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GROUND WATER RESOURCES OF WISCONSIN

by

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Bruce L. Cutright[1]

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With an Appendix by Phil A. Kammerer, Jr.[2]

GROUND WATER QUALITY ATLAS OF WISCONSIN

This Project was supported by a grant from The Wisconsin Department of Natural Resources under the Environmental Protection Agency, Underground Injection Control Program.

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INTRODUCTION

Water is unique and precious and fragile. There are no substitutes or alternatives to water or futuristic dehydrated or condensed versions. Without water life is impossible and when it is in short supply its value rises exponentially. And it is fragile. A teaspoon full of sugar in a swimming pool is harmless, but add the same amount of organically soluble mercury, or endrine or toxaphene and your beautiful, crystal clear swimming pool becomes unsafe for human use. This sensitivity of water resources to contamination by hazardous and other materials has led to many efforts to protect and preserve surface water resources.

In many instances in the past, ground water resources were not considered to be threatened in the same manner that surface water resources were threatened. Regulations protecting water quality were interpreted to apply to surface water only. Recent publicity of events such as Love Canal, or agricultural chemical pollution such as aldicarb, have shown that ground water quality is also in need of protection. The effects of neglecting ground water quality result in after-the-fact detection of contamination events that render large areas of once productive aquifers unsuitable for use for many years. Clean-up or restoration of a contaminated area is often economically improbable if not physically impossible.

Protection of the ground water resources of Wisconsin is essential for the continual well-being and prosperity of the residents of the State and the economy which supports them. Over 3 million people, 70% of the population, within Wisconsin depend on ground water for their water supply.

In order to efficiently regulate and protect ground water resources it is necessary to assemble as much information as possible related to the origin, occurrence, movement, quality, and use of ground water within the State.

It is the purpose of this investigation to present a summary of the data available at the present time on the ground water resources of Wisconsin.

This will begin with a review of the climate of the State and its relation to recharge, evaporation and transpiration. The geology of the State and some geologic history will be discussed as this is the framework within which the ground water systems exist. It is also appropriate to describe what a ground water system is and its relation to the geology, climate and topography. Lastly, each of the aquifers of the state will be discussed--their water quality, water transmitting capacity and their relationship to other aquifers and confining beds.

Acknowledgements

Support for this investigation was provided by the Wisconsin Department of Natural Resources under the Envrionmental Protection Agency, underground injection control program. The Wisconsin Geological and Natural History Survey provided office space and cartographic support. Tom Kern prepared many of the figures and assisted throughout the project period. M.E. Ostrom and Ron Hennings reviewed the manuscript and provided invaluable assistance and moral support. Although many friends and associates have played a part in this project, responsibility for the statements and conclusions are solely the responsibility of the Author.

Purpose of Investigation

The Environmental Protection Agency implemented the underground injection control program to protect aquifers now being used as sources of public water supply or aquifers potentially usable as sources of public water supply from degradation by the injection of wastes under ground. This program required that each state define the usable aquifers within their boundaries. The purpose of this investigation was to summarize the available information on the aquifers of Wisconsin to aid the Wisconsin Department of Natural Resources in their report to the Environmental Protection Agency; to establish the geologic units yielding water to wells, and to define the ground water quality in each aquifer.

Methods of Investigation

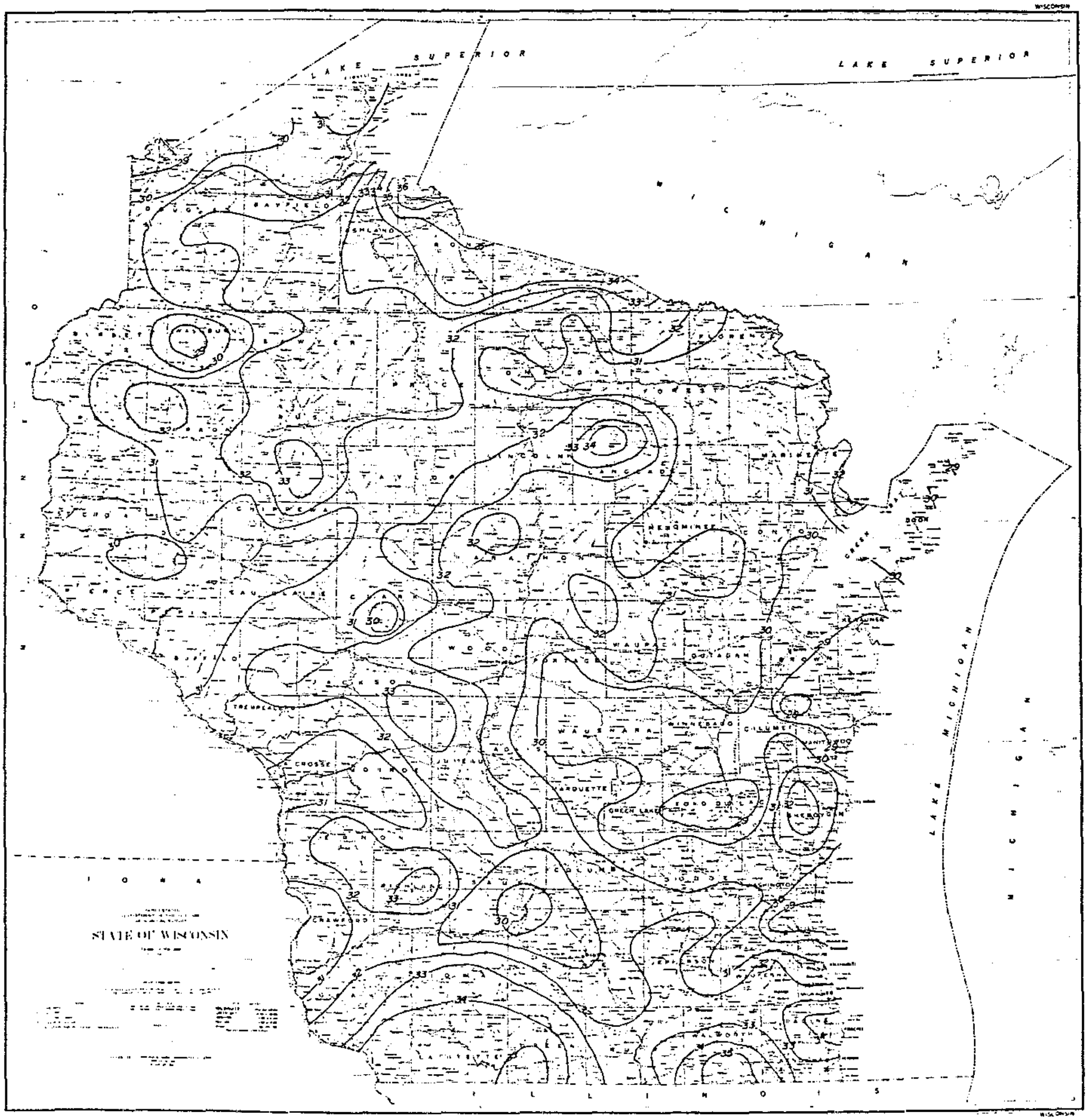
Information for this investigation has largely been acquired from previous county studies completed by the Wisconsin Geological and Natural History Survey and the U.S. Geological Survey. The present regional aquifer systems analysis being conducted by the USGS on the Cambrian-Ordovician aquifer provided new information. Because of the regional extent of this investigation and the limited amount of time available, no fieldwork directly related to this project was completed. The list of cited references comprises only a limited cross section of the published information actually reviewed. Unpublished cross sections compiled by M.E. Ostrom (1962) and well log files from the Wisconsin Geological Survey and the USGS were utilized to create the cross sections across the state.

Climate

Wisconsin has a temperate, continental climate. The summers are usually warm and muggy; the winters are cold. The presence of Lake Superior to the North and Lake Michigan to the East moderate the temperature extremes slightly so that the temperature fluctuations are not as radical as other more land-locked, mid-western States. On an annual basis the climate is humid with precipitation exceeding evaporation and transpiration. Precipitation averages about 30 inches per year across the state but varies from as low as 26 inches to as high as 36 inches. Rainfall averages 3 to 3-1/2 inches a month from early May to Mid-September while rain and snowfall averages around 1-1/2 to 2 inches of water equivalent per month from October through April. Figure 1 shows the areal variation of precipitation across the State averaged over a 30 year period from 1951 to 1980.

Evapotranspiration includes the amount of water lost through evaporation from streams, lakes and exposed surfaces and the water lost or used through transpiration by plants. On a statewide basis evapotranspiration accounts for about 20 inches of water per year, leaving about 10 inches of water for stream flow and ground water recharge. The amount of precipitation which immediately contributes to stream flow or which infiltrates into the ground water system is dependent on many factors such as vegetation cover, soil types, depth to the water table, topography, temperature and geology. Water which immediately joins surface streams contributes to peak discharges in stream flow. Water which infiltrates into the ground water system is eventually discharged into streams and rivers and actually accounts for the entire quantity of stream flow 80% to 90% of the time.

Quantities of runoff per unit area tend to increase from South to North with the maximum runoff occurring in Ashland, Bayfield, Douglas and Iron Counties and the minimum runoff originating from St. Croix and Pierce Counties and from the Dodge, Jefferson, Waukesha



MEAN ANNUAL PRECIPITATION 1951 – 1980

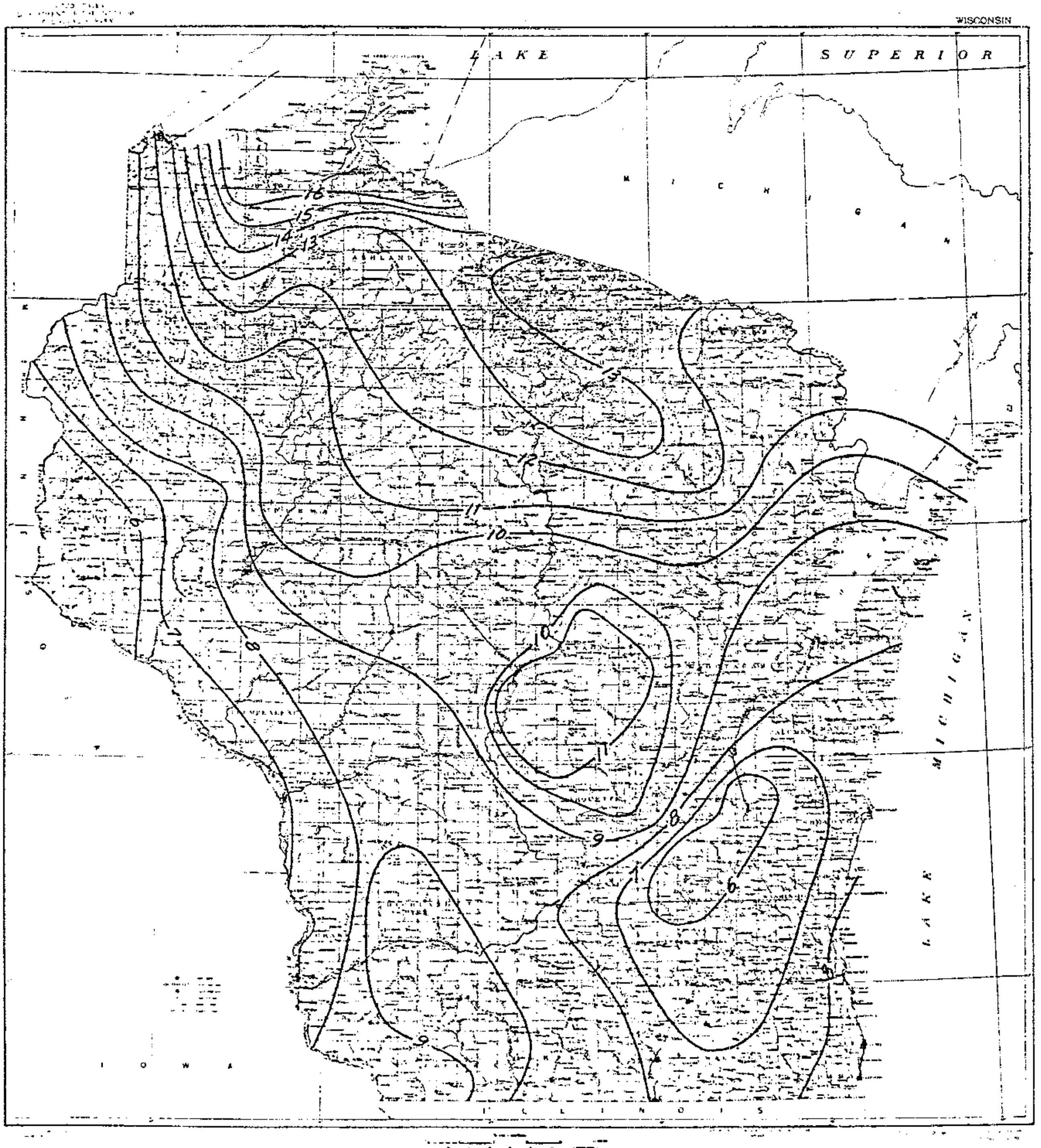
Figure 1. (After Mitchell, V., 1981)

Counties area. Figure 2 (U.S.G.S., 1981) shows the general trends of runoff throughout the state.

Geologic History

Three main sequences of rock occur in Wisconsin and represent three major periods in the history of the earth. Exposed in a broad dome in North Central Wisconsin are rocks of Precambrian age, the period of time from the origin of the earth to approximately six hundred million years before the present. These rocks are a complex series of plutonic and extrusive igneous rocks, metamorphic rocks and some shales and sandstones. They represent a period of time when Wisconsin was subject to long periods of extensive igneous activity, continental rifting and subsea volcanic activity. The area was first studied and interpretations of its history were made by investigators such as T.C. Chamberlin (1883) in 1873-1879. More recent summaries of the history of the area have been published by Sims and Morey (1972), and Mudrey and LaBerge (1979).

Away from the Wisconsin dome area the Precambrian rocks gradually become deeper and deeper and are overlain by rocks of Paleozoic age. The Paleozoic era spans the period of time from approximately six hundred million years ago to two hundred and twenty-five million years ago. Only a portion of this era is represented in Wisconsin, with the youngest rocks estimated to be at least three hundred and fifty to four hundred million years old. The Paleozoic rocks that are present represent a cyclical history of submergence and reemergence from the sea. Ostrom (1965, 1966, 1967) has defined five separate cycles wherein the seas covered much of Wisconsin depositing sands, muds and calcareous material and then retreated allowing some of



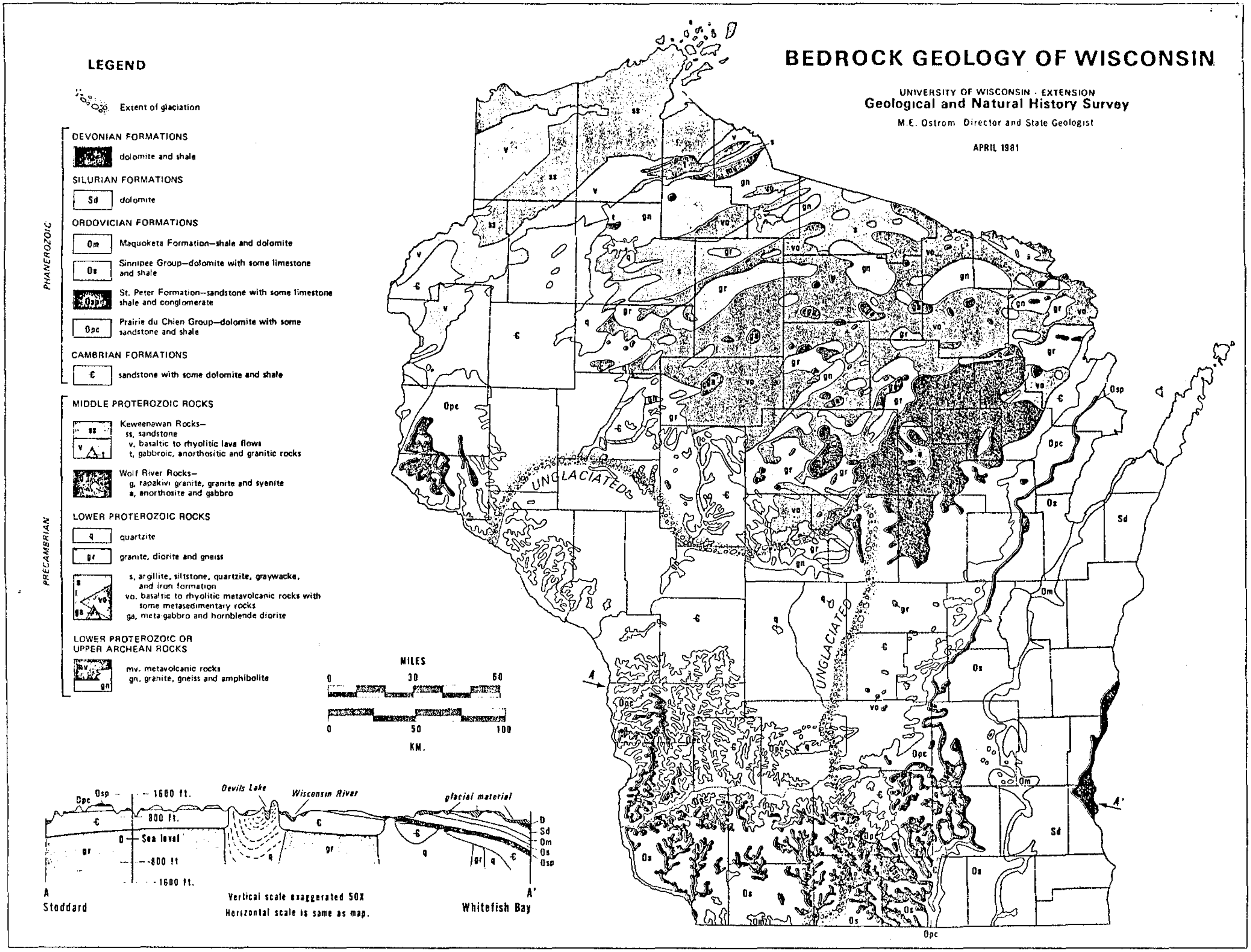
Mean Annual Runoff Per Unit Area.

Figure 2. (U.S.G.S., 1981)

the deposited sediments to be eroded and weathered before being resubmerged and covered by the next advance of the oceans. The bedrock geology map of Wisconsin (Fig. 3) depicts the outcrop areas of the Precambrian and Paleozoic age bedrock as if the younger, glacial age material had been removed.

From the period of time represented by the Peleozoic deposits to the younger glacial age material most of Wisconsin was exposed and subject to erosion. It is uncertain if extensive deposits were laid down over the bedrock deposits and then later eroded away or if they were never deposited. In any event, there is a gap in the depositional history from approxiamtely three hundred and fifty million years ago to perhaps seventy thousand years ago. Sediments in Wisconsin younger than seventy thousand years are a product of the continental ice sheets that expanded and contracted over the last one to two million years. Only the last expansion and contraction are well represented in Wisconsin. This is the period of time known as the Pleistocene. It is divided into four major subdivisions delineated by the advance of the ice sheets. The last of these periods is known as the Wisconsin stage because the deposits were first studied in Wisconsin. Flint (1971) provides an in depth discussion of the entire period while Black, et al (1970) provide information pertinent to Wisconsin.

The significance of each of the major divisions of rock units to the hydrogeology of Wisconsin will be discussed in the following sections.



BEDROCK GEOLOGY OF WISCONSIN
UNIVERSITY OF WISCONSIN - EXTENSION
Geological and Natural History Survey
M.E. Ostrom Director and State Geologist
APRIL 1981
LEGEND
Extent of glaciation
PHANEROZOIC
DEVONIAN FORMATIONS
dolomite and shale
SILURIAN FORMATIONS
Sd dolomite
ORDOVICIAN FORMATIONS
Om Maquoketa Formation—shale and dolomite
Os Sinnipee Group—dolomite with some limestone and shale
Osp St. Peter Formation—sandstone with some limestone shale and conglomerate
Opc Prairie du Chien Group—dolomite with some sandstone and shale
CAMBRIAN FORMATIONS
€ sandstone with some dolomite and shale
PRECAMBRIAN
MIDDLE PROTEROZOIC ROCKS
Keweenawan Rocks—
ss, sandstone
v, basaltic to rhyolitic lava flows
t, gabbroic, anorthositic and granitic rocks
Wolf River Rocks—
g, rapakivi granite, granite and syenite
a, anorthosite and gabbro
LOWER PROTEROZOIC ROCKS
q quartzite
gr granite, diorite and gneiss
s, argillite, siltstone, quartzite, graywacke, and iron formation
vo, basaltic to rhyolitic metavolcanic rocks with some metasedimentary rocks
ga, meta-gabbro and hornblende diorite
LOWER PROTEROZOIC OR UPPER ARCHEAN ROCKS
mv, metavolcanic rocks
gn, granite, gneiss and amphibolite
MILES
0 30 60
0 50 100
KM.
UNGLACIATED
UNGLACIATED
A
A'
Devils Lake
Wisconsin River
glacial material
1600 ft.
800 ft.
0 Sea level
-800 ft
-1600 ft.
A Stoddard
A' Whitefish Bay
Vertical scale exaggerated 50X
Horizontal scale is same as map.

GEOLOGIC HISTORY OF WISCONSIN'S BEDROCK

Introduction

The bedrock geologic record in Wisconsin is divided into two major divisions of time: the Precambrian, older than 600 million years, and the Paleozoic, younger than 600 million years. The Precambrian rocks are at the bottom and consist predominantly of crystalline rocks. They are overlain by Paleozoic rocks which consist of relatively flat-lying, in some cases fossil-bearing, sedimentary rocks.

Precambrian rocks form the bedrock beneath the glacial deposits in northern Wisconsin and occur beneath the Paleozoic rocks in the south (see the last paragraph and the cross-section on the reverse side). Paleozoic rocks may once have covered northern Wisconsin, but if they did, they have been removed by erosion. Glacial deposits, including clay and sand and gravel, cover bedrock in the northern and eastern three-fifths of the state.

In areas covered by glacial deposits, surface outcrops are so sparse that details of the bedrock geology are obscured. In such areas the only clues to the underlying rocks are obtained from rock cuttings and cores obtained from drill holes and from geophysical surveys which disclose magnetic and gravity variations.

Precambrian Eon

The Precambrian is divided into two eras, the older Archean and the younger Proterozoic. Each is subdivided into three periods–Early, Middle, and Late.

Archean

Rocks older than 2,500 million years are termed Archean. The oldest Archean rocks are gneisses (gn), or banded rocks. These are more than 2,800 million years old and are in Wood County. Similar old ages have been determined for rocks south of Hurley, where recognizable volcanic rocks (mv) have been intruded by 2,700 million year old granite (gn). All of these rocks have been extensively deformed, and in many areas they are so highly altered that their original nature and origin are extremely difficult to interpret. Because of this difficulty, both the older gneisses and some younger (Proterozoic) gneissic and crystalline rocks are combined on this geologic map.

Proterozoic

There are four principal groups of rocks in the Proterozoic. The oldest are around 1,800 to 1,900 million years old. These Early Proterozoic rocks consist of sedimentary (s) rocks including slates, graywacke and iron formation, and volcanic (vo) rocks. The sedimentary rocks dominate in the north, with volcanic rocks becoming more abundant in central Wisconsin. These layered rocks were intruded by gabbros (ga), diorities, and granites (gr) about the same time that they were being folded and deformed.

Quartz-rich Early Proterozoic sedimentary rocks (q) occur as erosional remnants, or outliers, on the older Proterozoic rocks; they were deformed about 1,700 million years ago. The Barron Quartzite in the Blue Hills of Rusk and Barron counties, the Baraboo Quartzite in Sauk and Columbia counties, and Rib Mountain Quartzite in Marathon County are some of the major remaining areas of once widespread blankets of sandstone.

The oldest Middle Proterozoic rocks include the granites, syenites, and anorthosites (g, a) of the Wolf River complex. This extensive body of related granitic rocks was intruded into Lower Proterozoic volcanic and sedimentary rocks around 1,500 million years ago.

The youngest Proterozoic rocks in Wisconsin are about 1,100 million years old and are called Keweenawan rocks. At the time of their formation a major rift or fracture zone split the continent from Lake Superior south through Minnesota and into southern Kansas. Keweenawan rocks can be divided into two groups: an older sequence of igneous rocks including lavas (v) and gabbros (t); and a younger sequence of sandstone (ss). These rocks occur in northwestern Wisconsin. In central Wisconsin diabase dikes were also emplaced at this time.

At the close of the Precambrian, most of Wisconsin had been eroded to a rather flat plain upon which stood hills of more resistant rocks such as the quartzites in the Baraboo bluffs.

Phanerozoic Eon

The Phanerozoic is divided into three eras. They are from the oldest to the youngest: the Paleozoic (old life), Mesozoic (middle life), and Cenozoic (most recent life). The Paleozoic is represented by a thick sequence of sandstones, shales and dolomites (dolomite is similar to limestone); the Mesozoic, possibly by gravels; and the Cenozoic, only by glacier-related deposits.

In the Paleozoic Era the sea advanced over and retreated from the land several times. The Paleozoic Era began with the Cambrian Period (Ꞓ) during which Wisconsin was submerged at least twice beneath the sea. Sediments eroded by waves along the shoreline and by rivers draining the land were deposited in the sea to form sandstone and shale. These same processes continued into the Ordovician Period (Opc, Osp, Os, Om) during which Wisconsin was submerged at least three more times. Animals and plants living in the sea deposited layers and reefs of calcium carbonate which are now dolomite. Deposits that built up in the sea when the land was submerged were partially or completely eroded during the times when the land was elevated above sea level. At the close of the Ordovician Period, and in the succeeding Silurian (Sd) and Devonian (D), Wisconsin is believed to have remained submerged. There are no rocks of the Paleozoic Era younger than Devonian in Wisconsin. Whether material was deposited and subsequently removed by erosion, or was never deposited, is open to speculation.

Absence of younger Paleozoic rocks makes interpretation of post-Devonian history in Wisconsin a matter of conjecture. If dinosaurs roamed Wisconsin, as they might well have in the Mesozoic Era some 200 million years ago, no trace of their presence remains. Available evidence from neighboring areas indicates that towards the close of the Paleozoic Era the area was gently uplifted and it has remained so to the present. The uplifted land surface has been carved by millions of years of rain, wind, running water, and glacial action. With the possible exception of some pebbles about 100 million years old, no Mesozoic age bedrock has been identified in Wisconsin.

In the last million years during a time called the Pleistocene, glaciers invaded Wisconsin from the north and modified the land surface by carving and gouging out soft bedrock, and depositing hills and ridges of sand and gravel as well as flat lake beds of sand, silt, and clay. In this manner, the glaciers smoothed the hill tops, filled the valleys, and left a deposit of debris over all except the southwestern part of the state. The numerous lakes and wetlands which dot northern Wisconsin occupy low spots in this Pleistocene land surface. Glacial deposits are not shown on the map of bedrock geology; however, the line of farthest glacial advance is shown. A separate glacial deposits map is available.

Cross Section

To assist in understanding the bedrock geology of Wisconsin, a cross section has been prepared (see reverse side). A cross section represents a vertical slice of the earth's crust showing the subsurface rock layers in much the same way as a vertical slice of cake shows the layers of cake and frosting. The Wisconsin cross section shows the subsurface geology along a line from Stoddard in Vernon County, through Devil's Lake near Baraboo in Sauk County, to Whitefish Bay in Milwaukee County. The horizontal scale is the same as that of the geologic map, but the vertical scale is exaggerated so that vertical thicknesses are expanded 50 times compared to horizontal distances. The Paleozoic rocks are shown as layers, the younger units lying above the older units. They are also shown dipping to the west in the western part of the state and dipping east in the eastern part of the state, thus forming an arch. The center and oldest parts of this arch are found in the Baraboo bluffs, where the Baraboo Quartzite is exposed at the surface. As shown in the cross section by fine lines in the quartzite, the Baraboo area was folded into a U-shaped structure, or syncline, before the Paleozoic rocks were deposited. Quartzite and granite underlie the Paleozoic rocks along this section.

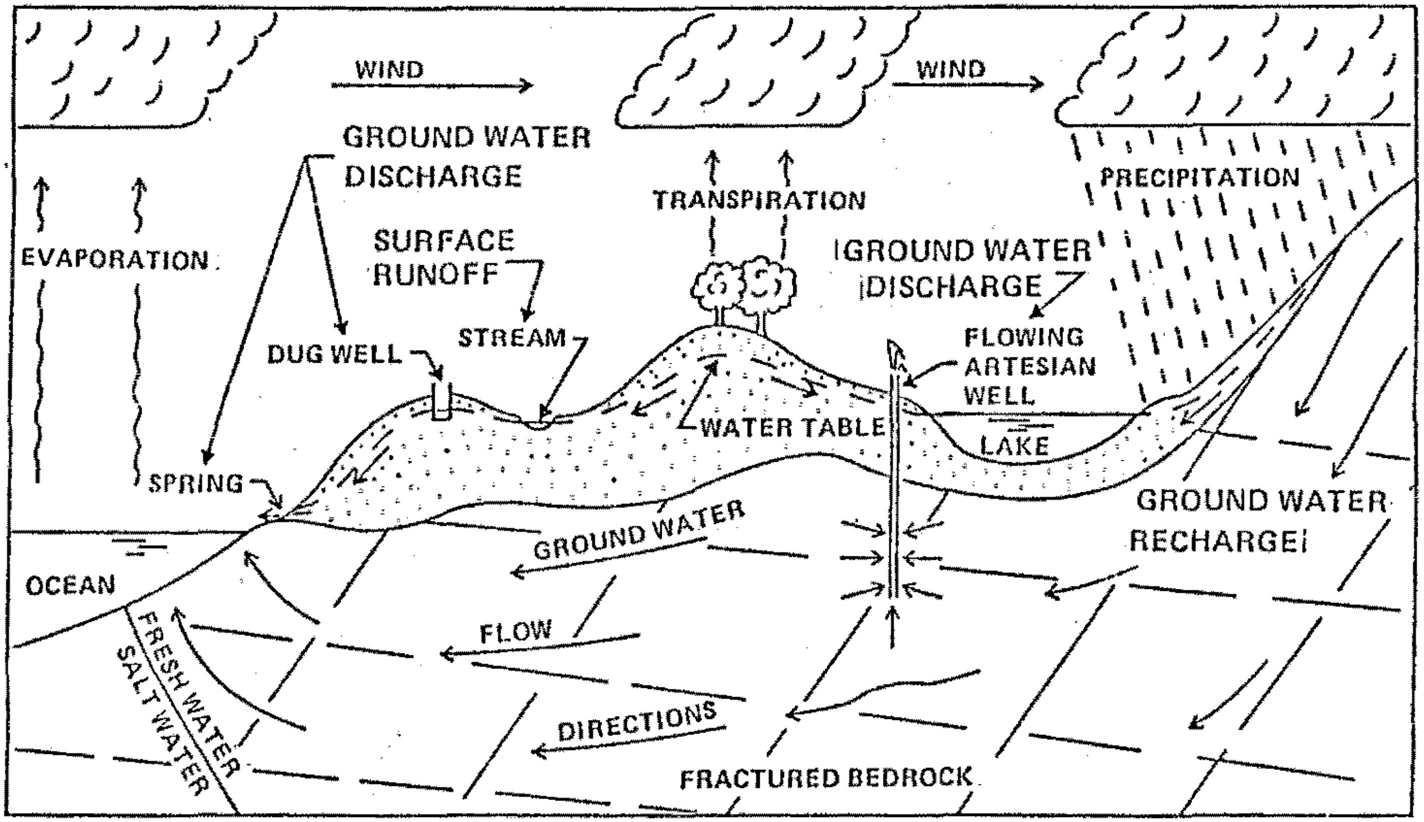
The gray unit shown at the top of the rock sequence in the eastern part of the cross section represents glacial materials which do not occur to the west.

Origin, Occurrence, and Movement Of Ground Water

Ground water is part of the endless solar powered circulation of water known as the hydrologic cycle. This is the constant interchange of water from the oceans to the atmosphere to surface water to ground water (Fig. 4). Residence time in the atmosphere of an individual water particle may be on the order of hours to a few days. In surface water it may be a week but in the oceans and in ground water an individual water particle may take thousands of years before it reaches the atmosphere to begin its cycle again.

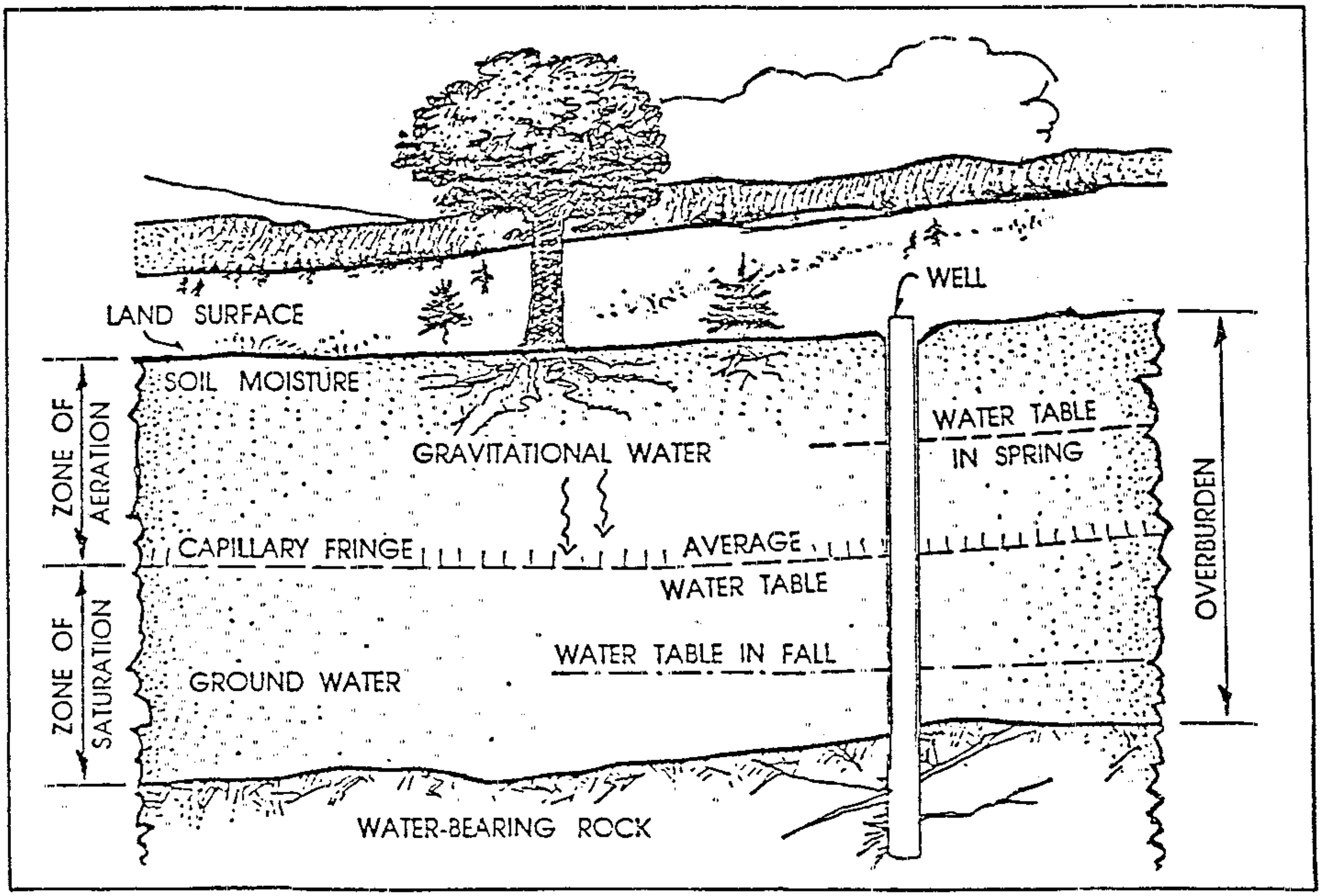
All of the water within the ground water system originated as precipitation. Some precipitation evaporates before it reaches the ground, some is lost to stream flow almost immediately and some infiltrates into the ground. Not all water that infiltrates into the ground becomes ground water. Some is lost again by evaporation from the near surface soils, some is absorbed by plant roots and used in their life process and some is bound to individual soil particles. Soils will hold water against the force of gravity until they have reached their field capacity. This soil moisture is available for the use of plants but is held too tightly by soil tension to infiltrate down to the water table. When the field capacity has been satisfied and infiltration from the surface continues then water will reach the water table. The water table defines the surface below which all the pore spaces of the soil or rock are filled with water, ground water. Figure 5 depicts the relationships of the various types of water below ground surface.

The geologic unit or units in which ground water exists is known as an aquifer if it will yield sufficient quantities of water to wells, springs or seeps to be usable or known as an aquitard or confining bed if it will not yield sufficient quantities of water



The hydrologic cycle.

Figure 4 (After Caswell, 1979)



Classification of Ground Water in Rock and Unconsolidated Overburden.

Figure 5 (After Caswell, 1979)

to be usable. The terms aquifer and aquitard are difficult to define because they depend on the idea of usability. For some uses a well producing only a few gallons per minute is sufficient and the source of the water would be considered an aquifer. For other uses several hundred gallons per minute may be needed. The Maquoketa Shale serves both definitions in much of Eastern Wisconsin. Permeable beds near the top of the formation provide limited quantities of water to wells while the entire formation acts as a confining bed for the underlying sandstone aquifer.

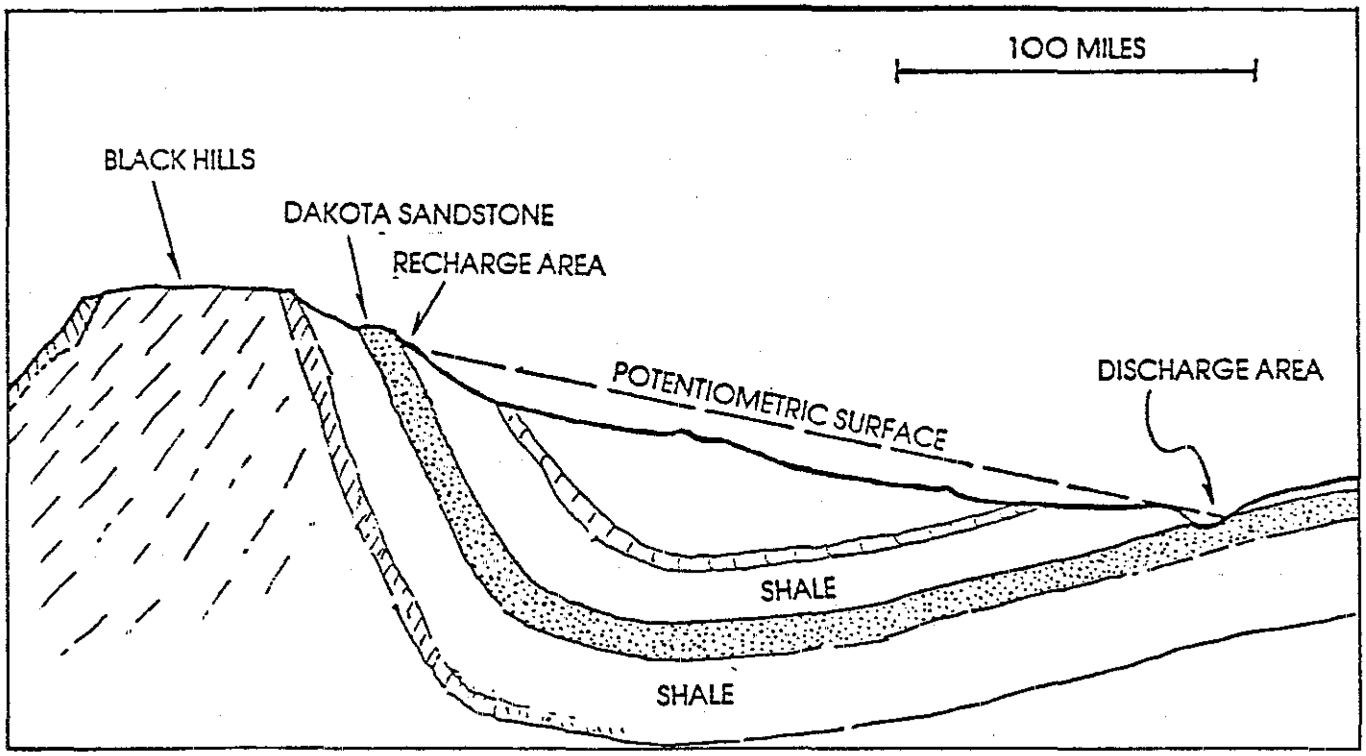
Where an aquifer is confined it is known as a confined or Artesian aquifer. Where the ground water within the aquifer is open to atmospheric pressure the aquifer is unconfined or known as a water table aquifer. In Eastern Wisconsin the Maquoketa Shale confines the sandstone aquifer while in Southern and Western Wisconsin the sandstone aquifer is essentially unconfined.

In Wisconsin a high percentage of the infiltration reaching the water table or recharge occurs in the early spring after the soil defrosts. During summer plants deplete much of the soil moisture and keep rainfall from augmenting the ground water supply. In early fall there may be another period of recharge before snowfall and falling temperatures freeze the soil. If clay lenses or lower permeability beds restrict the flow of infiltration from reaching the water table, a perched water table may form. If recharge occurs to the ground water but lower permeability beds prohibit the water table from rising, a confined or artesian ground water system will develop. If a well is drilled into an artesian system, when the well penetrates the bottom of the lower permeability bed or confining bed the water level in the well will rise until the weight of water in the well balances the pressure in the confined ground water system.

If the well is not deep enough for this to happen, water will flow out of the well until the pressure in the aquifer is less than the weight of a column of water the length of the well. Flowing wells may also occur where there is no confining bed but this will be discussed under recharge and discharge.

Ground water moves in response to gravity. It may also move in response to thermal or chemical gradients but these will not be considered here. Water falling on land at high elevations is pulled by gravity to flow to lower elevations, obviously water flows downhill. The same may be said for ground water but qualified somewhat by saying that ground water flows down gradient in its potential energy field. The water flowing up and out of our flowing artesian well is apparently not flowing downhill, but in terms of the potential field of the ground water system the top of the well is "downhill" from the point at which the well is open to the aquifer. This can be demonstrated in two ways. Figure 6 is an idealized cross section of the Dakota Sandstone in South Dakota. Water enters the sandstone where it is exposed near the top of the Black Hills, flows downward and then upward to a stream (discharge area). However, the potential energy field that the water is actually flowing in response to is shown by the line (in three dimensions it would be a surface) labeled Potentiometric Surface. The Potentiometric Surface is the level to which water will rise in a tightly cased well penetrating a confined aquifer.

A flowing well may be developed where there is not a confining bed over an aquifer. Figure 7 is a representation of a ground water flow system. Recharge occurs uniformly across the area with discharge occurring in the stream to the right. The flow lines indicate the



Idealized Cross Section Through The Dakota Sandstone in South Dakota (After Caswell, 1979).

Figure 6

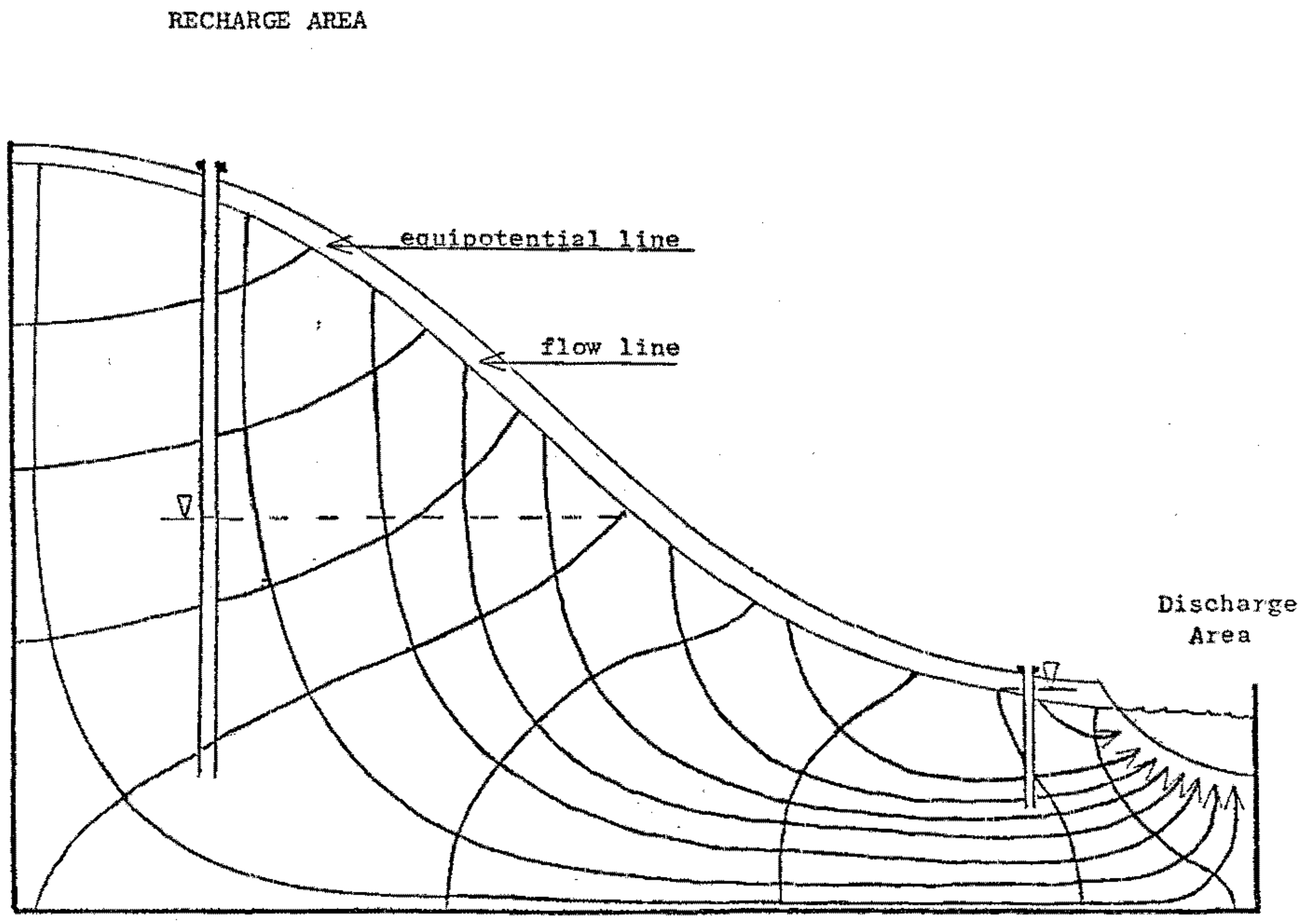


Figure 7: Sketch of ground water flow system in homogeneous sediments showing artesian well in discharge area.

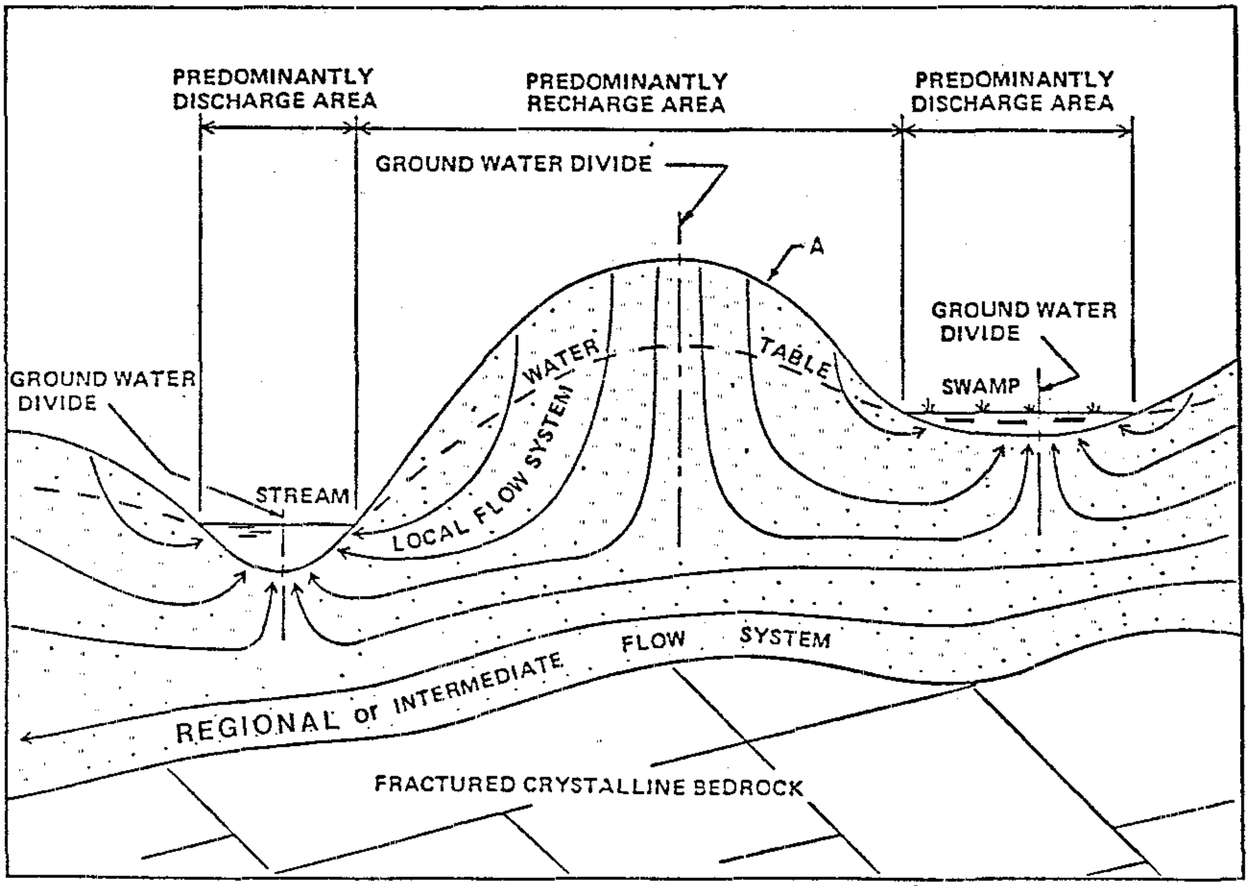
direction of flow while the equipotential lines indicate the potential energy in the ground water at each point. If a well is drilled as shown in a low area and intersects an equipotential line having more potential energy than the elevation of the top of the well, then the well will flow, without the presence of a confining bed.

The slope of the potentiometric surface in the Dakota Sandstone example is a smooth decline from the recharge area at high elevations to the discharge area at low elevations. If significant topographic relief is superimposed on the land surface between the regional recharge and discharge areas then local and intermediate flow systems may develop. The realization that most ground water flow systems do not strictly obey the type system shown by the Dakota Sandstone was demonstrated in 1962 by J. Toth. Further work by Freeze and Witherspoon (1966) and later by Toth in 1978 have increased our understanding of ground water flow systems. Figure 8 (Toth, 1962) shows the relationship of local, intermediate and regional flow systsms.

In a regional discharge area there is a continual increase in potential energy with depth while in a regional recharge area there is a continual decrease in potential with depth. In local or intermediate systems there may be a change with depth of the direction of change of potential energy.

Water Table Map of Wisconsin

There are many water table maps published for specific areas of counties of Wisconsin but no generally available statewide map has been assembled. It was deemed appropriate to create a water table map for the State for several reasons: its usefulness in determining the direction of flow, depth to water, quantities of ground water in storage, amount of fluctuations about a mean level and usefulness in planning purposes, are only a few.



Groundwater flow systems in unconsolidated materials.

Figure 8 (Toth, 1962)

Sources of information for the water table map were largely the series of Hydrologic Atlases prepared by the U.S. Geological Survey in cooperation with the Wisconsin Geological Survey for the twelve major river basins in Wisconsin. These are the Fox-Wolf River Basin (Olcott, 1968), the Rock-Fox River Basin (Cotter, et al, 1969), the Central Wisconsin River Basin (Devaul and Green, 1971), the Chippewa River Basin (Young and Hindall, 1972), the Lake Michigan Basin (Skinner and Borman, 1973), the St. Croix River Basin (Young and Hindall, 1973), the Pecatonica-Sugar River Basin (Hindall and Skinner, 1973), the Menominee-Oconto-Peshtigo River Basin (Oakes and Hamilton, 1973), The Trempealeau-Black River Basin (Young and Borman, 1973), the Lower Wisconsin River Basin (Hindall and Borman, 1974), the Lake Superior Basin (Young and Skinner, 1974) and the Upper Wisconsin River Basin (Oakes and Cottor, 1975).

Where available, county water table maps were used instead of the smaller scale (larger area) river basin maps to improve resolution of the contour lines. Water level records from the Wisconsin Geological Survey and the U.S. Geological Survey were also used to check the level of the contour lines. The water table map is included as Figure 9 in the map folder.

Usefulness of the Map

The map is drawn at the scale of 1;1,000,000 with the line width of the contours approximately at .02 inches. At this scale, the line covers approximately one-third of a mile on the map. It is not meant for detailed resolution of the water table surface. In addition, the mean annual level of the water table has been plotted. Because of seasonal variations in recharge and discharge, the level of the water may fluctuate several feet. In upland areas or recharge areas this may be greater than ten feet while it is usually less in lowland or discharge areas.

The real usefulness of this map should be for county or statewide planning purposes and to indicate the general direction of flow of the near surface ground water.

Recharge-Discharge Map

In the discussion of ground water movement, the idea of ground water flow from a recharge area to a discharge area was briefly discussed. This concept of a ground water flow system has been carried further by attempting to delineate major recharge areas and discharge areas for deep regional flow systsms of the state. A preliminary map showing these areas is presented as Figure 10 (in map folder).

In a humid area such as Wisconsin, the quantity of recharge can be considered relatively constant across the state. The topographic highs usually represent high levels in the water table surface and topographic lows usually represent low areas in the water table. Infiltration falling on the highest areas of the water table possesses the greatest gravitational potential energy. A quantity of recharge falling on the highest area will follow the longest path and traverse the greatest portion of the aquifer. It will move downward to the base of the aquifer then laterally and finally upward to the regional discharge area as shown in Figure 7. In contrast to the longest flow path described above, each quantity of recharge entering the aquifer closer and closer to the discharge area follows a shorter and shallower path. Since discharge areas in humid environments are normally surface waters such as lakes, streams or springs or wetland areas, the relative size of discharge areas compared to recharge areas is small. In Wisconsin Martin (1965) tabulated the area of the inland lakes and streams as 810 square miles and the area of land as 55,256 square miles. If every lake or stream were a discharge area then 1.5 percent of the state would be classified as a discharge area and 98.5 percent as a recharge area. This is not the actual case though it is illustrative. The recharge-discharge map delineates those areas where the predominate direction of ground water flow is either upward or downward from a regional perspective. Infiltration continues to enter the ground water system in areas between those designated as recharge or discharge areas. In the intervening areas, local or intermediate systems control the flow direction or within the regional systems horizontal flow is predominate. The location of the boundaries of the recharge and discharge areas are not meant to indicate that recharge only occurs within those designated areas and discharge only occurs where shown. The ground water systems in Wisconsin are complex and many-layered. Within the recharge areas the stream flows are maintained by ground water discharge from local systems. Within the discharge areas flood flows from rivers recharge the local systems, and all of these complex interlayer systems vary with time. The boundary lines were drawn to indicate major trends in the regional flow systems and not to indicate exclusion of other processes within the designated areas.

A preliminary understanding of where the major highs and lows in the ground water flow systems of the state occur is useful for many reasons, the primary one being an understanding of the quantities and directions of flow of the ground water resource. A concern at least as important deals with protecting ground water flow systems from the introduction of hazardous or polluting substances. If storage facilities for hazardous materials are located in recharge areas for deep regional flow systems, accidental spills threaten the entire aquifer. A hazardous material spill near a discharge area may be of no less concern to nearby wells than a spill in a regional recharge area but at least its potential area of influence is reduced. With some of these concerns in mind, a preliminary attempt to delineate the regional ground water flow systems of Wisconsin was begun.

An assumption was made that from a statewide perspective the sandstone aquifer and the sand and gravel aquifer respond essentially together as an unconfined or semi-confined aquifer system. This assumption is valid because of the variability of the geologic materials on a regional basis. Tight limestones or dolomites are fractured and jointed enough to allow verticle movement of water. Fine-grained sandstones, silts and clays are also variable and grade from fine to coarse to fine grained. Where a hydraulic gradient exists ground water will flow and preferentially along the more permeable pathways. Even though a unit restricts the flow of ground water, when the unit is considered in total, significant leakage occurs.

In the eastern portion of the state where the Maquoketa Shale overlies the sandstone aquifer, the sandstone aquifer responds as a confined or semi-confined aquifer. The Silurian Dolomite is the major aquifer in this area. Where the assumption is made that the sand and gravel aquifer and sandstone aquifer are essentially connected, it is with the understanding that there are many local or intermediate flow systems that are predominantly only within the sand and gravel system. The primary interest of this study was to attempt to define the major, regional systems. At the scale of 1:1,000,000 this was only practicable. The delineation of smaller systems was beyond the scope of this study and more appropriate at the county or area level.

The primary evidence for a regional recharge area is declining water table levels away from the area and decreasing potentiometric head with depth. Discharge areas have exactly the opposite criteria; increasing potentiometric levels with increasing depth and rising water table levels away from the area. A map of the level of water in wells penetrating the sandstone aquifer was published by Weidman and Schultz in 1915. By comparing this map with later work compiled by the Wisconsin Geological Survey and the U.S. Geological Survey during the river basin studies, past areas of flowing wells and areas which have consistently had high regional water table levels were delineated. Well records were examined to determine verticle gradients in areas of interest. As a further check, ground water temperatures were used as corroborating evidence for the existence of regional flow systems. The map shown as Figure 10 was the result. It should be stated that this map is preliminary. Only data available in presently published or freely accessible files was used. Constraints on time and finances prohibited any field work to check the existence of these flow systems. Even with these constraints in mind it is believed that the map contains new and useful information that may be modified or expanded by future investigations but will not be essentially changed.

Usefulness of the Map

Delineation of the recharge and discharge areas of Wisconsin was attempted as a first step in understanding the regional nature of ground water flow in the state. Superimposed on these regional systems are many local and intermediate systems. If this map is to be useful, it must be recognized that areas shown as recharge areas may contain many other recharge and discharge areas for local systems. The same restraints must be used in areas shown as discharge areas. The areas where discharge is actually taking place are smaller than the areas shown, the reason being that where an upward gradient exists there may also be strong lateral gradients and zones where water is actually leaving the aquifer are usually rather small.

The map is useful in considering county land use practices, but it should be remembered that for hazardous waste siting or any other type of siting problem where ground water flow must be considered the local flow systems should be considered first. The map deals only with regional systems.

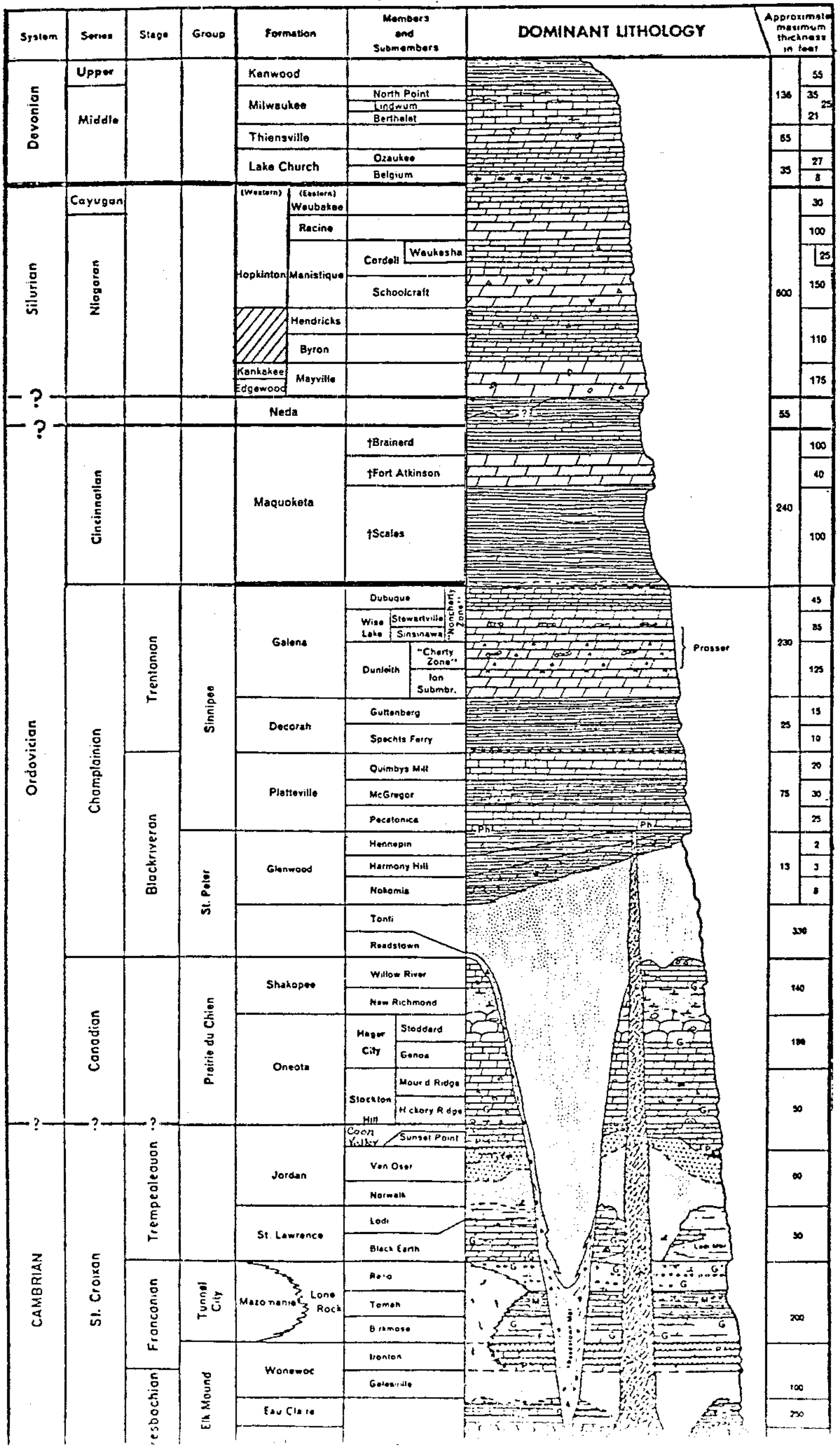
Aquifers of Wisconsin

Wisconsin is favored with thick sequences of permeable deposits across the entire State. In the early history of Wisconsin, Geologists classified these variable deposits based on their rock type, grain size, fossil content, mineralogy and other geologic criteria. These classifications have been modified occasionally by more recent studies to reflect increasing knowledge of the origin and character of the formations and beds. Figure 11 shows the presently accepted classification of the Paleozoic stratigraphy of Wisconsin (After Ostrom, 1967). In describing the water transmitting capabilities of these formations it is useful to utilize a broader but more descriptive term defined by Maxey (1964) for delineating ground water flow systems.

Recognizing that formations or beds that are distinct geologically may have similar hydrologic properties, Maxey (1964) proposed the category of hydrostratigraphic units to be defined as "bodies of rock with considerable lateral extent that compose a geologic framework for a reasonably distinct hydrologic system,". Although this term has not been formally applied in Wisconsin the concept itself has been used to define the aquifer systems of the State.

The major aquifer systems of the State based on areal extent, productivity and utility are the Cambrian-Ordovician sandstones, the Silurian (and Devonian) Dolomite, and the Pleistocene and Holocene alluvial and glacial deposits. Other aquifers that are considered minor are the Precambrian sandstones, lava flows, and crystalline rocks and the Maquoketa Shale. The Maquoketa Shale is classified both as an aquifer, and as a confining bed for the lower sandstone aquifer. Many wells are open to the Maquoketa and receive a sub-

STRATIGRAPHIC NOMENCLATURE
WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY



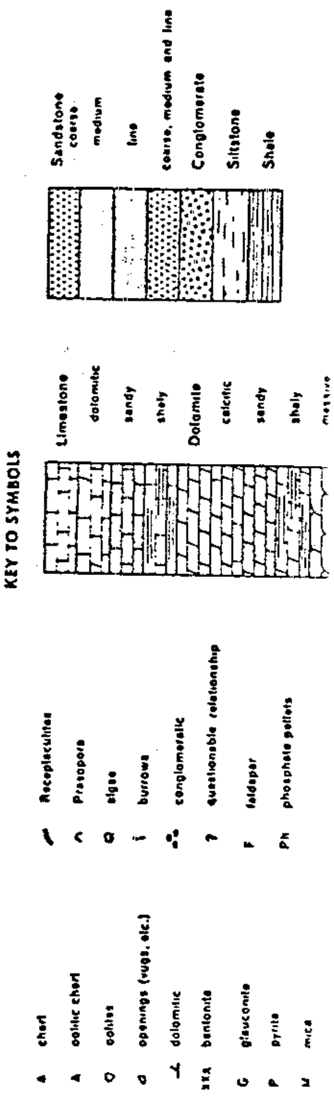


Figure 11

(Ostrom, 1967)

stantial portion of their production from limy or sandy beds within the shale. Because of this the Maquoketa will be considered as a separate although minor aquifer also. Hydrogeologic cross sections across the State showing the relationships of the various aquifers are shown in Figures 12 to 15 (in map folder).

The primary source of information on the aquifers of Wisconsin were the well log files maintained by the Wisconsin Geological Survey and the U.S. Geological Survey. These files are accessible through computer searches in the case of the U.S. Geological Survey or through a township-range filing system in the Wisconsin Geological Survey case. Both of these filing systems were utilized to determine approximate number of wells tapping each aquifer and aquifer characteristics such as, thickness, yield and extent.

Cambrian-Ordovician Sandstone Aquifer

The Cambrian-Ordovician sandstone aquifer is the most heavily pumped aquifer in the State. It is comprised of Cambrian and Ordovician sandstones, limestones, dolomitic limestones, dolomite and some shales and clays. The basal formation is the Mt. Simon Sandstone which rests unconformable on the crystalline basement rock. The Sandstone aquifer includes all of the rock units from the crystalline basement to the bottom of the Maquoketa Formation. Above the Mt. Simon Formation are the Eau Claire and Wonewoc Formations, the Tunnel City, Trempealeau and Prairie du Chien Groups, the St. Peter Formation and the Sinnipee Group. The location of selected wells utilizing the Sandstone aquifer as a source of water are shown in Figure 16.

Mt. Simon Formation

The Mt. Simon Formation is a predominately quartz sandstone with a significant feldspathic component. It is poorly cemented in some areas while being well cemented with calcareous cement in others. Its upper reaches contain occasional silty or shaley zones with some iron cementing present. The Mt. Simon is missing in Northeastern Wisconsin and in some areas of Sauk, Green Lake, Marquette, Washington, Dodge and Jefferson Counties where rises in the crystalline basement prohibited deposition of the Mt. Simon and several of the overlying formations. The formation is exposed in a broad band southwestward and southerly off the Wisconsin dome and in a narrow band along a limited area of the Southeastern Wisconsin dome. The formation thickens toward the south and exceeds over 1400 feet in thickness in Southeastern Wisconsin. The Mt. Simon is an important unit of the Sandstone Aquifer yielding large quantities of water to wells which penetrate it.

Eau Claire Formation

The Eau Claire Formation is a fine grained to shaley sandstone with some carbonate cementing. Sedimentary structures such as load casts and ripple marks are common and glauconite is abundant in some beds. The Eau Claire is also missing in Northeastern Wisconsin and in the same areas as the Mt. Simon Formation. Its average thickness is about 100 to 200 feet but does reach 400 feet thick in northern Rock County. The fine grained sand to silty texture limits its water yielding ability somewhat.

Wonewoc Formation

The Wonewoc Formation overlies the Eau Claire Formation with a sharp erosional unconformity at the boundary. It is widespread over Western, Southern and Eastern Wisconsin except for minor areas of non-deposition in the same locations as the Mt. Simon. It has been divided into two units, the Galesville and overlying Ironton Members. The Galesville Sandstone is predominantly medium to fine grained, well-rounded quartz sands. The Ironton is coarse to medium grained quartz sands, thick-bedded and cross-bedded. Occasional beds of silt and silty sand occur. The Wonewoc varies in thickness up to 100 feet. Near Milwaukee and from Sheboygan north along the east coast of Wisconsin over 200 feet of Wonewoc have been reported. It is usually less than 100 feet in Western Wisconsin but thickens toward the south where it ranges around 100 feet in thickness. Because of its coarse grained and highly permeable nature, it is an excellent source of ground water.

Tunnel City Group

The Tunnel City Group consists of the Mazomanie and Lone Rock Formations. The Lone Rock Formation is divided into the Birkmose, Tomah and Reno Members. The Mazomanie is a tongue in the Lone Rock Formation and thins southward, disappearing in Southern Wisconsin. The Tunnel City Group has been removed by erosion along the eastern border of Wisconsin northward from Milwaukee to Kewaunee County. It is present throughout most of Wisconsin not occupied by the Wisconsin dome. Lithologically the Tunnel City Group is highly variable, ranging from medium to fine sand, generally along the axis of the Wisconsin arch, to fine grained to silty glauconitic sandstone, calcareous shale or sandy, glauconitic, shaley dolomite. Its thickness is also variable but usually does not exceed 100 feet, the thickest areas being in the northeast and southwest areas of the State. It is permeable but yields less water to wells than the Wonewoc Formation.

Trempealeau Group

The Trempealeau Group is composed of the St. Lawrence and Jordan Formations. Based on data from outcrops (Ostrom, 1965) the St. Lawrence has been divided into two members, the Black Earth Member which is silty to medium bedded dolomite and the Lodi Member, which varies from sandy siltstone to dolomite to dolomitic fine grained sandstone. The St. Lawrence is over 50 feet thick in Southwestern Wisconsin and is absent to 40 feet thick in Eastern Wisconsin. The Jordan Formation is subdivided into five members, the Norwalk, the Van Oser, the Coon Valley, the Waukon and the Sunset Point Members. The Norwalk and Van Oser Members are predominantly fine to coarse quartz sand, variable in thickness with numerous cross bedding and burrows. The Sunset Point Member has beds of sandy dolomite, dolomitic sandstone, sandy shale and clayey siltstone. The formation is absent in much of Eastern Wisconsin but is up to 80 feet thick in areas of the Southwest.

The Mt. Simon, Eau Claire and Wonewoc Formations and the Tunnel City and Trempealeau Groups comprise the rock units of Cambrian age in Wisconsin. They outcrop in a broad band surrounding the Wisconsin dome of crystalline rock on the west, south and east sides, beginning in Washburn and Sawyer Counties southeast to Wood County and northeast to Marinette County. Along the Northwest and Western areas, the Cambrian units are at or near the surface for over 100 miles. Along the eastern flank of the Wisconsin dome, the units dip more steeply toward the Michigan basin, their outcrop area is only 10 to 20 miles wide and is usually covered with deposits of recent or Pleistocene age. As a group, the Cambrian age formations are predominantly sands of coarse to fine texture with occasional beds of more fine grained material. Where carbonate beds are present, they are usually dolomitic or dolomite. The entire sequence is highly productive for water wells throughout its thickness.

Prairie du Chien Group

The Prairie du Chien Group has been well described by Davis (1970). The group is divided into two formations and six members. The lower formation, the Oneota Dolomite, is sandy with occasional beds of quartz sandstone, chert and glauconite in the main dolomite matrix. The upper portion is relatively pure dolomite with minor chert and shale. The formation may be up to 300 feet thick but varies widely, it outcrops along Eastern and Southern Wisconsin with minor occurrence in Polk, St. Croix and Pierce Counties. The Shakopee Formation was deposited on top of the Oneota Dolomite. The lower member of the Shakopee is the New Richmond Sandstone. The New Richmond is predominantly interbedded sandy dolomite, quartz sandstone and shale. Its sand content increases and the unit thickens southward toward Illinois and Iowa. It is a sandy dolomite with minor amounts of grey-green shale and quartz sandstone. The water yielding properties of this group are largely dependent on the sand content and, as such, vary widely throughout its area of occurrence.

St. Peter Formation

Between the time of deposition of the Shakopee Formation and the St. Peter Formation an erosion surface developed with up to 300 feet of relief that cut as deep as the Eau Claire Formation in some areas of Eastern Wisconsin. As the sea advanced over the land again at the end of this erosional period, the St. Peter Formation was deposited. This formation possesses a shaley conglomerate at its base, a unit of pure well sorted quartz sand of highly variable thickness and an upper zone of green shale or poorly sorted silty and clayey sandstone. The formation is as much as 350 feet thick in filled stream valleys in Southeastern Wisconsin and may be completely absent in nearby areas. It is a productive aquifer in areas where thick sand sequences occur.

Sinnipee Group

The Sinnipee Group is the topmost unit of the Cambrian-Ordovician aquifer. It is composed of the Platteville, Decorah and Galena Formations. The entire group is dolomite, shaly dolomite and shale. The group is present in Eastern, Southern and Western Wisconsin and varies from 250 to 350 feet thick. Where it has been exposed at the surface, fractures and solutioned joints provide pathways for movement of ground water. Where it is overlain by the Maquoketa Shale, this weathering of joints and fractures has not taken place to such a degree.

Water Yielding Characteristics

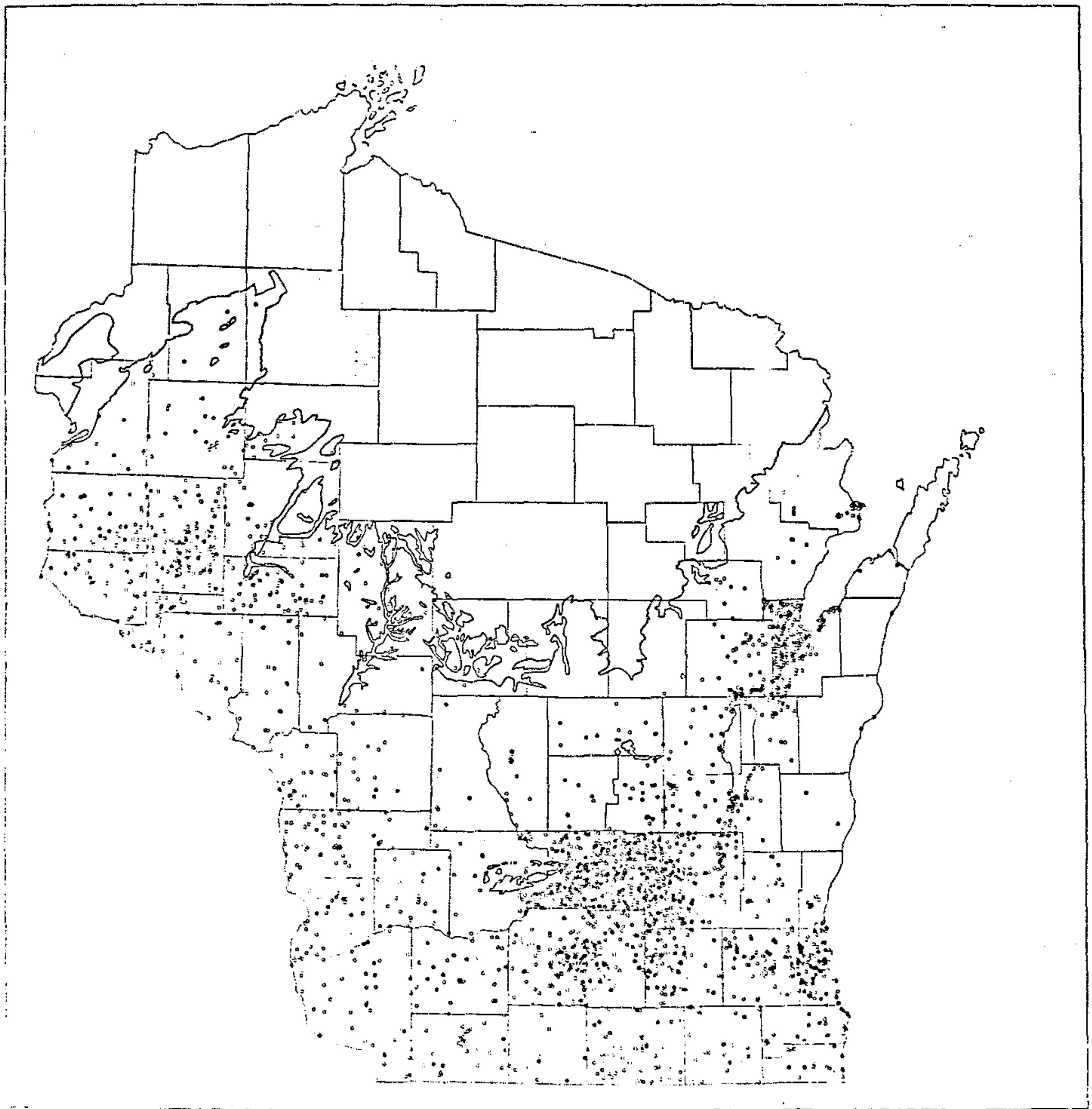
The Sandstone Aquifer is a complex series of differing lithologic materials that, from a statewide perspective, respond as one hydrogeologic unit. This is often not the case at specific well sites where lower permeability beds divide the aquifer into several sub-units. An example of this was documented by McLeod (1975) in Dane County. In order to accurately model the sandstone aquifer, McLeod was required to input two separate aquifers divided between the Wonewoc Formation and the Tunnel City Group. It is interesting to note that McLeod (1975, P. 25) also included all the glacial and quaternary deposits as part of his "upper aquifer". Based on his study, all the units from the Tunnel City Group to the glacial deposits were responding as one aquifer while the Mt. Simon, Eau Claire and Wonewoc responded as a separate confined aquifer.

Because of the variability of the Cambrian and Ordovician deposits it is not uncommon for the sandstone aquifer to react to pumping stress as two or more separate aquifers. Yet, from a regional perspective, the interformational flow is significant enough to effectively homogenize the response of the various sub-units into one coherent aquifer system. The location of selected wells utilizing the Sandstone aquifer as a source are shown in Figure 16.

Transmissivity is a measure of the ability of an aquifer to transmit water. It is a product of the hydraulic conductivity and the aquifer thickness. As discussed previously, the sandstone aquifer increases in thickness west, south and east off the Wisconsin dome. As the aggregate thickness of the geologic units increases, the calculated transmissivity also increases. In areas around the northern limit of the aquifer, values for transmissivity are commonly 5,000 to 10,000 GPD/Ft. In Dane County, McLeod used values ranging from 30,000 to 50,000 GPD/Ft., while in Grant and Rock Counties 80,000 GPD/Ft. are possible. Transmissivity may be estimated by knowing the specific capacity of a well without having to conduct an aquifer test. DeVaul (1975) examined well drillers' records for specific capacity data and converted this to an estimated well yield map for the Sandstone aquifer (Fig. 17 in map folder).

Water Quality of the Sandstone Aquifer. (See Appendix).

The most recent comprehensive study of ground water quality in



LOCATION OF SELECTED WELLS HAVING THE SANDSTONE AQUIFER AS A SOURCE

Figure 16.

Wisconsin has been purlished by Phil A. Kammerer, Jr. (1981) of the U.S. Geological Survey. Mr. Kammerer's report was prepared in co-operation with the Wisconsin Geological and Natural History Survey and is included as appendix one of this report. Most of the data and conclusions in this report related to water quality are based on his investigations. Wisconsin is fortunate in being the source area for all of the water entering the groundwater systems of the State. As water enters an aquifer and flows downgradient, it dissolves soluble components of the rock matrix through which it flows. The amount of material dissolved is in part a function of residence time and length of flow path, along with other geochemical parameters such as temperature, pH and oxidation potential. As a working rule, it can be assumed that total dissolved solids tend to increase along the flow path of an aquifer system. Because the sandstone aquifer is exposed through much of the State, fresh water is continually entering much of the aquifer and the overall water quality is exceptionally good.

Current Environmental Protection Agency Regulations (1975) do not specify a maximum contaminate level for total dissolved solids in public drinking water although it is recommended that values not exceed 500 parts per million (PPM) if other supplies are available. Aquifers containing up to 10,000 PPM are considered potentially useful as public water sources and subject to protection. Within the sandstone aquifer out of 1,137 wells tested by the U.S. Geological Survey less than 10% had values of total dissolved solids exceeding 500 PPM. Most of these wells are located east of a line running from Marinette to Columbia to Crawford County. One well in the City of Sheboygan has consistently yielded results around 9,000 to 10,000 PPM total dissolved solids. The well is located near the Lake Michigan shoreline withdrawing water from the sandstone aquifer. As the aquifer dips eastward toward the Mighican basin, there is an increase in TDS. This well is located far enough east to intercept some of this poorer quality water.

Silurian Dolomite Aquifer

The Silurian Dolomite aquifer underlies all or part of 15 counties along the eastern border of the State, from the Door County peninsula on the north to the Wisconsin-Illinois border on the south. The aquifer includes rocks of Silurian age and a small occurrence of Devonian age shales and dolomites. The Devonian age rocks occur near the Lake Michigan shoreline from Sheboygan to Milwaukee. The dominant unit of this aquifer is the Niagara Dolomite. Weidman and Schultz (1915, p. 37) provided a discription of this aquifer from which the following summary is taken.

The Niagara Dolomite

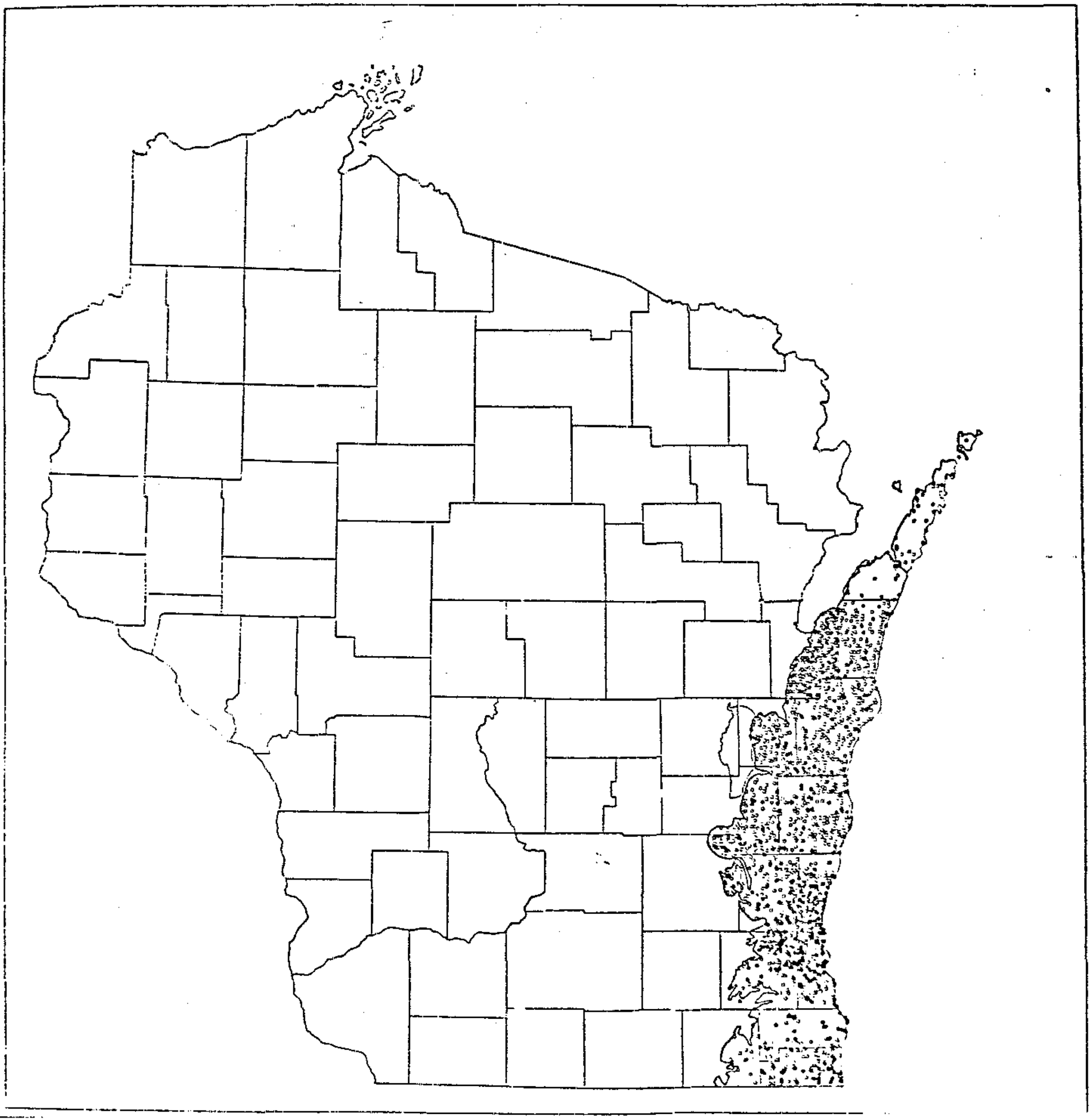
The Niagara Dolomite forms a broad belt in the eastern part of the state, along the shore of Lake Michigan. It extends as a continuous formation, from Door County on the north, to Kenosha County on the south, and forms the summits of isolated mounds farther to the southwest.

The Niagara is a pure dolomite. The number of beds composing the formation is greater in the north-central part of the belt than farther south. Schrock (1939) provides an excellent discussion of the reef complexes within the Niagara while Mukulic (1979) discusses the stratigraphy and provides an extensive list of references for the Niagara. Chamberlin (1883), in his report of Eastern Wisconsin, divides the Niagara in the south, into four groups of beds, while in the north, he recognizes six. In some places these beds are uniform in color and texture, while in others they possess many irregularities. The upper part of the Niagara Dolomite is highly siliceous and cherty. The dolomite beds are of varying colors; gray, blue, white, and buff being common. The thickness of the formations is somewhat irregular, varying from 200 feet in the southern part of the district to over 600 in the central and northern part. The greatest thickness apparently occurs at about the center of the dolomite belt in the vicinity of Sheboygan. From well records it is apparent that the thickness in the northern half of the belt is considerably greater than in the southern half.

In places, the beds are coarse, crystalline, and granular, occasionally soft, and earthy. These sandy beds, and some of the more porous dolomites, are the chief aquifers found in this horizon. Intersecting joints, fractures and solution cavities also provide easily accessible pathways for water and result in higher yields to wells. The location and density of selected wells withdrawing water from the Silurian Aquifer are shown in Figure 18.

Water Yielding Characteristics

Primary permeability in the Silurian Aquifer is very low, on the order of 10^{-5} cm/sec. Secondary permeability has been developed along joints and fracture planes that have been widened by solution. As a result, the yield to wells is highly dependent on how many fractures are intercepted by the open portions of the well. Thompson (1981) compiled a series of tests measuring transmissivity of the Silurian Aquifer near Wind Point, Racine County (Table 1).



LOCATION OF SELECTED WELLS HAVING THE SILURIAN AQUIFER AS A SOURCE

Figure 18

Table 1

Test No.	Permeability GPD/FT^2	Transmissivity GPM/FT
1	36.4	10,000
2	0.9	260
3	9.1	2,500
4	2.7	750
5	1.0	280

The variability in transmissivity is well demonstrated by these tests. Near Racine, Wisconsin where these tests were conducted, the Niagara is about 200 feet thick. Farther northward and eastward, the formation thickens and higher transmissivities are possible. Figure 19 (Devaul, 1975 in map folder) illustrates the probable well yeilds for the Niagara Aquifer.

Water Quality (See Appendix)

The concentration of dissolved solids for the Silurian Aquifer is shown in Section 3 of the appendix. In general, the water is a calcium-magnesium-bicarbonate type, very hard and high in iron.

Sand and Gravel Aquifer

The sand and gravel aquifer includes unconsolidated deposits of gravel, boulders, sand, silt and clay laid down by the last advance and retreat of the Continental ice sheets or deposited beyond their border as outwash or aeolian deposits. It is not a continuous unit but highly variable in areal distribution and in lithology.

Hadley and Pelham (1976) compiled the available information on the character and distribution of these deposits. Their discription follows.

"Study of the glacial deposits of North America has shown that there were four major advances and retreats of the ice. It is now believed that glacial deposits representing three of these advances are exposed in Wisconsin. The deposits from the early advances are, however, of quite limited areal extent. The great majority of the glacial deposits at the surface of the State were formed by the last of the four advances making the identification and study of the buried older deposits extremely difficult. The time during which the deposits of the last advance were laid down is know as the Wisconsin Age because deposits of the advance are well-preserved in the State and were studied here in detail.

During the fourth advance, differences in the rate of ice accumulation in the source areas, coupled with difference in topography, caused the ice front to split into a series of tongue-like lobes. Four major lobes of ice entered Wisconsin and each lobe tended to follow pre-existing low areas of the Earth's surface. One moved along and beyond the present Lake Michigan basin: a second was similarly related to the Green Bay area; the third was similarly related to the Lake Superior area and extended into the extreme northwest corner of the State; and a fourth lobe moved southwestward across that part of the northern peninsula of Michigan south of the Keweenaw peninsula.

As the glacial ice moved, it picked up vast quantities of soil and rock materials and these were subsequently deposited along its route of travel, especially at or near the margins of the ice. The general term for material deposited through glacial action is glacial drift.

Many of the glacial deposits consist of "till," an unsorted and unstratified heterogeneous mixture of clay, silt, sand, and boulders. Till is deposited directly by and under a glacier, either during glaciation or at the time of glacial melting, without being subsequently reworked by the water that is released as the glacier melts.

Till is normally deposited in the form of moraines, which are mounds, ridges, or other accumulations deposited chiefly by the direct deposition from glacial ice. Moraines can be divided into two main classes, namely ground moraine and end moraines. Ground moraine is a thin layer of till which generally has a gently rolling surface and which is formed from the rock debris that was dragged along, in, or under the glacial ice. End moraines are normally ridge-like deposits, often showing considerable relief, that form by the piling up of till at the leading edge of an actively flowing glacier during the periods when the positon of the ice front was essentially stationary. There are a number of types of moraines that are lumped under the heading of end moraines. One of the more important of these is the terminal moraine which forms at or near a more or less stationary edge marking the limit of an important glacial advance. Another type of end moraine is the recessional moraine. These form during temporary but significant pauses in the final retreat of a glacial front or during minor readvances of the ice front in a period of general recession. Finally there is interlobate moraine, which forms where the margins of adjacent glacial lobes come together. Figure 20 is a generalized map showing the distribution of end moraines in Wisconsin.

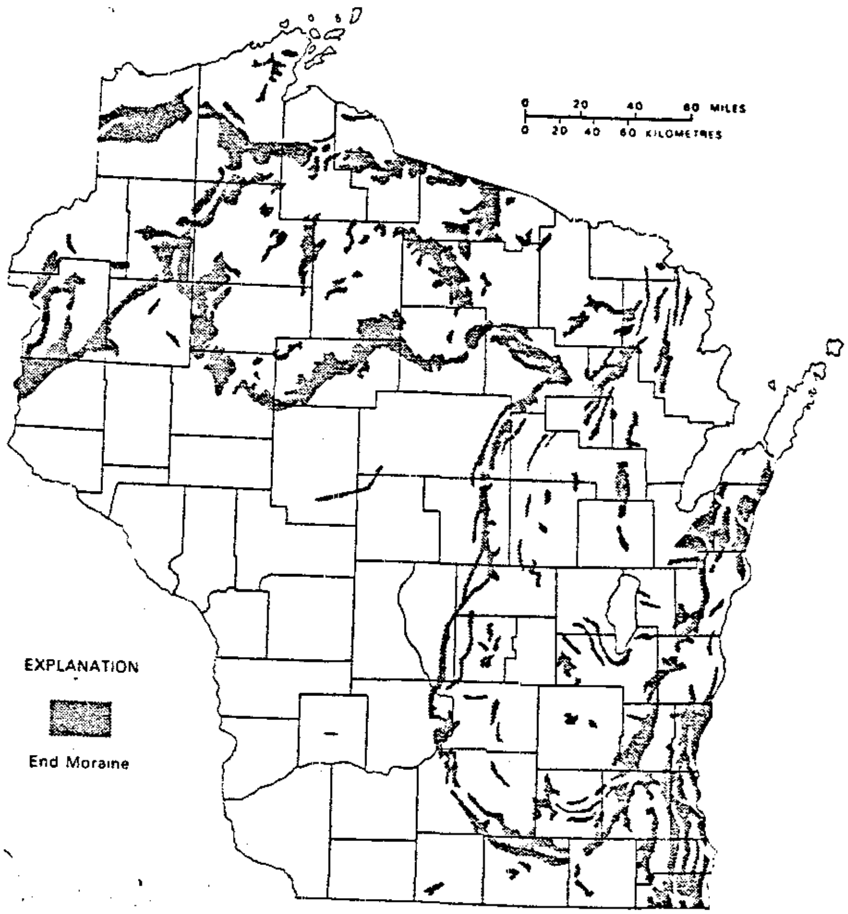


Figure 20

Generalized Distribution of End Moraines. (Hadley and Pelham, 1976)

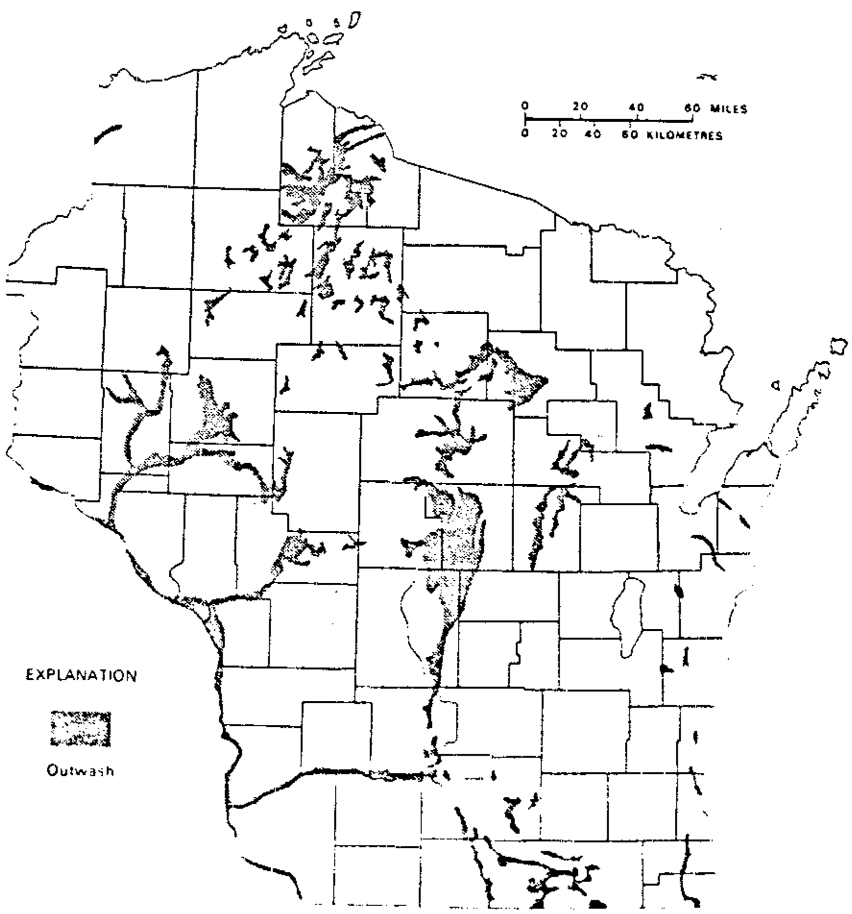


Figure 21 Major Outwash Deposits (Hadley and Pelham, 1976)

Rock and soil debris released from the melting glacier was carried by streams of meltwater and deposited at or near the ice front. These deposits normally consist of sorted and stratified materials, chiefly sand and gravel, and are called outwash. When the meltwater streams flowed out from the glacier across the terminal moraine, they deposited accumulations of sand and gravel called outwash fans. In many cases these fans coalesced forming broad sheets of outwash called outwash plains. Large bodies of outwash were also deposited along the valleys of the major streams that flowed from the glaciers. Outwash deposits confined to the valleys of the major streams are called valley trains. Valley train deposits dissected during erosion by later streams are preserved as bench-like deposits called outwash terraces. Figure 21 is a generalized map showing the distribution of the major deposits of outwash in the State.

When the glacial fronts retreated, the newly deposited materials were highly vulnerable to erosion. Vast quantities of fine-grained material, primarily silt, were picked up by the wind and redeposited elsewhere as a blanket on the surface. This wind-deposited, or aeolian, material is termed loess. In some areas of the State, fine sand was also wind-carried away from its original sites of deposition to form sand dunes. The distribution and thickness of the aeolian deposits of Wisconsin are shown on Figure 22.

A highly generalized map of glacial deposits of Wisconsin (fig. 23), indicates that a portion of southwestern Wisconsin has only valley train deposits and the deposits laid down in glacial lakes that formed when tributary valleys were dammed by the great volume of outwash deposited along the floors of the main valley. This region

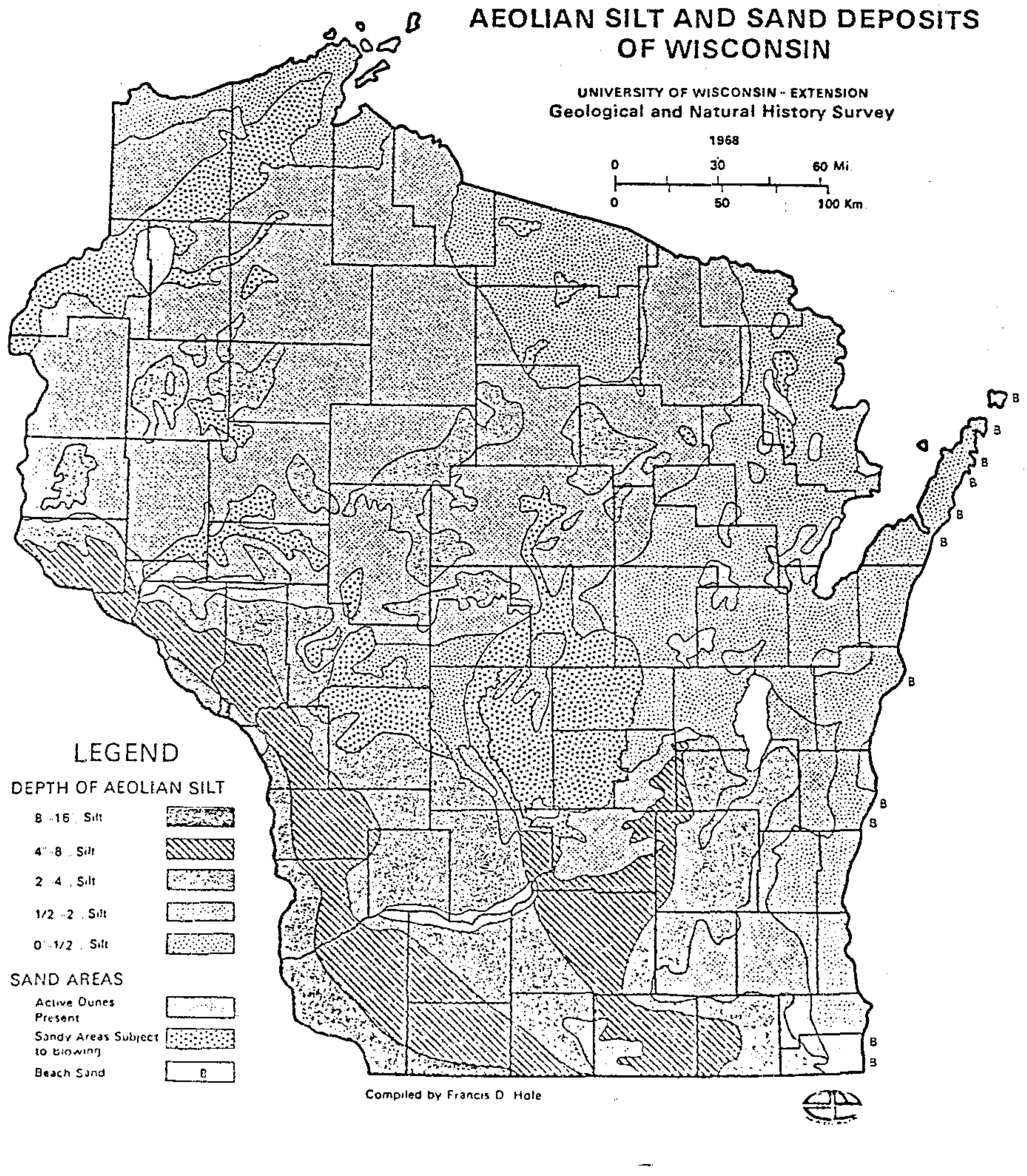

AEOLIAN SILT AND SAND DEPOSITS
OF WISCONSIN
UNIVERSITY OF WISCONSIN - EXTENSION
Geological and Natural History Survey
1968
0
30
60 Mi.
0
50
100 Km.
LEGEND
DEPTH OF AEOLIAN SILT
8"-16" Silt
4"-8" Silt
2'-4' Silt
1/2'-2' Silt
0'-1/2' Silt
SAND AREAS
Active Dunes Present
Sandy Areas Subject to Blowing
Beach Sand
B
Compiled by Francis D. Hole

Figure 22

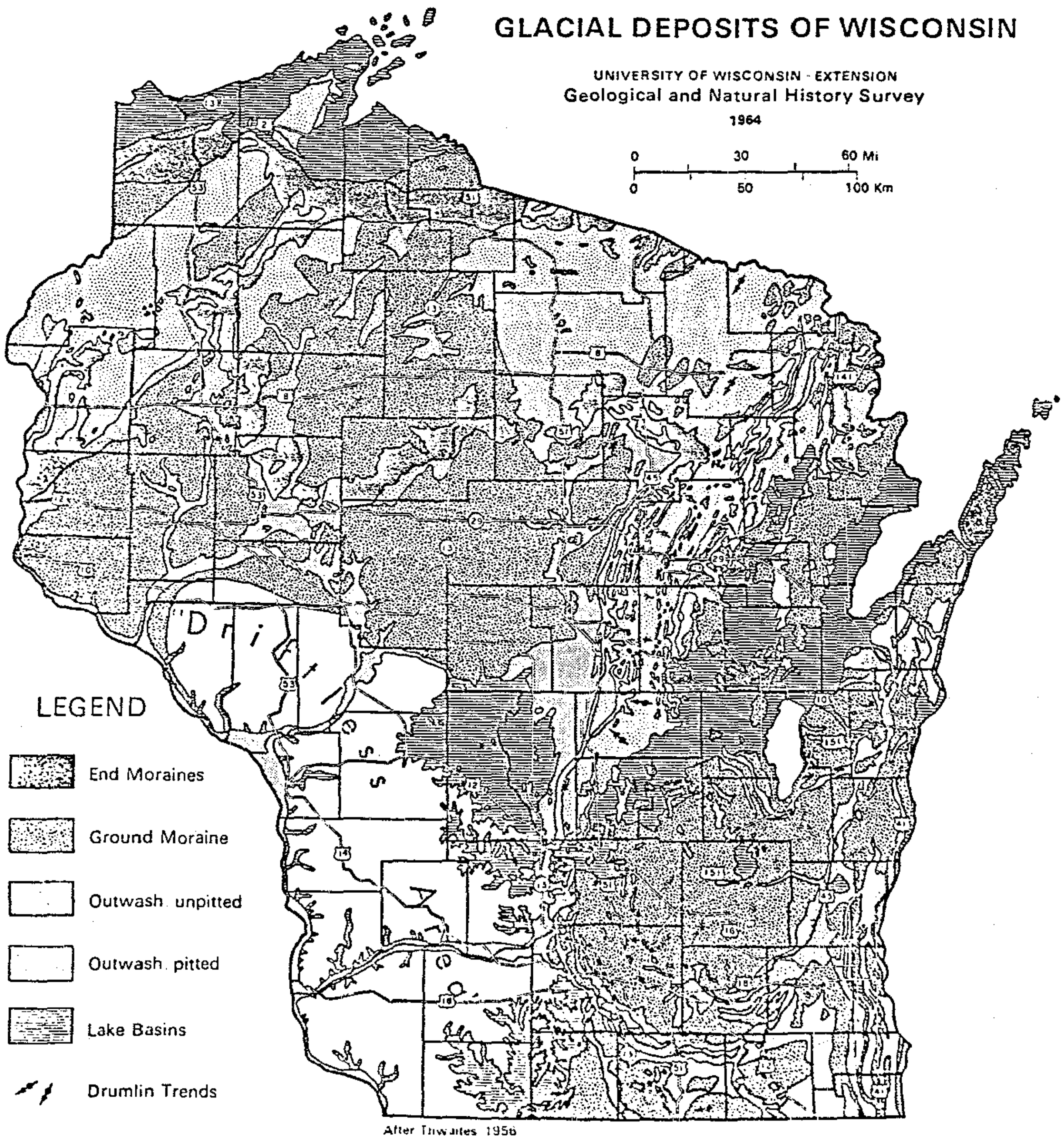

GLACIAL DEPOSITS OF WISCONSIN
UNIVERSITY OF WISCONSIN - EXTENSION
Geological and Natural History Survey
1964
0 30 60 Mi
0 50 100 Km
LEGEND
End Moraines
Ground Moraine
Outwash, unpitted
Outwash, pitted
Lake Basins
Drumlin Trends
After Thwaites 1956

Figure 23

is referred to as the Driftless Area. Most geologists familiar with the area believe that it was not glaciated during the Pleistocene epoch, but some investigators have taken the opposite view.

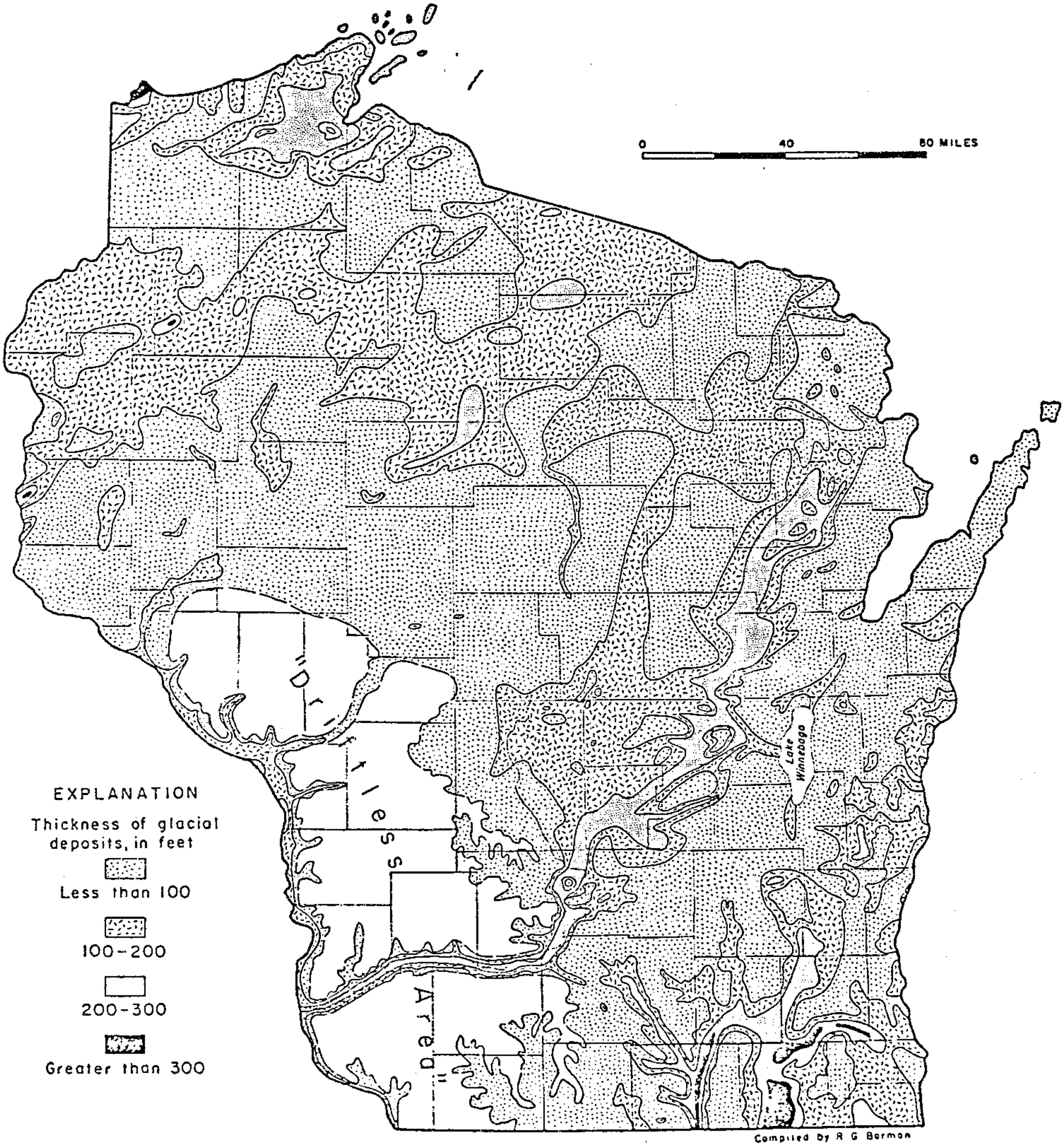
Before the onset of glaciation, the surface of Wisconsin had been deeply dissected by streams. Although no statewide map of the preglacial topography of the bedrock surface is available, a good approximation of its configuration can be obtained by reference to Figure 24, which is a map of the thickness of the glacial drift. Bedrock valleys are inferred from areas of thick drift.

Water Yielding Characteristics

The variability of the sand and gravel deposits have made it difficult to accurately predict the expected well yield. However, by examining many well records and drillers' reports, Devaul (1975) was able to construct a map showing the expected yield from the sand and gravel aquifer (fig. 25 in map folder). The highest well yields are found in the thick sequences of outwash sands and gravels and in preglacial valleys that were subsequently filled with coarse grained, permeable deposits. The central sand plain of Wisconsin is an example of such an area.

The central sand plain includes all or part of Wood, Portage, Waupaca, Juneau, Adams, Waushara, and Marquette Counties. Outwash sands, till, morainal deposits, dune sand, and alluvium have covered the area to as much as 300 feet thick. High-capacity irrigation wells developed in this area have supported the growth of intensive agriculture.

In the north central area of the state, the sand and gravel aquifer is the principal source of water where it directly overlies the crystalline rock. Yields vary throughout this area because of



PRELIMINARY MAP SHOWING THICKNESS OF GLACIAL DEPOSITS IN WISCONSIN

Cooperative Project of the U.S. Geological Survey and the
University Extension--The University of Wisconsin
Geological and Natural History Survey

Figure 24

the high clay content in much of the drift. Figure 26 shows the location and density of wells having the sand and gravel aquifer as a source while Figure 25 shows the probable well yields.

Water Quality (See Appendix).

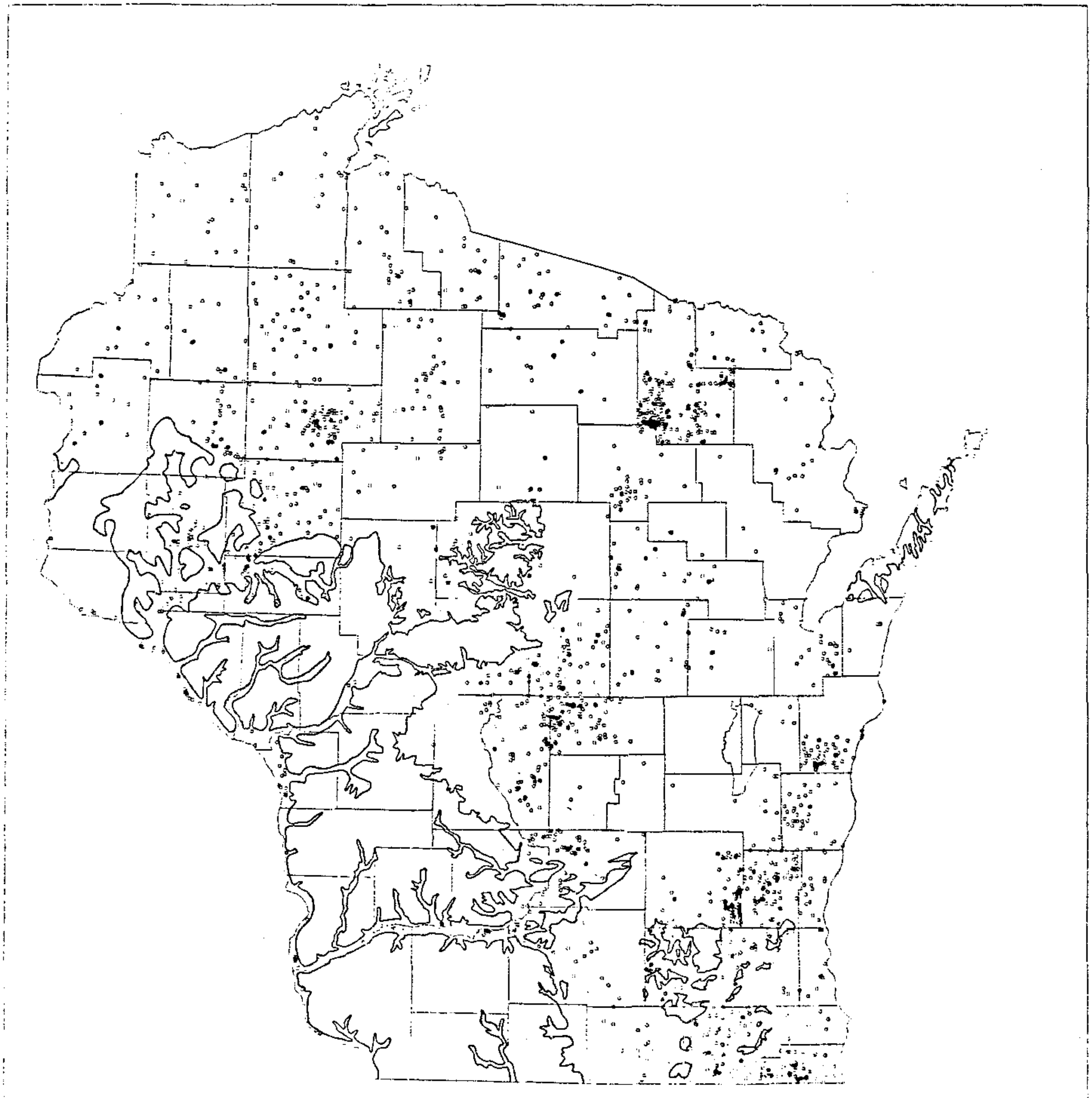
Water quality for the sand and gravel aquifer is presented in the appendix. Total dissolved solids are generally low but iron is often a problem. Areas of coarse sandy material have experienced problems with high nitrates and chlorides from surface sources of pollution.

Maquoketa Shale

The Maquoketa Shale of late Ordovician age overlies the Sinnipee Group and is overlain by the Neda Formation and the Niagara Dolomite. The formation occurs along the eastern border of the state from Door County to Walworth County. There are several minor occurrences in Southern Grant County and Lafayette County. Thickest sections of the Maquoketa occur in the north and are as much as 600 feet thick. Southward it thins to 150 to 200 feet thick. Lithologically the Maquoketa is a bluish to greenish shale with occasional sandy beds and thin beds of limestone. It is usually soft but may be slaty in some areas. It weathers quickly and is rarely exposed in cliffs or outcrops.

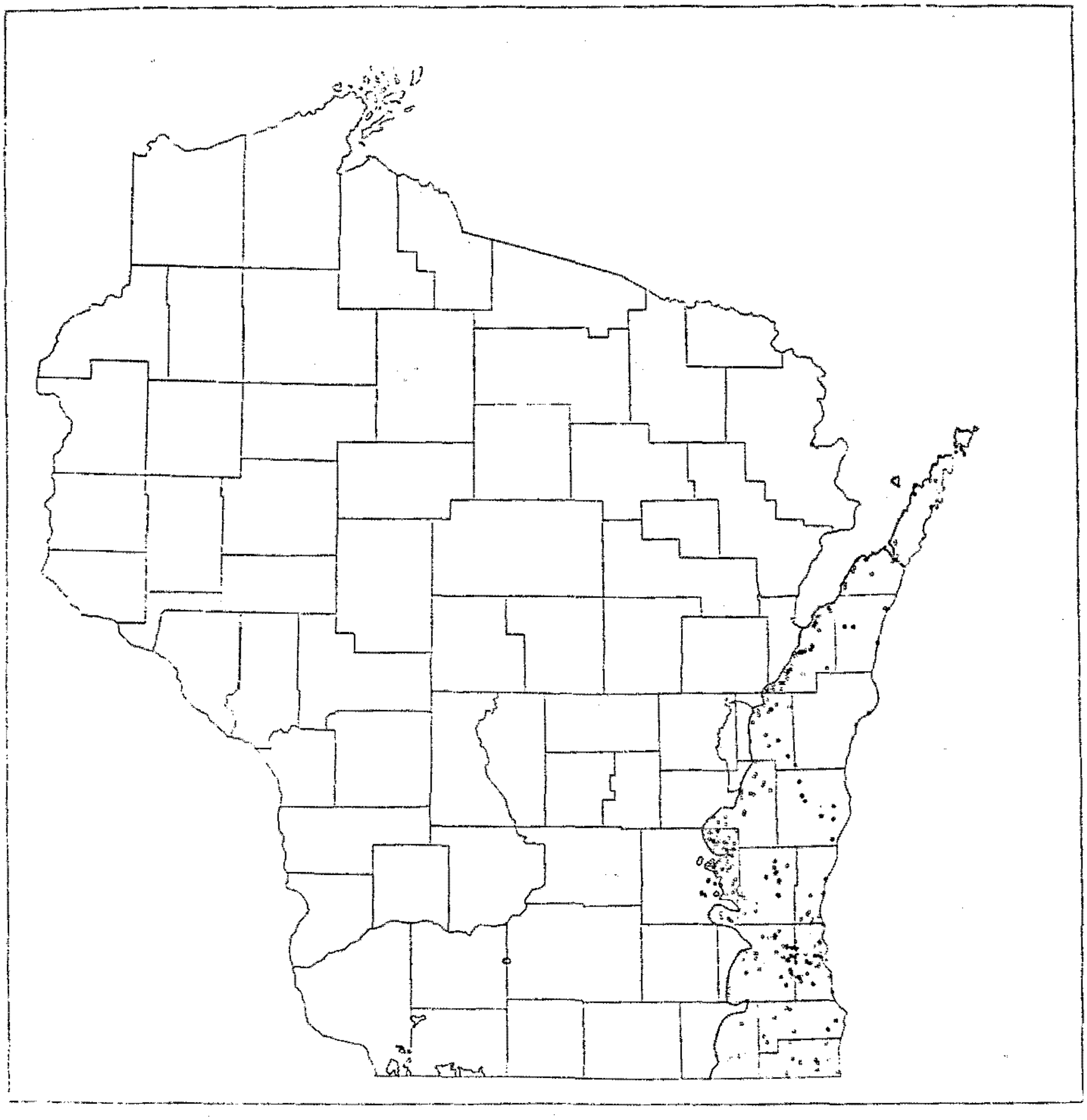
Water Yielding Characteristics

The Maquoketa Shale is the confining bed for the sandstone aquifer in Eastern Wisconsin. At the same time there are weathered zones near the top of the formation and some sandy carbonate beds within the unit that yield sufficient water to wells to be useful. The location of wells utilizing the Maquoketa as a source of ground water are shown in Figure 27.



LOCATION OF SELECTED WELLS HAVING THE SAND AND GRAVEL AQUIFER AS A SOURCE

Figure 26



LOCATION OF SELECTED WELLS HAVING THE MAQUOKETA SHALE AS A SOURCE

Figure 27

Water Quality

Water quality within the Maquoketa is generally good in those beds having sufficient permeability to yield usable quantities of water. Most wells tapping the Maquoketa are also open to other aquifers and provide only a composite sample for water quality analysis. Examination of records from the U.S. Geological Survey and Wisconsin Geological Survey well files indicate that the upper portions of the Maquoketa reflect the same trends in water quality as the overlying Niagara Formation. Most of the water contains less than 500 PPM total dissolved solids with some of the more easterly wells or wells tapping the more permeable zones from deeper within the Maquoketa showing total dissolved solids concentration up to and occasionally exceeding 1000 PPM.

Lake Superior Sandstones and Lava Flows

In northwestern Wisconsin in Ashland, Douglas, Bayfield, Washburn and Burnett Counties are a complex series of sandstones, quartzites and mafic volcanic rocks of approximately Late Precambrian age. Their age and stratigraphic relationship to other surrounding formations is not well defined because of a complex history of erosion, reworking, faulting and igneous events. Where the overlying Sand and Gravel Aquifer is too thin or clayey to yield adequate water supplies wells are usually deepened to include the underlying sandstone or volcanics. Cross section number 5 (fig. 31 in map folder) depicts the complicated relationship of these units.

The volcanic rocks predate the sandstones and dip steeply toward the axis of the Lake Superior syncline. Faulting and erosion have brought the sandstones adjacent to the volcanics in some areas.

This is demonstrated by the cross section and shown in the geologic map of the State (fig. 3).

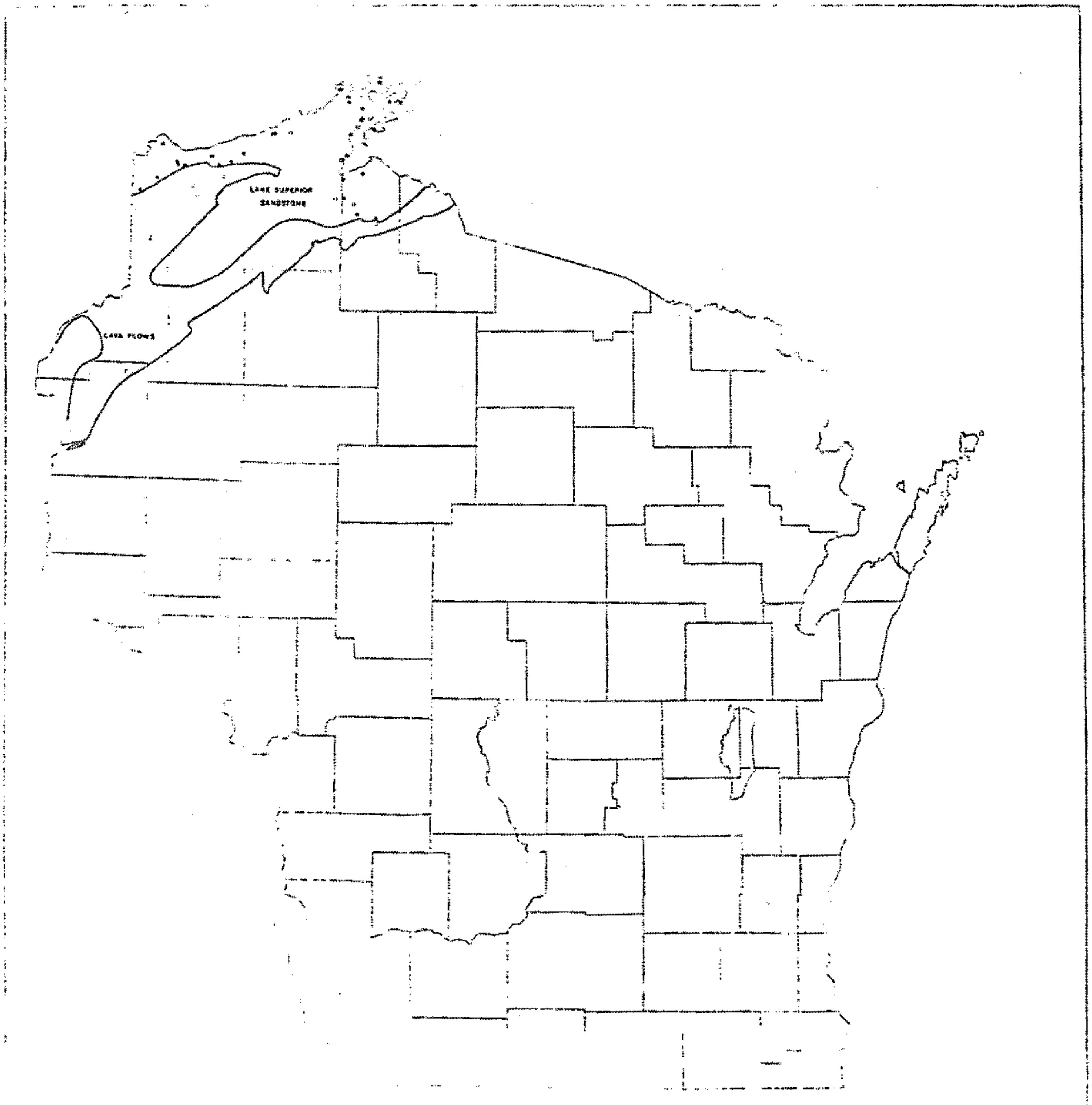
Lake Superior Sandstones is an informal term used to refer to several diverse groups that are predominately sandstones. Within Wisconsin the two most important groups are the Oronto composed of the Outer Conglomerate Formation, the Nonesuch Formation and the Freda Formation and the Bayfield Group composed of the Orienta, Devil's Island and Chequamegon Formations. The Nonesuch Formation is predominantly shale, all the other formations are coarse to fine grained sands with shale or silty beds common.

Water Yielding Characteristics

In the northwest areas of the State where the Sand and Gravel Aquifer does not yield sufficient water, wells are often deepened into the underlying sandstones or volcanics. Although these formations differ considerably in geologic character their hydrologic character is similar. Near the surface where the units have been weathered and fractured by faulting or joint systems, wells may yield several hundred gallons per minute. In other areas that are less disturbed, wells will produce very little water. The City of Washburn in Bayfield County drilled a well 700 feet deep in the Lake Superior Sandstones that tested at 688 gallons per minute with 197 feet of drawdown. Most wells yield much less than this. The location of selected wells tapping the Lake Superior sandstones and lava flows is shown in Figure 28.

Water Quality

Near the surface of these formations good quality water can usually be pumped by wells. However, many of the wells drilled



LOCATION OF SELECTED WELLS HAVING THE LAKE SUPERIOR SANDSTONE AND LAVA FLOW AQUIFERS AS A SOURCE

Figure 28

deeper into the formations have encountered water having high concentrations of iron, manganese, and chlorides.

Table 2 summarizes the water quality information for these aquifers.

Table 2

Summary of Total Dissolved Solids

In Lake Superior Sandstones and Lava Flows

Number of Wells Tested	146
Maximum Concentration	7625 PPM
Mean Concentration	388 PPM
Minimum Concentration	42 PPM
Percentage of Wells Having This Concentration or Less	
95%	1373 PPM
90%	716 PPM
75%	294 PPM
50%	199 PPM
25%	131 PPM
10%	95 PPM
5%	70 PPM

(Compiled by Phil Kammerer, 1981)

Precambrian Crystalline Basement Rock

The rock formations of precambrian age are at or near the surface in Northern Wisconsin. In other areas of the State, rocks of Paleozoic or younger age cover the crystalline rocks. Depth to the basement rocks is shown in Figure 29 (After Thwaites, 1957).

The Precambrian rocks are predominately intrusive igneous rocks but include extrusive volcanics, highly metamorphosed shales,

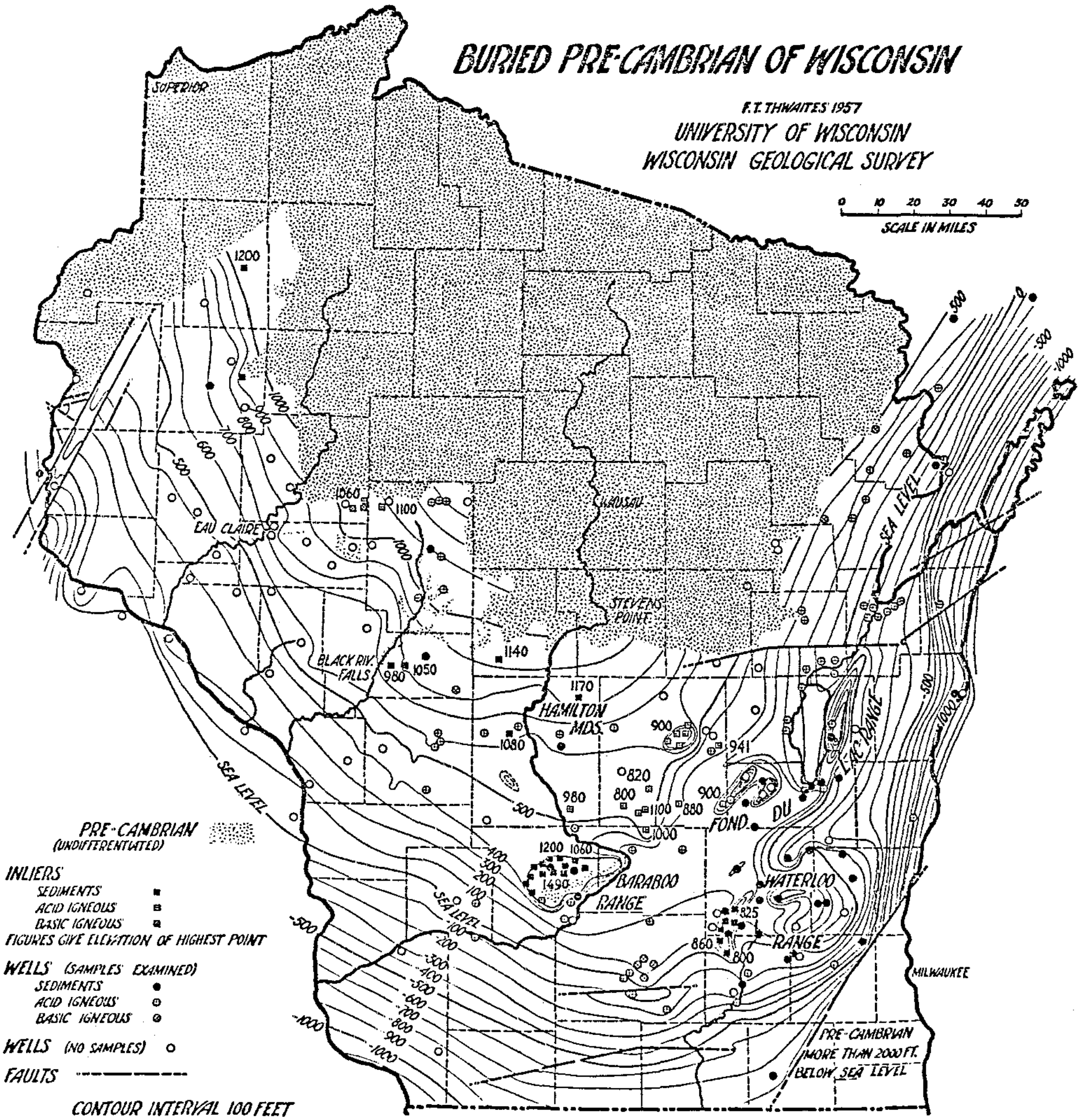

BURIED PRE-CAMBRIAN OF WISCONSIN
F.T. THWAITES 1957
UNIVERSITY OF WISCONSIN
WISCONSIN GEOLOGICAL SURVEY
0 10 20 30 40 50
SCALE IN MILES
SUPERIOR
EAU CLAIRE
WAUSAU
STEVENS POINT
BLACK RIV. FALLS
HAMILTON MDS.
FOND DU LAC RANGE
BARABOO RANGE
WATERLOO RANGE
MILWAUKEE
SEA LEVEL
PRE-CAMBRIAN MORE THAN 2000 FT. BELOW SEA LEVEL
PRE-CAMBRIAN (UNDIFFERENTIATED)
INLIERS
SEDIMENTS
ACID IGNEOUS
BASIC IGNEOUS
FIGURES GIVE ELEVATION OF HIGHEST POINT
WELLS (SAMPLES EXAMINED)
SEDIMENTS
ACID IGNEOUS
BASIC IGNEOUS
WELLS (NO SAMPLES)
FAULTS
CONTOUR INTERVAL 100 FEET

Figure 29

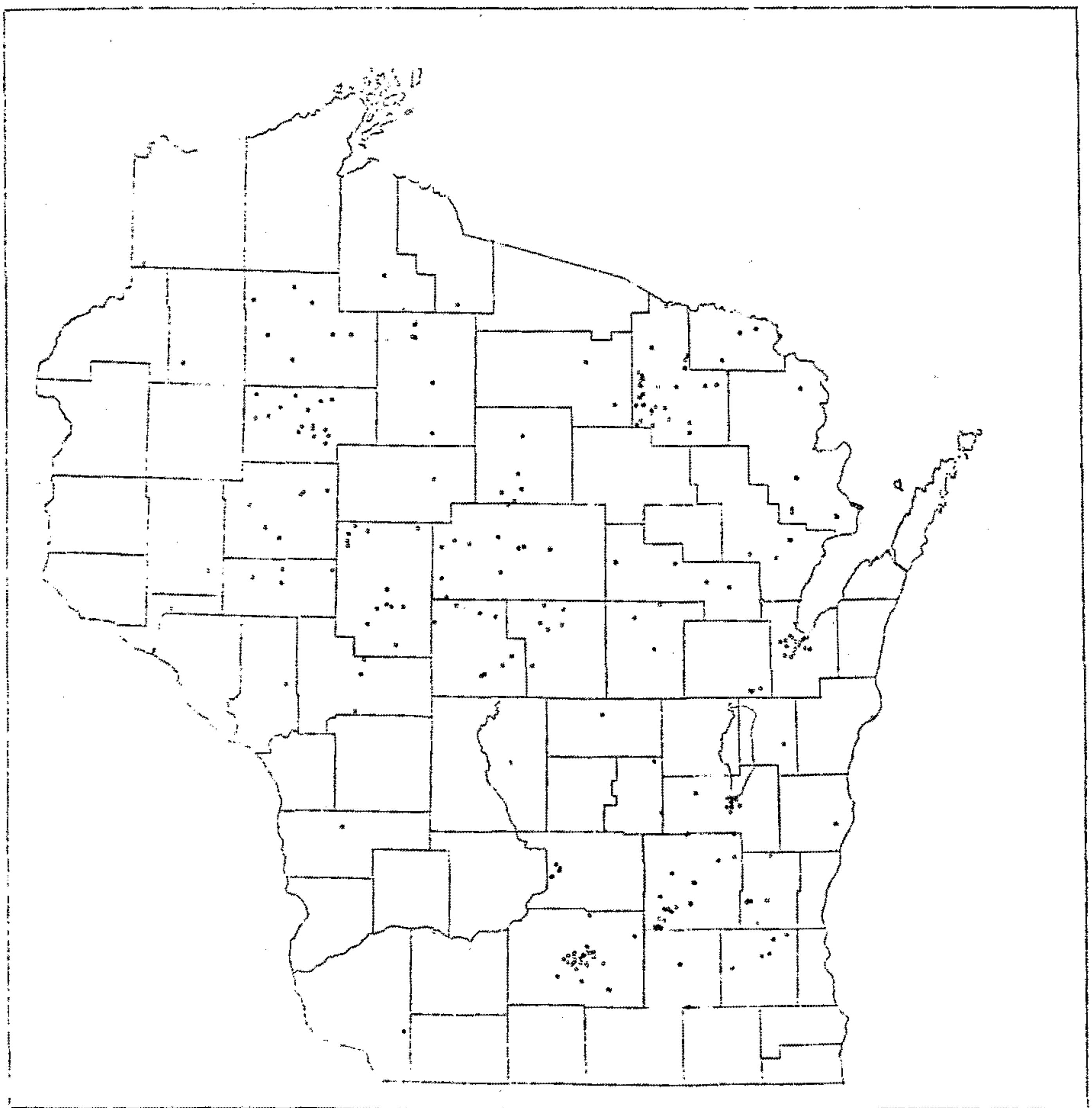
quartzites and marbles. The distribution of some of these rock types are shown on the bedrock geology map of Wisconsin (fig. 3).

Water Yielding Characteristics

Ground water within the crystalline basement moves through fractures and zones where the rock is weathered or broken by faulting. There is very little intergranular permeability. Where wells intersect these joints or fractures there may be significant flow; in other areas there is little flow. Figure 30 shows the location of selected water wells penetrating to the basement rock. A separate list compiled by Roshardt (1976) includes some water wells and stratigraphic test wells reaching the basement.

Water Quality

Many wells which derive significant quantities of water from the crystalline basement have provided good quality water. However, most of these wells do not penetrate deeply into the rock. Water samples from mineral exploration holes near Crandon and deep iron mines near Hurley have yielded total dissolved solids concentrations near or exceeding sea water concentrations. Little comprehensive information is available on water quality from the basement rocks.



LOCATION OF SELECTED WELLS HAVING THE CRYSTALLINE BASEMENT AQUIFER AS A SOURCE

Figure 30

Concluding Statement

The preceeding summary of the ground water resources of Wisconsin is an attempt to demonstrate the interrelations of all the Water resources of the State. Water falling as rain must pass through the sand and gravel aquifer to reach the Silurian Dolomite, or the sandstone or the crystalline basement. Water from these various aquifers is discharged to wetlands and streams. If any portion of this cycle of water is disturbed the entire resource will feel the effects. Our present civilization threatens the integrity of the hydrologic cycle, from acid rain to agricultural chemicals to urban runoff. Regulatory authorities are forced to walk a narrow path between prohibitive enforcement and permissive neglect. It is hoped that the above summary of the ground water resources of Wisconsin will aid in their understanding of the interrelationships of ground water systems and the formulation of rational means to protect and preserve them for use now and into the future.

LIST OF REFERENCES

Black, R.F., N.K. Bleuer, F.D. Hole, N.P. Lasca, and L.J. Maher, Jr., 1970, Pleistocene Geology of Southern Wisconsin, Wisconsin Geological and Natural History Survey Field Trip Guidebook.

Caswell, W.B., 1979, Groundwater Handbook for the State of Maine, Maine Geological Survey, Augusta, Maine, 54 p.

Chamberlin, T.C., 1883, Geology of Wisconsin, Survey of 1873-1879, Volume I, 725 p.

__________, 1882, Geology of Wisconsin, Survey of 1873-1879, Volume IV, 779 p.

Cotter, R.D., R.D. Hutchinson, E.L. Skinner and D.A. Wentz, 1969, Water Resources of Wisconsin: Rock-Fox River Basin, U.S. Geological Survey, Water Resources Division, Hydrologic Atlas No. 360, 4 Shts.

Davis, R.A., 1970, Lithostratigraphy of the Prairie du Chien Group, pp. 35-42, in Field Trip Guidebook for Cambrian-Ordovician Geology of Western Wisconsin, Wisconsin Geological and Natural History Survey, Information Circular No. 11, 131 p.

DeVaul, R. and J.H. Green, 1971, Water Resources of Wisconsin: Central Wisconsin River Basin, U.S. Geological Survey, Water Resources Division, Hydrologic Atlas No. 367, 4 Shts.

DeVaul, R.W., 1975, Probable Yields of Wells in the Sand-and-Gravel Aquifer, Wisconsin, U.S. Geological Survey, Wisconsin Geological and Natural History Survey, 1 Sht.

__________, 1975, Probable Yields of Wells in the Sandstone Aquifer, Wisconsin, U.S. Geological Survey, Wisconsin Geological and Natural History Survey, 1 Sht.

__________, 1975, Probable Yields of Wells in the Niagara Aquifer, Wisconsin, U.S. Geological Survey, Wisconsin Geological and Natural History Survey, 1 Sht.

Environmental Protection Agency, 1975, National Interim Primary Drinking Water Regulations, Environmental Protection Agency, EPA-570/9-76-003, 159 p.

Flint, R.F., 1971, Glacial and Quaternary Geology, John Wiley and Sons, 892 p.

Freeze, R. Allan, and P.A. Witherspoon, 1967, Theoretical Analysis of Regional Ground Water Flow, 2. Effect of Water Table Configuration and Subsurface Permeability Variation, Water Resources Research, v. 3, pp. 623-634.

Hadley, D.W., 1976, with J.H. Pelham, Glacial Deposits of Wisconsin: Sand and Gravel Resource Potential, Wisconsin Geological and Natural History Survey and Wisconsin State Planning Office's Land Resources Analysis Program, Technical Report, 19 p.

Hindall, S.M. and E.L. Skinner, 1973, Water Resources of Wisconsin: Pecatonica-Sugar River Basin, U.S. Geological Survey, Water Resources Division, Hydrologic Atlas No. 453, 3 Shts.

Hindall, S.M. and R.G. Borman, 1974, Water Resources of Wisconsin: Lower Wisconsin River Basin, U.S. Geological Survey, Water Resources Division, Hydrologic Atlas No. 479, 3 Shts.

Kammerer, P.A., Jr., 1981, Ground Water Quality Atlas of Wisconsin, Wisconsin Geological and Natural History Survey, Information Circular No. 39, 39 p.

Martin, L., 1965, The Physical Geography of Wisconsin, The University of Wisconsin Press, Madison, Wisconsin, 608 p., Wisconsin Geological and Natural History Survey, Bul. No. 36.

Maxey, G.B., 1964, Hydrostratigraphic Units, Journal of Hydrology, v. 2, pp. 124-129.

McLeod, R.S., 1975, A Digital-Computer Model for Estimating Drawdowns in the Sandstone Aquifer in Dane County, Wisconsin, Wisconsin Geological and Natural History Survey, Information Circular No. 28, 91 p.

Mikulic, D.G., 1979, The Paleoecology of Silurian Trilobites with a Section on the Silurian Stratigraphy of Southeastern Wisconsin, Ph.D. Thesis, Oregon State University, Corvallis, Oregon, 864 p.

Mitchell, V., 1981, Unpublished Compilation of Mean Rain Fall Data for Wisconsin, 1951 to 1980, State Climatologist's Office, Madison, Wisconsin.

Mudrey, M.G., Jr. and G.L. LaBerge, 1979, Stratigraphic Framework for the Wisconsin Middle Precambrian, Wisconsin Geological and Natural History Survey, Miscellaneous Paper 79-1.

Oakes, E.L. and L.J. Hamilton, 1973, Water Resources of Wisconsin: Menominee-Oconto-Peshtigo River Basin, U.S. Geological Survey, Water Resources Division, Hydrologic Atlas No. 470, 4 Shts.

Oakes, E.L. and R.D. Cotter, 1975, Water Resources of Wisconsin: Upper Wisconsin River Basin, U.S. Geological Survey, Water Resources Division, Hydrologic Atlas No. 536, 3 Shts.

Olcott, P.G., 1968, Water Resources of Wisconsin: Fox-Wolf River Basin, U.S. Geological Survey, Water Resources Division, Hydrologic Atlas No. 321, 4 Shts.

Ostrom, M.E., 1962, Unpublished Geologic Cross Sections for the Paleozoic Stratigraphy of Wisconsin, Wisconsin Geological and Natural History Survey, Madison, Wisconsin.

__________, 1965, Cambro-Ordovician Stratigraphy of Southwest Wisconsin, Wisconsin Geological and Natural History Survey, Information Circular No. 6, 29th Annual Tri-State Field Conference Guidebook, 57 p.

Ostrom, M.E., 1966, Cambrian Stratigraphy of Western Wisconsin, Wisconsin Geological and Natural History Survey, Information Circular No. 7, Guidebook for Annual Field Conference of Michigan Basin Geological Society, 79 p.

__________, 1967, Paleozoic Stratigraphic Nomenclature for Wisconsin, Wisconsin Geological and Natural History Survey, Information Circular No. 8, 1 Sht.

Roshardt, M., 1976, Index to Wells in Wisconsin Reaching Precambrian Rock, Wisconsin Geological and Natural History Survey, Open-file Report.

Shrock, R.R., 1939, Wisconsin Silurian Bioherms, Geological Society of America Bulletin, V. 50, pp. 529-562.

Sims, P.K. and G.B. Morey, Editors, 1972, Geology of Minnesota, pp. 425-430, Minnesota Geological Survey, St. Paul, Minnesota, 632 p.

Skinner, E.L. and R.G. Borman, 1973, Water Resources of Wisconsin: Lake Michigan Basin, U.S. Geological Survey, Water Resources Division, Hydrologic Atlas No. 432, 4 Shts.

Thompson, D., 1981, Unpublished Masters Thesis, University of Wisconsin-Milwaukee, Milwaukee, Wisconsin.

Thwaites, F.T., 1957, Buried Precambrian of Wisconsin, Wisconsin Geological and Natural History Survey, Map Series, 1 Sht.

Toth, J., 1962, A Theory of Ground Water Motion in Small Drainage Basins in Central Alberta, Canada, Journal of Geophysical Research, V. 67, pp. 4375-4387.

__________, 1978, Gravity-Induced Cross-Formational Flow of Formation Fluids, Red Earth Region, Alberta, Canada: Analysis, Patterns and Evolution, AGU Water Resources Research, V. 14, No. 5, pp. 805-843.

U.S. Geological Survey, 1981, Unpublished Summary of the Annual Runoff for the State of Wisconsin, U.S. Geological Survey, Water Resources Division, Madison, Wisconsin.

Weidman, S. and A.R. Schultz, 1915, The Underground and Surface Water Supplies of Wisconsin, Wisconsin Geological and Natural History Survey, Bul. No. 35, 664 p.

Wisconsin Geological and Natural History Survey, Publication, Bedrock Geology Map, 1 Sht.

Young, H.L. and S.M. Hindall, 1972, Water Resources of Wisconsin: Chippewa River Basin, U.S. Geological Survey, Water Resources Division, Hydrologic Atlas No. 386, 4 Shts.

Young, H.L. and R.G. Borman, 1973, Water Resources of Wisconsin: Trempealeau-Black River Basin, U.S. Geological Survey, Water Resources Division, Hydrologic Atlas No. 474, 4 Shts.

Young, H.L. and S.M. Hindall, 1973, Water Resources of Wisconsin: St. Croix River Basin, U.S. Geological Survey, Water Resources Division, Hydrologic Atlas No. 451, 4 Shts.

Young, H.L. and E.L. Skinner, 1974, Water Resources of Wisconsin: Lake Superior Basin, U.S. Geological Survey, Water Resources Division, Hydrologic Atlas No. 524, 3 Shts.

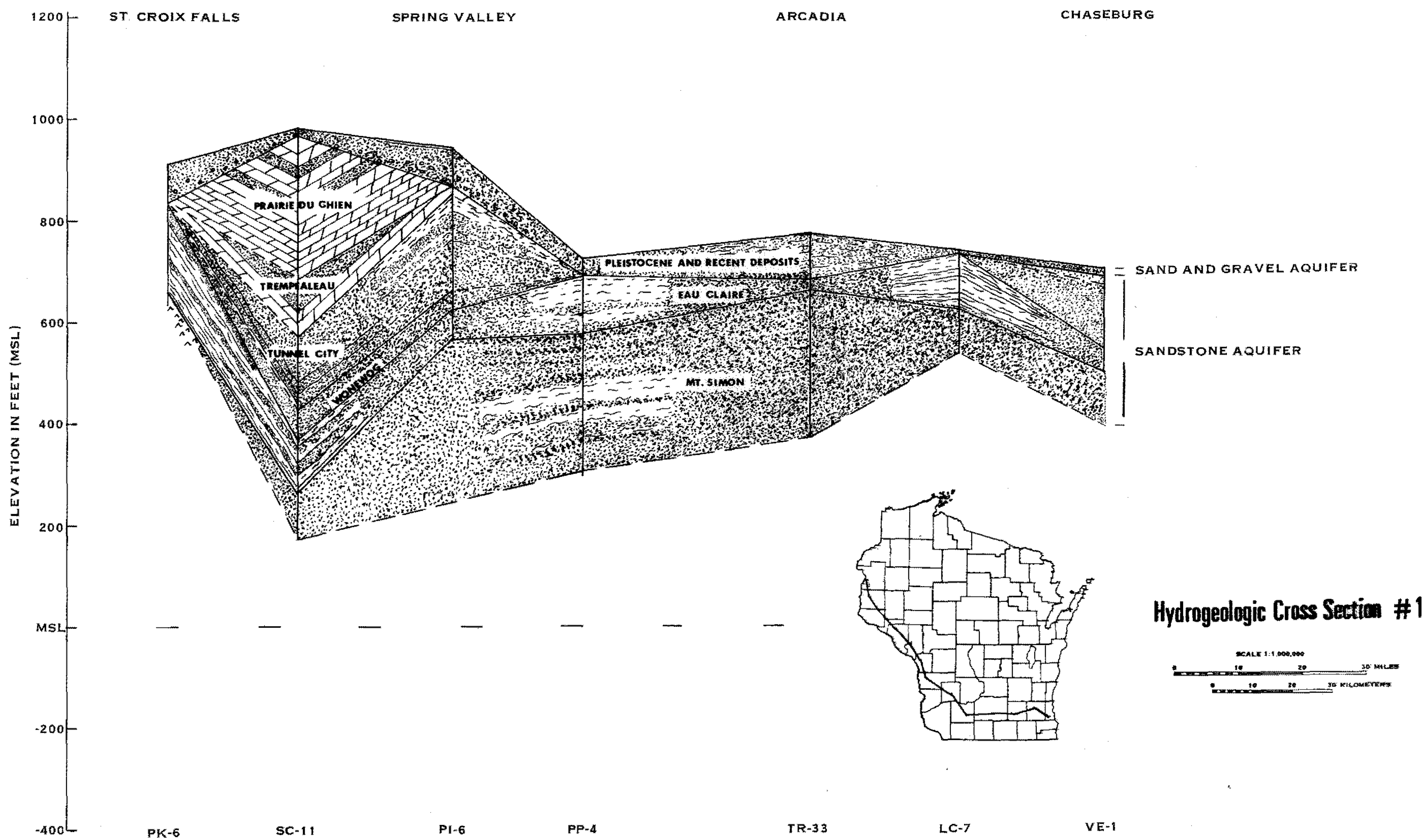


FIGURE 12

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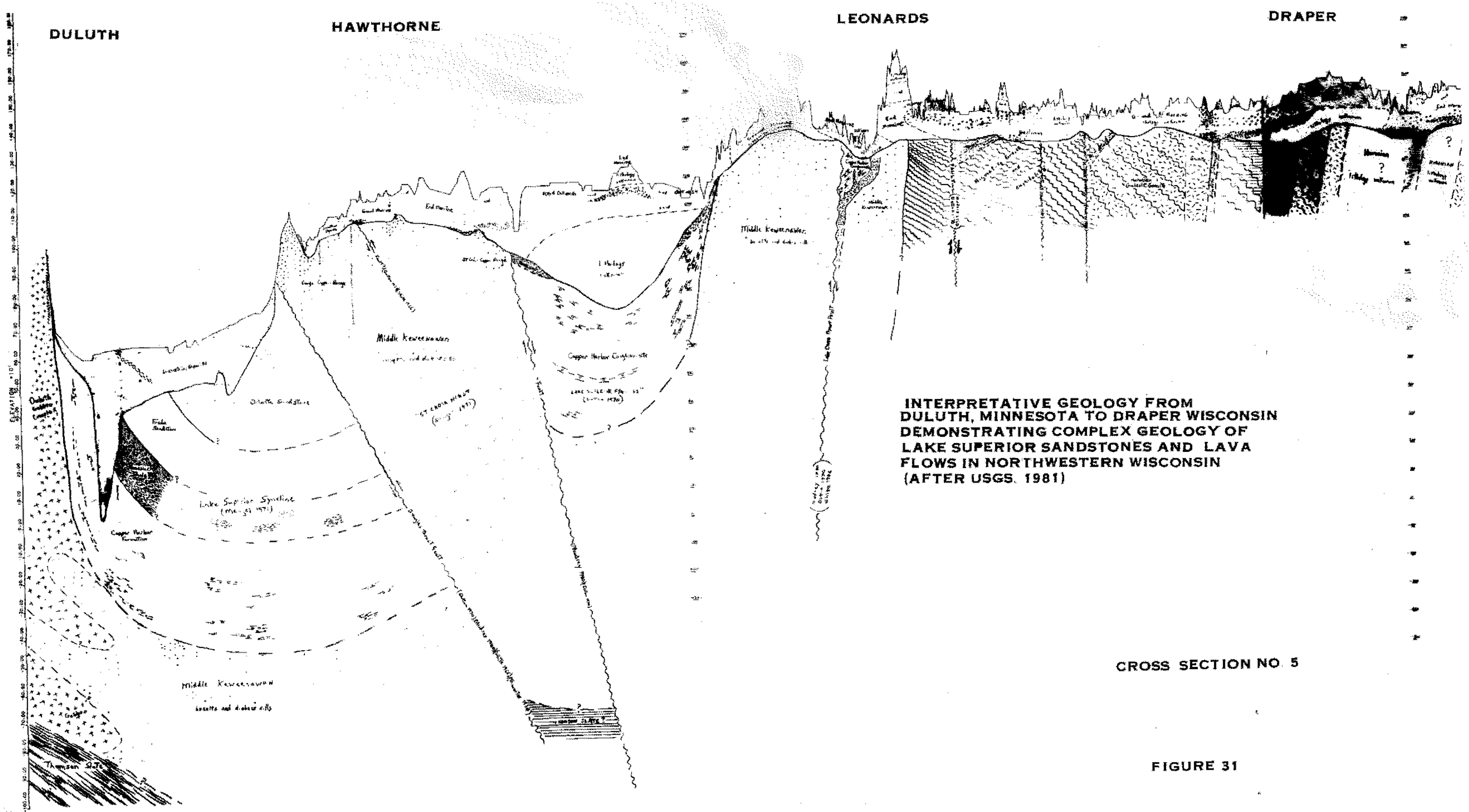
82-1



INTERPRETATIVE GEOLOGY FROM DULUTH, MINNESOTA TO DRAPER WISCONSIN DEMONSTRATING COMPLEX GEOLOGY OF LAKE SUPERIOR SANDSTONES AND LAVA FLOWS IN NORTHWESTERN WISCONSIN (AFTER USGS. 1981)

CROSS SECTION NO. 5

FIGURE 31

82-1

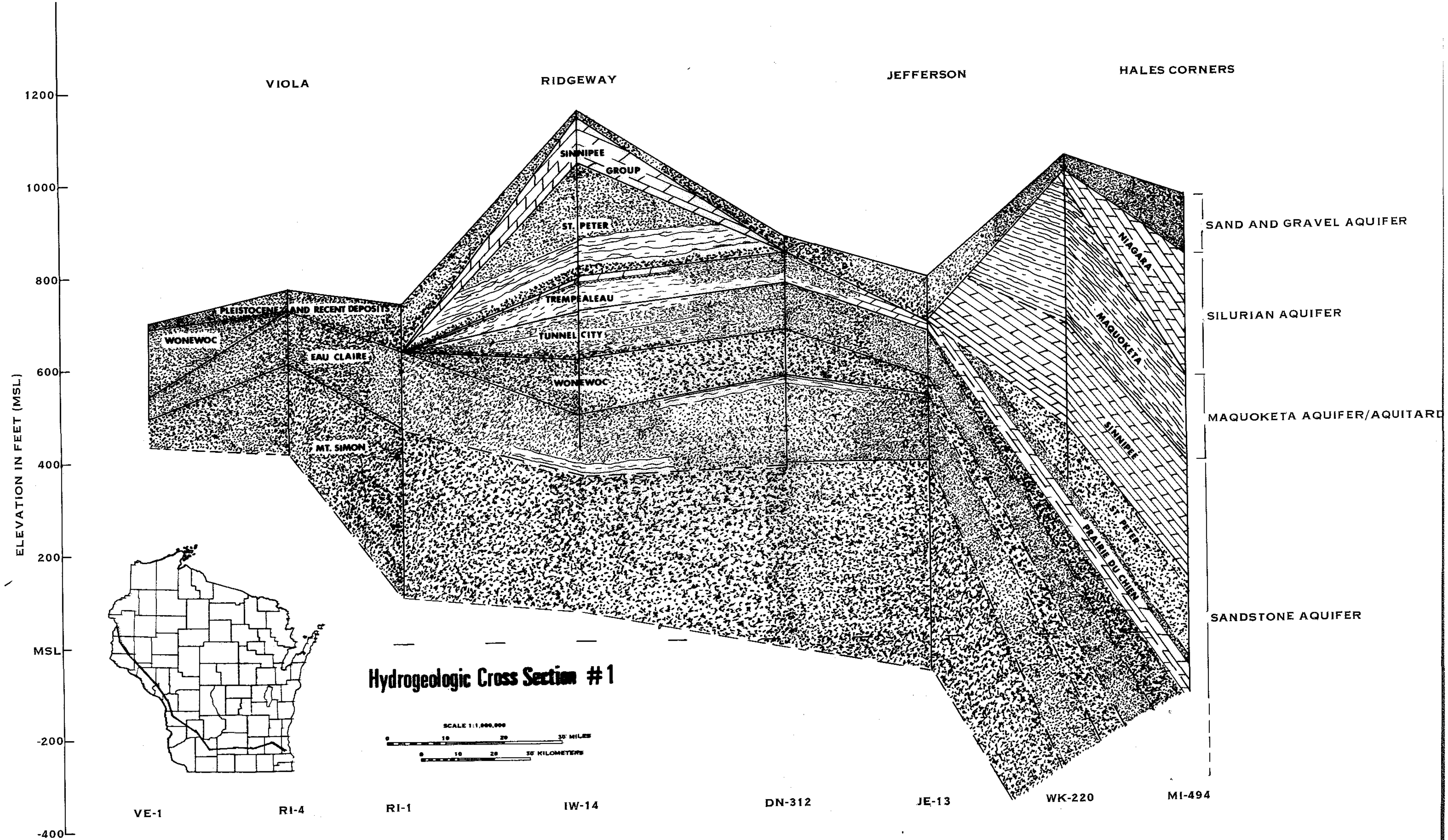
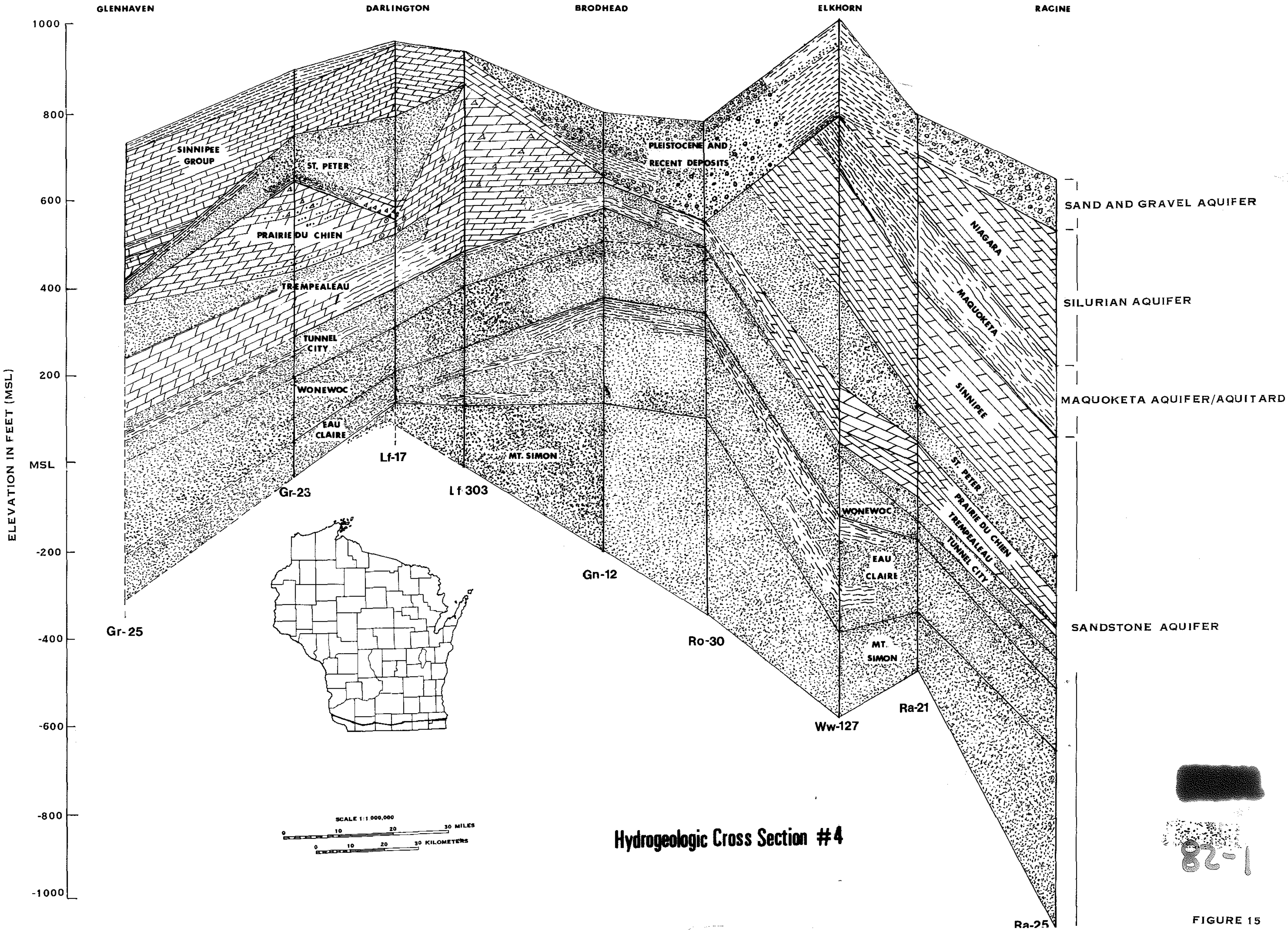


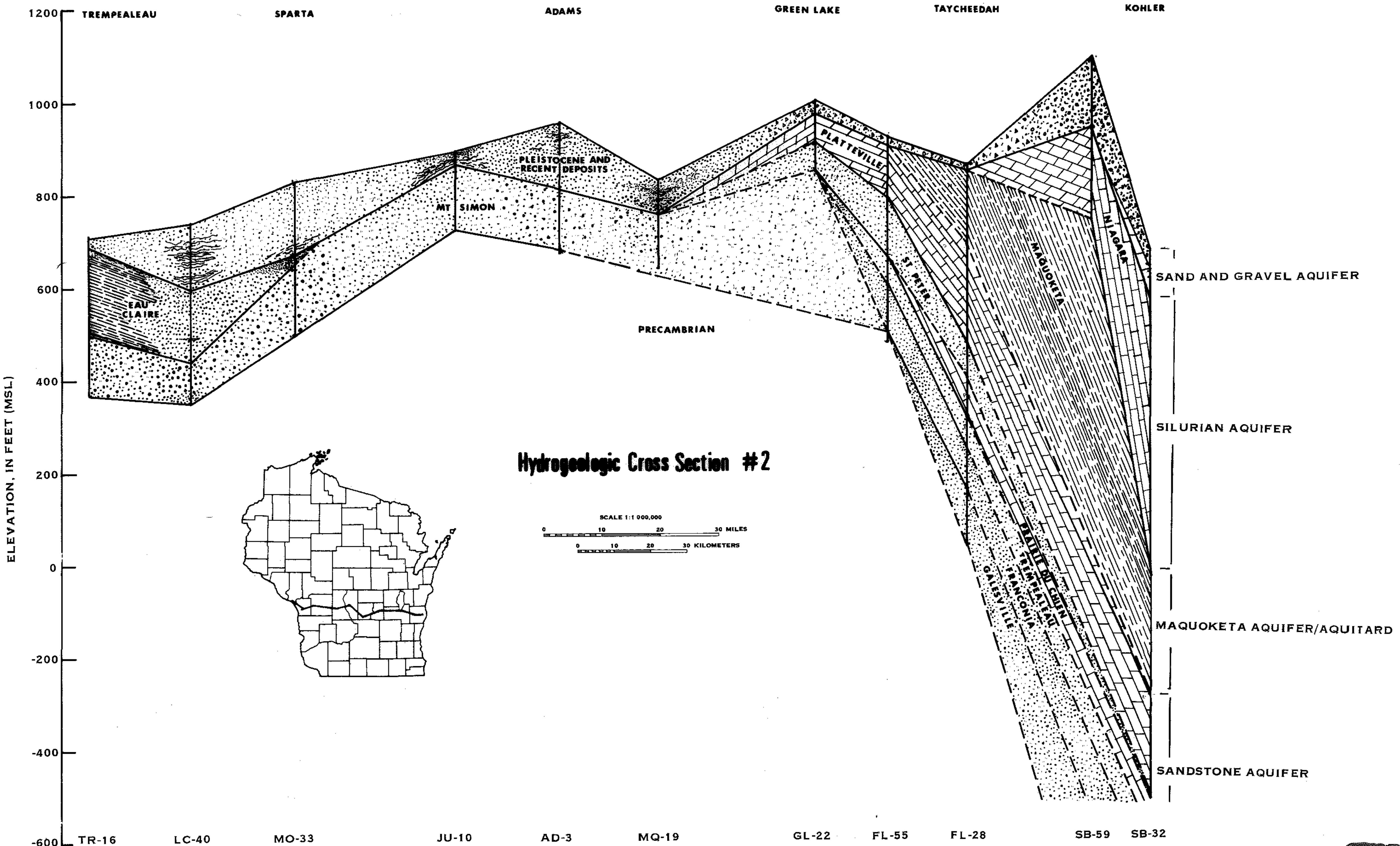
FIGURE 12A

82-1



Hydrogeologic Cross Section #4

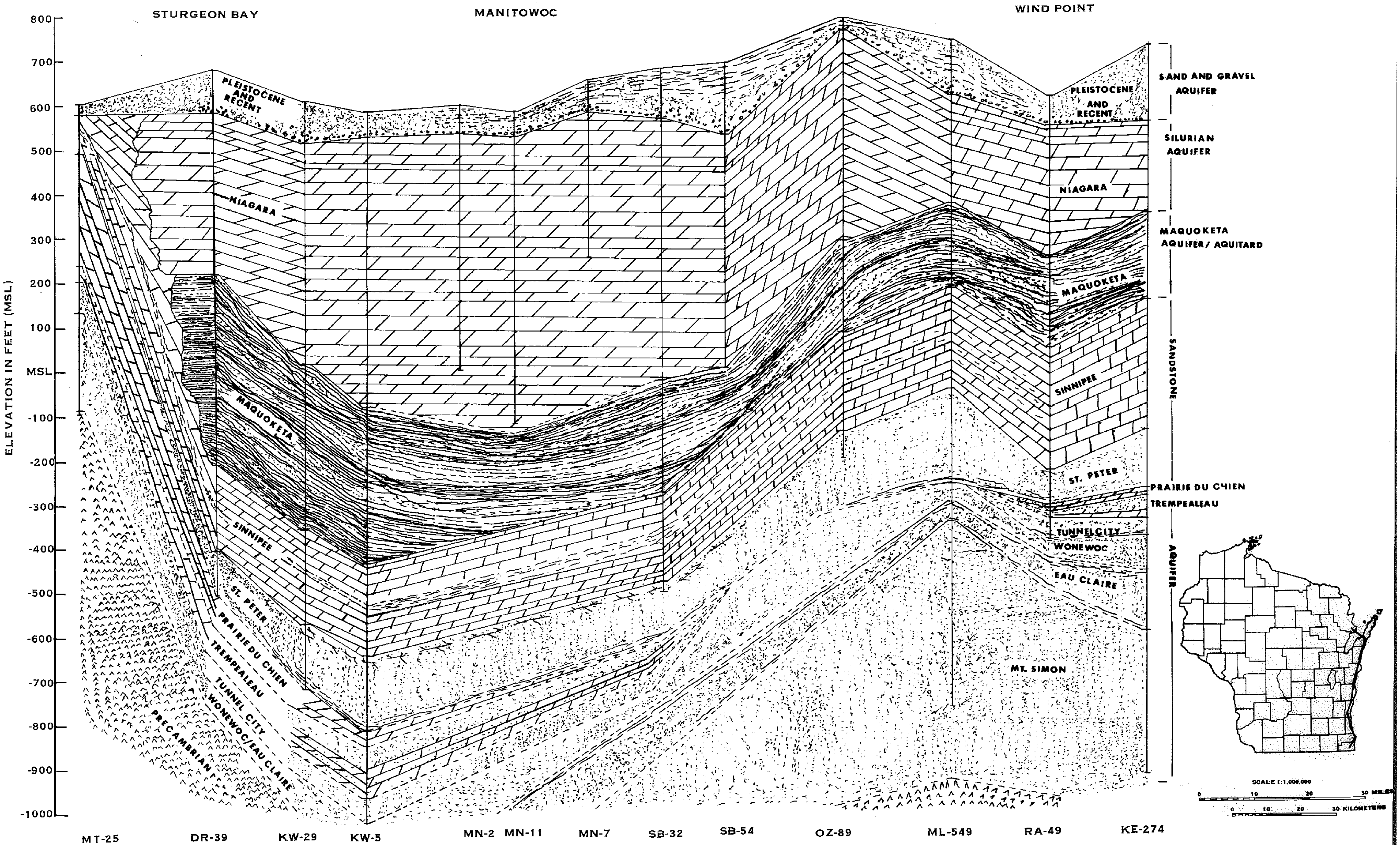
FIGURE 15



1200
1000
800
600
400
200
0
-200
-400
-600
ELEVATION, IN FEET (MSL)
TREMPEALEAU
SPARTA
ADAMS
GREEN LAKE
TAYCHEEDAH
KOHLER
PLEISTOCENE AND RECENT DEPOSITS
MT SIMON
EAU CLAIRE
PRECAMBRIAN
PLATTEVILLE
ST PETER
MAQUOKETA
NIAGARA
PRAIRIE DU CHIEN
TREMPEALEAU
FRANCONIA
GALESVILLE
SAND AND GRAVEL AQUIFER
SILURIAN AQUIFER
MAQUOKETA AQUIFER/AQUITARD
SANDSTONE AQUIFER
Hydrogeologic Cross Section #2
SCALE 1:1 000,000
0 10 20 30 MILES
0 10 20 30 KILOMETERS
TR-16
LC-40
MO-33
JU-10
AD-3
MQ-19
GL-22
FL-55
FL-28
SB-59
SB-32

82-

FIGURE 13



Hydrogeologic Cross Section # 3

FIGURE 14

82-L [redacted]