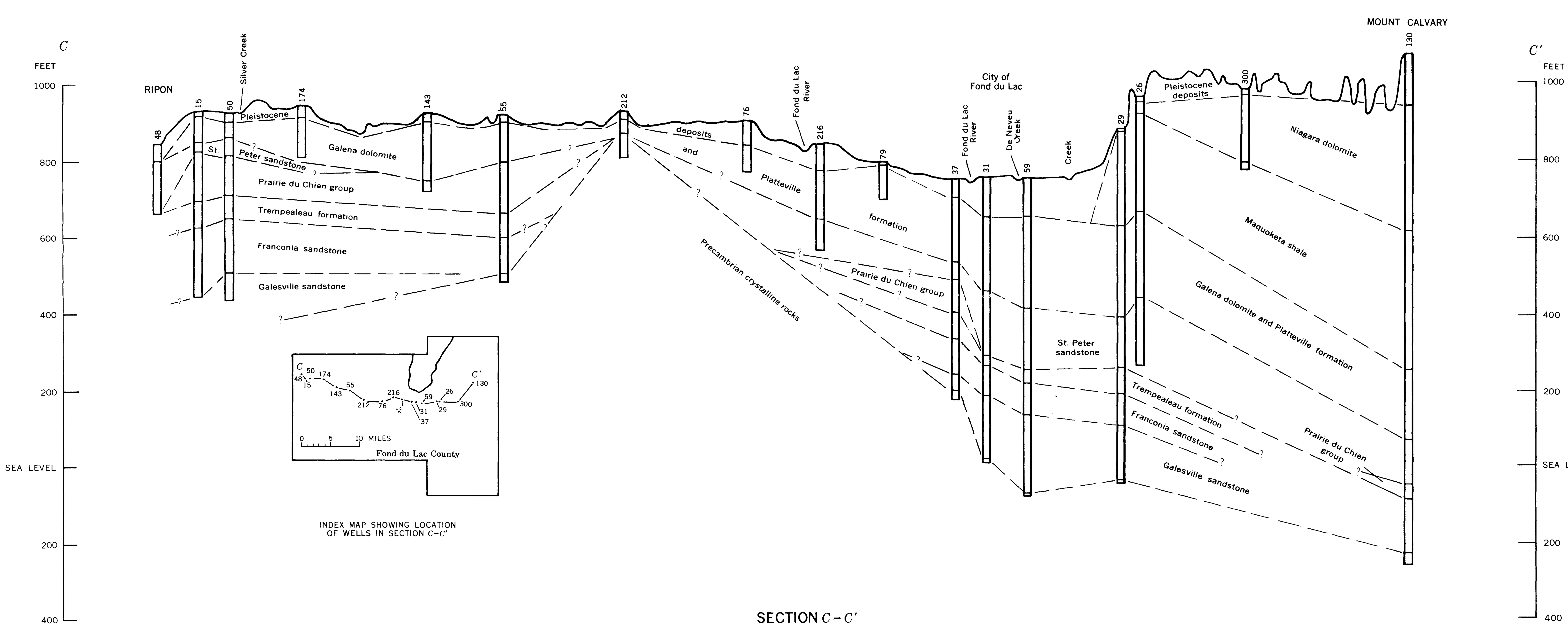
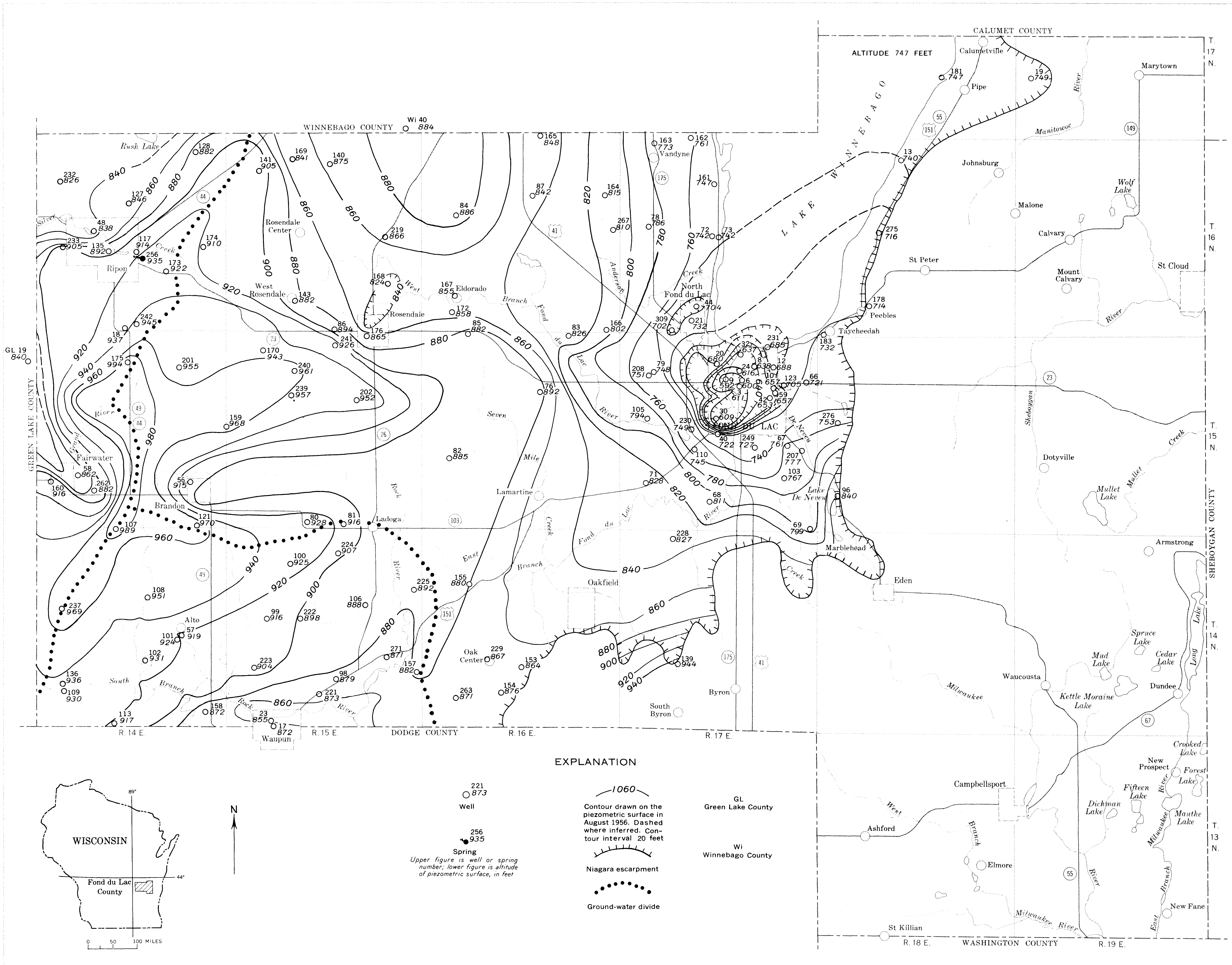


SECTION C–C'

STRATIGRAPHIC SECTIONS FROM FAIRWATER TO CAMPBELLSPORT, WAUPUN TO PIPE, AND RIPON TO MOUNT CALVARY, WISCONSIN

1 0 5 MILES

604855 O - 62 (In Pocket)



Base compiled from maps of the State Highway Commission of Wisconsin and field notes

MAP OF FOND DU LAC COUNTY, WISCONSIN, SHOWING PIEZOMETRIC SURFACE OF WATER IN THE CAMBRIAN AND ORDOVICIAN ROCKS IN THE AREA WEST OF THE NIAGARA ESCARPMENT

1 0 5 MILES
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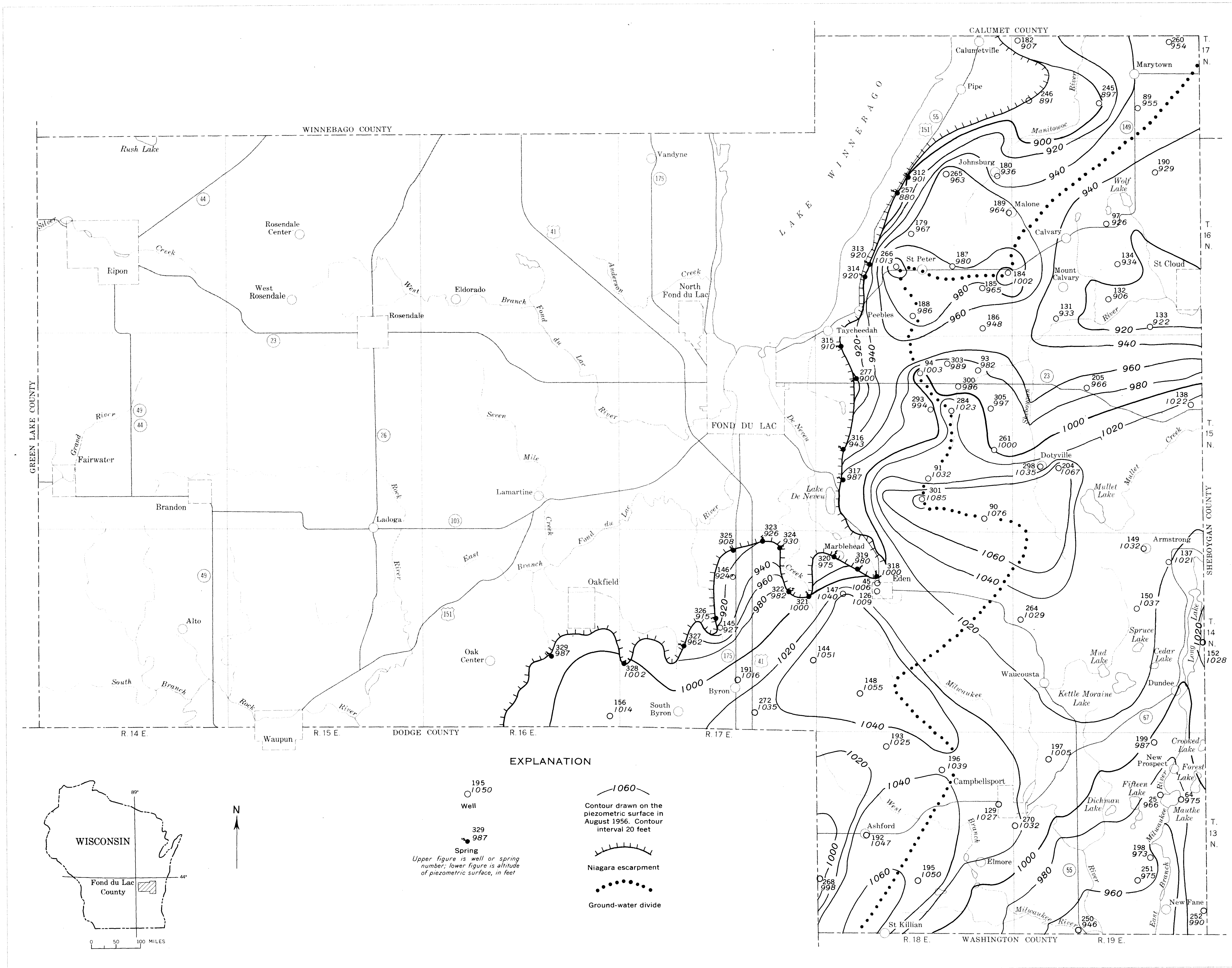

Base compiled from maps of the State Highway Commission of Wisconsin and field notes

MAP OF FOND DU LAC COUNTY, WISCONSIN, SHOWING PIEZOMETRIC SURFACE OF WATER IN THE NIAGARA DOLOMITE IN THE AREA EAST OF THE NIAGARA ESCARPMENT

1 0 5 MILES

DATUM IS MEAN SEA LEVEL