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Characterization of the Hydrostratigraphy of the Deep Sandstone Aquifer in Southeastern Wisconsin

CHARACTERIZATION OF THE HYDROSTRATIGRAPHY OF THE DEEP SANDSTONE AQUIFER IN SOUTHEASTERN WISCONSIN

A Final Report prepared for the

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I. INTRODUCTION

Over the last century and particularly within the last 40 years, the region in southeastern Wisconsin encompassing the counties of Washington, Ozaukee, Waukesha, Milwaukee, Walworth, Racine and Kenosha, has undergone increasingly rapid urban and suburban development. Centers of population have grown rapidly in outlying counties in contrast to the central urban area of Milwaukee. The major source of municipal and industrial water supply has traditionally been the Cambrian-Ordovician aquifer system (Figure 1) known as the "deep sandstone" aquifer. However, as an increasing number of deep wells have been constructed in this aquifer (beneath the Maquoketa shale confining unit), the potentiometric surface has declined significantly, by several hundred feet since the turn of the century. Municipalities along the lakeshore have largely converted to water supplies from Lake Michigan, but inland counties continue to rely on groundwater from the Cambrian-Ordovician aquifer system because of limits on diversion of surface water out of the Lake Michigan basin.

Since the 1970s, amid concern about the declining water levels, there has been increased interest in the hydrogeology of the region. In 1976, the U.S. Geological Survey (USGS), in cooperation with the Southeastern Wisconsin Regional Planning Commission (SEWRPC), constructed a two-dimensional computer model to simulate groundwater flow in the Cambrian-Ordovician aquifer (Young, 1976). The USGS later completed a much more general three-dimensional groundwater modeling study covering the entire upper Midwest (Young, 1992). Water utilities in Waukesha and Washington Counties recently commissioned a consultants' groundwater modeling study of southeastern Wisconsin (Bonestroo et al., 1998).

Meanwhile, much information on the geology of the Cambrian-Ordovician aquifer system has been collected at the Wisconsin Geological and Natural History Survey (WGNHS) in the form of detailed logs from deep wells. Reported well water levels have also been collected at the WGNHS and the Wisconsin Department of Natural Resources. The purpose of this study was to compile and analyze these data and present the results in a form which can be used for detailed three-dimensional groundwater modeling, in order to help better manage groundwater resources in southeastern Wisconsin.

II BACKGROUND/NEED

Recently, the WGNHS completed a multi-year study of the shallow groundwater resources in southeastern Wisconsin for the Southeastern Wisconsin Regional Planning Commission (SEWRPC, in preparation). However, increased localized pumping from the Cambrian-Ordovician system and resulting drawdown indicated that managing and protecting groundwater resources of southeastern Wisconsin required a more comprehensive study of both shallow and deep aquifers. So, in June 1997, the WGNHS and the USGS, in cooperation with SEWRPC, proposed a study to construct a three-dimensional groundwater flow model for southeastern Wisconsin.

A. Planned regional 3D groundwater flow model

Recent groundwater modeling studies for Dane County (Bradbury et al., 1998; Krohelski et al., 1997), the Fox valley area (Conlon, 1997) and the Green Bay area (Krohelski, 1986) have demonstrated the utility of three-dimensional groundwater flow modeling for estimation of drawdown, delineation of capture zones, and wellhead protection. Constructing such groundwater flow models requires the compilation and analysis of large amounts of data in order to determine the hydrostratigraphic framework of the area studied. In addition, these data need to be presented in a digital format suitable for construction of a computer model to simulate groundwater flow. The Wisconsin Geological and Natural History Survey has an extensive database of geologic logs for deep wells, and recently acquired a new tool which facilitates the analysis of these data. The Groundwater Modeling System (GMS) is a subsurface visualization software package and groundwater flow modeling preprocessor developed for the Department of Defense.

B. Information needs

The primary needs for establishing a three-dimensional hydrostratigraphic framework are the geometry of the aquifers and aquitards and the hydrogeologic properties of those units. For a hydrogeologic system which has undergone changing stress due to groundwater pumping, analysis of changes in potentiometric heads is useful for transient flow modeling. In the case of southeastern Wisconsin, the geometry of aquifer and confining units is particularly complex due to regional faulting and discontinuous units. Furthermore, accurate values of hydrogeologic properties, primarily hydraulic conductivity, are difficult to determine because deep wells commonly are open to great thicknesses of bedrock, which may have significantly different lithologies (Figure 1) and hydrogeologic properties.

III. OBJECTIVES

The objectives of this study are first, to define aquifers and aquitards which constitute the hydrostratigraphic units in southeastern Wisconsin, and determine their geometry and hydrogeologic properties. A second objective is to produce a map of the potentiometric surface in the Cambrian-Ordovician aquifer system, based on water-level records from various sources.

A. Geometry of hydrostratigraphic units

Rock samples from deep wells are studied at the WGNHS in order to publish geologic logs showing the succession of lithologic formations recognized in Wisconsin (Ostrom, 1967). Contacts between these formations can then be mapped among wells on a regional basis in order to define the thickness and shape of the formations. These formations were combined or in some cases subdivided based on their hydrogeologic properties and areal extent in order to define hydrostratigraphic units.

B. Hydrogeologic properties

When deep wells are constructed, drillers often check the productivity of the well by doing step-drawdown or specific capacity tests. These data can be analyzed to determine hydraulic conductivity of the aquifer units. In this case, the analysis is complicated because most wells are open to many different formations. Other data on properties of aquifer and confining units are obtained from reported values of hydraulic conductivity from pumping or packer tests in the region.

C. Updated potentiometric surface

Due to the increased pumping from the Cambrian-Ordovician aquifer system, as described above, the water levels reported in deep wells have changed over time, sometimes by several hundred feet. Various sources of reported water levels, including construction records and more recent information from the Wisconsin DNR, are analyzed to evaluate the evolution of the potentiometric surface over time.

IV. METHODS

A. Compilation of available data

The WGNHS subsurface digital database contains information on depths of formation contacts, which are interpreted at each well location by analysis of samples received. Several thousand wells with information of this type are found in southeastern Wisconsin. The location of these wells was digitized for each of the seven counties in the region. Digital locations of wells in the surrounding counties were approximated based on quarter-quarter, section and township locations. Digital locations are essential for the use of subsurface visualization software in mapping contact surfaces. For a few hundred wells in the database, more detailed information is available on type of lithology and grain size. An attempt was made to map out variations in lithology using this more detailed information, but not enough data was available in digital form.

Water level and specific capacity information, recorded at the time of well construction, is typically available in paper records at the WGNHS for a subset of deep wells in southeastern Wisconsin. These records were checked and combined, in a spreadsheet format, with similar information from the Wisconsin DNR High Capacity well database. Often, the same well was found identified with different agency-specific identification numbers, and well records from different sources had to be cross-referenced in order to verify depths or open intervals. In most cases, dates at which water levels were recorded were also entered into the spreadsheet, since multiple water-level information is available for many municipal wells.

In an ongoing parallel study (USGS, 1998), USGS personnel compiled published information on hydrogeologic properties for the aquifers and confining units in Wisconsin and northern areas of Illinois, which were compared to results of this study. Additional sources for water level information include the consultants' groundwater modeling study (Bonestroo et al., 1998) for which water level and pumping information was provided by numerous water utilities. A further attempt was made to collect more up-to-date water-level information via a survey sent to well operator addresses in the DNR High Capacity well database. Most of these addresses were no longer valid, or the surveys were not returned, but useful information was obtained for some deep wells in the region.

Many downhole geophysical logs for deep wells are on file at the WGNHS, but are in the form of paper records. These data were digitized as part of this study. In addition, a few wells in southeastern Wisconsin were logged as the opportunity presented itself. WGNHS geophysical logging equipment was used when possible, but the cable length was limited to 1000 ft or less, and most wells of interest are deeper. Several times, a winch with a 2000 ft cable was rented and deep logs collected, but these occasions were limited by financial and logistical constraints.

B. Analysis of hydrogeologic properties

Specific capacity data, time of pumping, length of open interval, and thicknesses of formations were compiled for as many wells in southeastern Wisconsin as possible, from WGNHS subsurface and DNR High Capacity databases and records. Estimated total thickness of the aquifer (depth to Precambrian) at each well location was found using GMS and regional interpolated surfaces for the top of the St.Peter sandstone and the Precambrian basement. These data were analyzed using TGUESS, an iterative computer program to estimate hydraulic conductivity (Bradbury & Rothschild, 1982). Well loss coefficient was assumed to be 1 for all wells, and storage coefficient was assumed to be 0.0001, a typical value for confined aquifers.

1. Distribution of open intervals across entire Cambrian-Ordovician sequence

Most deep wells in southeastern Wisconsin are cased down into the Sinnipee Group dolomite, below the Maquoketa shale regional aquitard. Depending on their depth, these wells can have open intervals spanning some or all of the formations in the Cambrian-Ordovician sequence above Precambrian crystalline basement. Some wells have liners sealing off subsections of this sequence and some formations do not occur at specific well locations. This complicates analysis of specific capacity data from wells in southeastern Wisconsin.

A total of 192 wells were found with data needed to estimate hydraulic conductivity using TGUESS. Of these, 25 wells are open only to the Sinnipee Group dolomite, 27 wells are open to only the Sinnipee and St.Peter sandstone, 7 wells are open to formations from the Sinnipee Group dolomites through the Wonewoc (Ironton-Galesville sandstone) formation, 16 wells are open to the Sinnipee Group dolomite through the Eau Claire formation, and 28 wells are open to all formations which are continuous throughout the region. Other wells are open to various unique combinations of formations, or do not have formation-specific geologic logs. Hydraulic conductivity estimates obtained using TGUESS for these groups of wells are shown in Table 1:

Table 1: Hydraulic conductivity estimates for wells in southeastern Wisconsin

Formations tested	Geometric mean K (ft/d)	Standard deviation logK	Number of wells
Sinnipee Group	0.79	4.19	25
Sinnipee + St.Peter	0.72	2.94	27
Sinnipee to Wonewoc	0.85	4.67	7
Sinnipee to Eau Claire	1.28	3.02	16
Sinnipee to Mt.Simon	1.34	2.81	28

2. *Methods for estimating hydraulic conductivity by formation*

The geometric means of the hydraulic conductivity data for groups of wells shown in Table 1 fall into a small range of values (0.72 ft/d to 1.34 ft/d) with large standard deviations. This narrow range and wide variability occurs because the data are averaged among wells and over a considerable thickness (several hundred feet) of different formations for each well. In contrast, published well testing and regional modeling data by formation (compiled in USGS, 1998) show a considerable range in hydraulic conductivity, implying that the variation in hydraulic properties *within* formations in the region is greater than differences *between* formations in any given well. Mean values as calculated above (Table 1), since they are generalized by the averaging process, are not representative of hydraulic properties for each of the formations open to the dataset of wells. Therefore, these values are not very useful for defining the hydrostratigraphic framework.

However, the subsurface database includes identification of formations within the open interval in each of these wells. It is reasonable to assume that the formations within a given well have locally differentiable hydraulic properties corresponding to these lithologies. In this case, the subsurface in the vicinity of each well can be viewed as a perfectly layered medium, and hydraulic conductivity estimated from specific capacity data is a function of the properties of each formation and their relative thicknesses. This equivalent hydraulic conductivity in the horizontal direction is expressed by the thickness-weighted arithmetic mean of individual layer conductivities (Domenico & Schwartz, 1990; Freeze & Cherry, 1979):

Equation 1: $\mathbf{K_x = \sum(m_i K_i) / \sum m_i}$ where K_x: equivalent conductivity
K_i: individual layer conductivity
m_i: thickness of layer

Since accurate data is available on the thicknesses of each layer (m_i) and the total length of the open interval ($\sum m_i$), in addition to the equivalent conductivity in each well (K_x, estimated using TGUESS), the above equation can be solved for each well in the dataset using a numerical optimization approach. This method is implemented in a spreadsheet, where initial estimates of the unknowns (K_i) are varied systematically to find a solution to the above equation at each well. Unfortunately, the solutions at each well are non-unique – that is, different combinations of K_i values can be solutions, depending on initial values and ranges of values specified for K_i. However, this non-uniqueness is not limiting because solutions at each well are less important than geometric mean values and ranges of K_i for each formation over the entire well dataset.

In conducting the optimization routine, the same initial values of K_i for each formation were used for all wells. This initial value of K_i was selected from a compilation of available well testing and regional modeling data (USGS, 1998), and possible values of each K_i were constrained appropriately for the entire well dataset. For example, formations generally considered to be aquitards were ultimately limited to values of less than 3.28 ft/d (1 m/d), whereas aquifer formations were not constrained to maximum or minimum values. Three optimization runs were used to test initial values and possible ranges of K_i for each formation, and in each optimization run, Equation 1 was solved for each well. Subsequent solutions for all wells showed progressively more distinct ranges of mean properties of each formation.

3. *Hydraulic conductivity analysis*

For all optimization runs, initial values and constraints for each formation were assigned as in Table 2. For Optimization Run 1, initial values of K_i for each formation were set based on various sources. Maximum and minimum value constraints were set for aquifers based on reported standard deviations of aquifer testing data (USGS, 1998) where available. For the formations generally considered aquitards, initial values were set based on modeling estimates with no maximum constraints. Absolute minimum values of 0.03 ft/day were set to avoid negative number solutions.

In the first optimization run, Equation 1 was solved for each well within the constraints assigned, and for approximately 11% of the wells, no feasible solution was found. In other words, no matter how the parameters K_i were varied for 11% of the wells, the known equivalent hydraulic conductivity K_x could not be found using Equation 1. Boxplots of the results by formation (not shown) showed that for the major aquifer units, the maximum constraints arbitrarily truncate the sample distribution at the upper end. Histograms (not shown) did not resemble expected log-normal distributions and were multimodal in many cases. Furthermore, values for the unconstrained aquitard units included many unrealistic outliers of values up to 6 ft/d and beyond.

Table 2: Initial values and constraints for K_i for each formation in each run (all values in ft/day):

Formation or Group	Optimization Run 1		Optimization Run 2		Optimization Run 3	
	Parameters	Sources*	Parameters	Sources*	Parameters	Sources*
Sinnipee	K_i: 0.79 max: 1.15 min: 0.03	Specific capacity estimate	K_i: 0.79 max: 1.15 min: 0.03	Specific capacity estimate	K_i: 0.79 max: 1.64 min: 0.003	Specific capacity estimate
St.Peter	K_i: 1.15 max: 1.90 min: 0.39	Hoover& Schicht, 1967	K_i: 1.38 max: N/A min: N/A	Optim-ization run 1	K_i: 2.69 max: N/A min: N/A	Optim-ization run 2
Prairie du Chien	K_i: 0.39 max: N/A min: 0.03	Burch, 1991	K_i: 0.39 max: 3.28 min: N/A	Burch, 1991	K_i: 0.39 max: 3.28 min: N/A	Burch, 1991
Trempealeau	K_i: 0.10 max: N/A min: 0.03	Weaver & Bahr, 1991	K_i: 0.10 max: 6.56 min: 0.03	Weaver & Bahr, 1991	K_i: 0.10 max: 3.28 min: 0.003	Weaver & Bahr, 1991
Tunnel City	K_i: 0.13 max: N/A min: 0.03	Burch, 1991	K_i: 0.13 max: 3.28 min: 0.03	Burch, 1991	K_i: 0.13 max: 3.28 min: 0.003	Burch, 1991
Wonewoc	K_i: 1.90 max: 2.53 min: 1.28	Walton & Csallany, 1962	K_i: 1.90 max: N/A min: N/A	Walton & Csallany, 1962	K_i: 3.15 max: N/A min: N/A	Optim-ization run 2
Eau Claire	K_i: 0.66 max: N/A min: 0.03	Young, 1976	K_i: 0.66 max: 3.28 min: 0.03	Young, 1976	K_i: 0.95 max: 3.28 min: 0.003	Optim-ization run 2
Mt.Simon	K_i: 0.43 max: 2.0 min: 0.03	Walton & Csallany, 1962	K_i: 1.21 max: N/A min: N/A	Optim-ization run 1	K_i: 1.90 max: N/A min: N/A	Optim-ization run 2

* Cited data is compiled in USGS, 1998

In successive optimization runs, some initial values and constraints were changed in an effort to improve the numerical solution. The maximum value constraint of the major aquifers was removed and maximum values were specified for the aquitards. Initial values for the aquifers were successively updated to the geometric mean of values calculated in previous runs, which were considerably higher, particularly in the case of the Mt.Simon (Table 2). Results for the second and third optimization runs were progressively better. The percentage of wells for which no feasible solution could be found decreased to 3% (Run 2) and 2% (Run 3), respectively. Results for the third and final optimization run are shown in Figure 2 and Table 3, and analyzed in Section V.

4. *Limitations of method*

Estimates of hydraulic conductivity by stratigraphic unit using this method are derived numerically from specific capacity data and relative thicknesses of formations within open intervals of the wells tested. They are non-unique, in that mathematically, results from all three optimizations are equally valid. However, by constraining the solutions using general knowledge of formation lithology and available hydrogeologic data, increasingly better results were obtained over three optimization runs. This is shown by the decrease in percentage of well data not fitting the model. The final results also have a more log-normal distribution, and a statistically significant distinction between data from different hydrostratigraphic units.

This numerical optimization approach is probably not as accurate as analytical methods for determining hydraulic conductivity from pumping tests on individual wells. But pumping test data are generally not available from these wells, nor are wells open to just one formation, a necessary requirement for analytical methods. Moreover, analytical methods are subject to error as well. These numerical results are the best estimates of hydraulic conductivity by hydrostratigraphic unit which satisfy available specific capacity data from the dataset of wells.

C. Analysis of aeromagnetic data for Precambrian basement

One of the difficulties in this study is the lack of deep wells that reach the Precambrian surface, which is the base of the aquifer system. Analysis of aeromagnetic data was attempted to better define this surface.

The magnetic field of the earth varies both in intensity and direction. The strength at any point depends on the amounts of magnetic material present and its distance and direction relative to the detector. The average magnetic field in Wisconsin is about 58000 nanoteslas (a unit of magnetic field measurement). The actual field varies from 50 nanoteslas to over 60,000 nanoteslas. The International Geophysical Reference Field (IGRF) is calculated by subtracting the average value (corrected for latitude and longitude, and other variables including day on which the measurement was made) from the actual field.

Like all dipole magnets, the earth has a magnetic field that has a north and south pole. The angle between a compass needle and true north is called the magnetic declination. The north-seeking end of a compass needle that is free to orient itself in an up-down direction will point down in the Northern Hemisphere and up in the Southern Hemisphere. The angle between the needle and the horizontal is called the magnetic inclination. In the central part of the seven county SEWRPC area, declination is near zero, and inclination is near 72 degrees. It is mathematically possible to convert total magnetic field measurements (typically measured from aircraft) into its horizontal and vertical components.

Although the force of the earth's magnetic field is not very strong, it is large enough to magnetize certain kinds of rock that contain iron or other magnetic material. Most sedimentary rocks in southern Wisconsin are not magnetic, whereas most of the buried Precambrian rock is magnetic. The distribution of patterns on a magnetic anomaly map represents the variation in magnetic susceptibility of the Precambrian basement. These variations, or anomalies, can be represented by a model consisting of geologic units of similar attraction but having different distances or depths from the detector. Hence, given a magnetized Precambrian basement, it is theoretically possible to constrain depths to basement by analysis of magnetic anomalies.

The total relief of the magnetic anomaly for a vertically magnetized basement is

$\Delta V = 2\mathbf{I}t/z$. where t and z represent relative depths to basement and $\mathbf{I}$ is the intensity of magnetization

Equivalent equations can be developed for other geometries, including vertical and inclined dikes, faulted basement, and so forth. All of the mathematical expressions include depth terms that (ideally) can be solved for by a variety of means, including evaluation of derivatives, mathematical modeling, and Fourier analysis. There is an extensive literature on techniques for processing and modeling magnetic data. In this investigation, a series of integrated geophysical programs by the U.S. Geological Survey (Cordell and others, 1992) were used. These programs are freeware and can be accessed from http://greenwood.cr.usgs.gov/pub/fact-sheets/fs-0076-95/FS076-95.html.

Numerous airborne magnetic datasets exist for Wisconsin. Detailed datasets exist for southeastern Wisconsin, however the set acquired in the late 1970s and early 1980s by the U.S. Department of Energy is internally consistent with a uniform set of survey specifications, obviating the need for complex adjustment of data. Recently, the U.S. Geological Survey (Duval & Riggle, 1999) reformatted that data and reproduced it on 2 CD-ROMs. These data were acquired on a six-mile east-west line spacing, with measurements taken approximately every 150 feet.

Our analysis consisted of correcting the data for the regional variations, averaging the data with a moving 0.5 km window to remove short-term noise and spikes, and modeling the data for depth using the auto-correlation method of Philips (1979). The technique varies the length of a modeling window: the longer the window, the more stable the solution. The technique is essentially a calculation of horizontal derivatives of the magnetic field.

The resulting modeled elevation of the magnetic basement (Figure 3) shows some similarities with the final mapped Precambrian surface based on well data (Figure 4). There is a regional mound in Washington County, and depressions in Waukesha County possibly corresponding to the abrupt increase in slope indicated by the well data (Figure 4). However, in the modeled magnetic basement surface, there is also apparently a spurious mound in eastern Waukesha County and a false depression in northwestern Washington County. The most interesting features of the magnetic basement are in areas where there is no well data. For instance, in eastern Walworth County, there appears to be a ridge in the magnetic basement surface which extends into southern Kenosha County. In general, however, there is a great deal of ambiguity in this surface resulting from analysis of aeromagnetic data.

D. Subsurface visualization

Records for thousands of deep wells in southeastern Wisconsin and depths of the formation contacts in each well are contained in the WGNHS subsurface database. These records were imported into GMS software for subsurface visualization. Digitization of the location of each of these wells allows mapping of the contact surfaces between each formation on a region-wide basis. This is accomplished by generating triangulated irregular network (TIN) surfaces between similar contacts for each well in the dataset. Each TIN surface is therefore equivalent to a structure contour surface of the top of each formation. TIN surfaces honor each data point and interpolate linearly among them, resulting in an angular, not smoothed, representation of the data.

TIN surfaces were generated from the well data for each of the major formation contacts in the Cambrian-Ordovician aquifer system and the overlying bedrock units: tops of the Mt.Simon, Eau Claire, and Wonewoc formations; Tunnel City, Trempealeau, Prairie du Chien, Ancell and Sinnipee Groups; and the Maquoketa formation. A Precambrian basement surface TIN was created from a contour surface mapped by the USGS, and then modified to account for the more recent deep well data in the database. Relatively few wells reach basement, but many deep wells in Waukesha County that are completed in the Mt.Simon formation provide an upper bound on the Precambrian basement elevation.

Although each of the TIN surfaces is a continuous representation of the bedrock contact; in reality, some bedrock units are absent due to erosion or non-deposition in parts of the region. Furthermore, many rock units are bevelled and truncated in the west because of the regional dip to the east-southeast. Hence, the regional uppermost bedrock surface is a composite of the St.Peter through Devonian rock surfaces. This bedrock surface was mapped as part of a previous study (SEWRPC, in preparation), and was used to create another TIN representing the uppermost bedrock surface.

GMS software was used to define the volume between the different TIN surfaces as a solid representation of the three-dimensional geometry of each bedrock unit. So, for instance, the volume between the TINs of the top of the Mt.Simon formation and the Precambrian surface became a solid representing the Mt.Simon formation. In some cases, these solids intersected where, in reality, bedrock units are discontinuous or eroded. Where this occurred, adjacent solids were subtracted to resolve inconsistencies. In this way, a solid created from the regional bedrock surface TIN was subtracted from each of the bedrock units to reproduce the bevelled erosional surface of the regionally dipping units. Similarly, a solid created from the Precambrian surface TIN was subtracted from the Cambrian-Ordovician bedrock units to reproduce the geometry of the Precambrian knobs present notably in Washington County.

The advantage of creating a three-dimensional representation of the geometry of the bedrock units, as described above, is that cross-sections and fence-diagrams can then be cut vertically at any orientation through the Cambrian-Ordovician sequence. Several representative sections are presented in this study, but many others could be created in order to investigate the detailed juxtaposition of rock units or offsets due to faulting. Furthermore, since the TIN surfaces are in digital form, they can be directly converted to gridded top and bottom elevation arrays for use in a regional numerical groundwater flow model.

E. Interpretation and mapping of subsurface data

In a subsurface visualization environment such as GMS, the simultaneous analysis of large numbers of wells brings to light errors in individual database records, as manifested by unusually high or low points in the various TIN surfaces. The most obvious errors were corrected as part of this project. However, regional structural features, such as faults, also occur in these bedrock units and can cause similar irregularities in the TIN surfaces. This accounts for the uneven appearance of the TIN surfaces presented in this study. Each of the irregularities needs to be examined closely to distinguish errors from actual bedrock geometry. For the purposes of this regional study, a detailed examination was not made of all irregularities in the TIN surfaces, only the most extreme ones. The TIN surfaces were therefore not smoothed, because they represent a work in progress in our understanding of bedrock structure. Further examination, beyond the scope of this study, can yield important information on the detailed bedrock structure in southeastern Wisconsin.

Because there are many more shallow wells than deep wells, the highest elevation TIN surfaces, such as the top of the Ancell Group (St.Peter sandstone) are better resolved than the deeper surfaces, such as the top of the Mt.Simon Formation. As a result, deep formations that are discontinuous may be relatively poorly defined because there are few wells in which they occur. This is why TINs representing contact surfaces between each Cambrian-Ordovician formation are not presented. Instead, when units are relatively poorly defined by the well data, they are combined with others for the purpose of determining the regional hydrostratigraphy. TIN surfaces representing the tops of the Sinnipee Group, Maquoketa Formation and Silurian Group were also created and used in cross-sections for completeness, but are not presented in plan view because they are not part of the main Cambrian-Ordovician aquifer system.

For the purpose of this study, since hydrogeologic properties were estimated by formation, the different hydrostratigraphic units will be referred to as "aquifers" and "aquitards" based on their relative conductivity, even though the entire sequence makes up a single Cambrian-Ordovician aquifer system. In addition to geometric considerations, hydrogeologic properties were compared in order to determine hydrostratigraphic units. The discontinuous Prairie du Chien Group, which is a minor aquifer, was combined with the Ancell Group to form the St.Peter aquifer. Furthermore, the discontinuous units comprising the Trempealeau or Tunnel City Groups have statistically indistinguishable, and very low hydraulic conductivities (see Table 3), so they were combined to form the Trempealeau-Tunnel City aquitard. The Jordan Formation, a sandstone unit within the Trempealeau Group, appears in only a handful of well logs and was assumed to be part of the St.Peter aquifer. Additional minor geologic units, such as the Glenwood Member of the Ancell Group, were disregarded for the purpose of this study because they are highly discontinuous.

For the purpose of potentiometric surface mapping, static water levels were selected from the WGNHS subsurface database for wells which reached the St.Peter sandstone. Additional water levels were selected from wells greater than 500 ft deep in the DNR High Capacity database, and the most recent water levels from the consultants' modeling report (Bonestroo et al., 1998). Altogether, over 800 static water levels were compiled for wells in the region at multiple dates. These data were stratified by date: before 1960, and then by recent decades, and imported into GMS for contour plotting. Some water levels had no reliable dates and were included in the most appropriate contour map based on consistency with nearby water levels.

V. RESULTS AND DISCUSSION

Results of this study are presented in a series of Tables and Figures which illustrate the estimated hydraulic conductivity and geometry of the different units comprising the hydrostratigraphic framework, and the potentiometric surface of the Cambrian-Ordovician aquifer in southeastern Wisconsin. Because of the limitations of the well data, described earlier, mapping the distribution of hydraulic conductivity within each of the hydrostratigraphic units was beyond the scope of this study, but could be estimated as more is learned about the distribution of lithologies in southeastern Wisconsin. The digital mapping environment (GMS), in which the figures were generated, allows the continuing refinement of the TIN surfaces as more well data is collected and details of the bedrock structure are resolved. Similarly, the cross sections presented are examples of many different cross-sections which can be generated as this hydrostratigraphic framework is refined for the purpose of groundwater flow modeling.

A. Estimates of hydraulic conductivity from optimization analysis

Hydraulic conductivity was estimated for each of the major formations in southeastern Wisconsin based on analysis of specific capacity for deep wells, as described earlier. Results are shown for the third and final optimization run in Figure 2 and Table 3. The distribution of results by formation is more distinct than for the first two runs (not shown), with the interquartile range of aquitards considerably narrower and generally lower than that of the major aquifer units, as would be expected based on the formation lithologies (Figure 1).

Histograms (not shown) of the resulting K_i values for each formation showed distributions which appear log-normal. No distributions appeared to be artificially truncated. Medians and interquartile ranges of the Sinnipee Group and St.Peter distributions (Figure 2) are more differentiated than in the first two runs. The median and interquartile range of the Wonewoc appears considerably higher than in previous runs. Two-sample t-tests show that the geometric mean hydraulic conductivities of all adjacent units, with one exception, are different at the 95% confidence interval. The geometric mean hydraulic conductivities of the Trempealeau and Tunnel City Groups cannot be distinguished at the 95% confidence interval.

Table 3: Final estimates, from optimization, of hydraulic conductivity by stratigraphic unit

Formation or Group	No. of wells	Geometric mean K_i (ft/d)	Standard deviation log K_i	Median K_i (ft/d)	Q1 First (25%) quartile (ft/d)	Q3 Third(75%) quartile (ft/d)
Sinnipee	168	0.13	1.52	0.36	0.03	0.85
St.Peter	166	2.30	0.83	2.43	1.97	2.76
Prairie du Chien	23	0.49	0.90	0.39	0.33	0.62
Trempealeau	47	0.07	1.51	0.10	0.003	0.16
Tunnel City	77	0.03	1.47	0.10	0.003	0.16
Wonewoc	88	3.38	0.72	3.12	2.98	3.25
Eau Claire	124	0.72	0.98	0.85	0.66	1.08
Mt.Simon	109	1.34	0.94	1.48	0.75	2.16

As a practical matter, the St.Peter Formation, the Wonewoc Formation and the Mt.Simon Formation can be considered regional aquifers based on their relatively high hydraulic conductivities. The Mt.Simon Formation in particular, and to a lesser extent the St.Peter Formation, show large interquartile ranges (Figure 2). Although part of these ranges is probably due to errors in reported specific capacity data, they also indicate considerable variability in the hydraulic conductivity of these units. The Trempealeau and Tunnel City Groups are clearly aquitards because of their extremely low conductivities, but are penetrated by relatively few wells, as is the Prairie du Chien, a minor aquifer. The Eau Claire Formation, because of its relatively low conductivity and stratigraphic position between the Wonewoc and Mt.Simon aquifers (Figure 1), probably acts as an aquitard. In contrast to the other aquitards, the Sinnipee Group has a large interquartile range, but a relatively low mean conductivity. This can be attributed to the dual nature of this bedrock unit, which is of relatively low conductivity where it is overlain by the Maquoketa shale, but is used as an aquifer where it is the weathered, uppermost bedrock unit in the western part of the region.

These results demonstrate that, although deep wells are generally open to great thicknesses of Cambrian-Ordovician bedrock units, these stratigraphic units do in fact have significantly different hydraulic properties in most cases. In comparison to published data on hydraulic conductivity of these formations (USGS, 1998), some interesting differences are apparent. Values for the Sinnipee Group in this study are considerably lower than published estimates, which are probably biased to shallow wells in areas where the Sinnipee is highly weathered and unconfined. Values for the St.Peter in this study are somewhat higher than most published data, but individual published values can be much higher. Few published estimates exist for the Prairie du Chien but values used for groundwater modeling are similar to these results. Similarly, published estimates for the Trempealeau and Tunnel City Groups are rare for southeastern Wisconsin, but these results are comparable to published groundwater modeling values. Results of this study for the Wonewoc and Mt.Simon are higher than published hydraulic conductivity estimates, but comparable to values used for groundwater modeling, as are those of the Eau Claire Formation. Published values for the Wonewoc are always relatively higher than those for the Mt.Simon, as in this study.

B. Regional contact surfaces

Six structure contour maps are presented in Figures 4-10. They represent the major bounding surfaces between hydrostratigraphic units in the Cambrian-Ordovician aquifer system. These hydrostratigraphic units are defined by combining lithostratigraphic units based on their regional extent, and are differentiated by their estimated hydraulic conductivity (Table 3). In stratigraphic order, the bounding surfaces are the Precambrian basement surface (Figures 3,4), the top of the Mt.Simon aquifer (Figure 5), the top of the Eau Claire aquitard (Figure 6), the top of the Wonewoc aquifer (Figure 7), the top of the Trempealeau-Tunnel City aquitard (Figure 8), and the top of the St.Peter aquifer (Figure 9).

1. Precambrian basement surface

The Precambrian basement surface (Figures 3,4) is the top of the Precambrian igneous and metamorphic rocks in southeastern Wisconsin. These rocks are thought to have low hydraulic conductivity, and so this surface represents the bottom of the Cambrian-Ordovician aquifer system. Although its elevation is extremely variable across the region, from over 300 ft above sea-level to at least 2800 ft below sea-level, little is known of the details of its shape because few wells reach it (shown in Figure 4). Regional aeromagnetic data were analyzed (Figure 3), with limited success, in an attempt to supplement the scarce well data. Analysis of aeromagnetic data results in non-unique solutions, and presents interpretation problems. For instance, the exact lithology of the Precambrian rock is poorly known across the region. Metamorphic rock of igneous origin is likely to be magnetized whereas quartzite is not, so aeromagnetic analysis would not detect quartzite.

For the purposes of this study, the elevation of the top of the Precambrian basement is considered to be most accurately represented by Figure 4, based on well data.

The major features of the Precambrian basement surface (Figure 4) include several high knobs in Washington County and neighboring Dodge County, and a lesser high point in the vicinity of Whitewater, in Walworth County, from which elevations decrease towards the east and south. A precipitous increase in slope to the southeast occurs along a line from the northeast corner to the center of Waukesha County then due south into Walworth County. The northern segment of this increased slope corresponds to the location of the Waukesha Fault, which trends N40E. No wells in Waukesha County to the southeast of this fault reach the Precambrian basement. However the abruptness of the offset is indicated by several very deep wells which do *not* reach basement within five miles to the southeast of much shallower wells which reach the Precambrian (see Figure 13).

In broad areas of the region, no well data is available to constrain the shape of the Precambrian surface because no wells are deep enough to reach it. The abrupt change in slope described above appears to flatten out at about 1500 ft below sea-level in southeastern Waukesha County, from which it is assumed to trend gradually downward toward the southeast. A single well in extreme northeastern Illinois reaches Precambrian basement at over 2800 ft below sea-level. However, any new deep well which reaches the Precambrian could potentially change our knowledge of this surface quite dramatically.

2. *Mt.Simon aquifer*

The top of the Mt.Simon aquifer (Figure 5), which is also the bottom of the overlying Eau Claire aquitard, is not continuous throughout the region, like all overlying units to the top of the St.Peter aquifer. This is because the Precambrian surface rises in Washington and Dodge Counties to the knobs described previously, and the Cambrian formations may never have been deposited over the Precambrian mounds. The extent of the Mt.Simon aquifer is shown in color, and the shape of the Mt.Simon surface is contoured in red, a format followed for surfaces presented in Figures 6 through 9 as well. Well data points are located at the vertices of the triangles which make up the TIN surface and the top of the solid defined by the TIN.

The Mt.Simon aquifer is absent in most of Washington County. It extends from about 100 ft above sea-level in northwestern Waukesha and Walworth Counties, to 300 ft below sea-level in southeastern Waukesha and Walworth Counties, to 600 ft below sea-level in Ozaukee, Milwaukee and eastern Racine and Kenosha Counties. As on the Precambrian surface, there is abrupt increase in slope in the vicinity of the Waukesha Fault. Some irregular features in the contoured surface near the fault and in southwestern Racine County suggest that the bedrock surface is more complex than portrayed here.

3. *Eau Claire aquitard*

The top of the Eau Claire aquitard (Figure 6) shows a similar discontinuity where it is absent in Washington and Dodge Counties around the rise in the Precambrian surface (Figure 4). In addition, it appears to be absent, probably due to erosion, in several areas near the northeast corner of Waukesha County and northern Milwaukee County. These areas are significant for three-dimensional groundwater flow modeling because they constitute windows where the underlying Mt.Simon aquifer is contiguous with overlying aquifers, such as the St.Peter.

The abrupt increase in slope in northeastern Waukesha is also present in the Eau Claire unit. There are additional irregularities in the contours which suggest a linear structure in northwestern Waukesha County, and structural complexity in southeastern Waukesha and southwestern Racine County. The top of the Eau Claire aquitard extends from an elevation of 150 ft above sea-level in western Waukesha and Walworth Counties, to 150 ft below sea-level in southeastern Washington, eastern Waukesha, and western Racine Counties, to about 550 ft below sea-level near the lakeshore.

4. Wonewoc aquifer

The Wonewoc aquifer (Figure 7) is absent in most of Washington and Ozaukee Counties and much of Milwaukee County. It appears to be absent in south-central Milwaukee and east-central Waukesha Counties. This complex subcrop pattern is probably related to the sub-St.Peter erosional surface, which eroded down into the Eau Claire aquitard in these locations. Some of the more irregular shapes of this unit are a consequence of extrapolation beyond available well data, and need to be refined.

The top of the Wonewoc aquifer extends from an elevation of 300 ft above sea-level in eastern Dodge, western Waukesha and western Walworth Counties to 150 ft below sea-level in northeastern Waukesha and western Racine and Kenosha Counties. It slopes down to about 450 ft below sea-level along the lakeshore.

5. Trempealeau-Tunnel City aquitard

This unit (Figure 8) is a combination of the Trempealeau and Tunnel City Groups because of their similar low hydraulic conductivity and very discontinuous nature in the study area. The TIN representing its upper surface is a composite of the top of the St. Lawrence Formation where present, the top of the Tunnel City Group otherwise, and the bottom of the overlying St.Peter aquifer. The Trempealeau-Tunnel City aquitard is absent in an irregular area of west-central Washington County, where the Precambrian surface rises into the overlying St.Peter aquifer. It is also absent in most of Milwaukee and parts of eastern Waukesha Counties. The top of this aquitard represents the pre-St.Peter erosional surface, which appears to have cut a wide valley opening and draining towards the east, where the St.Peter aquifer directly and unconformably overlies the Wonewoc aquifer and Eau Claire aquitard.

The top of the Trempealeau-Tunnel City aquitard extends from an elevation of about 400 ft above sea-level in eastern Dodge, western Waukesha and western Walworth Counties to 150 ft above sea-level in central Waukesha and Walworth Counties. It lies at an elevation of about sea-level in western Racine and Kenosha Counties, where complexity in the TIN surface suggests some structural irregularity, and slopes down to below 300 ft below sea-level at the lakeshore.

6. *St.Peter aquifer*

The final plan view map is that of the top of the St.Peter aquifer (Figure 9), which is also generally considered the top of the Cambrian-Ordovician aquifer system, since it is overlain by the Sinnipee Group dolomite, which has a much lower hydraulic conductivity. The St.Peter aquifer is present continuously throughout southeastern Wisconsin and covers the Precambrian basement knob in Washington County. The TIN surface used for this map uses a higher density of well points than any other TIN surface, particularly in Milwaukee County. There is an abrupt increase in slope in northeastern Waukesha County in the same general location as that noted for the Precambrian surface. If this corresponds to displacement on the Waukesha Fault, the surface of the St.Peter aquifer represents a 200 ft offset at this location.

Otherwise, the top of the St.Peter aquifer extends from an elevation of over 450 ft above sea-level in western Washington and Waukesha Counties, and over 600 ft above sea-level in western Walworth County, to approximately 150 ft above sea-level in eastern Waukesha and Washington, and western Racine and Kenosha Counties. Then it falls off to about 300 ft below sea-level near the lakeshore. The St.Peter aquifer is overlain by the succession of the Sinnipee Group dolomite, the Maquoketa confining unit and the Silurian and Devonian aquifer, which are illustrated in the selected cross-sections (Figures 11-16)

C. Three-dimensional geometry of hydrostratigraphic units

The three-dimensional shapes of the hydrostratigraphic units defined above are best appreciated by analysis of the selected cross-sections (Figures 11-16). The locations of these cross-sections are shown in plan view in Figure 10. Three cross-sections A-A', B-B' and C-C' (Figures 12-14) are oriented from west-northwest to east-southeast in the approximate direction of the regional bedrock dip and groundwater flow, and two sections D-D' and E-E' (Figures 15-16) are oriented perpendicularly from south-southwest to north-northeast. Selected wells are portrayed along the cross-sections, and extend above the top unit (Silurian) because unlithified Pleistocene deposits are not shown.

All the cross-sections are shown in a fence-diagram format in Figure 11. Major features apparent on this oblique view are the bevelling of the different hydrostratigraphic units in the western part of the study area and the dramatic thickening of the Silurian aquifer to the north and east. Also note the absence of the Mt.Simon through Trempealeau-Tunnel City units in Washington County.

1. West-northwest to east-southeast cross-sections

Cross-section A-A' (Figure 12) shows the hydrostratigraphy from Dodge County through Ozaukee County. The Precambrian surface rises into the St.Peter aquifer in Washington County, and the Mt.Simon aquifer appears to be relatively thin (250 ft) and essentially limited to Ozaukee County. However, few wells exist along this transect, and none reach the Precambrian surface, so the geometry of deep units is uncertain and determined by extrapolation of regional trends. The Wonewoc aquifer is absent east of the Precambrian mound and the Trempealeau-Tunnel City aquitard appears to pinch out in Ozaukee County, where the St.Peter aquifer rests on the Eau Claire aquitard. The other hydrostratigraphic units are of relatively uniform thickness, except the Silurian aquifer, which thickens markedly to the east. The prominent depression in the Silurian aquifer in Washington County is a deep bedrock valley that trends from north to south.

Cross-section B-B' (Figure 13) shows the hydrostratigraphy from Jefferson County through Milwaukee County. The bulk of the well data is found in Waukesha and Milwaukee Counties and the geometry of deep units is well defined here. The Mt.Simon aquifer, while fairly thin in Jefferson and western Waukesha Counties (less than 500 ft) where several wells reach the Precambrian surface, abruptly thickens in eastern Waukesha and Milwaukee Counties to 1200 ft or more. In the center of Waukesha County, at the approximate location of the Waukesha Fault, the Trempealeau-Tunnel City aquitard and Wonewoc aquifer pinch out, and are not present farther east. The St.Peter aquifer is therefore juxtaposed with the Eau Claire aquitard. At the bedrock surface, the Silurian aquifer and Maquoketa confining unit are truncated by erosion and the Sinnipee Group forms the upper bedrock unit in western Waukesha County.

Cross-section C-C' (Figure 14) shows the hydrostratigraphy from Rock County to Racine and Kenosha Counties. In contrast to cross-sections further north, the Trempealeau-Tunnel City aquitard and the Wonewoc aquifer are continuous along this section. In fact, the Trempealeau-Tunnel City aquitard appears to thicken from less than 100 ft in Walworth County to almost 200 ft near Lake Michigan. The presence of this continuous aquitard may have significant implications for three-dimensional groundwater flow in this area. The large depressions in the bedrock surface represent the buried Troy bedrock valley, which extends from southern Waukesha County south through Walworth County into Illinois. Note also the geometry of the Mt.Simon aquifer, which thickens from less than 200 ft in the vicinity of the Precambrian high (at Whitewater, Walworth County) to 1500 ft or more near Lake Michigan.

2. South-southwest to north-northeast cross-sections

Cross-section D-D' (Figure 15) shows the hydrostratigraphy from Illinois to Fond du Lac County. A major feature is the extent of the Precambrian mound underneath Washington County. The wedge of the Mt.Simon aquifer completely pinches out in northern Waukesha County and is not present north of the Precambrian high. Similarly, the Eau Claire aquitard, the Wonewoc aquifer, and the Trempealeau-Tunnel City aquitard are truncated and generally absent in

Washington County, but are present farther north. Hence, the Cambrian-Ordovician aquifer system is limited to 200 ft or less of the St.Peter aquifer over the Precambrian mound. The various depressions in the uppermost bedrock surface correspond to buried bedrock valleys noted in previous cross-sections.

Cross-section E-E' (Figure 16) shows the hydrostratigraphy from Illinois to Sheboygan County, closer to the lakeshore than cross-section D-D'. The wedge of the Mt.Simon aquifer is considerably thicker near Lake Michigan, at least south of Ozaukee County. Relatively few wells penetrate below the Silurian in Ozaukee County, so the relative thicknesses of deeper formations are poorly known. It is unlikely, for instance, that the Maquoketa aquitard completely pinches out as shown, but it may become thinner in northern Ozaukee County. In Milwaukee County, the St.Peter aquifer rests on the Eau Claire aquitard and for a short distance directly on the Mt.Simon aquifer, where all intervening hydrostratigraphic units are absent. The dip of the hydrostratigraphic units changes abruptly at locations in southern Milwaukee and near the Kenosha-Racine County line, indicating possible faulting perpendicular to the section line.

D. Regional potentiometric surface

It was not possible to map hydraulic head for each of the hydrostratigraphic units which have been defined in this study because the water level data available are from wells with long open intervals open to many of these units. The potentiometric surface is a representation of overall hydraulic head in the Cambrian-Ordovician aquifer system based on well water levels, which are a composite of heads in the different hydrostratigraphic units. Multiple water levels were available for many wells, and sufficient data exist to map the potentiometric surface for different periods in the last century. Four of these potentiometric surfaces, showing the evolution of the regional cone of depression, are shown in Figures 17-20.

In Figure 17, the potentiometric surface based on water levels from the first half of the century is shown. The major center of pumping is located in Milwaukee County, with little drawdown in the surrounding counties, still relatively undeveloped. In Washington County, in particular, the potentiometric surface reaches a maximum, over 950 ft above sea-level. Water levels between 800 and 850 ft above sea-level are found in western Waukesha and eastern Jefferson County south into Walworth County. This is the approximate location of the regional potentiometric surface divide between the Great Lakes and Mississippi River basins. Heads are still relatively high in central Waukesha, where water levels are at about 650 ft above sea-level, and in Racine and Kenosha Counties. The lowest water levels are below 450 ft above sea-level in central Milwaukee.

Figure 18 shows the potentiometric surface based on water levels from the 1960s. The major change is that the extent of the drawdown below 450 ft above sea-level has considerably expanded in Milwaukee, and now extends a little into eastern Waukesha County. Potentiometric head may have declined slightly in Washington County. The persistence of the potentiometric divide in the western part of the region in this and subsequent maps is probably related to the absence of the Maquoketa shale and the numerous large lakes in northwestern Waukesha County.

Figure 19 shows the potentiometric surface twenty years later, based on water levels in the 1980s. The major center of regional pumping below 450 ft above sea-level has clearly moved into eastern Waukesha County, with the decline in manufacturing in Milwaukee and growth of the suburbs. The cone of depression has expanded considerably to the south in Racine County and reaches the southeastern corner of Washington County. The regional potentiometric divide apparently remains in western Waukesha County at around 800 ft above sea-level, but the regional gradient has greatly increased in central Waukesha County.

Figure 20 shows the most recent potentiometric surface, based on water levels from the 1990s. Water levels in eastern Waukesha County are now well below 300 ft above sea-level and the cone of depression has deepened to the south as well, where it is below 450 ft in Racine and Kenosha Counties. The cone of depression also appears to extend to the Mequon area, north of Milwaukee. Although there are half a dozen deep wells in the area, all but one is open to the Silurian aquifer as well as the Cambrian-Ordovician aquifer system. Therefore, the relatively high water levels in the vicinity of Cedarburg (over 650 ft above sea-level) may not be representative of heads in the Cambrian-Ordovician aquifer.

VI. CONCLUSIONS/IMPLICATIONS/RECOMMENDATIONS

In preparation for a regional groundwater flow modeling project in southeastern Wisconsin, the hydrostratigraphic framework of the Cambrian-Ordovician aquifer system in the region has been defined. This hydrostratigraphic framework consists of the geometry of the regional bedrock aquifers and aquitards, mapped in a digital environment, and illustrated by numerous contoured TIN surface maps and representative cross-sections. The TIN surfaces can be converted to computer model layer arrays for groundwater flow modeling. The geometric mean hydraulic conductivity for each of these hydrostratigraphic units was estimated using a numerical optimization approach with specific capacity data. Static water level data was compiled for deep wells in the region and mapped as the evolution of the potentiometric surface over time, showing the development of the regional cone of depression.

Within the Cambrian-Ordovician aquifer system, three major aquifers were mapped: the St.Peter aquifer, the Wonewoc aquifer and the Mt.Simon aquifer. The St.Peter aquifer is continuous throughout the region and has a geometric mean hydraulic conductivity of 2.30 ft/d. The Wonewoc and Mt.Simon aquifers have mean hydraulic conductivities of 3.38 and 1.34 ft/d respectively, and are absent in a large portion of Washington County. The Wonewoc aquifer is relatively thin overall, and is absent due to erosion in parts of Waukesha, Milwaukee and Ozaukee Counties as well. The Mt.Simon aquifer is wedge-shaped and thickens away from Washington County to the east and south. It has an abrupt increase in thickness across the Waukesha Fault, where it changes from less than 500 ft to over 1200 ft, and continues to thicken to over 1500 ft at the extreme southeastern corner of the state.

The Cambrian-Ordovician aquifer system is considered to be bounded by the Maquoketa confining unit at the top and Precambrian basement surface at the bottom. A new map of the Precambrian surface is presented, constrained by the limited deep well data. Aquitards contained in this sequence include the Sinnipee Group, the Trempealeau-Tunnel City Groups and the Eau Claire Formation. The Sinnipee Group has a mean hydraulic conductivity of 0.13 ft/d but a large standard deviation because it acts as an aquifer in the western part of the study area where it forms the upper bedrock surface. The Trempealeau and Tunnel City Groups have statistically indistinguishable hydraulic conductivities, and are combined to form a single aquitard with a mean conductivity of 0.05 ft/d. This aquitard is not present in central Washington County and has been removed by erosion in eastern Waukesha and Milwaukee Counties, where the St.Peter aquifer overlies the Eau Claire aquitard and the Mt.Simon aquifer. The Eau Claire aquitard is absent in most of Washington County and small parts of northern Waukesha and Milwaukee Counties. It has a mean hydraulic conductivity of 0.72 ft/d.

Maps are presented of the potentiometric surface for the Cambrian-Ordovician aquifer system, based on data for the early part of this century and several recent decades. The increase in size of the regional cone of depression and the shift in the center of pumping from Milwaukee County to eastern Waukesha County are apparent. This change in the regional potentiometric surface will need to be simulated in transient mode as part of a regional groundwater flow modeling project.

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VIII. LIST OF TABLES AND FIGURES

Rock Stratigraphic Nomenclature	
Group	Formation
Quaternary	(undifferentiated)
Devonian	(undifferentiated)
Silurian	(undifferentiated)
	Maquoketa
Sinnipee	Galena
	Platteville
Ancell	Glenwood
	St Peter
Prairie du Chien	(undifferentiated)
Trempealeau	Jordan
	St.Lawrence
Tunnel City	(undifferentiated)
Elk Mound	Wonewoc
	Eau Claire
	Mt.Simon
Precambrian	

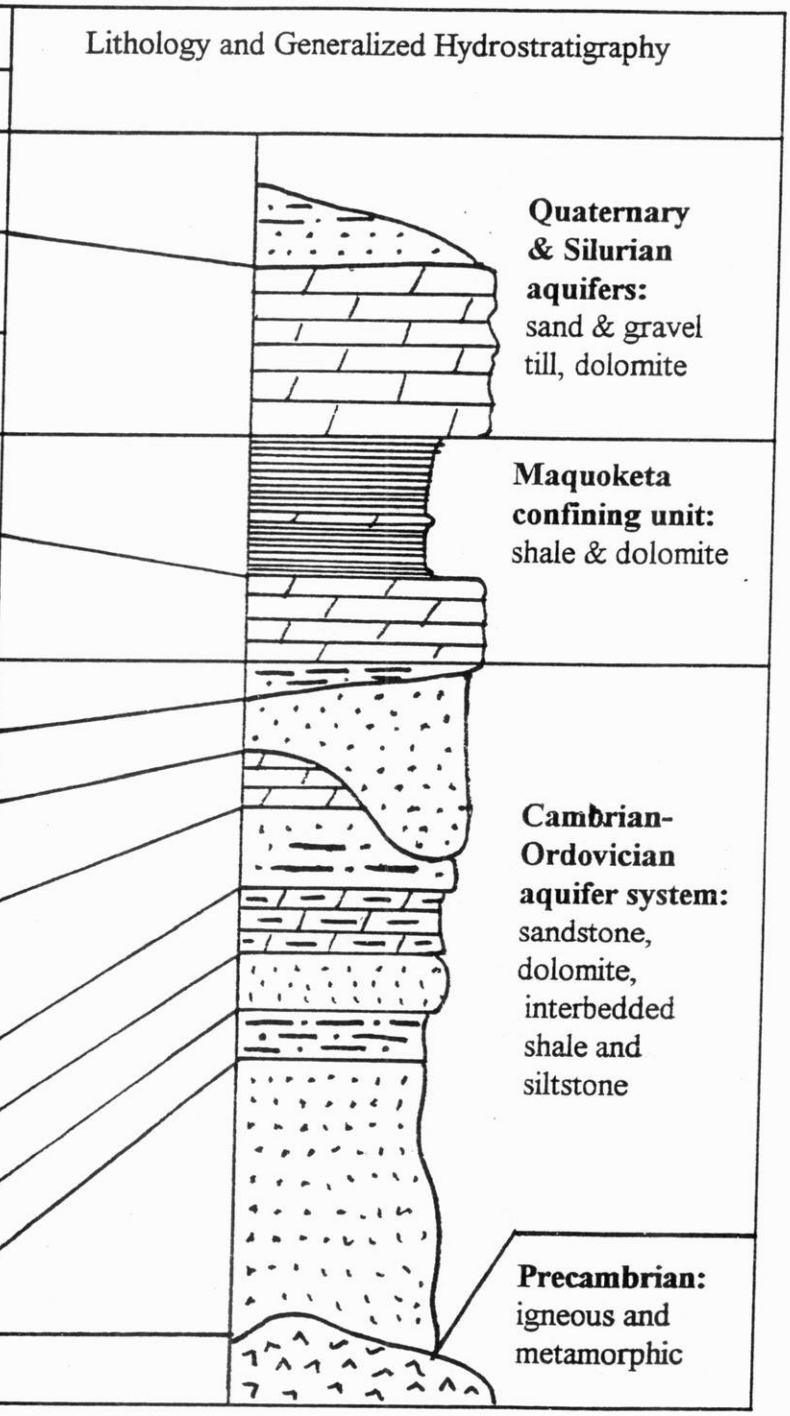
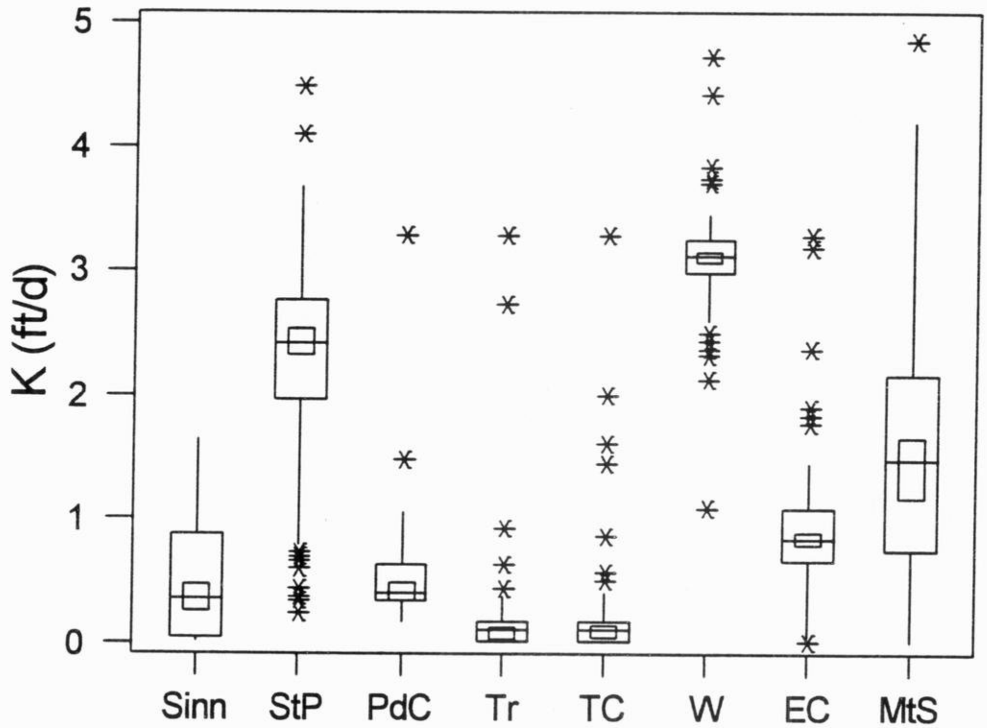


Figure 1. Simplified stratigraphic nomenclature for southeastern Wisconsin (Adapted from Ostrom, 1967)



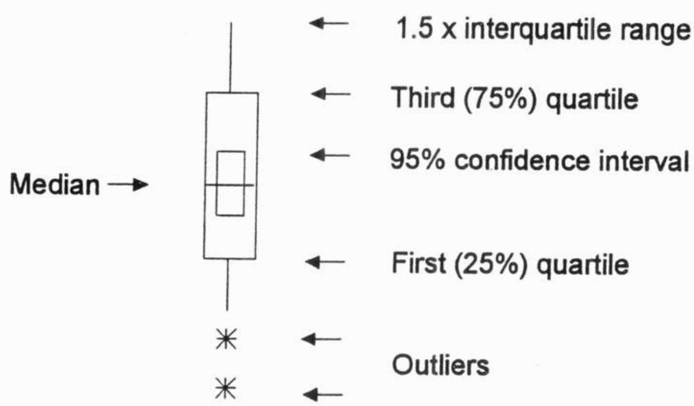


Figure 2: Estimates of hydraulic conductivity by stratigraphic unit, based on numerical optimization analysis of specific capacity data and unit thicknesses within open intervals

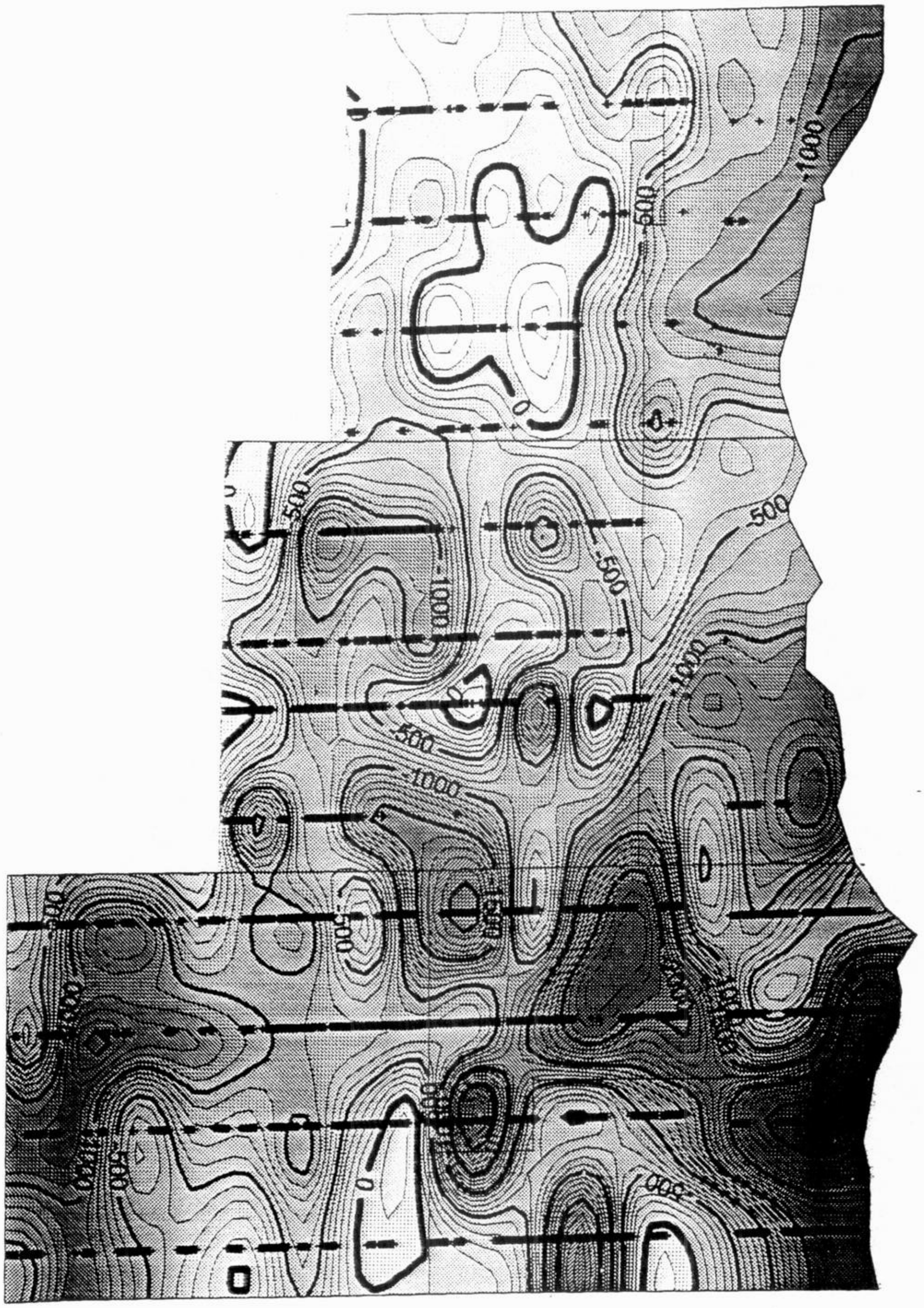


Figure 3. Modeled elevation of magnetic basement (100 ft contour interval, ft above msl).

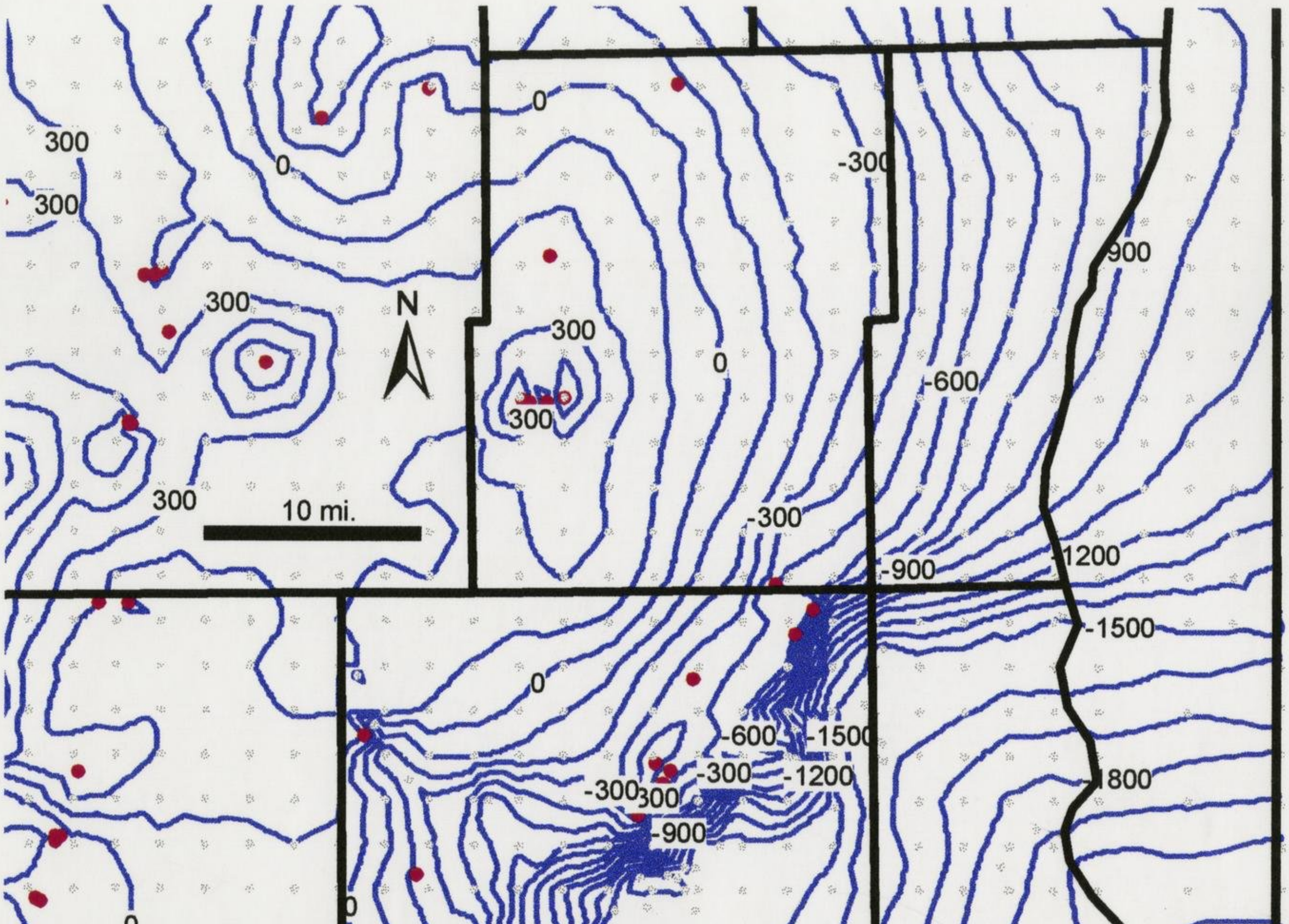


Figure 4. Precambrian basement surface (well points in red, 100 ft contour interval, ft above msl.)

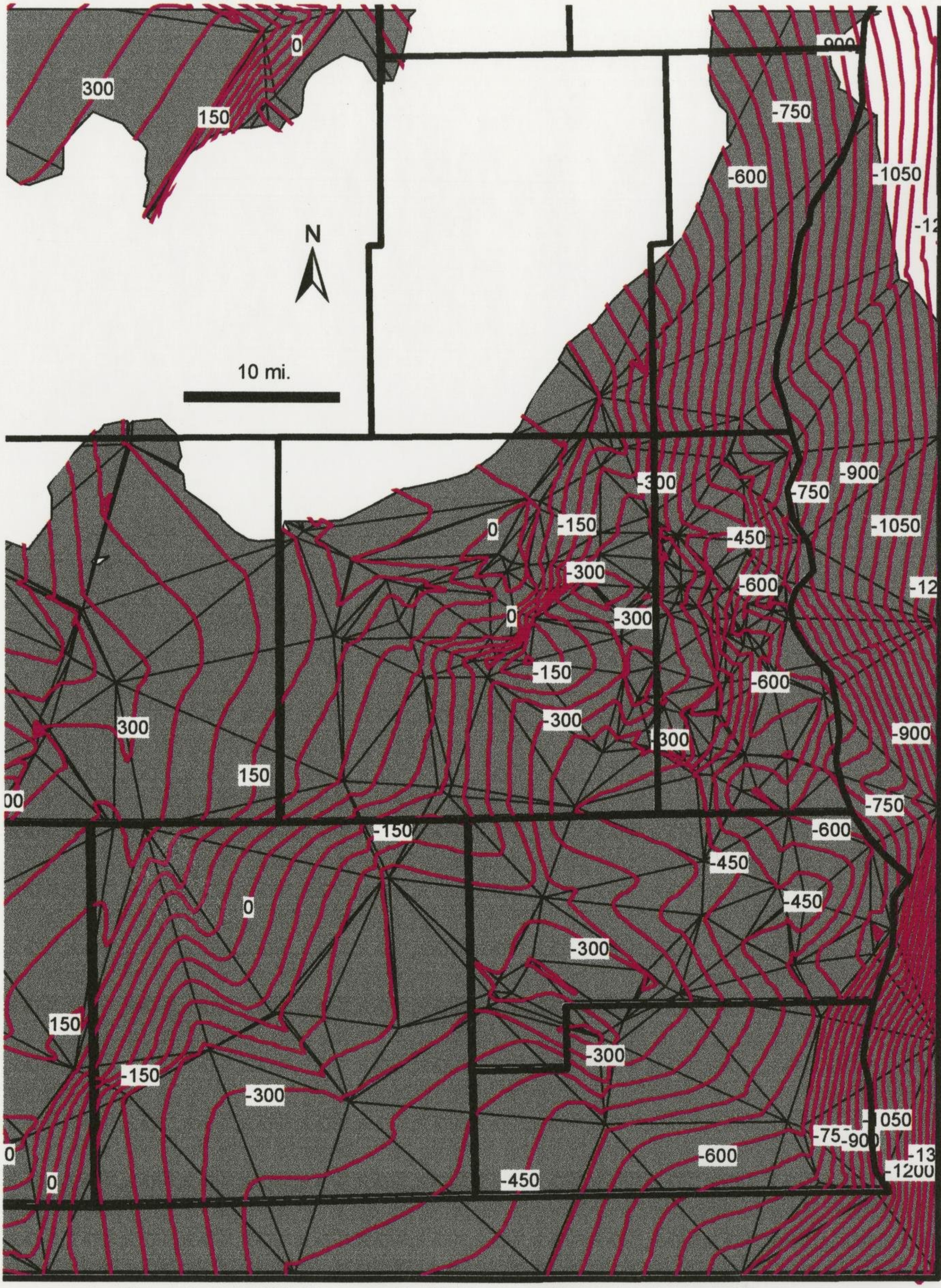


Figure 5: Top of Mt.Simon aquifer (50 ft contour interval, ft above msl.)

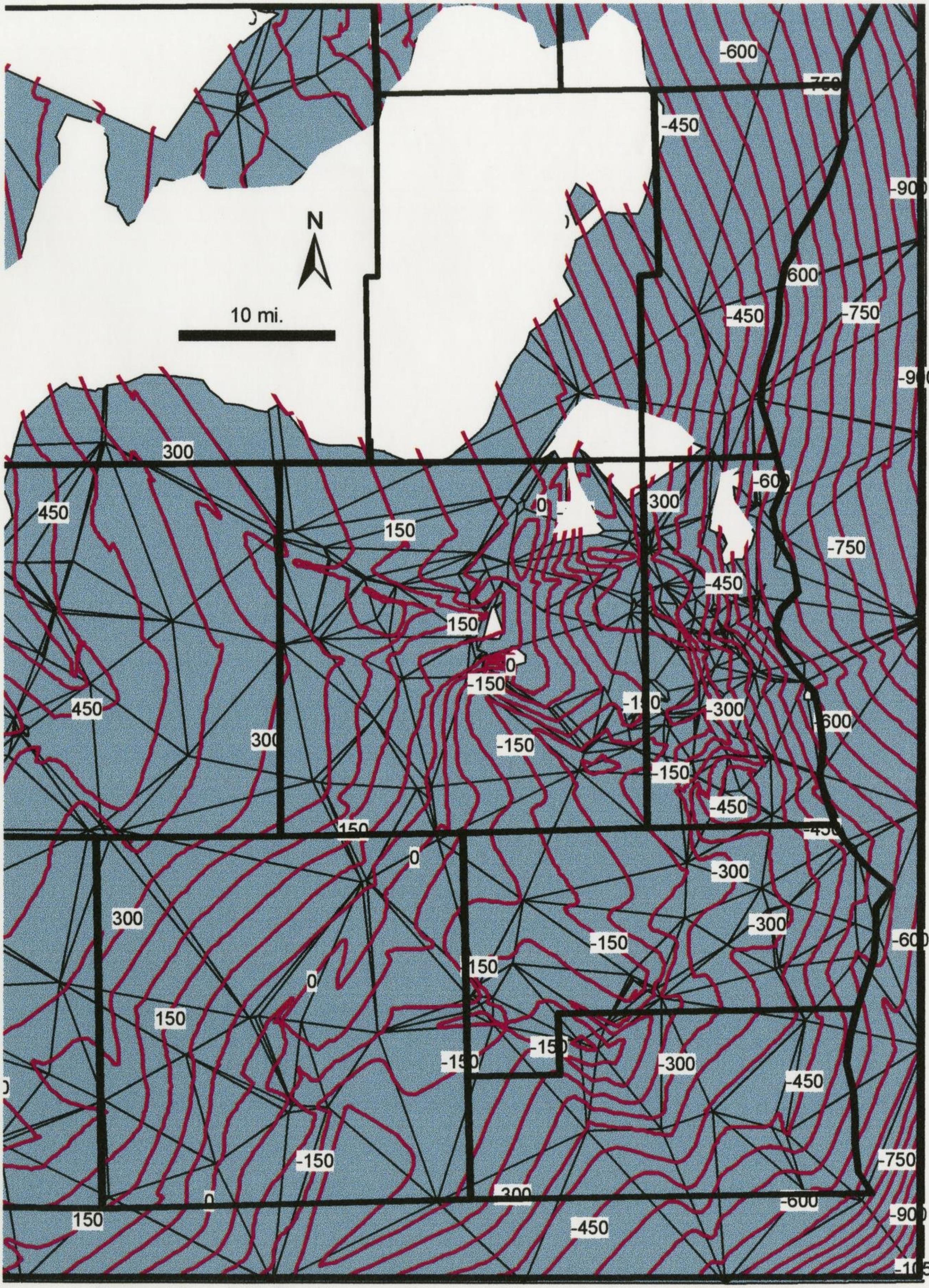


Figure 6. Top of the Eau Claire confining unit (50 ft contour interval, ft above msl.)

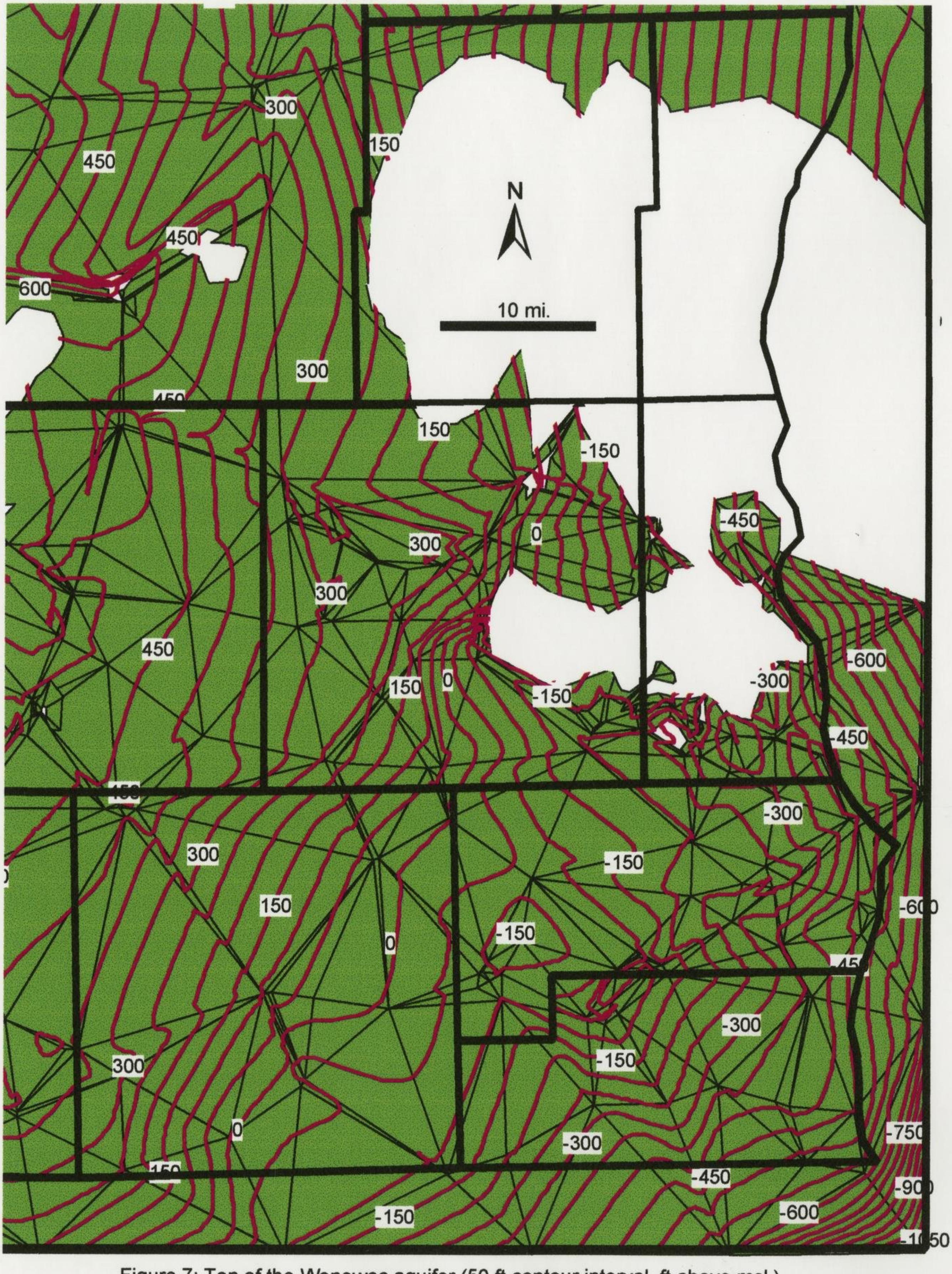


Figure 7: Top of the Wonewoc aquifer (50 ft contour interval, ft above msl.)

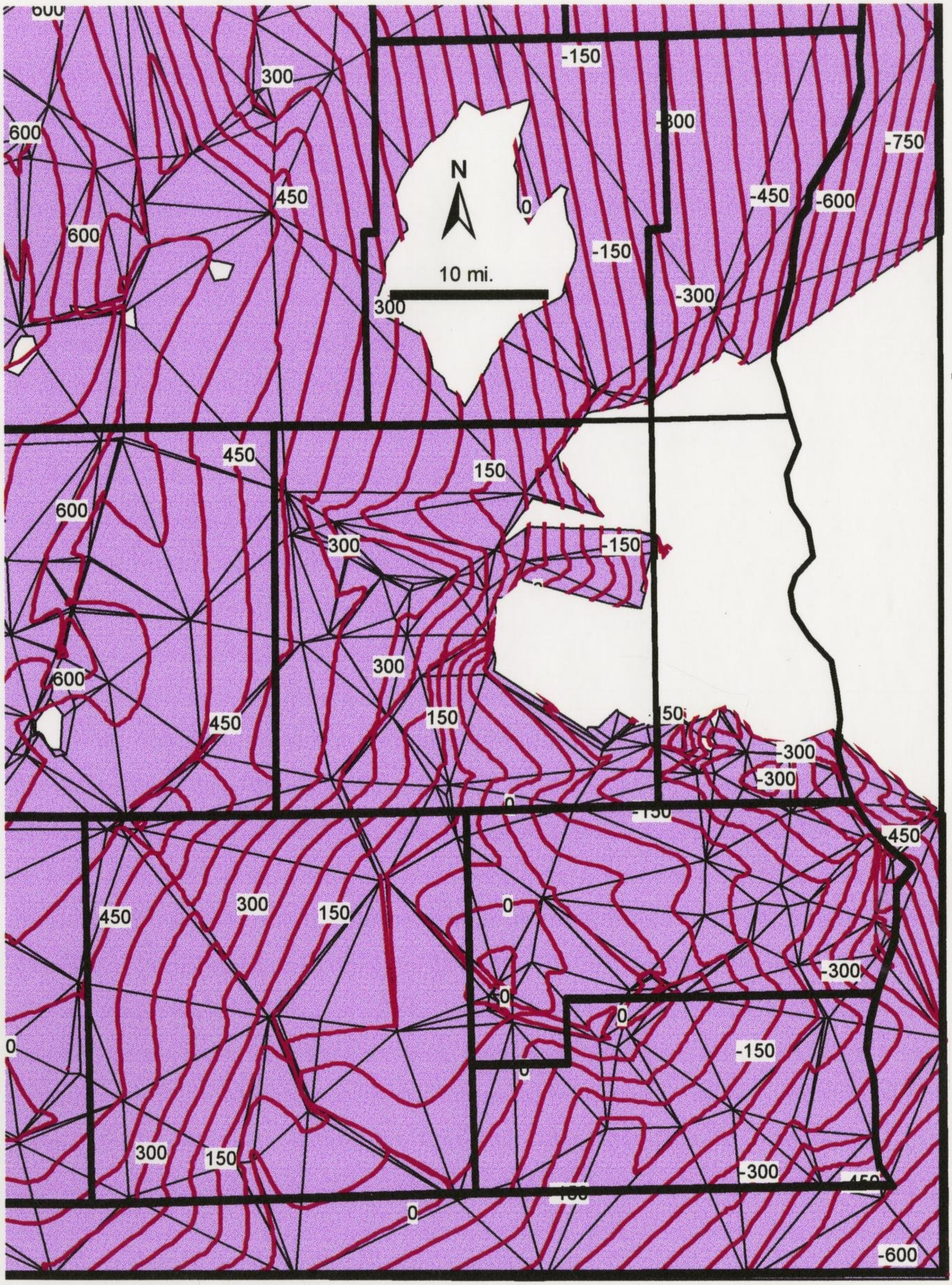


Figure 8. Top of the Trempealeau-Tunnel City aquitard (50 ft contour interval, ft above msl.)

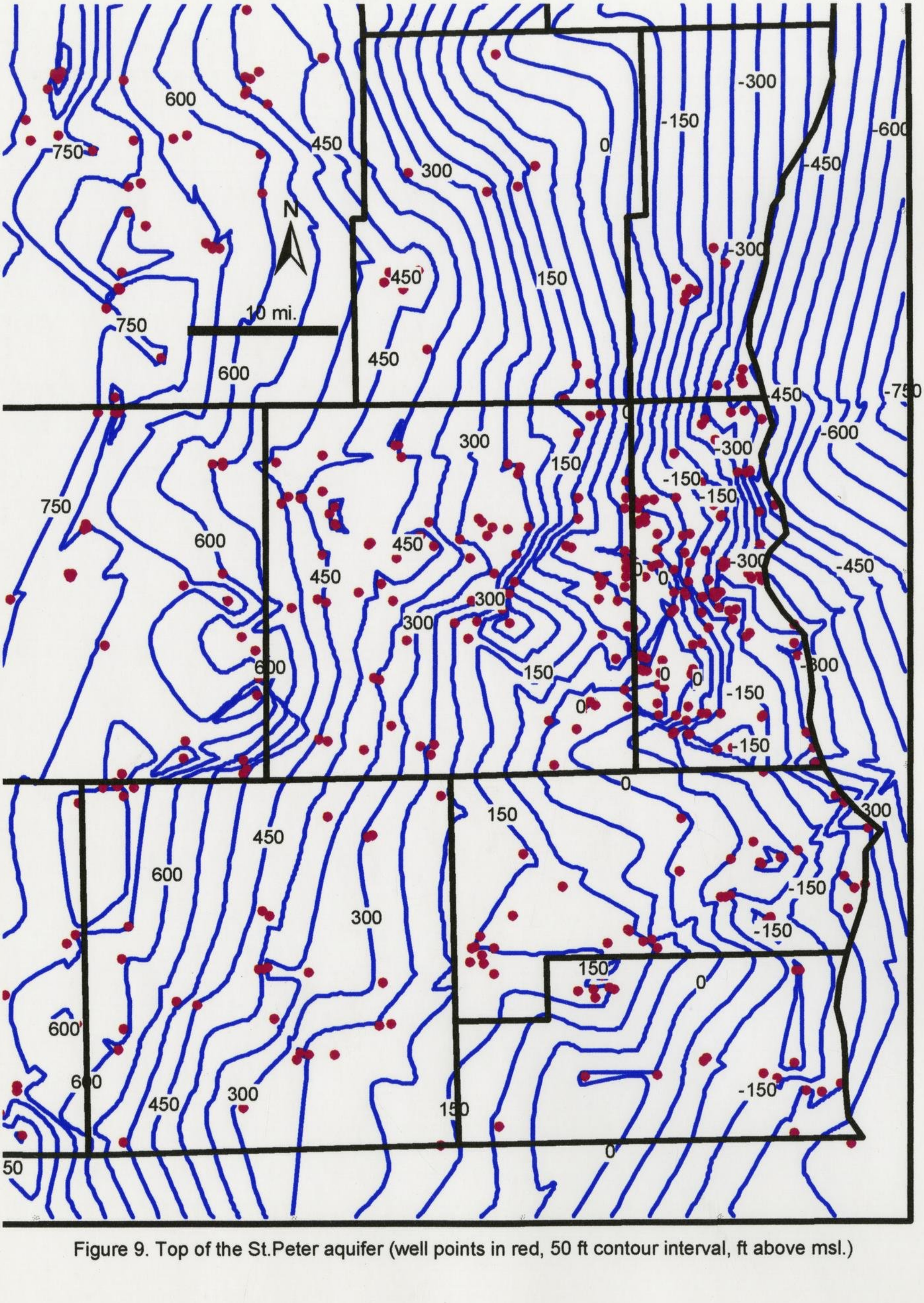


Figure 9. Top of the St.Peter aquifer (well points in red, 50 ft contour interval, ft above msl.)

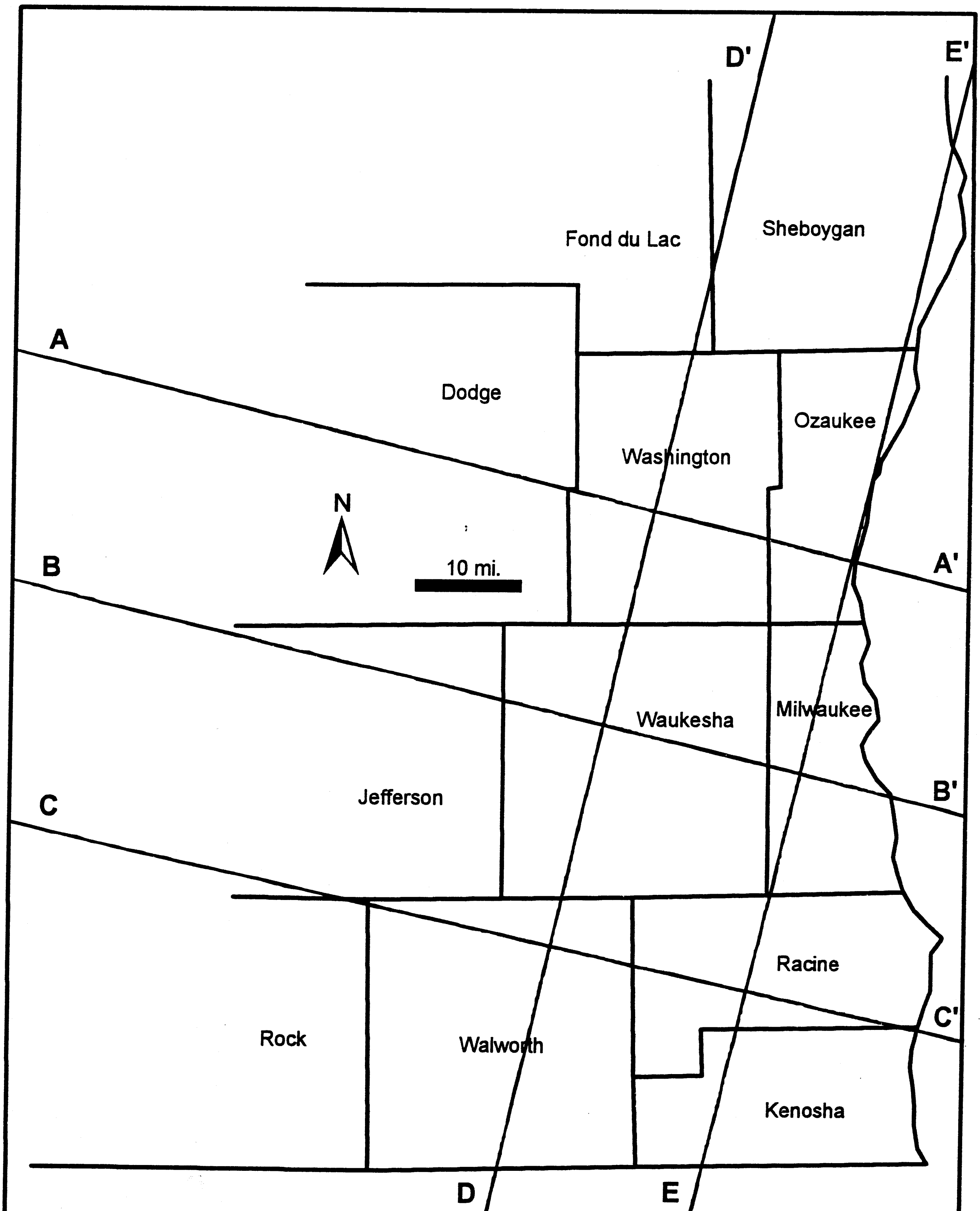


Figure 10: Location of hydrostratigraphic cross-sections

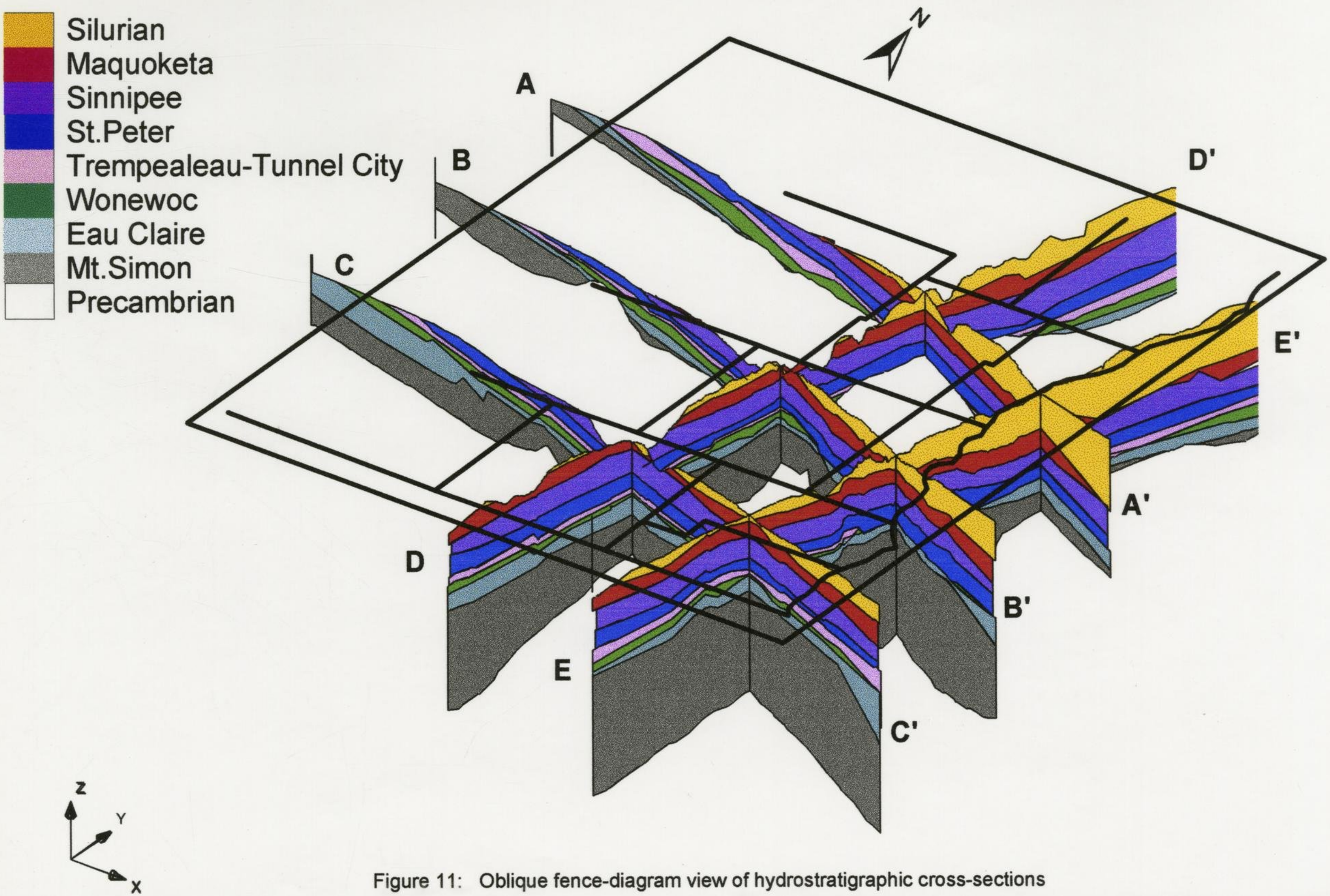


Figure 11: Oblique fence-diagram view of hydrostratigraphic cross-sections

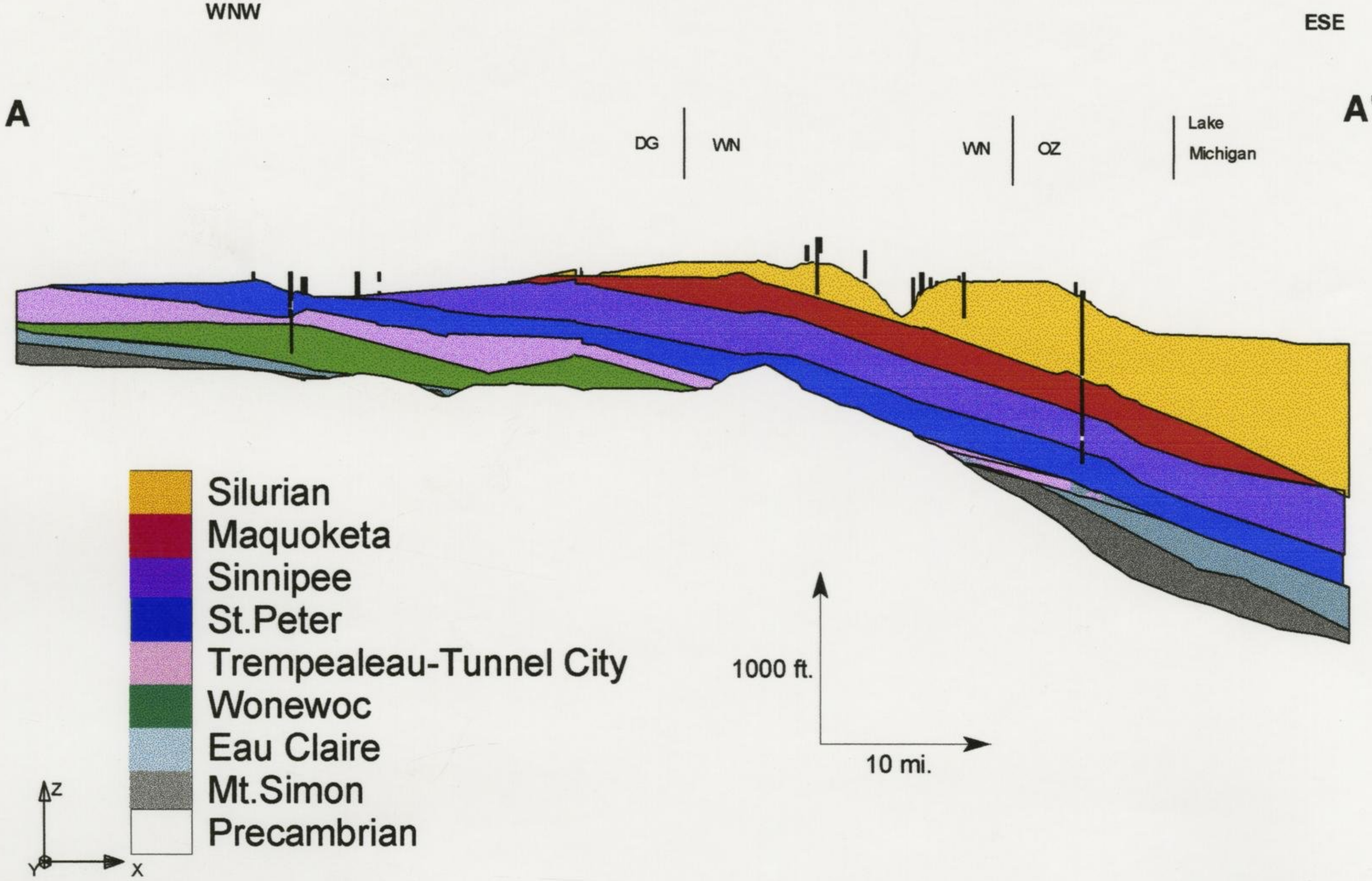


Figure 12: Hydrostratigraphic cross-section A-A' from Dodge through Ozaukee Counties

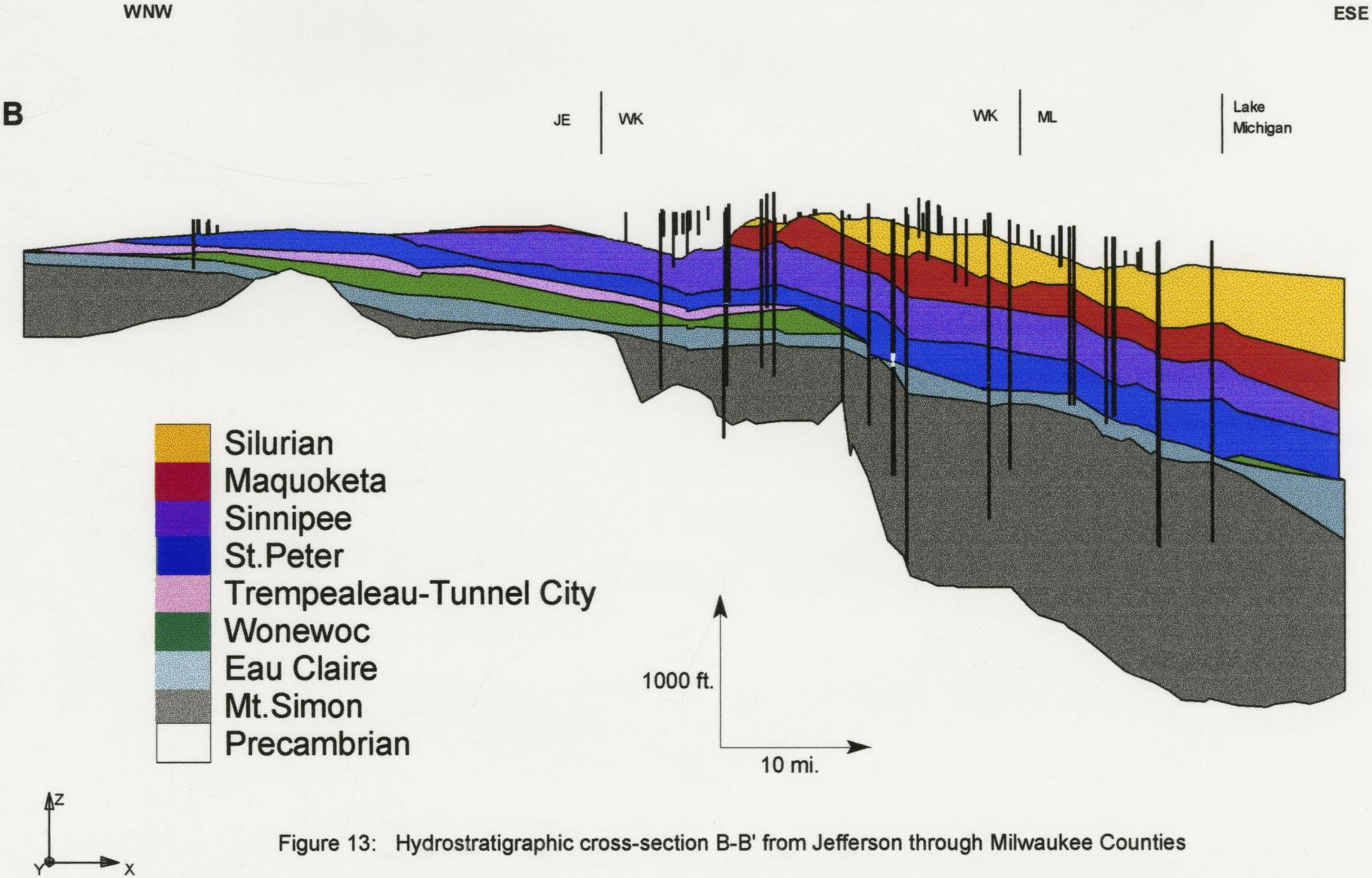


Figure 13: Hydrostratigraphic cross-section B-B' from Jefferson through Milwaukee Counties

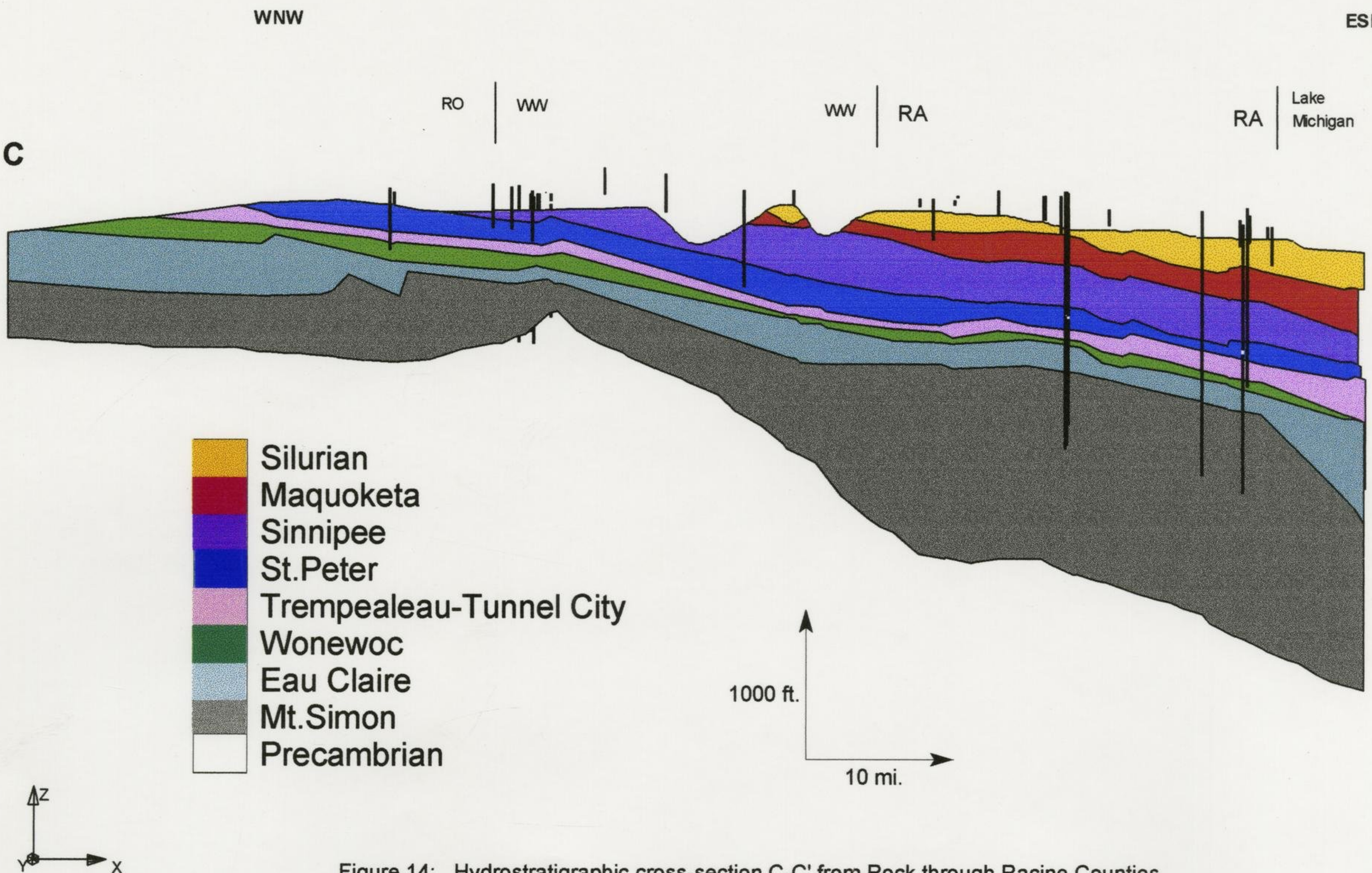


Figure 14: Hydrostratigraphic cross-section C-C' from Rock through Racine Counties

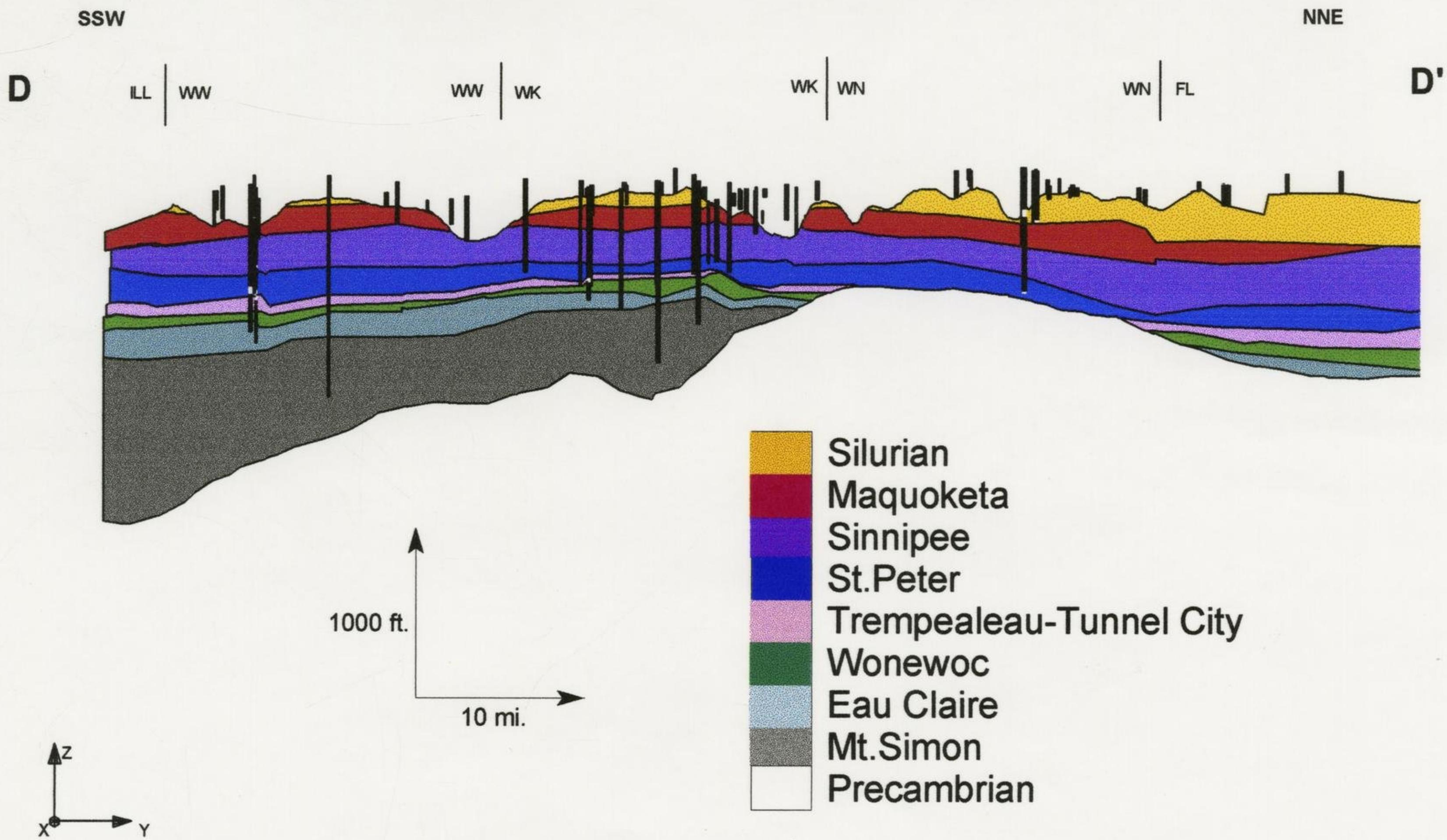


Figure 15: Hydrostratigraphic cross-section D-D' from Walworth through Fond du Lac Counties

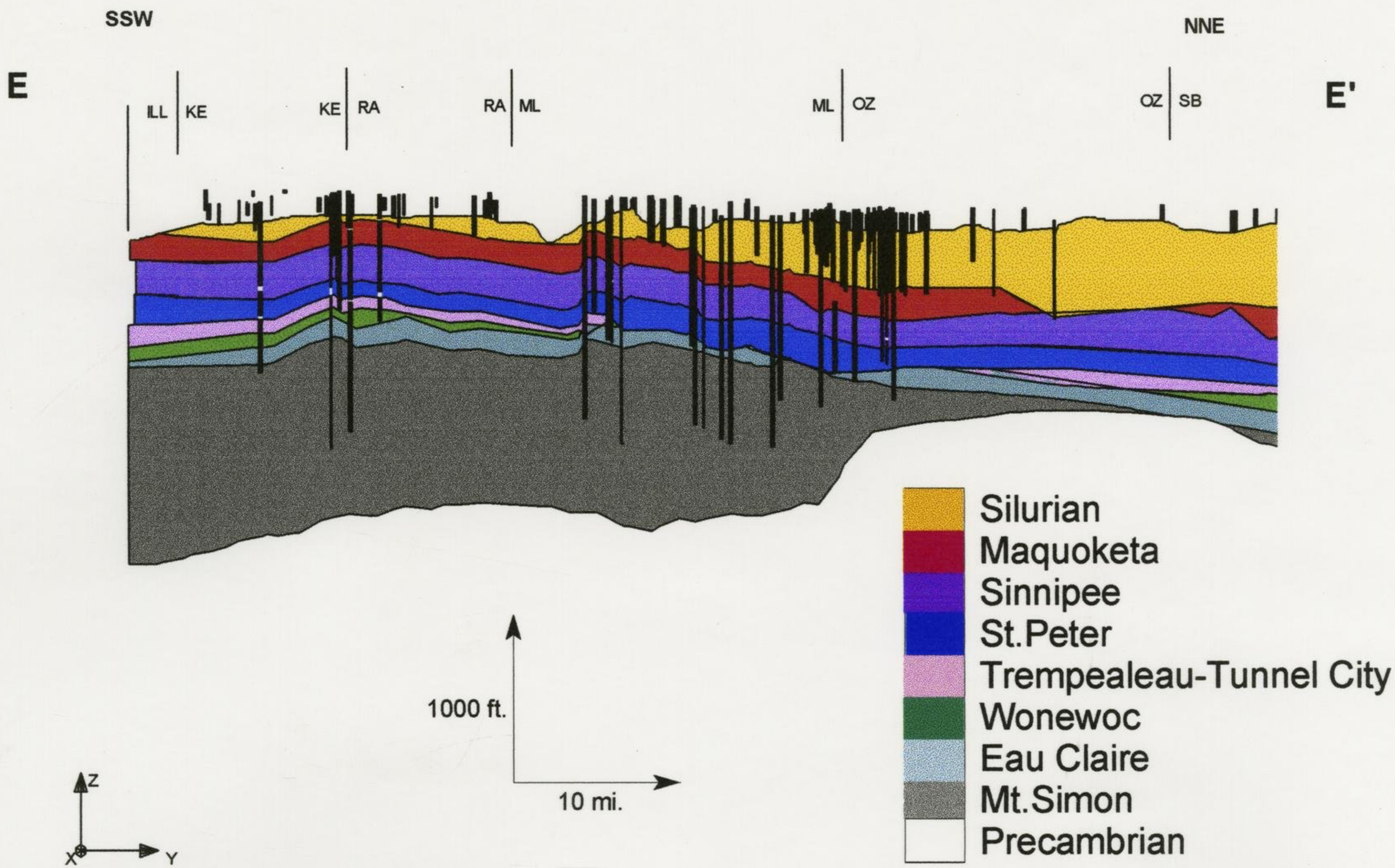


Figure 16: Hydrostratigraphic cross-section E-E' from Kenosha through Sheboygan Counties

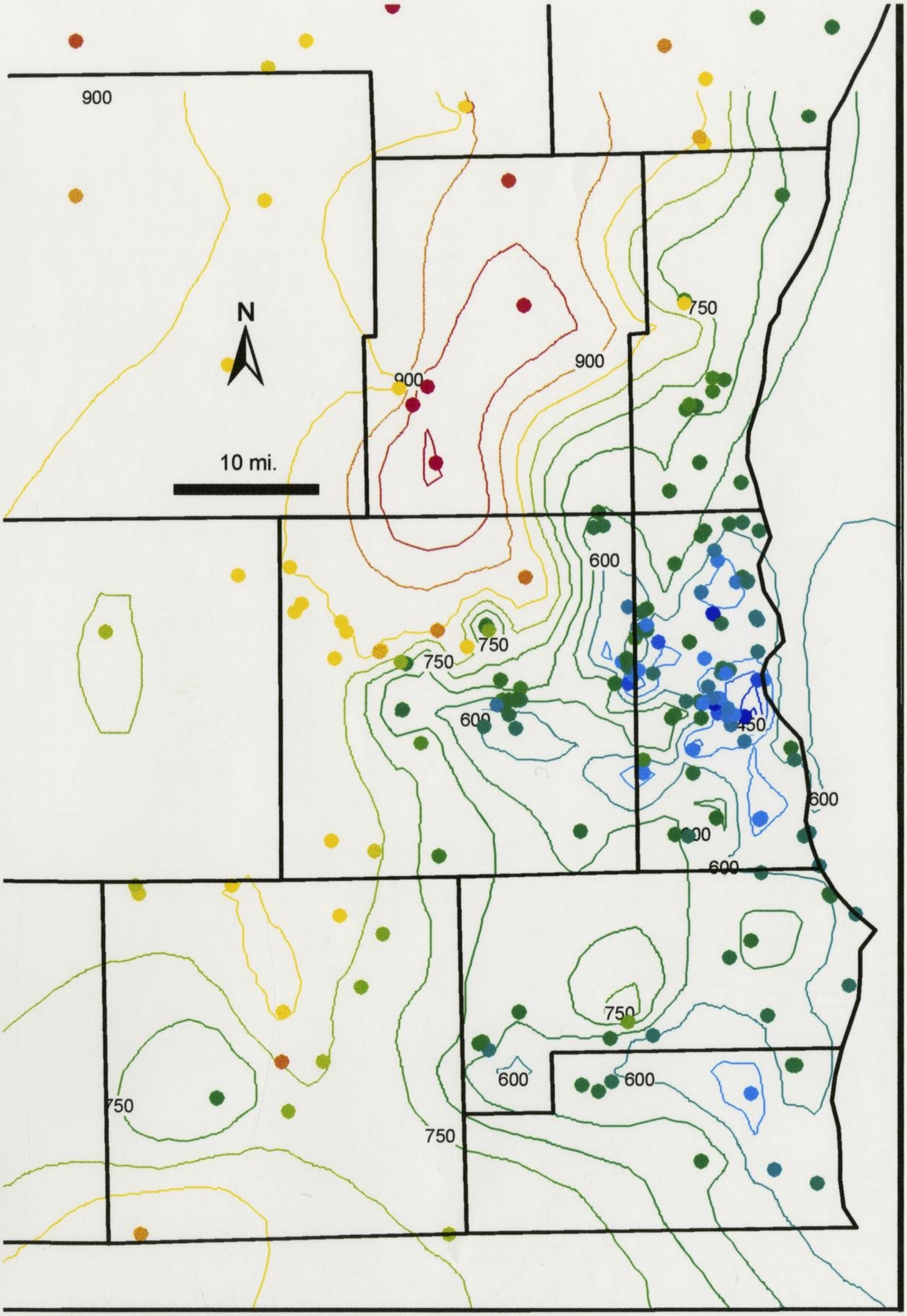


Figure 17: Potentiometric surface, Cambrian-Ordovician aquifer system, 1906-59
(Contour interval 50 ft, elevation above msl.)

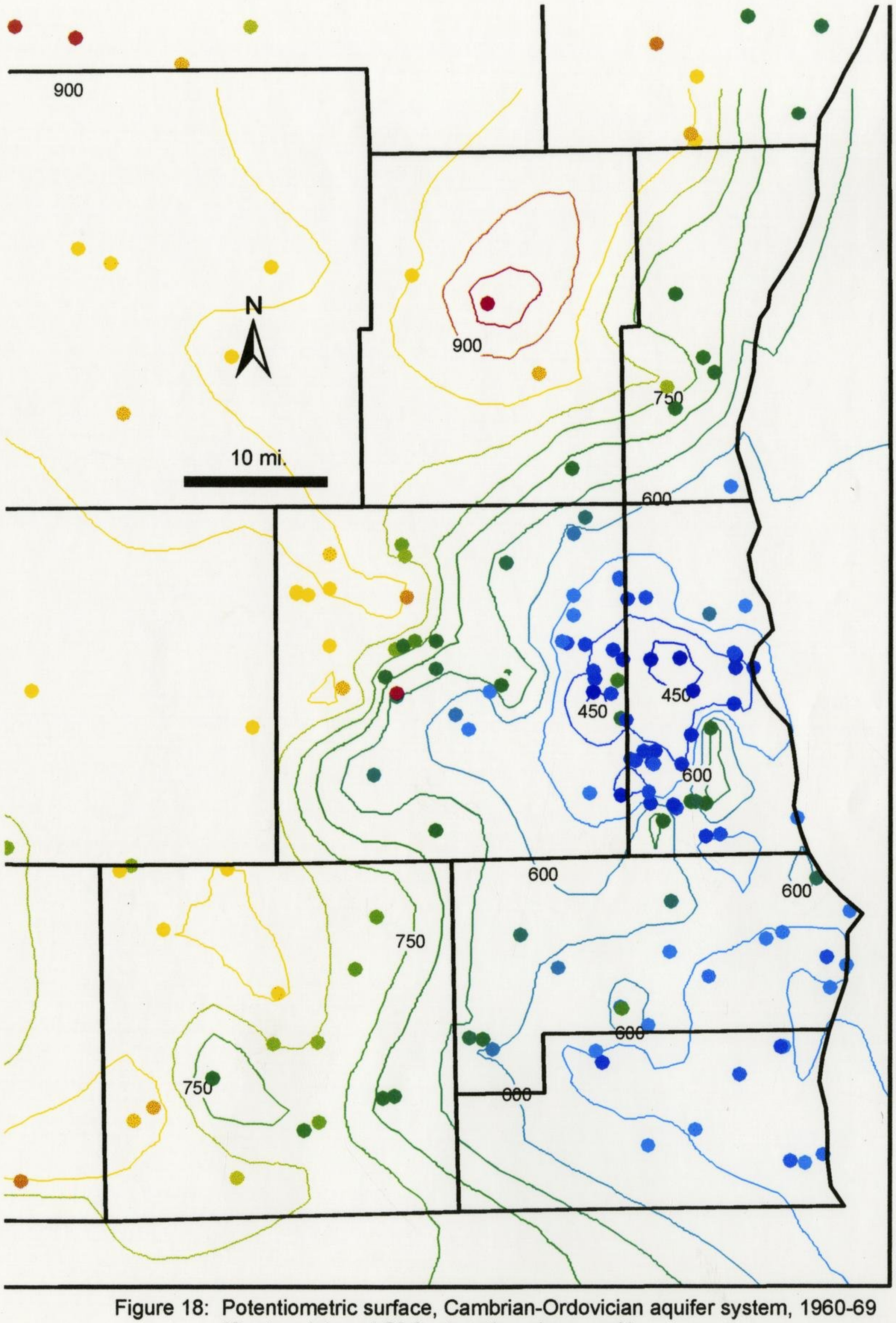


Figure 18: Potentiometric surface, Cambrian-Ordovician aquifer system, 1960-69
(Contour interval 50 ft, elevation above msl.)

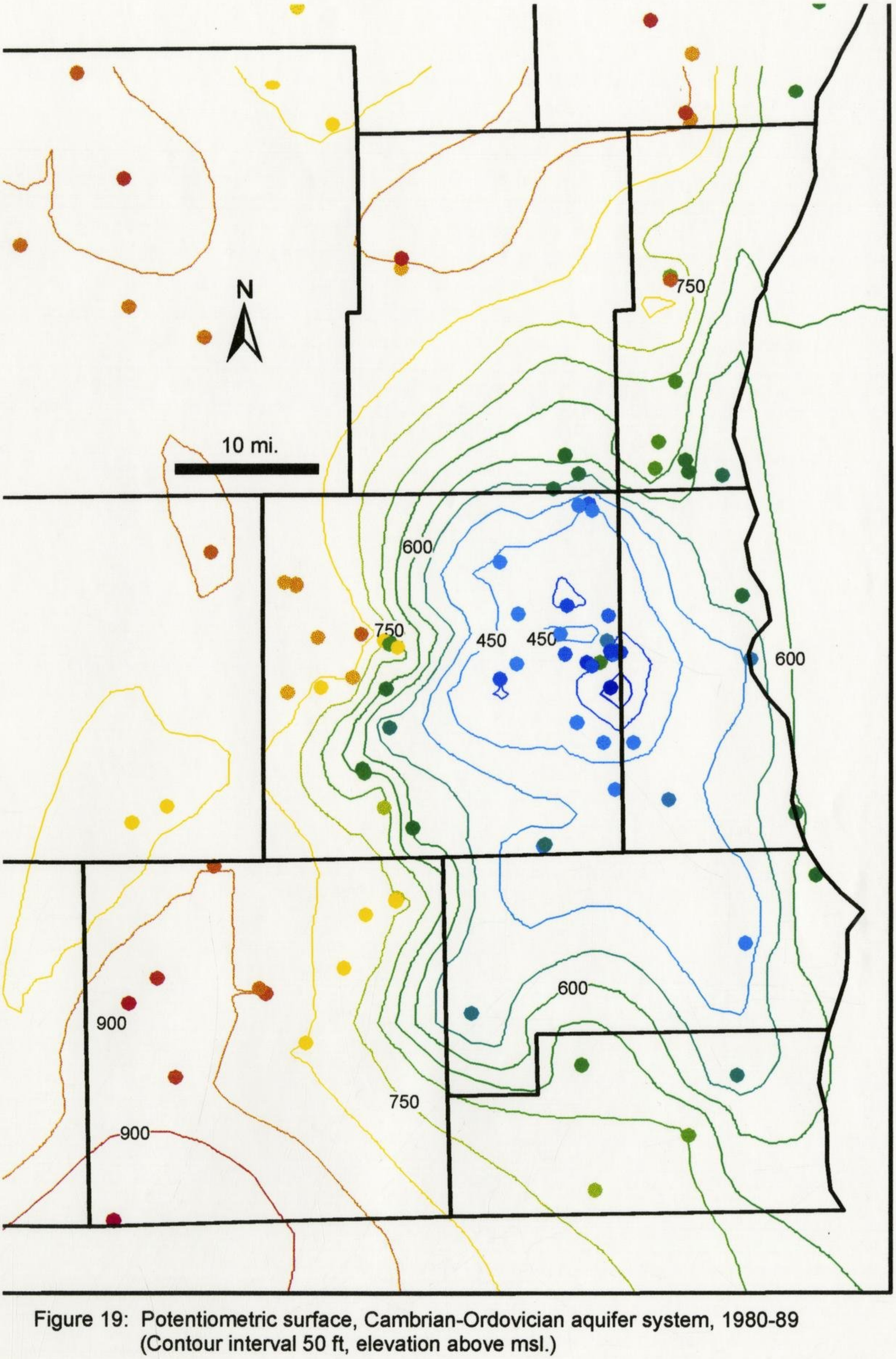


Figure 19: Potentiometric surface, Cambrian-Ordovician aquifer system, 1980-89
(Contour interval 50 ft, elevation above msl.)

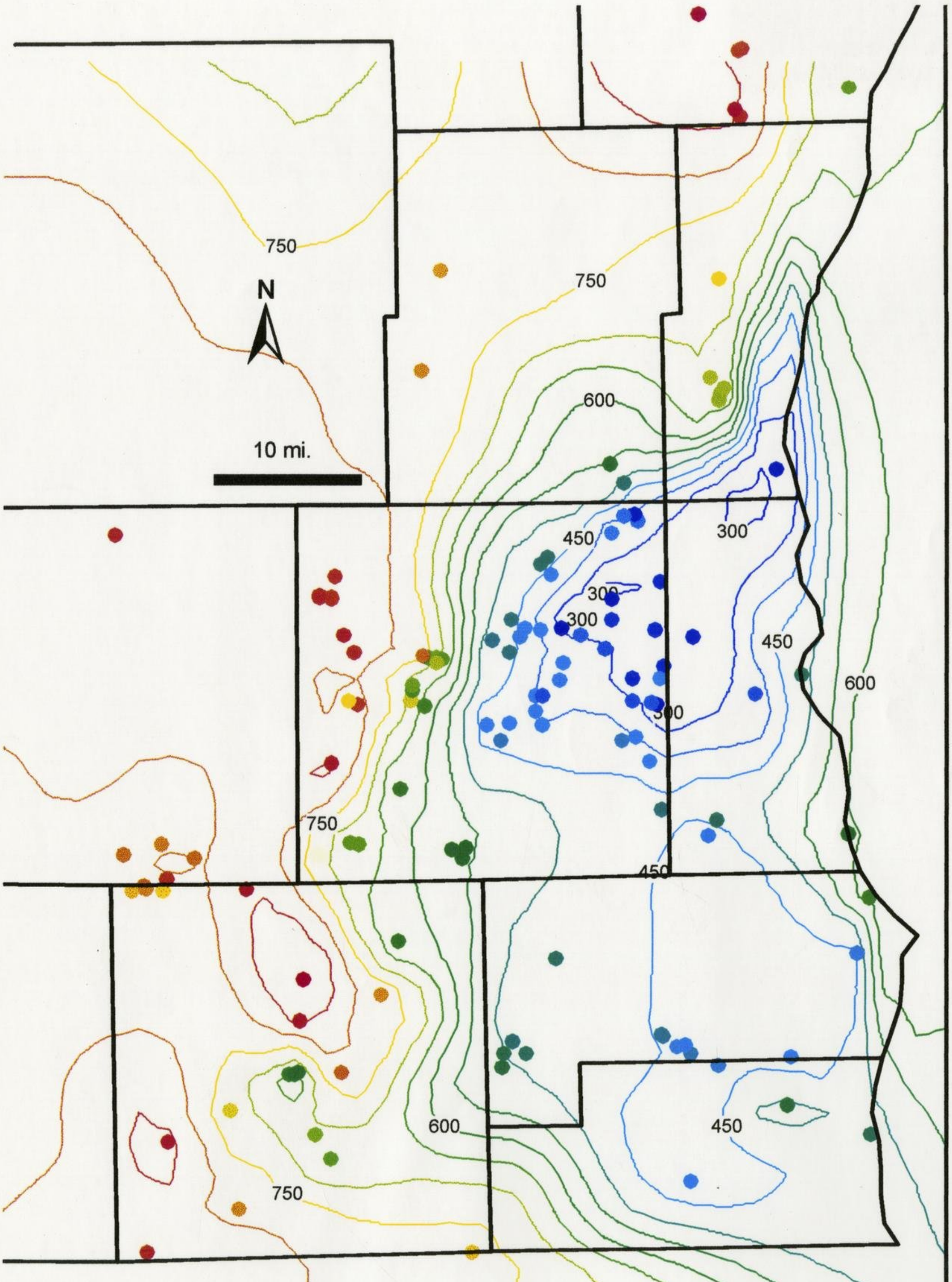


Figure 20: Potentiometric surface, Cambrian-Ordovician aquifer system, 1990-98
(Contour interval 50 ft, elevation above msl.)