HYDROGEOLOGY OF SCOTT COUNTY

Supplement to the Scott County Geologic Atlas

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Executive Summary

This report describes the hydrogeology of Scott County, based on the assembly of existing data and data acquired as part of this investigation. The focus of this report is on bedrock hydrogeology, with additional discussion of the hydrogeology of Quaternary unconsolidated deposits. The report is intended to supplement maps provided as part of the Scott County Geologic Atlas revision, produced with the support of the Scott County Board of Commisioners.

Major conclusions of the report with regard to bedrock hydrogeology are

- Secondary porosity and permeability of aquifers and confining units increases near bedrock surface, both in bedrock valleys and plateaus.
- The hydraulic connection between the Prairie du Chien Group and Jordan Sandstone is leaky confined on both sides of the major southwest-northeast trending bedrock valley.
- The Prairie du Chien Group is karsted, with large voids documented in places where it is upper-most bedrock unit.
- The Ironton-Galesville Sandstone may provide moderately better yields in north-central Scott County than it does to the northeastern part of the county where it is buried under a thicker section of younger bedrock. Secondary porosity in the form of vertical and bedding-plane fractures both within the Ironton-Galesville and overlying Franconia and St. Lawrence Formations may be enhanced near an east-west trending bedrock valley northeast of the city of Jordan, increasing downward infiltration and horizontal flow to the well.

- The yields of all aquifers appear to be dependent, in part, on the nature and thickness of overlying material. Calculated hydraulic conductivity is higher for aquifers where drift cover is thin or absent, or is composed entirely of sandy material. Much of the area in Scott County is covered by a thick sequence of glacial till, restricting the downward movement of water. While this sequence protects deeper aquifers from contamination from activities at the land surface, it also restricts vertical recharge and replenishment of the aquifers for large portions of the county.

The Scott County Atlas was designed to provide decision makers with tools for land use and water resource management. Recent advances in our understanding of how water moves through bedrock aquifers has prompted the need to incorporate that knowledge to atlas products. To this end, the hydrogeologic units defined in this report, along with the other atlas maps and supporting data have designed for use in a geographic information systems (GIS) environment – allowing the user to compare geologic and hydrogeologic data with other county data, such as land use, census, soils data, or parcel information, to aid in decision making regarding development, reconstruction, or natural resource management.

Introduction

This report describes the hydrogeology of Scott County, based on the assembly of existing data and data acquired as part of this investigation. The focus of this report is on bedrock hydrogeology, with additional discussion of the hydrogeology of Quaternary unconsolidated deposits. The report is intended to supplement maps provided as part of the Scott County Geologic Atlas revision, produced with the support of the Scott County Board of Commisioners.

Recent work on the hydrogeology of Paleozoic bedrock in southeastern Minnesota has revised our conceptual framework of how water moves through these rocks. Traditionally, aquifer and confining unit boundaries have corresponded to rock types and their formal stratigraphic names. These *lithostratigraphic* boundaries do not adequately describe changes in the rock's water-bearing characteristics. Recent investigations include regional studies (Runkel and others, 2003a, 2003b, Runkel and others, 2004, Runkel and others, 2006, Tipping and others, 2006), along recent investigations within Scott County (Runkel and others, 2005; this investigation). The conceptual approach used in these studies requires that *hydrogeologic* characterization, including classification of aquifers and confining units, is based on hydraulic data interpreted within the context of hydrostratigraphic attributes. *Hydrostratigraphic* analyses provide information about the distribution of porosity and permeability (Seaber, 1988), without regard to pumping tests or any other kind of hydraulic measurement of rock samples larger than inch-scale plugs; *Hydraulic* analyses of Paleozoic strata provide information on the manner in which ground water travels through pores and is evaluated chiefly through interpretation of borehole geophysical and video logs as well as through more standard aquifer tests.

Our approach of interpreting typical aquifer tests as well as relatively new techniques of borehole flowmeter logging, within the context of a hydrostratigraphic framework, results in improved definition of individual aquifers and confining units. It also enables quantification of their hydraulic properties, and more confident application of these values to areas where hydrostratigraphically similar strata have not been hydraulically tested.

Data and methods

Data compiled for this project, some of which was collected during the project time period, comes from a variety of sources, including aquifer test data, borehole geophysics, borehole video logs, specific capacity data from the state water well database – County Well Index (CWI), outcrop investigations , core analysis, and cuttings sets from well installations. Data collected specifically from or near Scott County include historical aquifer test data from Belle Plaine, Carver, Chaska, Elko, Jordan, the Shakopee Mdewakanton Sioux Community, Prior Lake, Shakopee, Savage, and Webster. Borehole geophysics (high resolution flowmeter data) was collected from Carver, Chaska, Prior Lake, the Shakopee Mdewakanton Sioux Community, Savage and Webster (Figure 1).

Hydrostratigraphic analysis was performed using borehole geophysical data – specifically gamma, caliper and video logs. Additional hydrostratigraphic information came from outcrop investigations, including the Kramer Quarry in Burnsville, core and well cuttings. Hydrostratigraphic data was used to distinguish between matrix porosity and permeability – typically intergranular spaces within the rock, and secondary porosity such as fractures and solution features appeared after the rock had formed.

Hydraulic analysis was performed using data from a wide range of scales. Permeablity estimates from plug tests were converted to hydraulic conductivity assuming water at 10°C. Additional data came from existing conventional aquifer tests, discrete interval packer tests, existing and newly collected borehole flowmeter and multi-tool (gamma, fluid resistivity, fluid temperature) logs, and specific capacity/derived hydraulic conductivity data from CWI.

Specific capacity data was separated into “shallow” versus “deep” bedrock conditions based on depth from bedrock surface to the bottom of the well casing. If this distance is less than or equal to 50 feet, then the data was identified as “shallow” bedrock conditions. If the distance is greater than 50 feet, then the data was identified as “deep” bedrock conditions. In order to make the data consistent for purposes of comparison between aquifers, specific capacity was calculated for 4 inch diameter wells only. For a number of wells in CWI, the listed pumping level was the same as static water level. It was assumed that this is real data, in that there was no measurable drawdown due to test pumping of the well. In order to include these data in the specific capacity dataset, 1 foot was subtracted from the pumping level so that a specific capacity could be calculated.

Hydrostratigraphic and hydraulic data were combined to describe the hydrogeolgic characteristics of each bedrock unit. In order to facilitate the interpretation of data, digital elevation models (DEMs) were created for each bedrock unit from structure maps of the Ironton-Galesville and Jordan Sandstones (See Scott County Atlas plates 2 and 5). Based on these interpretations, DEMs of hydrogeologic units were constructed based on thickness estimates between the boundaries of these units and lithostratigraphic contacts. The resulting GIS products can be used to produce three-dimensional models that illustrate the extent and hydrogeologic character of the bedrock units. A combined geologic and hydrogeologic column showing the sequence and thicknesses of lithostratigraphic and hydrogeologic units is shown in Figure 2.

General geologic setting

Scott County is located on the edge of the Twin Cities Basin (Figure 1). The bedrock lithostratigraphic units within the county in ascending order from bottom to top are the Mt. Simon Sandstone, the Eau Claire Formation, the Ironton-Galesville Sandstones, the Franconia Formation, the St. Lawrence Formation, the Jordan Sandstone, the Prairie Du Chien Group and the St. Peter Sandstone (Figure 2; Scott County Atlas plate 2). Beds are gently tilted to the northeast, with the steepest gradient occurring in the northeastern part of the county, where unit contacts decrease in elevation from about 10 to 25 feet per mile. Paleozoic rocks overlie Pre-Cambrian sedimentary rocks that filled the Mid-Continent Rift system. Faults associated with the rift system have resulted in offsets with in the Paleozoic rocks of as much as several hundred feet in the area near Belle Plaine (see Plates 2 and 5). Faults elsewhere in the county are also thought to be associated with the rift system.

The eroded surface of bedrock in Scott County is characterized by relatively flat plateaus of significant geographic extent, cut by narrow, sinuous valleys. The plateaus are capped by relatively resistant carbonate-rich rock of the Prairie du Chien Group to the east and St. Lawrence Formation to the west. The base of the valleys are locally more than 300 feet lower than the plateau surfaces, typically exposing the Franconia Formation and older rock units. Fine-to coarse-grained unconsolidated deposits from several glacial events cover the bedrock surface, filling the valleys with a complex assortment of gravel, sand, silt and clay-rich sediment (see Scott County Atlas plates 3 and 4).

Bedrock Hydrogeology

Overview - hydrostratigraphy

The methods of hydrostratigraphic analysis attempt to characterize rocks based on the holes within them - referred to as porosity. A further distinction is made between matrix porosity – typically intergranular spaces within the rock, and secondary porosity and permeability such as fractures and solution features appeared after the rock had formed.

The matrix hydrostratigraphic components in Scott County are similar to those defined regionally for Paleozoic strata of southeastern Minnesota by Runkel and others (2003a), broadly divisible into three distinct types: 1) fine clastic, 2) coarse clastic, 3) carbonate rock (e.g. Fig 2). The fine clastic component consists of very fine-grained sandstone, siltstone and shale, moderately to strongly cemented, and has low to very low porosity and permeability. Horizontal permeability is commonly about two orders of magnitude greater than vertical permeability. The coarse clastic component is a fine- to coarse-grained sandstone, poorly cemented, with moderate to very high porosity and permeability. Horizontal permeability is roughly equal to, or as much as and order of magnitude greater than vertical permeability. The carbonate rock component is largely a very fine-to fine-grained dolostone with variable amounts of sand, silt and shale as interbeds or admixed into the carbonate matrix, and has very low matrix porosity and permeability. Limited tests of horizontal permeability indicate that is commonly about two orders of magnitude greater than vertical permeability in laminated carbonate rocks. Horizontal permeability is probably roughly equal to vertical permeability in plug samples of structureless carbonate rocks.

The hydrostratigraphic character of the three matrix components can be strongly affected by the abundance and distribution of secondary pores such as fractures and solution features (places where the rock has dissolved). Permeability is extremely high where these features are well developed and interconnected, and very low, even on a large scale, where they are not well developed (e.g. Gianniny and others, 1996; Libra and Hallberg, 1985; Graese and others, 1988; Liesch, 1973; Eaton and others, 2000; Runkel and others, 2003a). Secondary pores come in four basic types: 1.) *systematic fractures* are flat sided openings perpendicular to bedding, commonly referred to as joints. Together, joints form an orthogonal pattern in plan view; 2.) *non-systematic fractures* are commonly sub-parallel to bedding or sub-vertical, most often with apertures less than systematic fractures, and typically do not connect more than a few bedding plane fractures in the vertical direction; 3.) *bedding plane fractures* are openings in the rock that preferentially align parallel to bedding. In many Minnesota outcrops where the rocks are typically flat-lying, bedding plane fractures appear as long, horizontal cracks that can be traced several tens of feet or farther; and 4.) *non-mechanical voids* due to dissolution and weathering. This category includes irregularly shaped vugs or other holes that do not fall into the first three classifications.

The frequency and interconnectedness of vertical and horizontal secondary pores increases near valley walls, regardless of the rock matrix component (Figure 3). In this way permeability for a given bedrock unit is expected to be higher than it would be some distance from the valley wall.

The abundance and interconnectedness and size of secondary pores diminish with depth. Within tens of feet of the bedrock surface, systematic, non-systematic, bedding plane and dissolution features are present in all matrix components, even shales, regardless of the thickness of overlying glacial drift. As depth increases, the frequency of secondary pores decreases, and are often limited to discrete stratigraphic intervals within the rock.

Overview – hydraulic attributes

The second part of building a hydrogeologic model is to estimate how well the spaces in the rock are connected – referred to as permeability. Closely related to permeability is the measurement of hydraulic conductivity, which specifically addresses the question of how well *water* moves through rocks or other geologic material. These measurements are made on many different scales – from small hand size samples or smaller (plug samples) to multi-well aquifer tests. In this investigation, data on hydraulic conductivity were compiled from plug samples, specific capacity data from CWI, conventional aquifer tests, and high resolution flowmeter measurements. Data are summarized in this report by lithostratigraphic unit in order from youngest (nearest to the land surface) to oldest.

St. Peter Sandstone/weathered residuum - hydrostratigraphy

The St. Peter is a fine-to medium-grained quartz sandstone. In the Twin Cities metropolitan area, lower portion contains thin to thick shale and siltstone beds. In Scott County, variegated siltstone and shale beds are found in the lower 10 to 30 feet. It has a very patchy distribution, and is limited to the eastern most portion of the county. Thickness of the St. Peter is highly variable. It has has an average thickness of 20 feet, but reaches a maximum of 120 feet in places. Much of the variability in thickness is because the top of the underlying Prairie du Chien Group was heavily eroded prior to St. Peter deposition.

The majority of the St. Peter Sandstone is composed of the coarse clastic component. As such, it is expected to have horizontal and vertical hydraulic conductivities similar to the Jordan Sandstone (1 to 2 ft/day). Interbeds of the fine clastic component found in the lower St. Peter have not been tested for permeability but are expected to have vertical hydraulic conductivity from $2x10^{-10}$ to $2x10^{-8}$ ft/day. Weathered residuum commonly found at the St. Peter – Prairie du Chien contact is composed of variegated siltstone, shale and clay. As such it is expected to have low vertical and horizontal hydraulic conductivity.

Outcrop investigations show that the St. Peter Sandstone contains both systematic and non-systematic vertical fractures. In areas where the St. Peter is uppermost bedrock, vertical fractures that are hydraulically connected to voids in the underlying Prairie du Chien Group have been documented (Braun Intertec, 2006). Similarly, the contact between the St. Peter Sandstone and the Prairie du Chien Group may be a zone of enhanced secondary porosity where weathered residuum is not present.

St. Peter Sandstone/weathered residuum - hydraulic attributes

Hydraulic conductivity calculated from specific capacity data from southeastern Minnesota range from 2 to 50 ft/day, with an average value of 16 ft/day (Runkel and others, 2006a). Standard aquifer tests of several boreholes in the Twin Cities area and a single well in Rice County yielded hydraulic conductivity values ranging from 20 to 30 ft/day under similar shallow bedrock conditions as found in Scott County. (Barr Engineering, 1976, 1986, Madsen and Norvitch, 1979).

St. Peter Sandstone/weathered residuum - hydrogeologic synthesis

Distribution is patchy in the county (see Plate 2, Scott County Atlas). Ninety-six wells are designated as receiving water from the St. Peter Sandstone in CWI. It is not a major source of water for the county, and may be most important hydrogeologically for how it impacts recharge to the underlying Prairie du Chien Group. In areas where weathered residuum at the St. Peter-Prairie du Chien contact is thick, vertical movement of groundwater to the underlying Prairie du Chien Group is expected to be limited. In contrast, thin weathered residuum combined with fractured, poorly cemented coarse clastic component will provide rapid vertical recharge. An important consideration is that the elevation and lithology of the contact between the St. Peter Sandstone and the Prairie du Chien Group is highly variable. As a consequence, hydrogeologic conditions along the contact are not expected to be uniform even at local scales.

Prairie du Chien Group - hydrostratigraphy

The Prairie du Chien Group is composed of fine-grained dolostone, sandstone and shale. The lower 60 to 100 feet (Oneota Dolomite) is primarily dolostone, while the upper 75 to 100 feet (Shakopee Formation) is composed of mixed dolostone and fine-to coarse-grained quartz sandstone. The Prairie du Chien Group is mostly present in the northeastern and southeastern parts of the county as relatively flat, buried plateaus, and in fault blocks southeast and southwest of Belle Plaine. Typical thickness of the Prairie du Chien Group is 100 to 150 feet - up to 200 feet near the Rice County border. It is less than 100 feet thick moderate distances (1000 feet or more) from its mapped contact with the underlying Jordan Sandstone along bedrock valleys.

The matrix porosity of the Prairie du Chien Group within Scott County is typical of its regional properties described by Runkel and others (2003a); both the Oneota Dolomite and overlying Shakopee Formation consist largely of the carbonate component, with horizontal hydraulic conductivity ranging from $2x10^{-7}$ to $2x10^{-4}$ ft/day and a porosity of less than 10 %. Horizontal conductivity is typically as much as 10 times vertical conductivity. Fine and coarse clastic interbeds are common in the lowermost part of the Oneota Dolomite – the Coon Valley Member – and as subordinate beds in the Shakopee Formation. Individual siliciclastic beds are typically less than 3 feet thick, and are expected to have horizontal hydraulic conductivity values similar to the coarse clastic component of the Jordan Sandstone (1 to 2 ft/day or greater).

Secondary porosity within the Prairie du Chien Group is present in solution enlarged systematic and non-systematic vertical fractures, and along bedding planes. Unlike younger bedrock in southeastern Minnesota, tracing individual beds in outcrop for more than a few feet within the Prairie du Chien is often not possible, due to the recrystallized (dolomitized) nature of this bedrock unit and because original bedding was lenticular and irregular in thickness. Although bedding planes are often obscured, linear arrangements of multiple cavities are not, and they typically can be traced over distances of several tens of meters along a line parallel to master bedding. Cavities along the same plane range from a few inches to more than several feet in height. Near Scott County, these features are best exposed at the Kramer Quarry in Burnsville, where large cavities are visible at similar elevations around the quarry walls, particularly in the lower Shakopee Formation. In general, secondary porosity in the form of systematic and non-systematic fractures and solution features is more pronounced in the Shakopee Formation, with thinner beds and and a greater abundance of fractures than the Oneota Dolomite. Vertical fractures, and enhanced secondary porosity within the Oneota Dolomite are more frequent near the valley walls of both exposed and buried bedrock valleys. Secondary pores have been discovered in the form of fluid loss, bit drops and hole collapse while drilling test wells on the western edge of the major southwest-northeast trending bedrock valley for the city of Prior Lake (Barr, 2006, unpublished data).

Prairie du Chien Group - hydraulic attributes

Specific capacity was calculated for 378 Prairie du Chien wells in Scott County. Of these, 14 were identified as deep bedrock conditions and the remaining 364 were identified as shallow bedrock conditions. Data from shallow bedrock conditions had a mean value of 9.3 gpm/foot of drawdown, and data from deep bedrock conditions had mean value of 14.8 gpm/foot of drawdown. Data from shallow conditions had greater variability, with a higher number of outliers in the upper range of values (greater than 20 gpm/foot of drawdown) (Figure 4).

Aquifer test data for the Prairie du Chien Group were collected from several locations. Aquifer tests were conducted by the Minnesota Department of Natural Resources in 1998, to determine the impact pumping in the Prairie du Chein and Jordan aquifers on a calcareous fen near Savage, Minnesota. The Prairie du Chien portion of the test consisted of pumping Savage well 6 (unique well number 453857) for seven days and observing drawdown in 14 surrounding wells.

Information on estimated hydraulic conductivity derived from the Savage-DNR aquifer test was not provided with the data. However, the results reveal anisotropy within the Prairie du Chien Group and provide qualitative information on the degree of hydraulic connection between the Prairie du Chien Goup and the underlying Jordan Sandstone. Pumping from Savage well 6 produced approximately 36 feet of drawdown in its water level, and minor drawdown in observation wells, including a well completed in glacial drift above the Prairie du Chien surface. These results are representative of unconfined conditions within the Prairie du Group at this location. Pumping from Savage well 6 also produced 3 feet of drawdown in Savage well 3 – a well drawing water from the Jordan Sandstone located approximately 1000 feet from Savage well 6 – indicating a moderate hydraulic connection between the Prairie du Chien Group and Jordan Sandstone at this site. When the Jordan aquifer well – Savage well 3 – was pumped at a later date, moderate drawdown was also observed in the Savage well 6. In this case, pumping produced nearly 60 feet of drawdown the Jordan pumping well, in contrast to 6 feet of drawdown down in the Prairie du Chien well – Savage well 6. The sharp drawdown in the Savage well 3 with moderate drawdown in Savage well 6 is indicative of leaky confined conditions in the Jordan at this site, with leakage occurring presumably through vertical fractures in the lower Prairie du Chien. Drawdown in the Prairie du Chien due to pumping from Savage well 3 was also noted in distant observation wells, with more pronounced drawdown occurring in a northwesterly direction from Savage well 3 – perhaps indicative of fracture anisotropy in the lower Prairie du Chien Group.

Drawdown was also monitored within the Prairie du Chien Group during a Jordan aquifer test for the Shakopee Mdewakanton Sioux Community (Ruhl, 1999) (Figure 1). This test was conducted just west of the major southwest-northeast trending bedrock valley. Pumping in the Jordan produced 0.32 feet of drawdown in a Pairie du Chien observation well located approximately 1200 feet away, and 9 feet of drawdown a Jordan observation well located approximately 750 feet from the pumping well. As with the previous aquifer test, these results are indicative of leaky confined conditions within the Jordan aquifer, with leakage occurring through vertical fractures in the lower Prairie du Chien Group.

Prairie du Chien Group - hydrogeologic synthesis

The Prairie du Chien Group within Scott County is composed of a high yielding upper portion, herein referred to as the Shakopee aquifer that is, in places, hydraulically connected to shallow, water table aquifer systems, such as found at the Savage Fen. Permeability within the upper portion of the Prairie du Chien Group is due primarily to secondary porosity features such as systematic and non-systematic fractures, bedding plane fractures, and voids due to dissolution and weathering of the carbonate rock. The lower Prairie du Chien Group is composed of less permeable, massively bedded dolostone, herein referred to as the Oneota confining unit which, combined with the Coon Valley member (lowest interval within the Prairie du Chein Group), provide confinement to the underlying Jordan Sandstone. Leakage through the Oneota confining unit is expected to be through systematic joints in areas distal to buried bedrock valleys, and through a combination of systematic, non-systematic and bedding plane fractures near bedrock valleys.

Jordan Sandstone - hydrostratigraphy

Although commonly thought of as a homogenous quartz sandstone, the Jordan Sandstone is, in fact, composed of two interlayered facies: a medium- to coarse-grained quartz sandstone and fine-grained feldspathic sandstone with lenses of siltstone and shale. The Jordan Sandstone is present in the northeastern and southeastern parts of the county, in portions of the area west of the Belle Plaine fault system, in fault zone southeast of Belle Plaine and as eroded patches in the central and southeast central parts of the county. Uneroded thickness of the Jordan Sandstone in Scott County is 80 to 100 feet.

Estimates of matrix porosity come from plug samples, where samples from the coarse clastic component of the Jordan Sandstone commonly have hydraulic conductivities greater than 2 ft/day (MUGSP, 1980; Setterholm and others, 1991). Plug samples from the fine clastic component have horizontal hydraulic conductivities that range from $2x10^{-4}$ to $2x10^{-8}$ ft/day, and vertical hydraulic conductivities that range from $2x10^{-6}$ to $2x10^{-8}$ ft/day.

Observations of secondary porosity features within the Jordan Sandstone come from several sources. Systematic joints and non-systematic vertical and subvertical fractures have been recognized in outcrop. Recent borehole video and geophysical logs reveal bedding plane fractures within the Jordan Sandstone that are hydraulically active (see discussion below).

Jordan Sandstone - hydraulic attributes

Specific capacity was calculated for 170 Jordan wells in Scott County. Of these, 159 were identified as having deep bedrock conditions and the remaining 11 were identified as having shallow bedrock conditions. Data from shallow bedrock conditions had a mean value of 11.2 gpm/foot of drawdown, and data from deep bedrock conditions had mean value of 20.8 gpm/foot of drawdown. Data from shallow conditions had less variability, with a lower number of outliers in the upper range of values (greater than 20 gpm/foot of drawdown) (Figure 4).

Aquifer test data for the Jordan Sandstone comes from several sources. The Jordan aquifer test for the Shakopee Mdewakanton Sioux Community discussed earlier in the Prairie du Chien section, estimated bulk hydraulic conductivity for the Jordan Sandstone as 31 ft/day, assuming a saturated aquifer thickness of 204 feet (Ruhl, 1999). If a 96 foot aquifer thickness is used, then a bulk hydraulic conductivity value of 65 ft/day is reached. This value agrees well with other Jordan aquifer data collected as part of this investigation.

In Prior Lake, a Jordan well - Prior Lake No. 3 was tested (unique well number 207308; Minnesota Department of Health, 1998a) (Figure 1). At this site, the Jordan aquifer is overlain by the Prairie du Chien Group and a relatively thick sequence sand, gravel and glacial till. A buried tributary to the main southwest-northeast trending bedrock valley exists just north of the Prior Lake well field. Bulk hydraulic conductivity for the Jordan at this site was estimated to be 51 ft/day, assuming an aquifer thickness of 96 feet. Water level in a Prairie du Chien well, located approximately 1 mile east-northeast of the well field (unique number 549754), was monitored during the test. It showed no response to pumping in the city well.

In Shakopee, two city wells that draw water from the Jordan aquifer were tested. At Shakopee No. 6 (unique well number 180922; Minnesota Department of Health, 1998b) (Figure 1), the Jordan aquifer is overlain by the Prairie du Chien Group, which in turn is overlain by 3 to 8 feet of drift. At this site, the Jordan aquifer appears to be in good hydraulic connection with the land surface; water levels in the pumping and observation well responded to changes in atmospheric pressure which was also monitored during the test. Well response during the test indicates semi-leaky confined conditions within the Jordan (Minnesota Department of Health, 1998b).

Shakopee No. 12 (unique number 626775; Bonestroo, Rosene, Anderlik, and Associates, 2001) (Figure 1) is located near the edge of the terrace/base of the bluff along the Minnesota River. Shakopee wells 9 and 11, both completed in the Jordan Sandstone were used as monitoring wells for this test. They are located downgradient from Well No. 12, under the river terrace deposits. No response was documented in either of these wells due to pumping of Well No. 12. Based on the aquifer test results, bulk hydraulic conductivity for this well was estimated to be 125 ft/day, assuming an aquifer thickness of 90 feet (Bonestroo, Rosene, Anderlik, and Associates, 2001).

No Jordan wells were flowmeter logged in Scott County as part of this investigation. However, flowlogs from a nearby well in Webster Minnesota (unique well number 699024) (Figure 1) provide useful information applicable to Jordan aquifer conditions within the county. A combination of flowmeter, caliper and video logging documented several hydraulically active fractures within the Jordan Sandstone at this site. One in particular accounted for most of the yield within the open hole (Figure 5).   Bulk hydraulic conductivity calculated from injection rates during flowlogging was 60 ft/day. This value agrees well with the value calculated from a conventional aquifer test of the same hole of 63 ft/day (Peer Engineering, 2004 - Transmissivity reported as 52,000 gallons per day/foot – hydraulic conductivity value calculated using an aquifer thickness of 110 feet). If the only fracture apertures of less than a foot are used for aquifer thickness, then the hydraulic conductivity is considerably higher.

Jordan Sandstone   - hydrogeologic synthesis

Unlike results for the greater metropolitan area and southeastern Minnesota, specific capacity values were slightly lower and less variable in Scott County under shallow bedrock conditions than they were under deep bedrock conditions (Figure 4). Although the differences are slight and there are a relatively limited number of samples for shallow conditions, they invite further investigation to see if these results are specific to the Scott County region.

The Jordan Sandstone is composed largely of the same coarse clastic component as the Ironton-Galesville Sandstone, yet estimated hydraulic conductivity values are typically 5 to 6 times larger (Appendix; Minnesota Health, 1998a, 1998b. Peer, 2005). This may in part be due to contribution through leakage via fractures in the overlying Oneota confining unit, whereas the Ironton-Galesville is covered by the low permeability rocks of the lower Franconia Formation. Recent video and flow logging of the Jordan

Sandstone has documented the presence of hydraulically active fractures within the Jordan, Flowmeter results clearly indicate that intergranular flow also occurs within the this unit; the combination of a typically thick moderately cemented, coarse clastic component providing intergranular porosity and permeability with hydraulically active fractures contributes to high yields from Jordan aquifer wells.

St. Lawrence Formation - hydrostratigraphy

The St. Lawrence Formation is composed of very fine-grained, dolomite cemented sandstone and siltstone. Laminated green shale and pink to red, coarsely crystalline dolostone occur as interbeds. The lower one-half of the formation contains more abundant dolostone. The St. Lawrence Formation has an eroded top through most of the central part of the county, is absent in major bedrock valleys and in southern tributaries of the main southwest-northeast bedrock valley. Its uneroded thickness in the northeastern part of the county is 50 to 60 feet, and increases to 70 feet in the southest. Thickness west of the Belle Plaine fault system is estimated to be 80 feet.

Estimates of matrix porosity come from plug samples, where samples from the carbonate and fine clastic components of the St. Lawence Formation have low to very low hydraulic conductivities, ranging from $2x10^{-5}$ to $2x10^{-9}$ ft/day. Estimates of secondary porosity come from a combination of outcrop and core observations, video and caliper logs. These data indicate that the St. Lawrence has bedding plane, systematic and non-systematic fractures, which are most abundant where the unit is uppermost bedrock. The St. Lawrence has a greater abundance of carbonate in the lower one-half of the formation than elsewhere in the metropolitan area. As such, secondary pores in the form of solution features or vugs are also expected to be present. Dissolution cavities as seen in borehole video and outcrop from elsewhere in the metro area are as large as 2 inches, and are typically elongate in a direction parallel to bedding. The pores exhibit features typical of hydraulically active pores, including oxidation and deposits of minerals such as pyrite and calcite (Runkel and others, 2003b; Runkel, 2006).

St. Lawrence Formation - hydraulic attributes

Not enough wells identified as receiving water from the St. Lawrence Formation in Scott County given the criteria of 4 inch diameter wells were available to construct a specific capacity data set with a reasonably large sample size. Hydraulic conductivity calculated from specific capacity data for the St. Lawrence Formation in the greater metro area has a mean value of 26.8 ft/day for shallow bedrock conditions and a mean value of 11.9 deep bedrock conditions. (hydraulic conductivity converted from specific capacity according methods of Bradbury and Rothschild, 1985; Runkel and others, 2003b).

No aquifer test data for Scott County wells finished solely in the St. Lawrence Formation was acquired as part of this investigation. An aquifer test from Minnesota Fracsand Co (MNDNR, 1981) was performed on a well partially open the St. Lawrence Formation and is discussed below in the Ironton-Galesville section of this report. Bulk vertical hydraulic conductivity from Ramsey County based on aquifer tests and thermal profile data from the Aquifer Thermal Energy (ATES) study was calculated at 10^{-4} to 10^{-5} ft/day where the formation is overlain by hundreds of feet of younger bedrock (Kanivetsky, 1989). Bulk horizontal conductivity was not calculated as part of the ATES project, but a single packer test from a discrete interval in the lower part of the formation resulted in a value of 6.7 ft/day for that interval. A bedding plane fracture within the St. Lawrence calculated from flowmeter data in a well near Greenfield in Hennepin County had a conductivity of 17 ft/day.

St. Lawrence Formation - hydrogeologic synthesis

Yield to a wells finished in the St. Lawrence Formation appear to occur mainly through bedding plane fractures and solution cavities as opposed to matrix porosity. While vertical permeability is low, horizontal permeability can be high, particularly in shallow bedrock conditions. In this way, the St. Lawrence Formation can act both as a confining unit by restricting vertical flow to the underlying Franconia Formation, and as an aquifer by transmitting useable quantities of water horizontally through secondary pores. Bulk horizontal conductivity appears to be as much as 5 orders of magnitude greater than vertical conductivity, based on the moderately high discrete interval packer and specific capacity data. Under shallow bedrock conditions, the St. Lawrence Formation can yield useful amounts of water, supporting specific capacity data collected from the greater metropolitan area. In Scott County, 307 wells are listed in CWI as receiving water solely from the St. Lawrence Formation. Its confining characteristics under shallow bedrock conditions, or how well it can transmit water to and from the underlying Franconia Formation, are less well understood.

Franconia Formation - hydrostratigraphy

The Franconia Formation is composed of sandstone, siltstone and shale with subordinate beds of sandy dolostone. Sand and grain size increase upward in the formation. The lower one-half of the formation contains abundant shale and very finely crystalline dolostone. It is absent in north-south trending bedrock valley south of Belle Plaine, east-west trending bedrock valley northeast of Jordan, and in the southern half of the main southwest-northeast trending bedrock valley. The Franconia Formation is eroded in northern half of the main bedrock valley and in several of its southern tributaries. Its uneroded thickness is typically 120 to 140 feet through most of the county.

The Franconia Formation in Scott County is similar its composition through most of the metropolitan area. It is broadly divisible into a fine clastic component, with subordinate beds of carbonate strata, and a coarse clastic component with relatively high permeability (Runkel and others, 2003b) The coarse clastic component is largely absent in Scott County, thus the bulk of the Franconia Formation matrix porosity is similar to that of the Eau Claire Formation. As such, it is expected to have vertical hydraulic conductivity values in the range of $2x10^{-6}$ to $2x10^{-8}$ ft/day. The coarse clastic component, where present, is commonly moderately cemented by carbonate. In this way, it differs from more friable coarse clastic components found in the Jordan and St. Peter Sandstones. Plug samples from the coarse clastic component have vertical conductivity values that range from 0.02 to 2 ft/day (Runkel and others, 2003b).

Information on secondary porosity within the Franconia comes from a variety of scales and sources. Relatively detailed, site specific investigations have provided excellent data on the development of non-systematic and systematic fractures within the

Franconia Formation under shallow bedrock conditions (summarized in Runkel and others, 2003a). This data has been augmented with downhole video and borehole geophysical logging that, when combined with previous work, has greatly improved our understanding of secondary porosity within the Franconia both in shallow and deep bedrock conditions (Runkel and others, 2003b; Runkel and others, 2006). As with other bedrock units, secondary pores diminish with depth. However, bedding plane fractures within the upper one-half of the Franconia have been shown to persist, even when covered by several hundred feet of younger bedrock (Runkel and others, 2006). In addition, bedding plane fractures are also found in shallow and deep bedrock conditions in the lower Franconia, within 10 feet of the top of the Ironton-Galesville Sandstone (Runkel and others, 2006). Borehole video logs show that fractures in the upper part of the formation typically occur at contacts between facies. They similarly occur in the lowermost part of the formation. In addition, solution features are also present in the carbonate-dominated strata of the lower Franconia Formation. Although not documented in borehole videos from within Scott County, secondary pores in the form bedding plane fractures are seen in county borehole geophysical logs (see discussion below).

Franconia Formation – hydraulic attributes

Specific capacity was calculated for 47 Franconia wells in Scott County. Of these, 23 were identified as deep bedrock conditions and the remaining 24 were identified as shallow bedrock conditions. Data from shallow bedrock conditions had a mean value of 13.6 gpm/foot of drawdown, and data from deep bedrock conditions had mean value of 8.7 gpm/foot of drawdown (Figure 4).

No aquifer test data for Scott County wells finished solely in the Franconia Formation was acquired as part of this investigation. An aquifer test from Minnesota Fracsand Co (MNDNR, 1981) was performed on a well partially open the Franconia Formation and is discussed below in the Ironton-Galesville section of this report. Detailed information on the hydraulic characteristics of the Franconia Formation comes from work summarized by Miller and Delin, (1993; and references therein). Values of horizontal hydraulic conductivity in the fine clastic and the less common carbonate rock components of the Franconia Formation in deep bedrock conditions ranges from 10^{-2} to 10^{-3} ft/day. Vertical hydraulic conductivity is roughly two orders of magnitude less than horizontal hydraulic conductivity. Some 20 ft intervals of Franconia tested by Miller and Delin (1993) yielded no discharge and must have significantly lower hydraulic conductivity values. In marked contrast, coarse clastic beds of the Mazomanie member in the upper part of the Franconia yielded moderately high horizontal conductivity values of about 1.4 to 7.5 ft/day and a bulk conductivity of about 2 ft/day. In Scott County, the Mazomanie member of the Franconia Formation is less than 10 feet thick.

High resolution flowmeter tests were conducted on several Franconia-Ironton Galesville wells both within and bordering Scott County (Figures 1, 6, 7, 8). Abrupt changes in downflow within the upper Franconia Formation under both ambient and injection conditions correlated to bedding plane-parallel fractures identified in video and caliper logs indicate the secondary porosity in the form of fractures characterize permeability in the upper Franconia. Furthermore, downflow past the lower Franconia to the Ironton-Galesville indicate the lower Franconia acts as a confining unit.

Franconia Formation – hydrogeologic synthesis

Most wells in Scott County that get water from the Franconia Formation are in areas where the Franconia or overlying St. Lawrence Formation is uppermost bedrock. Wells are typically finished in the upper portion of the Franconia, and are expected to be receiving water primarily through secondary porosity horizontal and vertical fractures. The spatial distribution of specific capacity data for the Franconia Formation also suggests that the formation is more permeable near bedrock valleys (Figure 9).

Based on data from this investigation and data from the greater metropolitan area, the Franconia Formation is divisible to two distinct hydrogeologic units (Runkel and others, 2003b; 2006) The upper half of the Franconia is a moderately productive aquifer that yields water primarily through bedding plane fractures, and to a lesser degree through intergranular flow in the coarse clastic component where present. In contrast, the middle to lower Franconia Formation is analogous to other low permeability fine clastic units such as the Eau Claire Formation, as described in this report and elsewhere (Runkel and others 2003a, 2003b). Detailed information on the hydrogeology of the Franconia Formation in the greater metropolitan area and southeastern Minnesota is provided in Runkel and others, (2006).

Ironton-Galesville Sandstones – hydrostratigraphy

The Ironton-Galesville Sandstones are composed of medium-to coarse-grained, friable quartz sandstone with minor intercalated shale and siltstone beds and matrix fill between sand grains near the middle of the unit. It is absent in the north-south trending bedrock valley south of Belle Plaine, portions of the east-west trending bedrock valley northeast of Jordan, and in the southern third of main southwest-northeast trending bedrock valley. Its uneroded thickness through the county is 50 to 65 feet.

The Ironton-Galesville Sandstone can be subdivided into a “clean” coarse clastic component containing the quartz sandstone, and a shaly coarse clastic component containing the thin shale and silt interbeds and matrix (Runkel, 1996). Hydraulic conductivity for the clean clastic component, as determined from plug samples, has values ranging from 0.2 to 2 ft/day in both the horizontal and vertical directions (Runkel and others, 2003a). Vertical hydraulic conductivity of the shaly component should be markedly less because of shale and silt particles present in the sand matrix and as thin beds.

Data on secondary porosity in the Ironton-Galesville sandstone comes primarily from outcrop investigations. Non-systematic fractures and systematic joints are common in outcrops both in Minnesota and Wisconsin, including irregular, systematic joints a few inches in width and bedding plane fractures that can be traced tens of feet laterally. In Scott County, such features are likely to occur near buried bedrock valleys, where the Ironton-Galesville Sandstone subcrops, or in places where the overlying Franconia Formation is thin. Blasting of the Ironton-Galesville near Savage produced modest increases in yield (E.H. Renner and Sons, 2005), which is likely the result of fracture enhancement.

Ironton-Galesville Sandstones – hydraulic attributes

Not enough wells identified as receiving water from the Ironton-Galesville Sandstone in Scott County given the criteria of 4 inch diameter wells were available to construct a specific capacity data set with a reasonably large number of samples. Hydraulic conductivity calculated from specific capacity data for the Ironton-Galesville in the greater metro area has a mean value of about 30 ft/day for shallow bedrock conditions and a mean value of about 15 ft/day for deep bedrock conditions (Runkel and others, 2003b).

Aquifer test data for the Ironton-Galesville Sandstones within Scott County come from several different sources. An aquifer test was conducted by the United States Geological Survey to determine hydraulic properties of the Ironton-Galesville Sandstones in the vicinity of the Shakopee Mdewakanton Sioux Community (Winterstein, 2005). At this site, located west of the major southwest-northeast trending bedrock valley, the Prairie du Chien Group is uppermost bedrock. Two observation wells were used, both open to the lower 20-30 feet of the Franconia, and the entire thickness of Ironton-Galesville. A bulk hydraulic conductivity value for the Ironton-Galesville was estimated to be 12 ft/day, which is similar to results obtained from injection/flowmeter logging of the observation wells (Runkel and others, 2005).

The Minnesota Department of Health conducted an aquifer test on a Ironton-Galesville-Eau Claire well for the city of Jordan (Jordan well 6, unique well number 596649). The St. Lawrence Formation is upper-most bedrock at this site. The St. Lawrence is thin or absent to the north, near the edge of a east-west trending bedrock valley. Well number 6 is open to the Ironton-Galesville and a portion of the underlying Eau Claire Formation. Jordan city well No. 5, open to the Franconia and Ironton-Galesville was used as an observation well during the test. Bulk hydraulic conductivity for well 6 was estimated to be 37 ft/day using an open hole length of 75 feet for aquifer thickness. Bulk hydraulic conductivity for well 5 was estimated to be 15 ft/day using an open hole length of 72 feet for aquifer thickness (Minnesota Department of Health, 2001). If it is assumed that the Ironton-Galesville is the sole productive interval for the open hole, then using an aquifer thickness of 60 ft gives bulk hydraulic conductivity values of 46 ft/day and 18 ft/day for the two wells respectively.

The Minnesota Department of Natural Resources conducted an aquifer test of a multi-aquifer well at the Minnesota FracSand (Shiely) facility (unique well number 213577 - Minnesota Department of Natural Resources, 1981).   This well is located near an isolated, buried Prairie du Chien plateau at the base of the bluff bordering the Minnesota River. The Jordan Sandstone is the uppermost bedrock unit at this site. The well is open hole from a portion of the St. Lawrence Formation through the Ironton-Galesville Sandstone. A buried valley cuts down to the Franconia Formation just east of the well; approximate 40 feet of Franconia remains along the axis of the valley. Drawdown was measured at several wells during the test – most in unconfined/water table conditions, with the exception of one well with similar construction the the pumping well, located approximately 6,500 feet to the northeast (unique number 211866). Of the monitored wells whose water levels could be confirmed, only this well showed drawdown, with a measured drawdown of 2.2 feet. Transmissivity for this well was estimated to be 11,150 gallons per day/ft. This converts to a hydraulic conductivity value of 6 ft/day if the entire open hole length of 245 feet is used for aquifer thickness. If the 60 foot thickness of Ironton-Galesville Sandstone is used for aquifer thickness, then the hydraulic conductivity based on the aquifer test is 25 ft/day.

High resolution flowmeter tests were conducted on several Franconia-Ironton Galesville wells both within and bordering Scott County (Figure 1). The gradual dissipation of downflow into the Ironton-Galesville both under ambient an injection conditions indicate that flow through this unit is primarily intergranular. Furthermore, the Ironton-Galesville Stone is the primary producing interval of the open hole in these tests, even though the lower Franconia is exposed.

Ironton-Galesville Sandstones – hydrogeologic synthesis

Hydraulic conductivity in the Ironton-Galesville Sandstone in from data collected as part of this investigation ranges from 2 to 37 ft/day with the majority of values falling in the range from 6 to 14 ft/day. The high value of 37 ft/day, estimated from the City of Jordan aquifer test (48 ft/day if Ironton-Galesville thickness alone is used), may be due in part to proximity to the east-west trending bedrock valley northeast of the city. Secondary porosity in the form of vertical and bedding-plane fractures both within the Ironton-Galesville and overlying Franconia and St. Lawrence Formations may be enhanced near the valley, increasing downward infiltration and horizontal flow to the well. In the City of Jordan test, well number 5, located south of well 6 and further from the buried bedock valley, had a estimated bulk hydraulic conductivity value roughly half that of well 6. Similarly, a high hydraulic conductivity value for the Ironton-Galesville from the MN Fracsand (Shiely) aquifer test (25 ft/day) also suggests the contribution of fractures to overall yield. In the case of the MN Fracsand (Shiely) aquifer test, the open hole extends through both the Franconia and a portion of the St. Lawrence Formation; based on the response of the similarly constructed observation well at a distance of 6500 feet, and previous borehole geophysical logs of similar wells, it is likely that fractures in those intervals contribute to the yield of this well.

In contrast to the estimated higher hydraulic conductivities for the Ironton-Galesville in the north-central part of the county, values from the area near Savage and Prior Lake are lower. Borehole flowmeter logging results from Savage, Shakopee Mdewakanton Sioux Community and Prior Lake all show intergranular-type flow through the Ironton-Galesville Sandstone, with hydraulic conductivity estimates ranging from 6 to 12 ft/day that agree well with values estimated from conventional aquifer tests for this area. Without flowmeter logging results from north-central Scott County, it is not possible to determine the presence or the hydraulic influence of fractures on Ironton-Galesville productivity in that part of the county.

Consistency in the flow patterns in the results of high resolution flowmeter tests of wells open to both the Franconia Formation and the Ironton-Galesville Sandstone both in Scott County and the greater metropolitan area contradicts the traditional conceptual model of the Franconia Formation and Ironton-Galesville Sandstones as a single aquifer unit (Runkel and others 2006). The “FIG” aquifer is actually composed of an upper Franconia aquifer dominated by secondary porosity in the form bedding-plane parallel fractures, a lower Franconia confining unit, and an Ironton-Galesville Sandstone dominated by intergranular flow.

Eau Claire Formation – hydrostratigraphy

The Eau Claire Formation is composed of shale, siltstone and very fine-grained sandstone. It is absent in north-south trending bedrock valley south of Belle Plaine, portions of east-west trending bedrock valley northeast of Jordan, and in the southern third of main se-nw trending bedrock valley. Uneroded thickness of the Eau Claire Formation in Scott County ranges from 70 to 80 feet thick.

Matrix porosity of the Eau Claire Formation within Scott County is typical of its regional properties described by Runkel and others (2003a); it is composed of mainly the fine clastic component, and is expected to have vertical hydraulic conductivity values in the range of $2x10^{-6}$ to $2x10^{-8}$ ft/day.

The Eau Claire Formation is overlain by younger bedrock through most of the county, with the exception of those areas listed previously where it is thin or absent. Our knowledge of secondary porosity in the Eau Claire Formation in relatively deeply buried conditions is limited. Runkel and others (2003a) suggested that secondary pores are rare in the Eau Claire where it is overlain by more than 200 feet of overlying bedrock. In those areas where the Eau Claire is eroded or near the bedrock surface in buried bedrock valleys, non-systematic and systematic fractures and systematic joints are expected. Additional fractures, both vertical and horizontal, are expected near faults.

Eau Claire Formation – hydraulic attributes

Hydraulic data from Scott County for the Eau Claire Formation is limited. Estimated horizontal conductivity from discrete interval pump tests in the Eau Claire Formation in Ramsey County was less than 10^{-2} ft/day; vertical conductivity from the same investigation was estimated to be 10^{-4} ft/day (Miller and Delin, 1993). These values are consistent with intergranular permeability as the chief control on hydraulic behavior in deep bedrock settings (Runkel and others, 2003a). In the greater metropolitan area, wells are often finished in the Eau Claire Formation where the formation is within 75 feet of the bedrock surface. Hydraulic conductivity calculated from specific capacity data for these wells averages 13.7 ft/day (Runkel and others, 2003b). A higher hydraulic conductivity value supports the hypothesis that fracture porosity contributes to ground-water flow in the Eau Claire Formation under shallow bedrock conditions.

Eau Claire Formation – hydrogeologic synthesis

The Eau Claire Formation is expected to behave as a confining unit through most of Scott County; only 4 wells in CWI list the Eau Claire Formation the contributing aquifer. Bedding plane fractures may contribute to increased horizontal hydraulic conductivity in shallow bedrock conditions. Relatively higher Ironton-Galesville hydraulic conductivity values estimated from the Jordan city well 6 discussed earlier, may in part due to contribution s from bedding plane fractures from the Eau Claire Formation partly exposed in the lower portion of the open hole. In light of these data, greater permeability should be expected near bedrock valleys, where the Eau Claire Formation is uppermost bedrock, or thinly covered by younger bedrock units. In these settings both vertical and horizontal hydraulic conductivity is expected to be higher due to the presence of networks of hydraulically connected fractures.

Mt. Simon Sandstone – hydrostratigraphy

The Mt. Simon Sandtone in Scott County is composed of fine- to coarse-grained quartzose sandstone and siltstone. The upper one-half of the formation commonly contains subordinate red and green shale beds. It is present throughout the county and eroded only in the north-south trending bedrock valley south of Belle Plaine. Few wells penetrate the entire thickness of the Mt. Simon, and the Precambrian surface below it is highly irregular, but uneroded thicknesses of at least 160 to 200 feet are expected to exist over much of the county, and may be as high as 300 feet.

Matrix porosity of the Mt. Simon in Scott County is hydrostratigraphically consistent with its regional attributes described by Runkel and others, (2003a). It can be divided into two parts. The lower Mt. Simon consists of moderately to poorly cemented coarse clastic strata. Plug test hydraulic conductivity commonly greater than 2 ft/day in both vertical and horizontal directions (MUGSP, 1980). Fine clastics are a minor component of the lower Mt. Simon. The upper Mt. Simon is more hydrostratigraphically complex. Approximately equal parts coarse clastic and fine clastic strata intercalated in beds from a few feet to as much as 30 feet thick Plug tests demonstrate vertical hydraulic conductivity over 10 orders of magnitude, with coarse clastic components having values of 2 ft/day whereas fine clasitc intervals commonly have values from $2x10^{-3}$ to $2x10^{-6}$ ft/day.

This investigation did not provide new information on secondary porosity in the Mt. Simon to add to that of Runkel and others, (2003a) who noted that fracture porosity will diminish with increasing depth beneath younger bedrock. It is expected that secondary porosity, both in the form of vertical and bedding plane fractures within the Mt. Simon in Scott County will occur in and near the Belle Plaine Fault system, both near faults and where the Mt. Simon is eroded along the axis of the valley.

Mt. Simon Sandstone – hydraulic attributes

No wells identified as receiving water from the Mt. Simon Sandstone in Scott County given the criteria of 4 inch diameter wells were available to construct a specific capacity data set. Specific capacity data from the greater metro area and southeastern Minnesota divided into shallow and deep bedrock conditions show differences in calculated hydraulic conductivity values (Runkel and others, 2003b). Under deep bedrock conditions where wells were cased greater than 50 feet below the bedrock surface, hydraulic conductivity values calculated from specific capacity averaged 15.3 ft/day. In contrast, wells open to the Mt. Simon under shallower bedrock conditions (cased to a depth less than 50 feet below the bedrock surface) have an average hydraulic conductivity value of 31.4 ft/day, and greater variability than under deep bedrock conditions.

No aquifer test data for Scott County wells finished solely in Mt. Simon Sandstone was acquired as part of this investigation. Hydraulic attributes of the Mt. Simon in Scott County, however, are expected to be consistent with attributes for the greater metro area described by Runkel and others, 2003b. A large number of discrete interval and standard aquifer tests in southeastern Minnesota and nearby areas estimated hydraulic conductivity for the Mt. Simon from 0.4 to 21 ft/day (Runkel and others, 2003a). The tests were conducted under deep bedrock conditions, as such are expected to be representative of largely intergranular as opposed to fracture flow. The highest values are from large diameter wells and may reflect fracture flow due to well development, however. In contrast, the lower values are smaller diameter wells in settings where the Mt. Simon is deeply buried by younger bedrock. In either case, the bulk hydraulic conductivity values are most likely representative of the coarse clastic component of the Mt. Simon.

Individual beds of the fine clastic component, which are abundant in the upper Mt. Simon, are expected to have horizontal hydraulic conductivity of about 10^{-1} to 10^{-3} ft/day and a vertical hydraulic conductivity between 10^{-3} to 10^{-5} ft/day based on tests of similar strata from other Paleozoic formations in southeastern Minnesota (e.g. Miller and Delin, 1993).

Mt. Simon Sandstone – hydrogeologic synthesis

The hydrogeology of the Mt. Simon is complex because is it composed of intercalated coarse clastic and fine clastic components. The common practice of considering the Mt. Simon as a single aquifer should be re-evaluated as more data become available. In this report, the unit is divided into an upper and lower aquifer to highlight the potential for fine clastic components in the upper portion of the formation to act as confining beds.

The greater range and higher average hydraulic conductivity calculated from specific capacity data in shallow compared to deep bedrock conditions reflects a high percentage of wells that intersect networks of hydraulically connected fractures under shallow bedrock conditions. In Scott County, such conditions occur in the north-south trending bedrock valley south of Belle Plaine, where the Mt. Simon is exposed as uppermost bedrock along the axis of the valley. Additional development of secondary porosity within the Mt. Simon is expected near faults in this part of the county.

Quaternary Hydrogeology

The majority of Scott County is covered by a thick sequence of glacial till with scattered intercalated sand beds, with total unconsolidated thickness ranging from a few tens of feet up to over 400 feet along the axes of the deeper bedrock valleys. The hydrogeology of these deposits is undoubtedly complex; glacial events that produced these deposits included repeated flooding, erosion, excavation and mixing. The results are deposits that, unlike the bedrock units, are discontinuous, variable in thickness, and lithologically heterogeneous. The Quaternary stratigraphy DEMs that together build a three-dimensional model of unconsolidated deposits in Scott County (see plate 4) summarize the general distribution of high permeability (sand) and low permeability (till) materials, but do not provide a site by site predictive model. None the less, it is helpful to distinguish these units by their expected hydrogeologic characteristics.

Table 1 lists units found surface and subsurface unconsolidated deposits in Scott County and their expected hydraulic conductivity. These data have been adapted from Kanivetsky as reported in Meyer and others, 1998, who based estimates on available consultant's reports and textbook values.

		cm/sec	**ft/day**
till 1 (units Qd, Qdl, Qdc, Qdl	max	0.000005	0.014
	min	0.0000005	0.001
till 2 (units Qdt, Qdd)	max	0.0025	7.10
	min	0.000025	0.07
till 3 (not on surfical map)	max	0.000005	0.014
	min	0.0000005	0.001
sand and gravel (units Qe, Qts, Qtg, Qtl, Qtr, Qdo, Qdi, Qdo, Qdi, Qci)	max	20	56692.913
	min	0.5	1417.323
fine sand, (units Qe)	max	0.01	28.346
	min	0.0001	0.283
sandy silt (units, Qf, Qa	max	0.001	2.835
	min	0.00005	0.142

Table 1. estimated ranges of hydraulic conductivity for unconsolidated deposits in Scott County.

Scott County hydraulic data for unconsolidated deposits comes from an aquifer test for the city of Belle Plaine (unique number 538038, Minnesota Department of Health, 2002). Belle Plaine well 3 is completed in unconsolidated sand and gravel deposits on the eastern edge of the north-south trending bedrock valley that passes below the city. Drawdown in an observation well 1165 feet from the pumping well began to level off approximately ten minutes into the test. After 200 minutes, drawdown increased and began to follow a different trend than the earlier stage of the test. The results were consequently divided into “early time” and “late time” with hydraulic conductivity estimates for late time slightly higher than early time. Overall estimates of hydraulic conductivity ranged from 825 ft/day to 1600 ft/day based on an aquifer thickness of 86 feet.

The results of this test reveal hydraulic complexity typical of glacial deposits. Although the estimated hydraulic conductivity values fall within the range typical for sand and gravel deposits, the change in drawdown during the course of the test reveals that water supplying Belle Plaine well 3 comes from at least 2 sand and gravel deposits differing in some combination of thickness, extent and permeability. After 200 minutes of pumping, an initial boundary condition is reached and the well begins to be supplied with water from at least one additional source.

Additional insights into the hydrogeology of unconsolidated deposits come from a cursory analysis of bedrock potentiometric surfaces in the vicinity of the major southwest-northeast bedrock valley in the vicinity of Prior Lake. Generalized potentiometric surfaces of the Prairie du Chien and Jordan aquifers produced from static water elevations in CWI both show a deflection across the valley, with contours shifting further southward on the west side of the valley than on the east (Figure 10). This shift suggests higher permeability to the northern end of the valley, as more water discharges into the valley from these units on the valley's eastern side. This conceptual model is supported by the higher sand content in the northern end of the valley represented by the Quaternary stratigraphy model (plate 4), and by the lack of drawdown in the Quaternary observation well due to pumping in the Jordan during the Shakopee Mdewakanton Sioux Jordan aquifer test (Ruhl, 1999). Further insights into the hydrogeology of this buried bedrock valley are expected to come from a regional aquifer test of the Jordan in planning stages at the time of this report (Barr, 2006, personal communication).

Discussion

The Scott County Atlas was designed to provide decision makers with tools for land use and water resource management. Recent advances in our understanding of how water moves through bedrock aquifers has prompted the need to incorporate that knowledge to atlas products. This is particularly useful when the products can be applied in a GIS environment – allowing the user to compare geologic and hydrogeologic data with other county data, such as land use, census, soils data, or parcel information, to aid in decision making regarding development, reconstruction, or natural resource management.

To this end, the information provided in this report has been included in GIS products as part of the atlas. Our understanding of ground-water flow within the Franconia Formation and Ironton-Galesville Sandstones has revised our conceptual model of a single "FIG" aquifer with uniform hydraulic conductivity into an upper Franconia aquifer characterized by fracture flow, a lower Franconia confining unit, and an Ironton-

Galesville aquifer characterized primarily by intergranular flow. Likewise, the Prairie du Chien-Jordan aquifer is subdivided into a Shakopee aquifer, Oneota confining unit, and Jordan aquifer, each with distinct water bearing characteristics. In a GIS environment, the extent and thicknesses of these units can be displayed or incorporated into ground water models by the construction of additional DEMs that subdivide lithostratigraphic units (Figure 11).

The extent to which the hydrogeologic character of these rocks changes near bedrock valleys, or near the bedrock surface can also be incorporated into a GIS environment. A DEM of the bedrock surface provided with the atlas can be used to construct an additional surface defining the lower boundary of “shallow” bedrock conditions as described in the report, by substracting 50 feet from the bedrock surface DEM. Within this upper zone, ground-water flow within the bedrock is expected to be dominated by both horizontal and vertical secondary porosity features, regardless of lithology, and hydraulic conductivity for bedrock units under deep bedrock conditions, can, as a rule of thumb, be doubled (Figure 12).

The importance of fracture flow versus intergranular flow becomes significant when considering issues of wellhead protection. Contaminant transport through fractures is considerably faster than through intergranular flow. Time of travel estimates based on estimates of bulk hydraulic conductivity from conventional aquifer tests may not accurately represent actual movement of contaminants, even though they provide useful estimates of aquifer yield.

Knowledge of fracture distribution can also help target high-yield intervals during the construction of high capacity wells. As development in Scott County moves westward beyond the extent of the highly productive Prairie du Chien Group and Jordan Sandstone, the distribution of vertical and bedding plane fractures within the St. Lawrence and Franconia Formations, along with yield variations in the Ironton-Galeseville Sandstones will become an important consideration in well design. There appears to be an inverse relationship between the degree in the development of secondary porosity features and depth of burial beneath bedrock and its effect on hydrogeologic properties. Hydraulic properties measured in deep conditions of burial cannot be confidently extrapolated to shallower conditions. Borehole flowmeter data demonstrate that boreholes open to relatively shallow bedrock conditions have relatively high, complex ambient flow rates and patterns compared to the relatively subdued and simpler patterns of ambient flow in boreholes cased to greater depths beneath the bedrock surface (Runkel et al., 2003). These attributes in a sense are an expression of the presence of two "flow systems" superimposed on all aquifers and confining units: a relatively shallow bedrock system and a deeper bedrock system (cf. Mayo et al., 2003). The shallow system reflects the higher permeability due to enhanced fracture porosity and the greater stresses of near-surface recharge and discharge in shallow bedrock conditions. Additionally, this enhanced fracturing may be relatively well-connected to overburden ground-water sources such as sand and gravel deposits compared to fractures in deeper bedrock conditions. Flow paths and time-of -travel, and well yields in such conditions should be regarded as less predictable than in more deeply buried settings.

Based on these observations, several conclusions can be reached with regard to Scott County bedrock hydrogeology:

- Secondary porosity and permeability of aquifers and confining units increases near bedrock surface, both in bedrock valleys and plateaus.
- The hydraulic connection between the Prairie du Chien Group and Jordan Sandstone is leaky confined on both sides of the major southwest-northeast trending bedrock valley.
- The Prairie du Chien Group is karsted, with large voids documented in places where it is upper-most bedrock unit.
- The Ironton-Galesville Sandstone may provide moderately better yields in north-central Scott County than it does to the northeastern part of the county where it is buried under a thicker section of younger bedrock. Secondary porosity in the form of vertical and bedding-plane fractures both within the Ironton-Galesville and overlying Franconia and St. Lawrence Formations may be enhanced near an east-west trending bedrock valley northeast of the city of Jordan, increasing downward infiltration and horizontal flow to the well.
- The yields of all aquifers appear to be dependent, in part, on the nature and thickness of overlying material. Calculated hydraulic conductivity is higher for aquifers where drift cover is thin or absent, or is composed entirely of sandy material. Much of the area in Scott County is covered by a thick sequence of glacial till, restricting the downward movement of water. While this sequence protects deeper aquifers from contamination from activities at the land surface, it also restricts vertical recharge and replenishment of the aquifers for large portions of the county.

Appendix: Summary of bedrock hydraulic conductivity values applicable to Scott County

Figure 13. Generalized stratigraphic column of a portion of the Paleozoic strata in Scott County showing matrix hydrostratigraphic components, regionally extensive bedding plane fractures, selected hydraulic conductivity along with additional information on travel times for selected bedrock units. Data compiled for this report and along with previous studies (Runkel, et.al., 2003; Runkel, et. al., 2005, Runkel et.al., 2006, Tipping, et.al., 2006). Figure is not to scale. Kh indicates horizontal hydraulic conductivity, Kv indicates vertical hydraulic conductivity. Data listed in italics known to be from wells where the distance from the bottom of the casing to the top of the bedrock surface is less than or equal to 120 feet. Numbers in parentheses are from the following:

1. Borehole flowmeter logging and injection, Greenfield test well (unique number 658157) K values calculated from transmissivity values modeled using FWRAP program (Palliet, 2000)
2. Discrete interval packer tests and other techniques at the Aquifer Thermal Energy Storage (ATES) Project in southwestern Ramsey County (Miller and Delin, 1993, and references within)
3. Discrete interval packer tests and thermal profiling at the ATES Project site in southwestern Ramsey County by Kanivetsky (1989).
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6. Standard aquifer test of Chaska test well 4 (unique number 674317) by Bonestroo and Associates, 2002. Hydraulic conductivity values calculated from transmissivity using an aquifer thickness of 195 feet.
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11. Standard aquifer test of Carver test well (unique number 657344) by Bonestroo and Associates, 2001. Hydraulic conductivity value calculated from transmissivity using an aquifer thickness of 172 feet.
12. Standard aquifer test of Carver test well (unique number 657345) by Bonestroo and Associates, 2001. Hydraulic conductivity value calculated from transmissivity using an aquifer thickness of 174 feet.
13. Standard aquifer test of Shakopee Mdewakanton Sioux Community production well by USGS, 2004. Hydraulic conductivity value calculated from average transmissivity using an aquifer thickness of 45 feet.
14. Borehole flowmeter logging, Webster test well (unique number 699024) Rice County. Bulk hydraulic conductivity value calculated using an aquifer thickness of 110 feet. Fracture conductivity calculated using an aquifer thickness of 0.5 feet for each fracture. If the lower fracture accepts all injected water as indicated by the flowmeter log, then the hydraulic conductivity of the lower fracture is 12,500 ft/day.
15. Standard aquifer test of Webster test well (unique number 699024) by Peer Engineering. Hydraulic conductivity value calculated from average transmissivity using an aquifer thickness of 110 feet.
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21. Discrete interval tests and dye-trace studies at Oronoco Landfill, Olmsted County, by Donahue and Associates, Inc. (1991) and RMT, Inc. (1992).
22. Borehole flowmeter logging and pumping at wells in: (A) Faribault (unique number 625327), Rice County. (B) Rochester (unique number 485610), Olmsted County.
23. Average value of hydraulic conductivity calculated based on specific capacity tests in the County Well Index database, southeastern Minnesota.
24. Values from southeastern Minnesota, Wisconsin, and Illinois reported by Runkel and others, (2003).

25. Standard aquifer test of St. Louis Park Well 11 (unique number 206439), Hennepin County. Included in USGS-DNR aquifer properties spreadsheet, source -USGS.
26. Values from southeastern Minnesota reported by Runkel and others, (2003).
27. Borehole flowmeter logging and injection, Savage observation well 8 (unique number 593579). Hydraulic conductivity estimate based on injection rate, assumes radial flow away from the well and zone of influence equal to 20 feet.
28. Borehole flowmeter logging and pumping, Chaska test well 3 (unique number 674316) K values calculated from transmissivity values modeled using FWRAP program (Palliet, 2000).
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30. Standard aquifer test of Jordan Well 6 (unique number 596649) by Minnesota Department of Health, 2001. Hydraulic conductivity value calculated from transmissivity using an aquifer thickness of 75 feet.
31. Standard aquifer test of Prior Lake Well 3 (unique number 207308) by Minnesota Department of Health, 1998. Hydraulic conductivity value calculated from transmissivity using an aquifer thickness of 96 feet.
32. Standard aquifer test of Shakopee Well 6 (unique number 180922) by Minnesota Department of Health, 1998. Hydraulic conductivity value calculated from transmissivity using an aquifer thickness of 96 feet.
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Figure Captions

Figure 1. Location of Scott County in context of geology of the Twin Cities basin. Lower Paleozoic bedrock is characterized by relatively thin, but widespread layers dominated by sandstone, shale, or carbonate rock. The bedrock across much of the area is overlain by 50 to over 400 ft of unconsolidated Quaternary strata, “glacial drift” that include sand, gravel and clay-rich till. Location map shows Cambrian and Ordovician strata where they are uppermost bedrock. A-A’ is location of cross section for this figure.

Figure 2. Standard bedrock stratigraphic column showing Paleozoic lithostratigraphic and hydrogeologic units mapped in Scott County, and typical natural gamma log. Rock lithology is shown in two columns: “Lithology” shows the relatively detailed attributes, including those used to distinguish traditional lithostratigraphic unit boundaries. The “Matrix hydrostratigraphic component” column shows the essential rock matrix components that differ fundamentally from one another in intergranular porosity and permeability. Properties of the hydrogeologic units are depicted and described in greater detail in Figure 12. Modified in part from Mossler (1987).
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Figure 3. Typical development of stress-relief fractures in layered Paleozoic bedrock. Note that non-systematic stress-relief fractures decrease in abundance at greater distances from the bedrock surface. Diagrammatic sketch based on studies of Paleozoic bedrock in eastern North America (Ferguson, 1967), modified with observations from southeastern Minnesota discussed in this report (From Runkel and others, 2003).

Figure 4. Specific capacity data from selected aquifers for 4 inch diameter wells, Scott County. For wells that reported pumping level equal to static water level, pumping levels were increased by 1 (drawdown equal to 1 foot) to allow for specific capacity calculation. 4 inch wells were chosen exclusively for data consistency. Differences in shallow versus deep bedrock conditions are apparent in Franconia wells but not in Prairie du Chien or Jordan wells. See text for discussion. cfrn – Franconia aquifer; cjdn – Jordan aquifer; opdc – Prairie du Chien aquifer.

Figure 5. Borehole geophysical log for a well open to the Jordan Sandstone in the vicinity of Scott County. (well unique number 699024, Webster, Minnesota). Trolling (at 10 ft per minute), stationary flowmeter, and video logs identify hydraulically active fractures within the Jordan Sandstone. Under ambient conditions, a fracture in the lower part of the formation yields water that flows up the borehole past fine-grained sections of the Jordan before exiting at or near another hydraulically active fracture in the middle for the formation. Under injection conditions (water injected into the hole at 18 liters/minute), water moves past a hydraulically active fracture in the middle of the formation and continues downward before exiting through the lower fracture that yielded water under ambient conditions.

Figure 6. Borehole geophysical logs of two monitor wells open to the Franconia-Galesville interval within the Shakopee Mdewakanton Sioux Community (Runkel and others, 2005). For both wells, the signature of the interpretation line during injection demonstrates that the coarse clastic-dominated Ironton and Galesville Sandstones accept, in intergranular fashion, nearly all of the injected water. In contrast, injected water largely bypasses the overlying fine clastic, lower Franconia Formation strata, which serve as a confining unit. The subtle "stairstep" pattern of the interpretation line corresponding to where water exits the borehole may reflect the relatively limited ability of fine-clastic interbeds within the Ironton-Galesville to accept injected water. Troll flowmeter data were collected while trolling up at 10ft per minute. Logs in upper part of illustration collected from well with unique number 705731, lower logs from well with unique number 705730. (From Runkel and others, 2005).

Figure 7. Borehole geophysical logs of water wells open to the Franconia-Galesville interval within or close to Scott County. In **A)** the signature of the interpretation line for the flowmeter station measurements during injection demonstrates that the coarse clastic-dominated Ironton and Galesville Sandstones accept, in intergranular fashion, nearly all of the injected water (interval labeled K1), together having the properties of an aquifer. In contrast, injected water largely bypasses the overlying fine clastic, lower Franconia Formation strata, which serve as a confining unit. Troll flowmeter data were collected while trolling up at 10 ft per minute. (well unique number 593579, Savage, Minnesota) **B)** Trolling (at 10 ft per minute) and stationary flowmeter logs indicate that bedding-plane fractures in the upper part of the Franconia Formation (labeled K2-K6) yield water that travels down the borehole at a minimum rate of over 10 gallons per minute under ambient conditions. This downflow exits the hole gradually, in intergranular fashion, in the Ironton– Galesville Sandstones. The intervening middle to lower Franconia Formation serves as a confining unit. Hydraulic conductivity of individual fractures in the upper Franconia aquifer, and of the intergranular Ironton-Galesville aquifer, is listed below the logs. (well unique number 674316, Chaska, Minnesota). **C**) Conditions in this borehole, in southernmost part of study area, are remarkably similar to conditions known to the north and west of study area (e.g. Chaska, Fig 9B. This demonstrates the predictability in hydrogeologic properties of the Franconia-Galesville interval and application of regional studies (e.g. Runkel and others 2004) to Scott County proper (well unique number 672729, Prior Lake, Minnesota). See Fig. 1 for locations of these three wells.

Figure 8. Borehole geophysical logs of a test hole open to the Franconia-Galesville interval, city of Prior Lake (well unique number 721847) Fracture contribution in the Franconia Formation is indicated by slight increase in downflow under injection conditions, along with deflections in the fluid resistivity and temperature logs. Injection stations show slow dissipation of downflow through the Ironton-Galesville portion of the open hole, characteristic of intergranular flow through that interval. Approximate hydraulic conductivity of the open hole calculated using the Theim equation with an aquifer thickness of 70 feet and a zone of influence of 20 feet is 5 ft/day.

Figure 9. Spatial distribution of specific capacity values for Franconia wells in Scott County, shown over a shaded relief model of the top elevation of the Franconia Formation. Higher values are located in the Franconia Formation in or near places where it has eroded along the walls of bedrock valleys.

Figure 10. Potentiometric contours for Jordan (A) and Prairie du Chien (B) wells, based on static water level measurements from the Minnesota water well database, County Well Index (CWI). Flow in both aquifers is generally from south-southeast to north-northwest. A noticeable deflection in both sets of contours occurs across the bedrock valley near Prior Lake, suggesting a hydraulic connection with higher permeability fill within the bedrock valley that enhances flow north towards the Minnesota River. Black dots indicate water well locations. Contour interval 25 feet.

Figure11.   Digital Elevation Models (DEMs) of the **A.1** Prairie du Chien lithstratigraphic unit, and the **A.2** Shakopee aquifer and Oneota confining unit (hydrogeologic designations); **B.1** Franconia lithostratigraphic unit and the **B.2** Upper Franconia aquifer and Lower Franconia confining unit (hydrogeologic designations).
Color gradients show relative elevation, with higher elevations shown in lighter shades.

Figure 12. Three-dimensional image highlighting hydrogeologic properties of Paleozoic bedrock in northeastern Scott County. The image shows aquifers and confining units, and highlights the distribution of secondary porosity features. Note that all Paleozoic bedrock has a relatively great abundance of secondary pores where it is near the bedrock surface-this is the “shallow bedrock flow system” where the hydraulic conductivity of both aquifers and confining units is markedly enhanced and more variable. This hydrogeologic characterization is based on information contained in this report collected specifically within or close to the study area, as well as on similar data from regional investigations such as Runkel et al. (2003; 2006). Depiction of secondary pores is schematic and not consistent in scale with depiction of host rock. Hydraulic conductivity values for the Franconia-Galesville interval are based on the information described in this report, as well as data from across the greater Twin Cities Metropolitan area that was synthesized by Runkel and others (2006) (From Runkel and others, 2005).

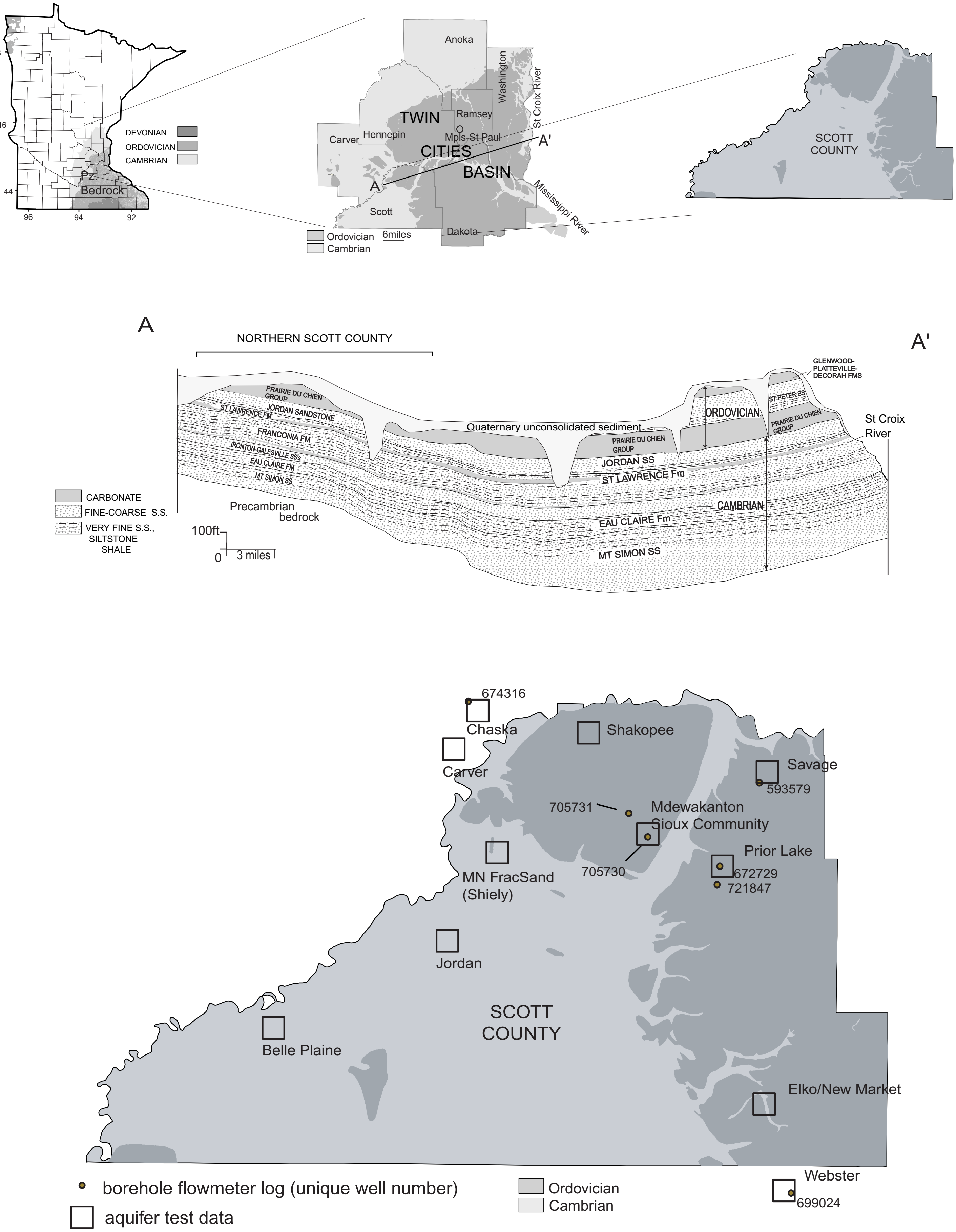

48
46
44
96
94
92
DEVONIAN
ORDOVICIAN
CAMBRIAN
Pz.
Bedrock
Anoka
Washington
St Croix River
Ramsey
TWIN
CITIES
BASIN
Carver
Hennepin
Mpls-St Paul
A
A'
Scott
Dakota
Mississippi River
Ordovician
Cambrian
6miles
SCOTT
COUNTY
A
NORTHERN SCOTT COUNTY
A'
GLENWOOD-
PLATTEVILLE-
DECORAH FMS
PRAIRIE DU CHIEN GROUP
JORDAN SANDSTONE
ST LAWRENCE FM
FRANCONIA FM
IRONTON-GALESVILLE SS's
EAU CLAIRE FM
MT SIMON SS
Quaternary unconsolidated sediment
ORDOVICIAN
ST PETER SS
PRAIRIE DU CHIEN GROUP
St Croix
River
PRAIRIE DU CHIEN GROUP
JORDAN SS
ST LAWRENCE Fm
CAMBRIAN
EAU CLAIRE Fm
MT SIMON SS
CARBONATE
FINE-COARSE S.S.
VERY FINE S.S.,
SILTSTONE
SHALE
Precambrian
bedrock
100ft
0
3 miles
674316
Chaska
Shakopee
Carver
Savage
593579
705731
Mdewakanton
Sioux Community
705730
Prior Lake
672729
721847
MN FracSand
(Shiely)
Jordan
SCOTT
COUNTY
Belle Plaine
Elko/New Market
Webster
699024
borehole flowmeter log (unique well number)
aquifer test data
Ordovician
Cambrian

Figure 1

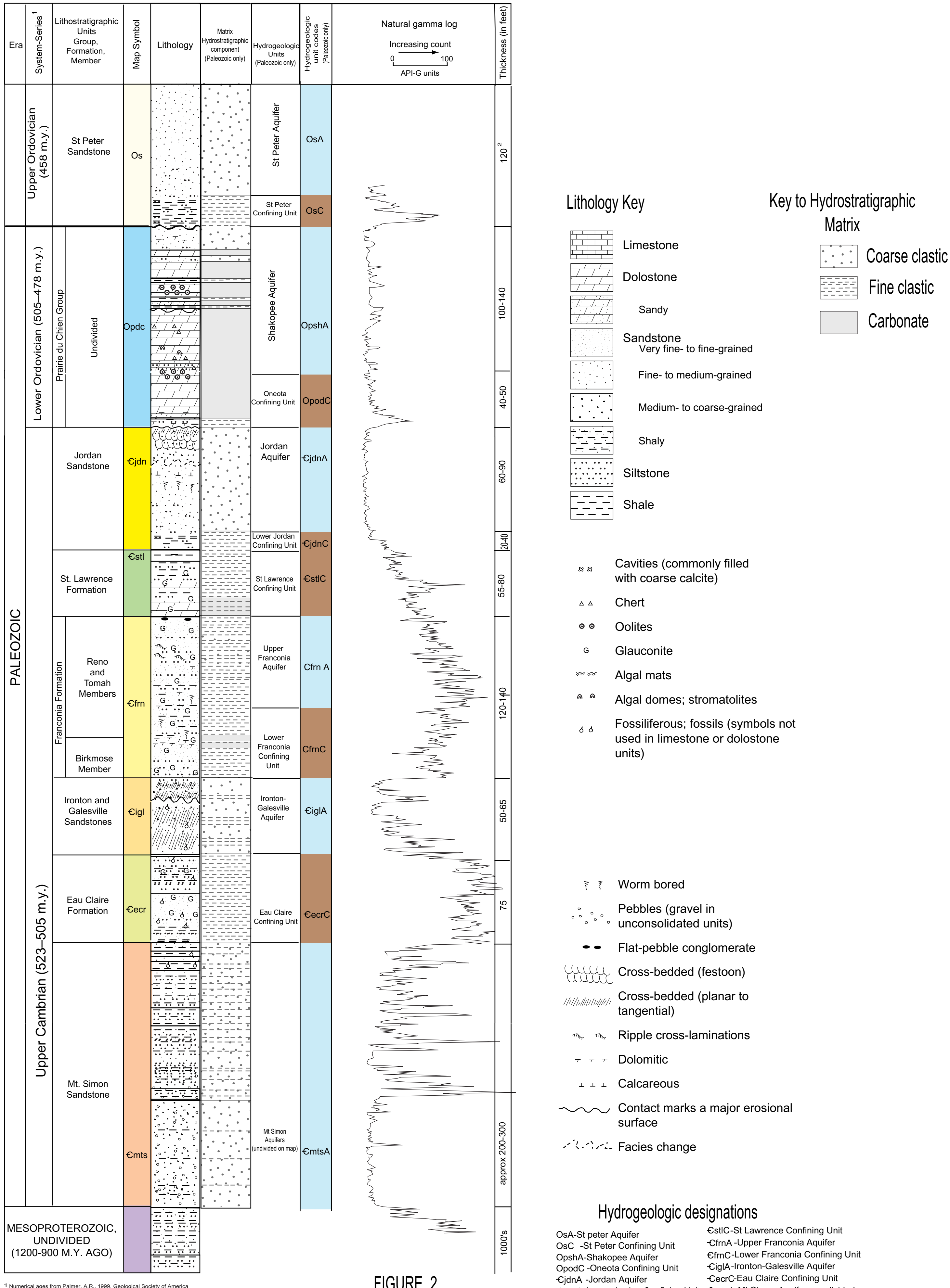


FIGURE 2

[1] Numerical ages from Palmer, A.R., 1999, Geological Society of America

[2] Maximum eroded thickness; St Peter Sandstone eroded everywhere in Scott County

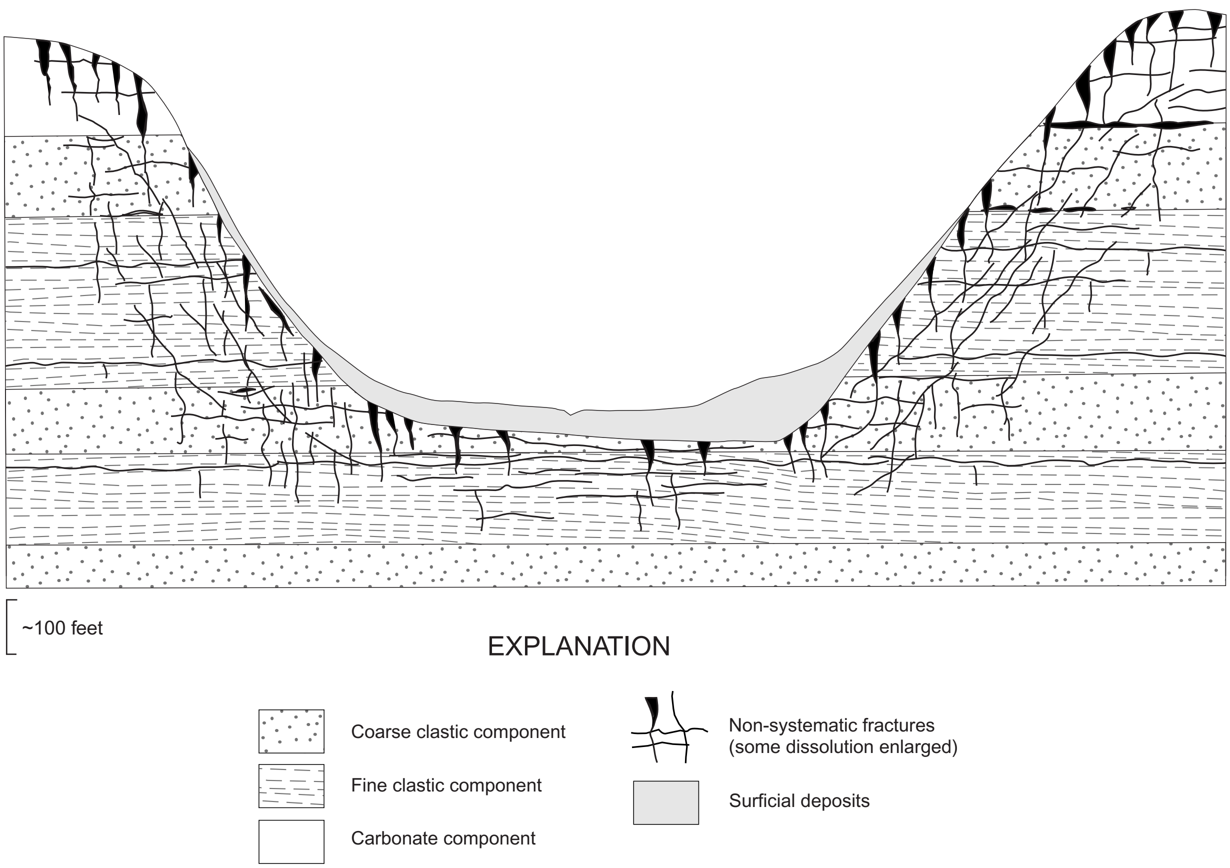

~100 feet
EXPLANATION
Coarse clastic component
Fine clastic component
Carbonate component
Non-systematic fractures
(some dissolution enlarged)
Surficial deposits

Figure 3

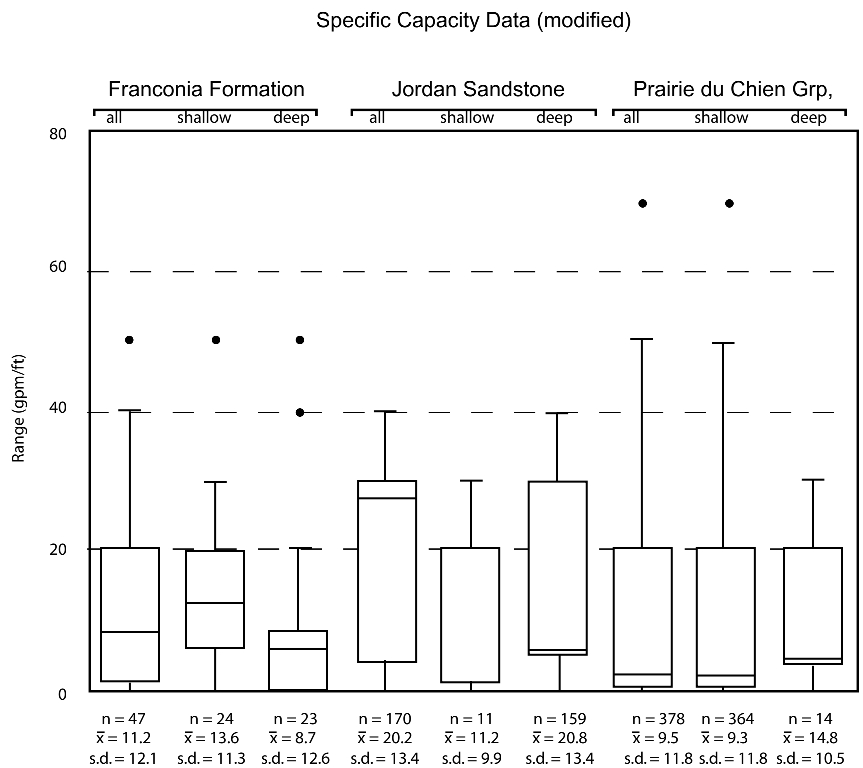
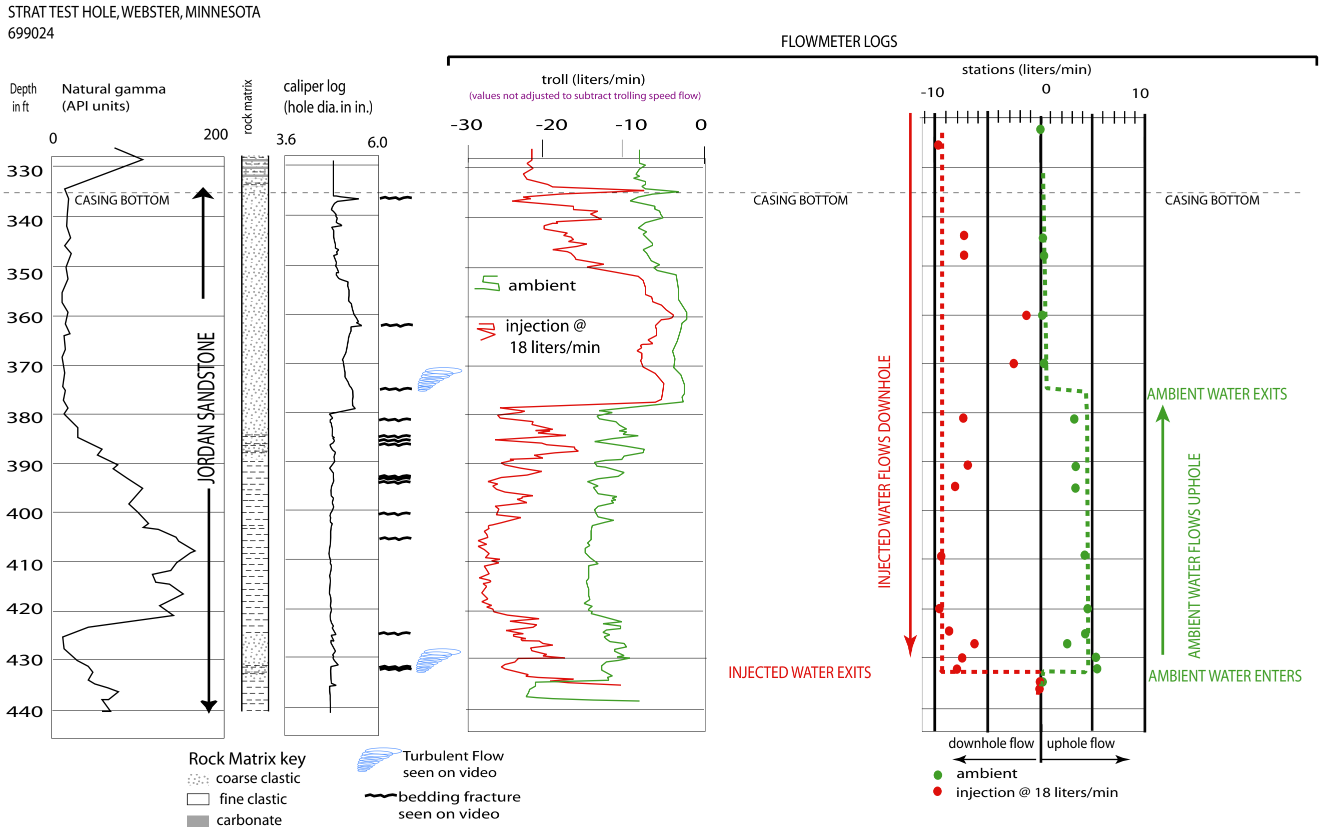

Specific Capacity Data (modified)
Franconia Formation
Jordan Sandstone
Prairie du Chien Grp,
all
shallow
deep
all
shallow
deep
all
shallow
deep
Range (gpm/ft)
80
60
40
20
0
n = 47
x̄ = 11.2
s.d. = 12.1
n = 24
x̄ = 13.6
s.d. = 11.3
n = 23
x̄ = 8.7
s.d. = 12.6
n = 170
x̄ = 20.2
s.d. = 13.4
n = 11
x̄ = 11.2
s.d. = 9.9
n = 159
x̄ = 20.8
s.d. = 13.4
n = 378
x̄ = 9.5
s.d. = 11.8
n = 364
x̄ = 9.3
s.d. = 11.8
n = 14
x̄ = 14.8
s.d. = 10.5

Figure 4



STRAT TEST HOLE, WEBSTER, MINNESOTA
699024
FLOWMETER LOGS
Depth in ft
Natural gamma (API units)
0
200
rock matrix
caliper log (hole dia. in in.)
3.6
6.0
troll (liters/min)
(values not adjusted to subtract trolling speed flow)
-30
-20
-10
0
stations (liters/min)
-10
0
10
330
340
350
360
370
380
390
400
410
420
430
440
CASING BOTTOM
JORDAN SANDSTONE
ambient
injection @ 18 liters/min
INJECTED WATER FLOWS DOWNHOLE
INJECTED WATER EXITS
AMBIENT WATER EXITS
AMBIENT WATER FLOWS UPHOLE
AMBIENT WATER ENTERS
downhole flow
uphole flow
ambient
injection @ 18 liters/min
Rock Matrix key
coarse clastic
fine clastic
carbonate
Turbulent Flow seen on video
bedding fracture seen on video

Figure 5

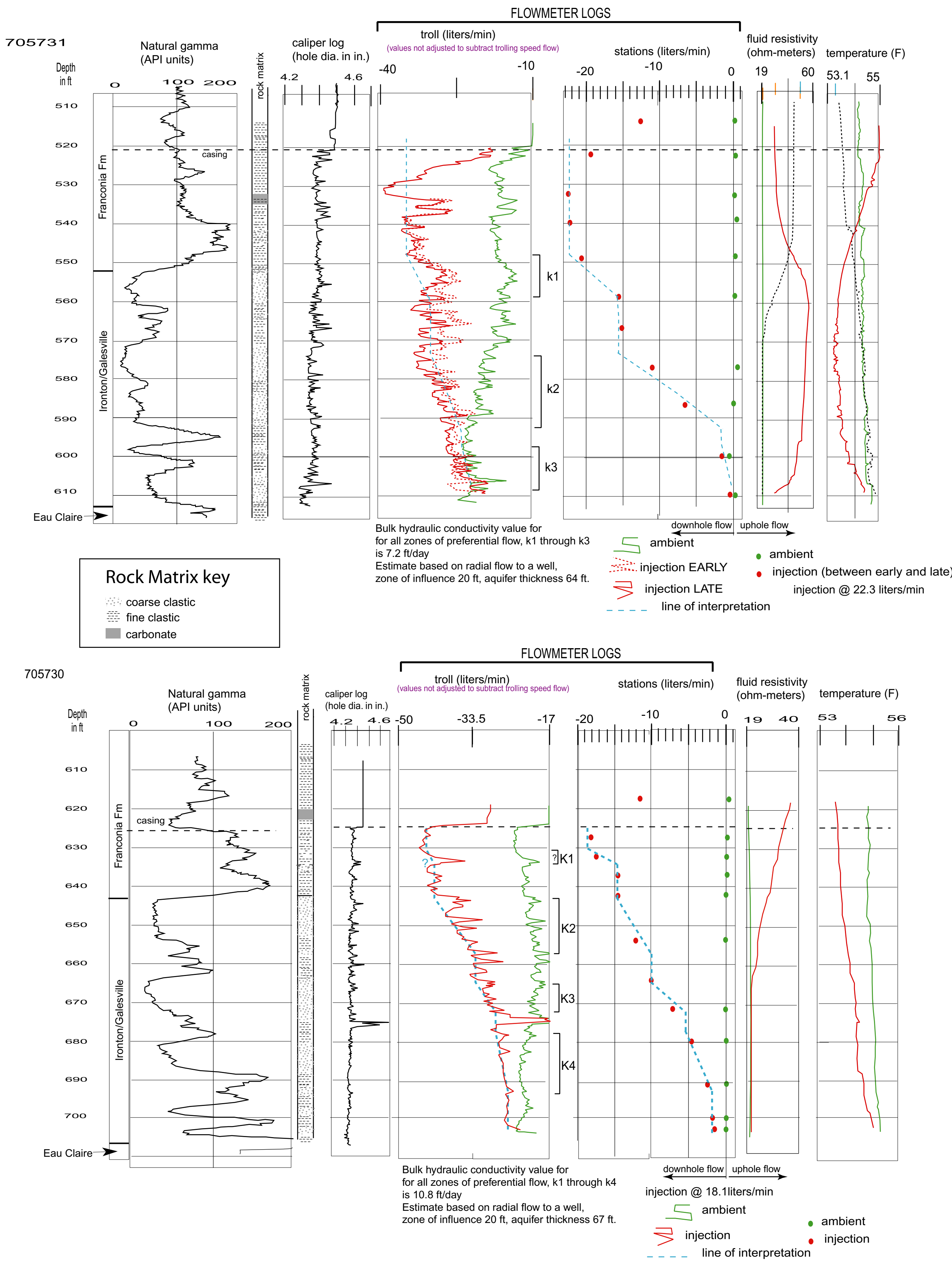

705731
Depth in ft
Natural gamma (API units)
0 100 200
rock matrix
caliper log (hole dia. in in.)
4.2 4.6
FLOWMETER LOGS
troll (liters/min)
(values not adjusted to subtract trolling speed flow)
-40 -10
stations (liters/min)
-20 -10 0
fluid resistivity (ohm-meters)
19 60
temperature (F)
53.1 55
510 520 530 540 550 560 570 580 590 600 610
casing
Franconia Fm
Ironton/Galesville
Eau Claire
k1
k2
k3
Bulk hydraulic conductivity value for for all zones of preferential flow, k1 through k3 is 7.2 ft/day
Estimate based on radial flow to a well, zone of influence 20 ft, aquifer thickness 64 ft.
downhole flow
uphole flow
ambient
injection EARLY
injection LATE
line of interpretation
ambient
injection (between early and late)
injection @ 22.3 liters/min
Rock Matrix key
coarse clastic
fine clastic
carbonate
705730
Depth in ft
Natural gamma (API units)
0 100 200
rock matrix
caliper log (hole dia. in in.)
4.2 4.6
FLOWMETER LOGS
troll (liters/min)
(values not adjusted to subtract trolling speed flow)
-50 -33.5 -17
stations (liters/min)
-20 -10 0
fluid resistivity (ohm-meters)
19 40
temperature (F)
53 56
610 620 630 640 650 660 670 680 690 700
casing
Franconia Fm
Ironton/Galesville
Eau Claire
?
K1
K2
K3
K4
Bulk hydraulic conductivity value for for all zones of preferential flow, k1 through k4 is 10.8 ft/day
Estimate based on radial flow to a well, zone of influence 20 ft, aquifer thickness 67 ft.
downhole flow
uphole flow
injection @ 18.1liters/min
ambient
injection
line of interpretation
ambient
injection

Figure 6

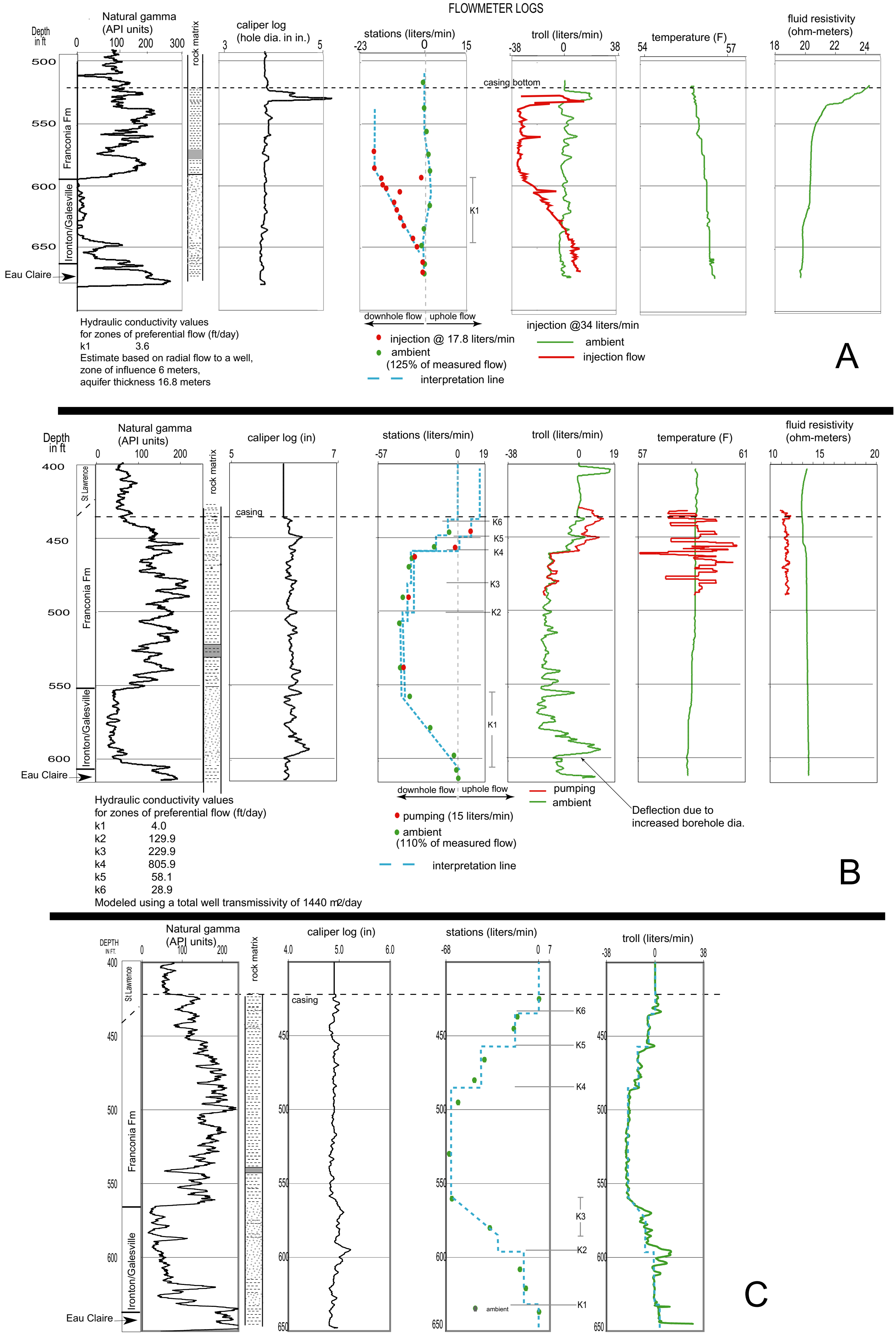
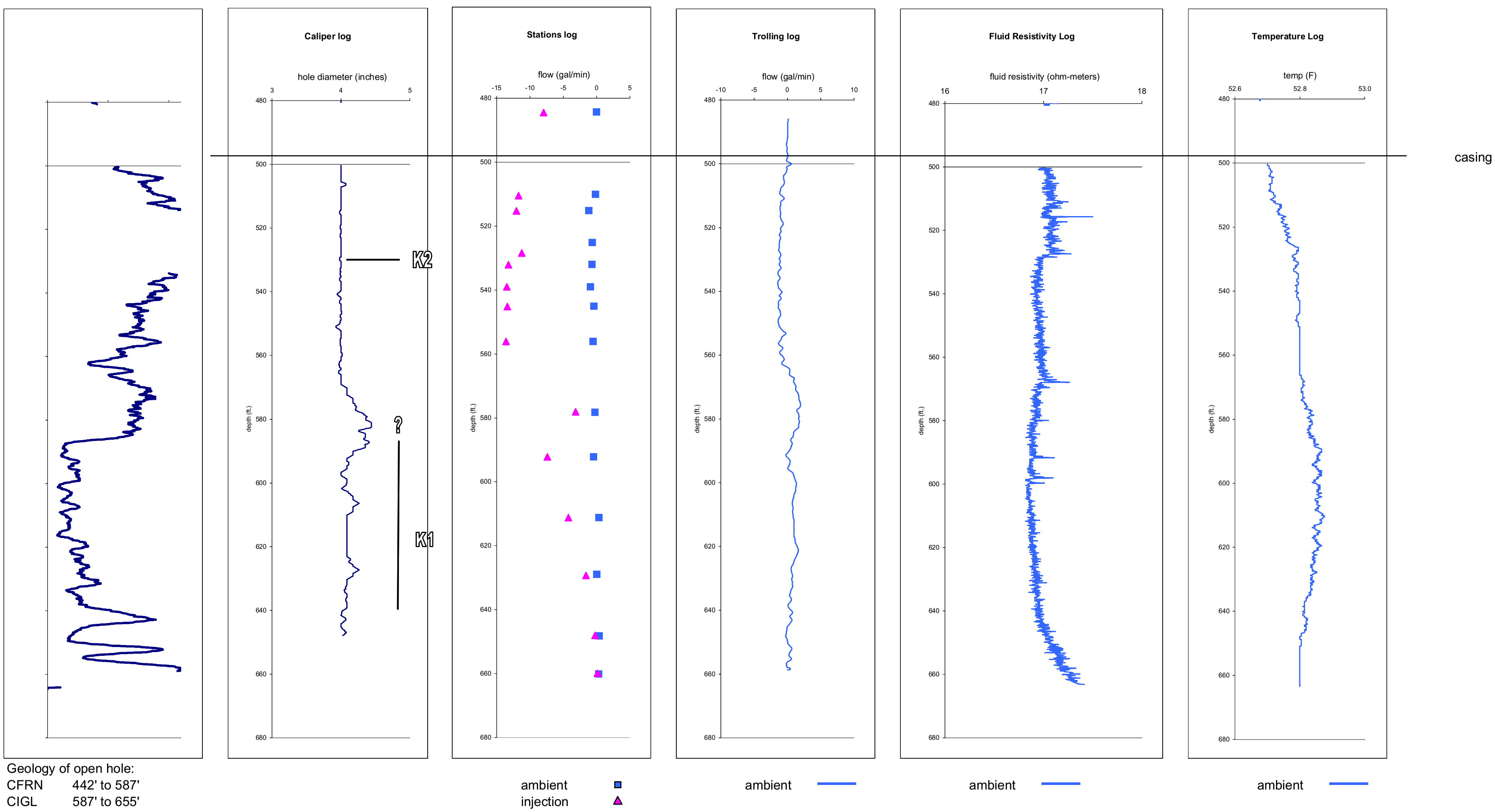

FLOWMETER LOGS
Depth in ft
Natural gamma (API units)
rock matrix
caliper log (hole dia. in in.)
stations (liters/min)
troll (liters/min)
temperature (F)
fluid resistivity (ohm-meters)
casing bottom
Franconia Fm
Ironton/Galesville
Eau Claire
K1
downhole flow
uphole flow
Hydraulic conductivity values
for zones of preferential flow (ft/day)
k1 3.6
Estimate based on radial flow to a well,
zone of influence 6 meters,
aquifer thickness 16.8 meters
injection @ 17.8 liters/min
ambient
(125% of measured flow)
interpretation line
injection @34 liters/min
ambient
injection flow
A
caliper log (in)
casing
St Lawrence
K6
K5
K4
K3
K2
pumping
ambient
Deflection due to
increased borehole dia.
Hydraulic conductivity values
for zones of preferential flow (ft/day)
k1 4.0
k2 129.9
k3 229.9
k4 805.9
k5 58.1
k6 28.9
Modeled using a total well transmissivity of 1440 m2/day
pumping (15 liters/min)
ambient
(110% of measured flow)
interpretation line
B
DEPTH IN FT.
ambient
C

Figure 7

Prior Lake Test Well   Prior Lake, Minnesota
Unique Well Number 721847
T 114 R 22 Section 1   DCCDBA



Geology of open hole:
CFRN   442' to 587'
CIGL   587' to 655'
CECR   655' +
Hydraulically active zones:
K2 @ 530'.   Fracture contribution, slight downflow under ambient conditions to around 570'
K1 @ 570'? - 640'.   Mostly Intergranular flow, characterized by linear decrease in downflow station measurements under injection conditions.
Top of zone depth not distinguishable due to increase in hole diameter. Fracture flow likely near 570 based on gamma and fluid resistivity logs.
Average injection rate: 21 Liters/min (5.5 gal/min)
Change in water level due to injection: +9 ft.
Approximate hydraulic conductivity of zone K1 using Thiem equation, aquifer thickness of 70 feet and radius of influence 20 ft.: 5 ft/day

Logged by Minnesota Geological Survey
September 30, 2005

Figure 8

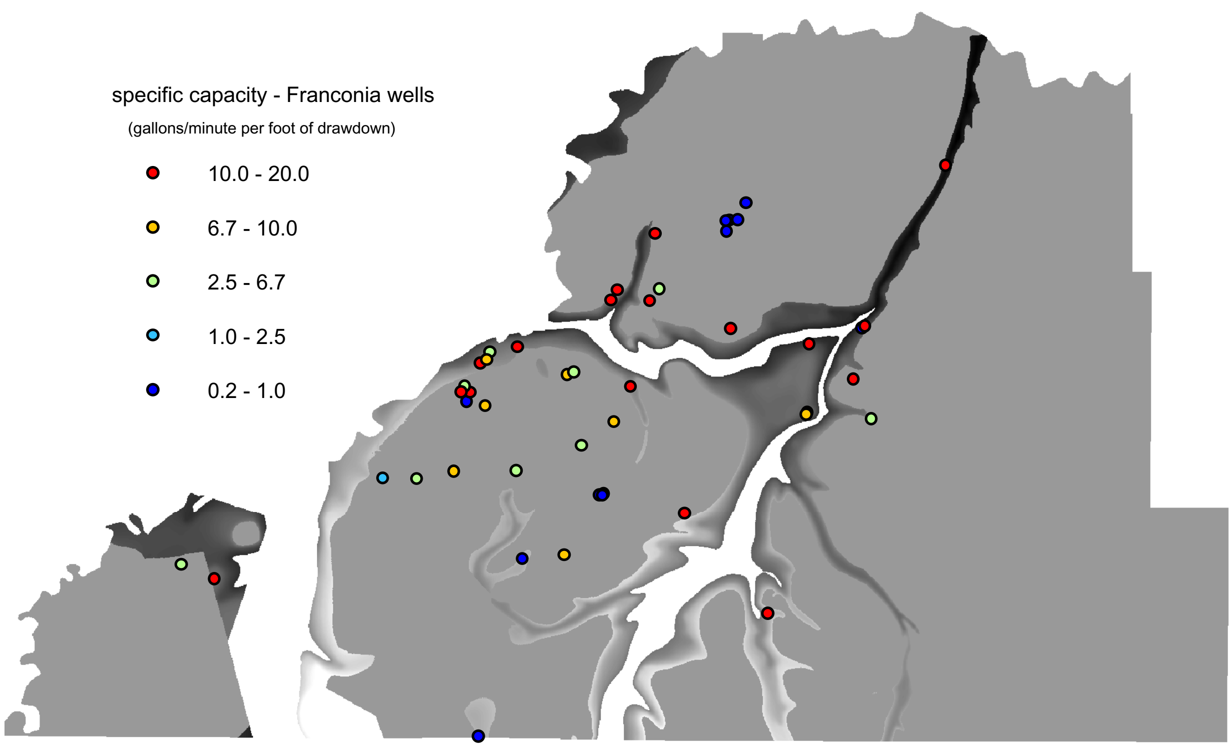

specific capacity - Franconia wells
(gallons/minute per foot of drawdown)
10.0 - 20.0
6.7 - 10.0
2.5 - 6.7
1.0 - 2.5
0.2 - 1.0

Figure 9

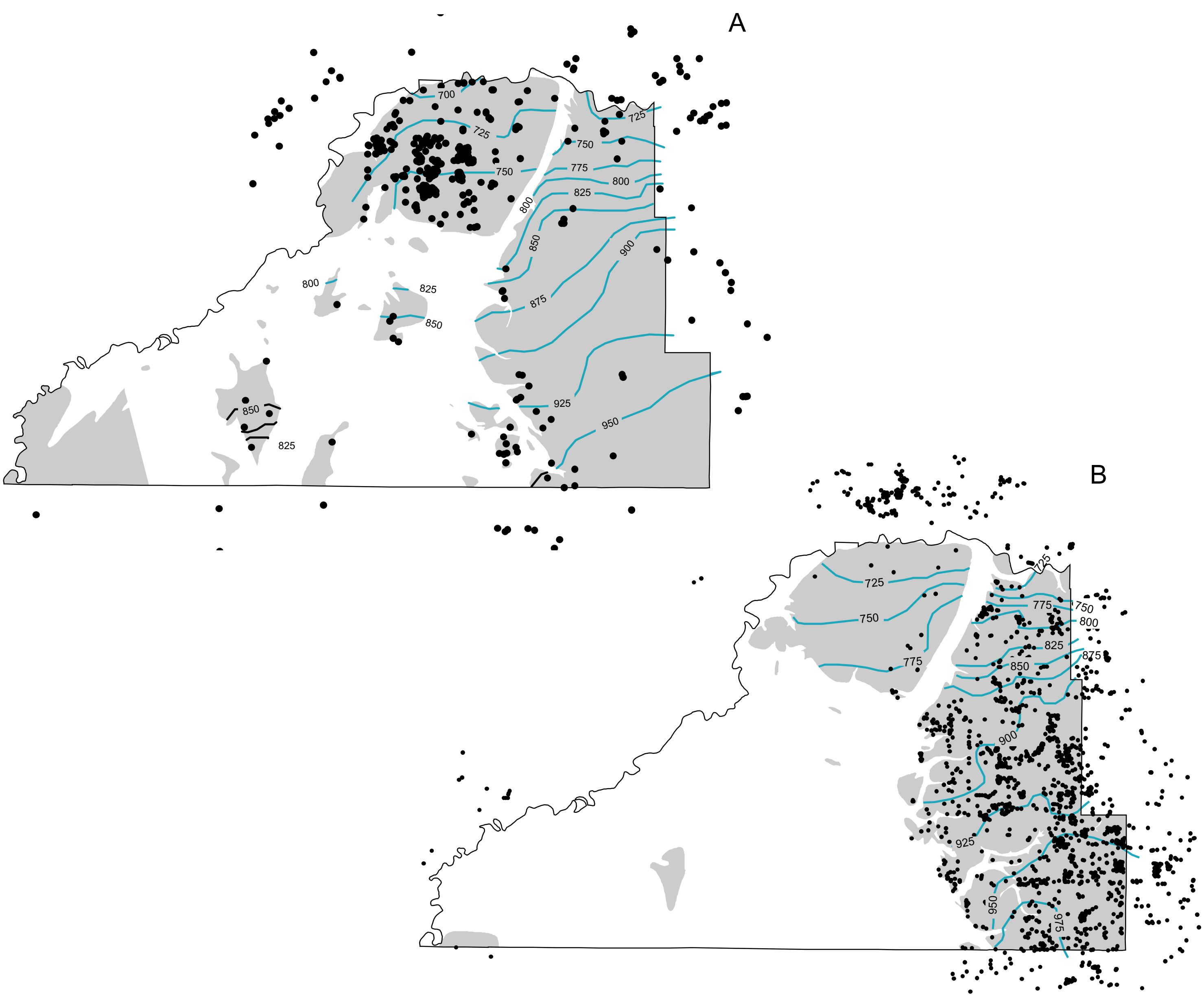

A
700
725
725
750
750
775
800
800
825
800
850
900
825
850
875
925
950
850
825
B
725
725
750
750
775
800
775
825
875
850
900
925
950
975

Figure 10

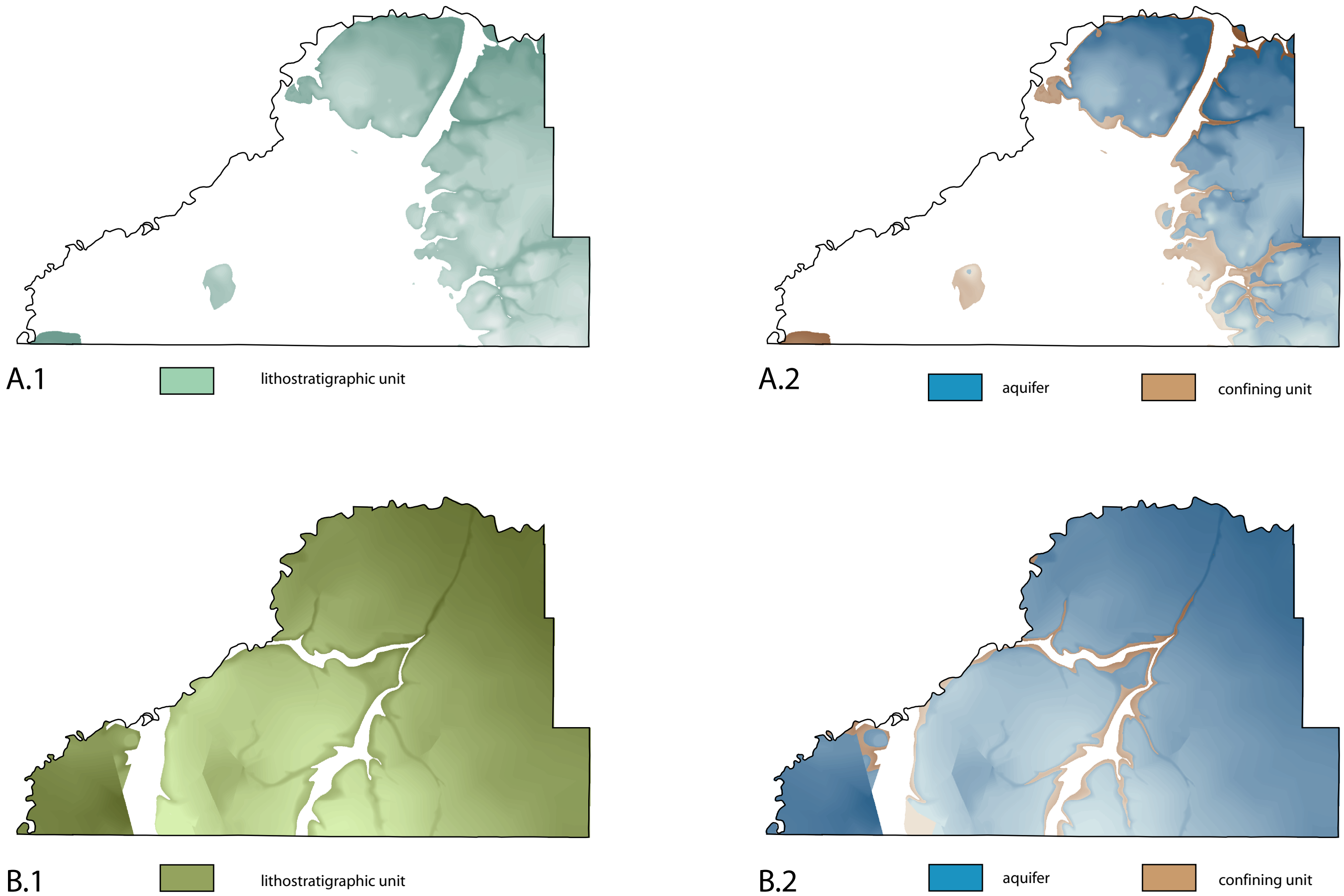
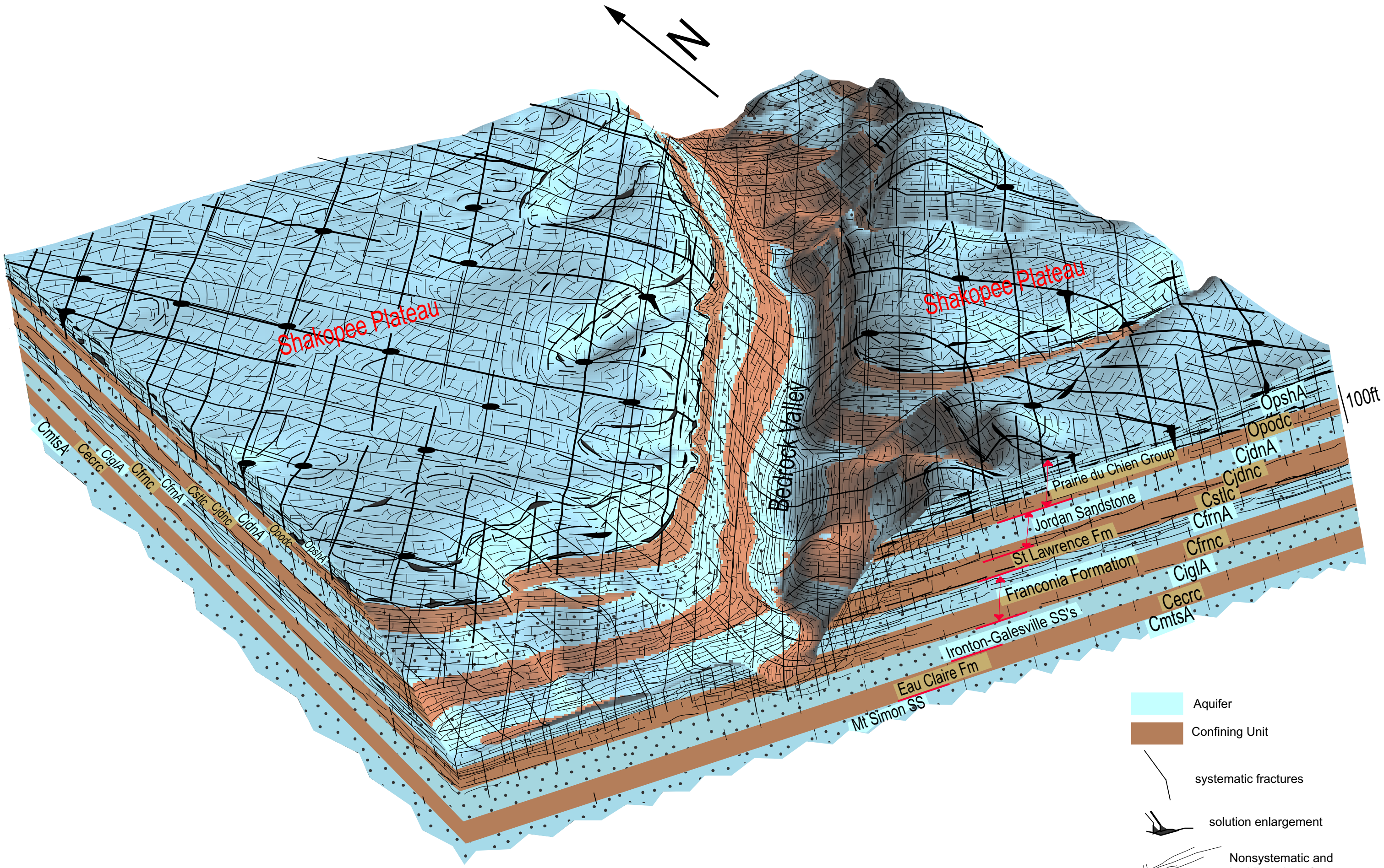

A.1
lithostratigraphic unit
A.2
aquifer
confining unit
B.1
lithostratigraphic unit
B.2
aquifer
confining unit

Figure 11



HYDROGEOLOGIC UNIT	PROPERTIES IN DEEP BURIAL CONDITIONS (most of nw metro area) ◄— transitional —►	PROPERTIES IN SHALLOW CONDITIONS OF BURIAL (within about 50 ft of bedrock surface)
OpshA Shakopee Aquifer		Bulk horizontal conductivity from a few to several hundreds of ft/day, varying widely even locally. Discrete intervals with abundant secondary pores have conductivities in thousands of ft/day. Highly karstic
Opodc Oneota Confining unit	Bulk horizontal conductivity poorly known,but limited tests indicating most intervals only a few ft/day or less. Individual bedding plane fractures and cavities can be 10's ft/day. Vertical conductivity about .0001 ft/day.	Fracture flow even more important. Conductivity uncertain, but known to provide confinement locally, and elsewhere to be breached by vertical fractures. Bulk hydraulic conductivity of tens of ft/day with discrete high permeability fractures yielding water are likely Other intervals locally with properties similar to deep conditions. Conductivity markedly variable.
CjdnA Jordan Aquifer	Bulk horizontal conductivity typically from a few to 30 ft/day, inferred to be largely intergranular, but values greater than about 20 ft/day may be from fracture contribution. Regionally averages about 17 ft/day.	Fracture flow even more important. Bulk horizontal conductivity more variable, and averages 43 ft/day regionally. Other intervals locally with properties similar to deep conditions.
Cjdnc Cstlc Lower Jordan and St Lawrence Confining Unit	Bulk horizontal conductivity from a few to perhaps 20 ft/day, achieved through fractures with conductivities of tens to perhaps thousands ft/day. Unfractured intervals with about .0001 ft/day vertical and .01 ft/day horizontal cond.	Fracture flow even more important. Bulk hydraulic conductivity of tens of ft/day with discrete high permeability fractures yielding water. Other intervals locally with properties similar to deep conditions. Conductivity markedly variable.
CfrnA Upper Franconia Aquifer	Bulk horizontal hydraulic conductivity typically 2-30 ft/day. Where few or no fractures present from about one to 10 ft/day. Individual frac's with conductivity's of tens to thousands of ft/day. Vertical conductivity uncertain, but where mostly fine clastic beds could be .01 ft/day or less	Fracture flow even more important. Bulk hydraulic conductivity double that of deeper conditions. Conductivity may well be markedly variable.
Cfrnc Lower Franconia Confining Unit	Horizontal hydraulic conductivity .01 ft/day, vertical .0001 ft/day. High conductivity bedding plane fractures may be encountered near base.	Fracture flow important. Bulk hydraulic conductivity of a few ft/day with discrete high permeability fractures. Other intervals locally with properties similar to deep conditions. Conductivity markedly variable.
CiglA Ironton-Galesville Aquifer	Horizontal hydraulic conductivity 3-11 ft/day, largely reflecting intergranular permeability. Vertical conductivity estimated at about order of magnitude less.	Fracture flow more important. Bulk hydraulic conductivity on average double that of deeper conditions. Conductivity will be markedly variable.
Cecrc Eau Claire Confining Unit	Horizontal hydraulic conductivity .01 ft/day, vertical .0001 ft/day.	Fracture flow important. Bulk hydraulic conductivity of 10 to 15 ft/day, but likely with individual intervals locally with properties similar to deep conditions. Conductivity will be markedly variable.
CmtsA Upper Mt Simon Aquifer	Bulk hydraulic conductivity from a few feet to 25 ft/day, Lower values largely reflect intergranular permeability of coarse clastic beds, higher values may largely reflect fracture flow in developed wells. Compartmentalization of discrete aquifers separated by fine clastic confining units.	Fracture flow more important. Bulk hydraulic conductivity on average double that of deeper conditions. Conductivity will be markedly variable.
Lower Mt Simon Aquifer	Bulk hydraulic conductivity ranges from a few feet to 25 ft/day. Lower values largely reflect intergranular permeability, higher values may reflect fracture flow in developed wells.	Fracture flow more important. Bulk hydraulic conductivity on average double that of deeper conditions. Conductivity will be markedly variable.

Figure 12

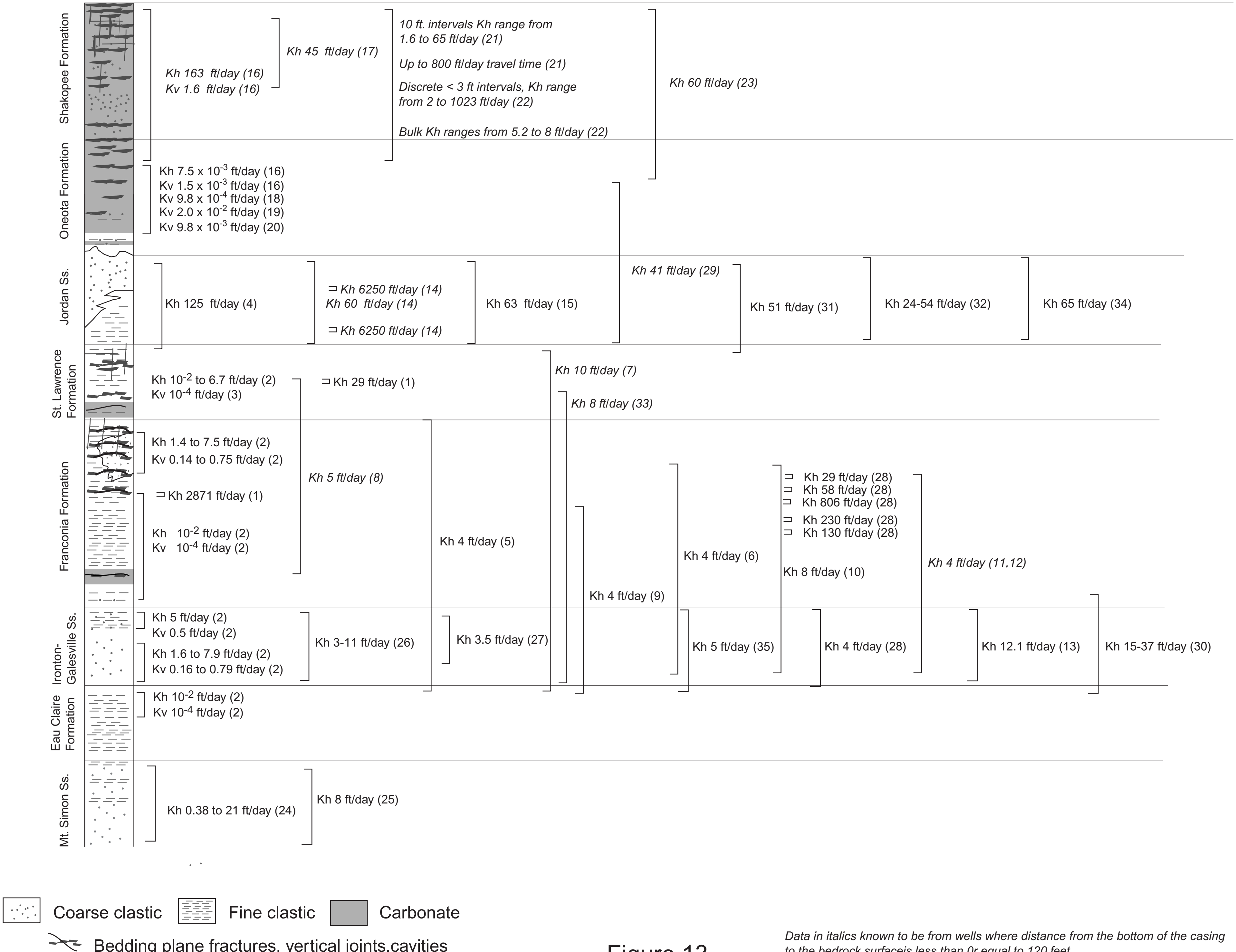


Figure 13

Data in italics known to be from wells where distance from the bottom of the casing to the bedrock surfaceis less than 0r equal to 120 feet.