

**IDENTIFYING THE CONTROLS ON FLOW AND CONTAMINANT DISTRIBUTION
IN SILICICLASTIC BEDROCK AQUIFER SYSTEMS**

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**Identifying the controls on flow and contaminant distribution
in siliciclastic bedrock aquifer systems**

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Project Summary

Title:	Identifying the controls on flow and contaminant distribution in siliciclastic bedrock aquifer systems
Project ID:	WR12R001
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Period of Contract:	July 1, 2012 through June 30, 2014
Background/Need:	Sandstone aquifers are commonly assumed to be homogeneous porous media dominated by intergranular flow. However, recent studies suggest that heterogeneous features, such as fractures, can be prevalent in sandstone aquifers and can significantly affect the aquifer flow regime. It has long been recognized that heterogeneity and preferential flowpaths significantly influence contaminant transport and distribution. As a result, identifying fractures in sandstone aquifers and determining their impact on aquifer flow is necessary to have an accurate understanding of system behavior.
Objectives:	The goal of this research is to determine the degree to which heterogeneous features such as fractures control flow in the Cambrian aquifer system of south-central Wisconsin.
Methods:	We evaluated aquifer flow conditions by measuring borehole flow in eight bedrock boreholes installed in the Cambrian aquifer system of south-central Wisconsin. We measured borehole flow using in-well heat tracer tests monitored by a distributed temperature sensing (DTS) system. DTS-monitored in-well heat tracer test results were used in conjunction with borehole geophysical data and other available geological data to identify zones of preferential flow within the sandstone aquifers.
Results/Discussion:	Seven of the eight boreholes tested had borehole flow under unstressed conditions. Results from DTS-monitored in-well heat tracer tests were used to identify borehole flow direction and changes in borehole flow rates. Changes in borehole flow rate occurring at discrete depths are attributed to fracture inflows and outflows, while changes in borehole flow rate occurring gradually with depth are attributed to porous media flow. Depths at which fracture flow is indicated by heat tracer test results correlate well with fracture depths determined from borehole geophysical data.

Conclusions/

Recommendations:

Study results indicate that bedding-parallel fractures are commonly found in the Jordan Formation, Tunnel City Group, and Wonewoc Formation sandstones, and that these fractures commonly dominate the observed borehole flow regime. These results suggest that fractures likely have a significant impact on the flow within these aquifers. In addition, our results indicate that not all fractures within these formations are hydraulically active under unstressed conditions, emphasizing the need for employing hydrogeologic characterization techniques, such as borehole flowing logging, to obtain an adequate understanding of aquifer behavior. Finally, our results suggest that head gradients commonly exist between the bedrock formations in south-central Wisconsin, and therefore, it is important to evaluate boreholes for flow and take measures to prevent cross-contamination in boreholes that cross-connect aquifers.

Keywords:

DTS, borehole flow, fracture flow, sandstone aquifers

Funding:

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Introduction

Siliciclastic aquifers are often assumed to consist of homogeneous porous media in which intergranular flow (i.e., porous media flow) is the only flow mechanism of significance. These aquifers often consist of thick intervals of sandstone having significant primary porosity, and as a result, the potential effects of preferential flow paths or discrete flow zones, such as fractures, are often disregarded even when the aquifers are known to be fractured. This can lead to inaccurate conceptual and numerical models of aquifer behavior, resulting in poor water resource management strategies. Therefore, understanding how discrete flow zones affect flow in porous aquifers remains an important subject of hydrogeologic research.

The Cambrian-Ordovician aquifer system of south-central Wisconsin is a stacked sequence of sedimentary rocks consisting primarily of sandstone, siltstone, and dolostone overlying Precambrian crystalline rock. A significant portion of this bedrock sequence is made up of Cambrian sandstone formations having thicknesses of meters to hundreds of meters. These rocks are generally flat-lying and are usually encountered within tens of meters of the surface in south-central Wisconsin. The Cambrian sandstone aquifers include the Mt. Simon Formation, Wonewoc Formation, Tunnel City Group, and the Jordan Formation. Stratigraphic relationships for Paleozoic rocks of south-central Wisconsin are shown in Figure 1. The Mt. Simon and Wonewoc Formations are separated by the Eau Claire Formation, which includes intervals of siltstone and mudstone (Aswasereelert et al. 2008) that serve as a regional aquitard (Bradbury et al. 1999), generally referred to as the Eau Claire aquitard. However, the Eau Claire aquitard is absent in parts of south-central Wisconsin (Aswasereelert et al. 2008). When the Eau Claire aquitard is absent, the sandstones of the Mt. Simon, Eau Claire (if present), and Wonewoc Formations are lumped together as the undifferentiated Elk Mound Group. The Cambrian sandstone aquifers are a significant source of water. In 2000, 47 percent of groundwater withdrawals in Wisconsin came from the Cambrian sandstone aquifers (Ellefson et al. 2002).

Runkel et al. (2006) report that these Cambrian sandstone formations in Minnesota have rock matrix porosity values ranging from 0.05 to 0.30 for fine-grained sandstones and 0.15 to 0.30 for fine- to coarse-grained sandstones. Porosity measurements from thirteen sandstone samples collected from cores in Wisconsin and northern Illinois ranged from 0.11 to 0.30 (WGNHS 2015). Despite having significant matrix porosity, multiple studies over the last decade suggest fractures significantly affect flow in these sandstones. Fracture flow has been identified in the Cambrian sandstones of south-central Wisconsin and their stratigraphic equivalents in Minnesota based on hydraulic testing and geophysical logging data as well as head profiles (Gellasch et al. 2013; Meyer et al. 2008; Meyer et al. 2014), water chemistry (Gellasch et al. 2013), reverse water level fluctuations (Gellasch et al. 2014), and outcrop and core studies (Runkel et al. 2006; Swanson 2007). In addition, multiple numerical model studies of Cambrian sandstones in south-central Wisconsin produced better simulations of aquifer conditions when laterally-extensive bedding plane-parallel preferential flow paths were included in the models (Anderson 2002; Swanson and Bahr 2004; Swanson et al. 2006). These studies emphasize the importance of recognizing fracture flow in sandstone aquifers.

We investigate flow in the Cambrian sandstones by measuring borehole flow in open boreholes installed through multiple formations within the system. Boreholes that cross-connect formations (or fractures) with different heads have vertical flow under unstressed conditions in response to the vertical head gradient. The measurement of vertical borehole fluid flow in open boreholes or wells with long screens, termed borehole flow logging, is a well-established method of characterizing heterogeneity and identifying preferential flow zones, such as fractures, in bedrock boreholes. For this study we experiment with the use of heat as an in-well tracer to measure borehole flow. We monitor borehole temperatures using a fiber optic distributed temperature sensing (DTS) system. DTS allows for measurement of temperatures along a fiber optic cable at combined spatial and temporal resolutions not possible with other borehole temperature measurement methods, resulting in temperature measurements over the length of the borehole nearly continuous in time. Detailed descriptions of the principles of DTS can be found in Tyler et al. (2009).

A recent study by Leaf et al. (2012) demonstrated the use of DTS to monitor in-well heat tracer tests. While the focus of their research was borehole dilution testing, in which a significant length of the water column is heated, in one experiment the authors inserted pulses of heated water into the water column and then measured the magnitude and direction of heat movement. Using the recorded movement of the warmed water the authors were able to identify borehole flow changes resulting from fracture flow in the tested borehole. The test initiation method employed by Leaf et al. (2012) involved heating water at the surface and pumping the heated water into the water column at the desired depth. Drawbacks of this method include unintended loss of heat from the hose used to inject the heated water and disturbance of the ambient flow regime during pumping and injection.

The work presented in this report builds off the work of Leaf et al. (2012) by presenting an improved method of tracer initiation and testing the method in a range of borehole flow conditions. The overarching goal of this study is to examine the influence of fracture flow in sandstone aquifers. We accomplish this goal by implementing the DTS-monitored in-well heat tracer test flow logging method in a study of flow conditions in the Cambrian sandstone aquifers of south-central Wisconsin.

Methods

Our method of measuring borehole flow using DTS-monitored in-well heat tracers requires warming a quantity, or slug, of water at a depth of interest and monitoring the movement of the heated water using a fiber optic cable deployed in the borehole and connected to a DTS interrogator. We initiated in-well heat tracer tests using an electrical resistance heater. We used two different heaters for the subject work. Both are rated for 2,000 watts with one designed for use in a 120 volt circuit and the other designed for 240 volts. Use of electrical heaters allowed for a high degree of control for test initiation. A test is initiated by lowering the heater into the water column to the desired test depth and running the heater until a change in temperature of 1 or 2 °C is observed in the DTS temperature measurements at the test depth. Heating times ranged from 1 to 12 minutes depending on borehole diameter and flow rates.

We monitored borehole fluid temperatures using a Sensornet Oryx™ fiber optic DTS. The Oryx was configured to take temperature measurements at 1.015 m intervals along the fiber optic cable using an integration time of 30 s and a repetition time of 40 s. Our fiber optic cable was deployed in each test borehole in a looped (duplexed) configuration so that both ends of the cable were at the ground surface. Sections of the fiber optic cable were coiled and placed in an ambient temperature water bath (mixed) and a water-wetted ice bath for calibration purposes (Tyler et al. 2009). For all tests the instrument performed dynamic field calibration using temperatures measured in the two calibration baths. All data were collected using a single-ended cable configuration to minimize data acquisition time.

We conducted in-well heat tracer testing in eight bedrock boreholes in south-central Wisconsin. Seven of the eight boreholes were found to have borehole flow under unstressed conditions. The tested boreholes ranged in depth from 79 m to 305 m with diameters between 0.076 m and 0.15 m. The tested boreholes were all open to Paleozoic sedimentary rocks and two of the boreholes were also open to Precambrian crystalline rock. Geological descriptions for the boreholes were compiled using existing geological information, which for each borehole included geophysical logs and either core or drill cuttings logs. Geophysical logs for a given borehole included a subset of natural gamma, fluid temperature, fluid conductivity, resistivity, caliper, and optical borehole image (OBI) logs. Potential fractures in sandstone intervals were identified in OBI logs for six of the eight studied boreholes. The heat tracer testing results for four of the boreholes that represent the range of flow characteristics observed are presented below. Borehole locations are shown in Figure 2 and borehole construction information is summarized in Table 1.

Period	Group	Formation	Thickness (m) ¹	Description	
Ordovician	Ancell	St. Peter	NA	Fine- to coarse-grained sandstone with basal cherty conglomerate and shale ²	
	Prairie du Chien	Shakopee/Oneota	12 m	Dolostone with chert, shale partings, and sandy zones ²	
Cambrian	Trempealeau	Jordan	11 m	Very fine- to medium-grained sandstone ³	
		St. Lawrence	3 m	Silty, stromatolitic dolostone and siltstone ⁴	
	Tunnel City	Lone Rock	27 m	Very fine- to medium-grained, glauconitic, feldspathic, bioturbated sandstone ⁵	Very fine- to medium-grained, slightly glauconitic sandstone ⁵
		Mazomanie			
	Elk Mound	Wonewoc	33 m	Well-sorted, fine- to coarse-grained sandstone ⁶	
		Eau Claire	0 to 7 m	Fine sandstone with intervals of mudstone and siltstone ⁷	
Mt. Simon		>100 m	Well-sorted, fine- to coarse-grained sandstone ⁸		
Precambrian			NA	Undifferentiated crystalline basement rocks	

¹Based on thicknesses observed in the studied boreholes

²Cline 1965

³Dott 1978, Odom and Ostrom 1978

⁴Byers 1978

⁵Odom 1978, Swanson 2007

⁶Dott et al. 1986, Runkel et al. 1998

⁷Aswasereelert et al. 2008

⁸Ostrom 1978

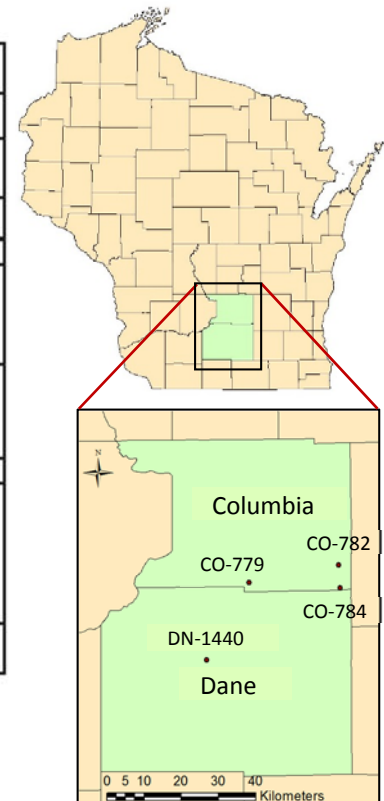


Figure 1 – Generalized stratigraphic column for bedrock of south-central WI.

Figure 2 - Locations of studied boreholes.

Table 1 – Summary of borehole construction information

Borehole	Borehole Diameter (m)	Depth to Water (m)	Casing Depth (m)	Total Depth (m)
DN-1440	0.13	6.3	24	87
CO-782	0.076	8.1	7	79
CO-784	0.15	14	11	258
CO-779	0.15	28.3	79	305

Results

DN-1440

We conducted initial DTS-monitored in-well heat tracer tests at DN-1440, which is the same borehole in which Leaf et al. (2012) conducted four heat pulse tests. In-well heat tracer tests were initiated at 14 depths within the open borehole. A plot of tracer test data is shown in Figure 3. Each region of elevated temperature in Figure 3 is the temperature record of an individual tracer test. Each tracer test record indicates the direction of heat movement in the borehole (up or down). In addition, the tracer test records can be used to determine the rate of heat movement in the borehole by measuring the slope of each feature on the distance versus time plot. When tracer test records do not have a constant slope, for example in the case of the deepest tracer test shown on Figure 3, this indicates a change in the heat migration rate with depth, which is attributed to a change in the vertical borehole fluid flow rate. For

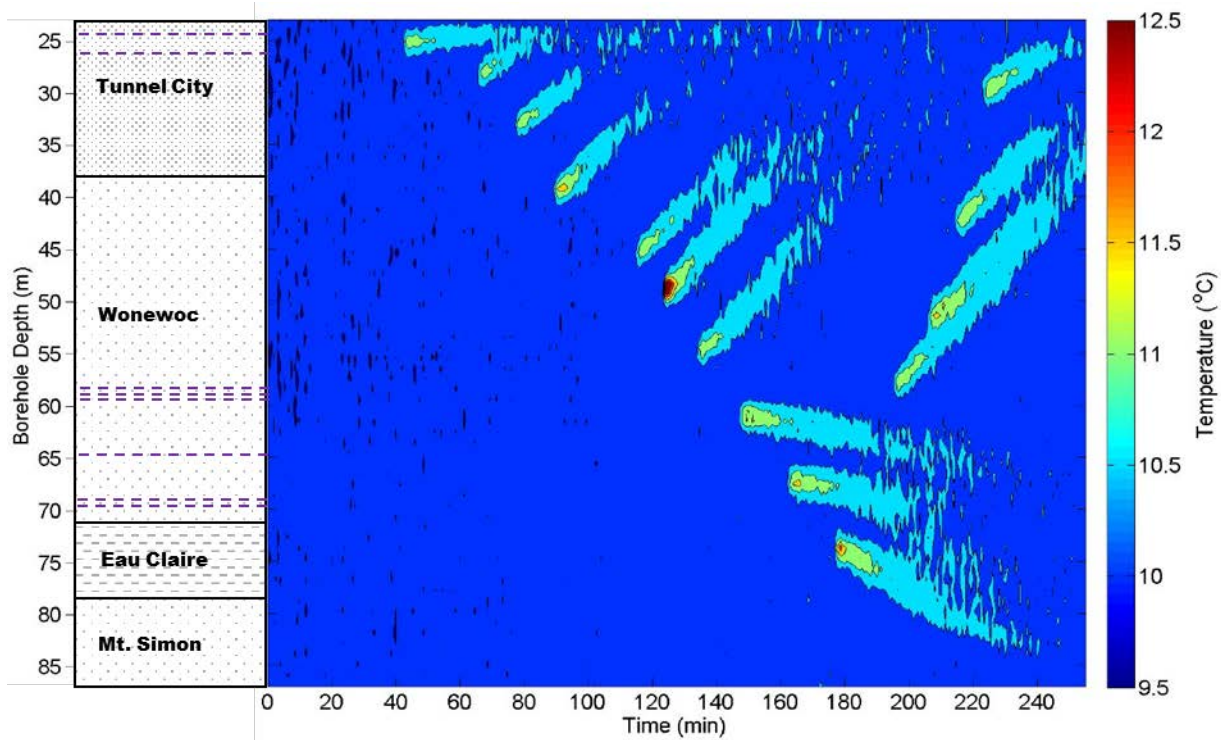


Figure 3 – Generalized stratigraphic column and plot of heat tracer test data for borehole DN-1440. Dashed lines in the stratigraphic column indicate the depths of fractures observed in the optical borehole image (OBI).

these tracer tests, heat migration velocities can be calculated as the slopes of different portions of the tracer test record.

If heat were a conservative tracer, we would expect the heat migration velocity calculated from the heat tracer tests to equal the borehole fluid flow velocity. However, other heat transfer mechanisms (e.g., radial conduction) might cause the heat migration velocity to differ from the actual borehole fluid velocity, and for this reason we refer to the heat migration velocity as the *apparent* fluid velocity. Evaluating the potential difference between heat migration velocity and borehole fluid velocity is the subject of ongoing research. Regardless of the potential error in flow rate magnitude, the heat tracers clearly indicate flow direction, and changes in heat migration velocity can be confidently attributed to changes in borehole flow rate.

Tracers initiated between depths of approximately 29 m and 59 m all move upward with time (Figure 3), indicating upward borehole flow over this interval. Conversely, the three tracer tests initiated below a depth of approximately 59 m move downward indicating the borehole fluid flow direction is downward below a depth of 59 m in this borehole. The divergence of borehole flow at a depth of approximately 59 m indicates the presence of a discrete flow feature, such as a fracture, at this depth within the Wonewoc Formation from which water is flowing into the borehole. This agrees with the observation of Leaf et al. (2012) of divergent fracture flow within the Wonewoc interval in this borehole at a similar depth (58 m). Note that Leaf et al. (2012) collected temperatures at a spatial sampling interval of 2 m and the current study used a spatial sampling interval of 1 m; thus a difference in fracture depth of 1 m is within the expected spatial resolution error. The fracture flow depth of approximately 59 m observed in the heat tracer test data also coincides with the depth of a set of fractures observed in the OBI log for this borehole between depths of 58 m and 59.5 m.

In addition to fracture flow at 59 m our tracer test results show a loss of borehole flow between a depth of approximately 29 m, where flow is upward, and the bottom of the well casing at a depth of 24 m. This decrease in flow over a short interval also suggests the presence of a fracture between the depths of 24 m and 29 m in this borehole. Fractures were observed at depths of 25 m and 26.5 m in the OBI log for this borehole.

The apparent upward borehole flow rates measured between the fractures near 59 m and 29 m decrease gradually, from an apparent flow rate of 0.35 m/min upward (4.7 L/min using the borehole diameter of 0.13 m) just above the fracture at 59 m to an apparent flow rate of 0.25 m/min upward (3.3 L/min) just below 29 m. This suggests that there is a 1.4 L/min loss in borehole flow over a distance of approximately 30 m. The gradual decrease suggests that flow is leaving the borehole via porous media flow into the Wonewoc and Tunnel City over this interval. In contrast, the decrease in apparent flow rate between 29 m and the bottom of the well casing is from 0.25 m/min upward (3.3 L/min) to zero over a distance of approximately 5 m. In this case the flow in one or two fractures in the Tunnel City is more than double the flow entering a 30 m interval of sandstone of which 21 m is porous Wonewoc sandstone.

The results from DN-1440 indicate fracture flow dominates the borehole flow regime in this borehole even though it is open almost entirely to sandstone. In-well heat tracer test results for DN-1440 support the findings of other researchers who have observed effects of hydraulically-active fractures in the Tunnel City Group and Wonewoc Formation sandstones (Anderson 2002; Gellasch et al. 2013; Gellasch et al. 2014; Leaf et al. 2012; Meyer et al. 2008; Meyer et al. 2014; Runkel et al. 2006; Swanson and Bahr 2004; Swanson et al. 2006). Also of significance, a fracture was identified on the OBI log at a depth of 64.5 m, however, there is no indication in the heat tracer test data of a change in borehole flow velocity at this depth (Figure 3), indicating that this fracture is not hydraulically active under unstressed conditions. This emphasizes the importance of characterizing the hydrogeology of a system beyond simply identifying where fractures exist.

CO-782

Borehole CO-782 is a bedrock corehole open from the St. Peter Formation to the Wonewoc Formation (upper Elk Mound Group). A generalized stratigraphic column and a plot of tracer test data for the CO-782 borehole are shown in Figure 4. All tracer tests measured in this borehole slope upward with time, indicating upward borehole flow. However, it is apparent from Figure 4 that the magnitude of the apparent borehole flow rate varies with depth. For example, the shallowest slopes are measured between depths of approximately 10 m and 29 m, while the steepest slopes are measured between depths of approximately 29 m and 63 m. The distinct change in slope of heat tracers at the 29 m depth indicates a discrete change in apparent borehole flow rate at this depth. Because the tracer data transition from steeply upward below 29 m to shallow upward above 29 m, it is clear that the borehole flow rate significantly decreases at this depth, indicating that borehole water is leaving the borehole via a fracture at a depth of approximately 29 m.

The slope of the heat tracer just above 29 m indicates an upward apparent velocity of 0.17 m/min (0.76 L/min). The slopes of tracers just below 29 m indicate upward apparent velocity of approximately 5.5 m/min (25 L/min). These values suggest that the fracture zone at 29 m is receiving approximately 24 L/min of flow from the borehole.

Similarly, the discrete change in flow pattern at 63 m again indicates an abrupt change in borehole flow, this time with an increasing flow rate above the transition depth. This again indicates the presence of a fracture at the 63 m depth, and in this case, the fracture is delivering water to the borehole resulting in an increase in the magnitude of upward flow. Slope and discharge calculations indicate that the apparent borehole flow rate increases from approximately 3.5 L/min to approximately 35 L/min across this preferential flow zone.

The in-well heat tracer test data for CO-782 indicate that the borehole flow regime is dominated by the two or three discrete fracture zones, rather than porous media flow, even though the borehole is open to a long interval of sandstone. Between the 29 m and 63 m fractures flow decreases from

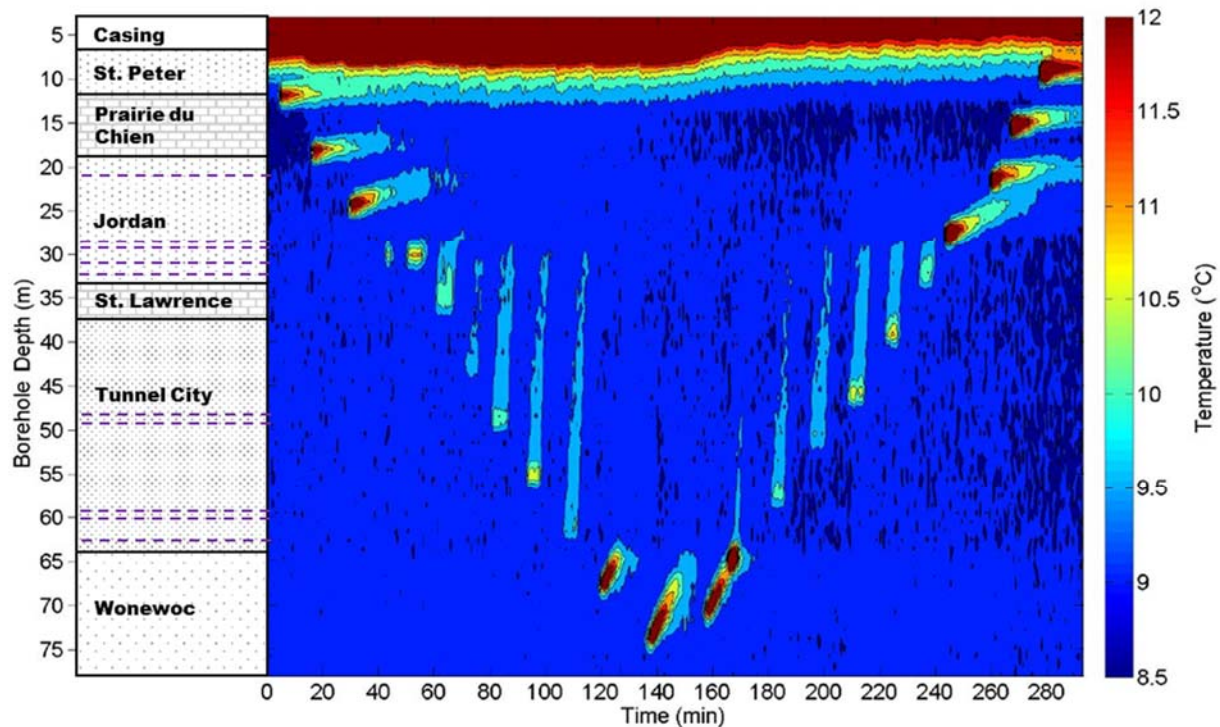


Figure 4 – Generalized stratigraphic column and plot of heat tracer test data for borehole CO-782. Dashed lines in the stratigraphic column indicate the depths of fractures observed in the OBI log.

approximately 35 L/min to approximately 25 L/min, a 29% decrease that is attributable to porous media outflow. In contrast, the apparent flow rate increases by an order of magnitude across the 63 m fracture and decreases by an order of magnitude across the 29 m fracture. While there is significant potential for error in the stated flow rates due to calculating apparent velocities from steep slopes, the results from this borehole again clearly indicate fracture flow dominates over porous media flow in this borehole.

To confirm our interpretation of fractures at depths of 29 m and 63 m, we reviewed the OBI log for this borehole. The OBI log confirms that a set of visible fractures is present at depths of 29 to 31.5 m, which falls within the Jordan Formation sandstone, and another visible fracture is present at a depth of 63 m, within the Tunnel City Group sandstone. The OBI log also shows the presence of fractures at depths of approximately 48 m, 49.5 m, 59 m, and 61 m, however, there is no indication in the heat tracer test data of changes in borehole flow velocity at these depths (Figure 4). These fractures are additional examples of clearly visible fractures that are not hydraulically active under unstressed conditions.

In-well heat tracer test results for CO-782 again confirm the Tunnel City Group sandstone includes hydraulically-active bedding plane-parallel fractures that act as preferential paths for horizontal aquifer flow. In addition, our results indicate that fractures can significantly affect flow in the Jordan sandstone as well. The results again demonstrate that not all fractures identified in these formations are hydraulically active under unstressed conditions, emphasizing the importance of conducting hydrogeologic characterization of the system.

CO-784

Borehole CO-784 was drilled using rotary drilling methods to a total depth of 258 m and is open from the St. Peter Formation through the entire Cambrian interval and penetrates 7 m into Precambrian crystalline rock. At CO-784 there is no indication in the borehole geophysical data of an interval of mudstone and siltstone that would mark the presence of the Eau Claire aquitard. A generalized

stratigraphic column and a plot of tracer test data for the CO-784 borehole are shown in Figure 5. Heat tracer tests initiated above a depth of 110 m did not produce measurable heating of the borehole water, indicating that flow rates in the upper portion of this borehole are above the upper range of measurement for our method. The results for heat tracer tests initiated below 110 m show downward tracer migration and decreasing magnitude of borehole velocity with depth for a significant length of the borehole. There is a discrete change in the ambient temperature profile at a depth of approximately 41 m within the Prairie du Chien Group dolostone, indicating the presence of fracture inflow. However, below 41 m there is no indication of fracture inflows or outflows. The gradual decrease in velocity magnitude with depth below 110 m indicates water is leaving the borehole via porous media flow. Fractures were visible in the OBI log for this borehole within the Prairie du Chien Group, the Tunnel City Group, and the Jordan Formation, but no fractures are obvious within the Elk Mound Group, consistent with our observation of porous media flow within this borehole interval.

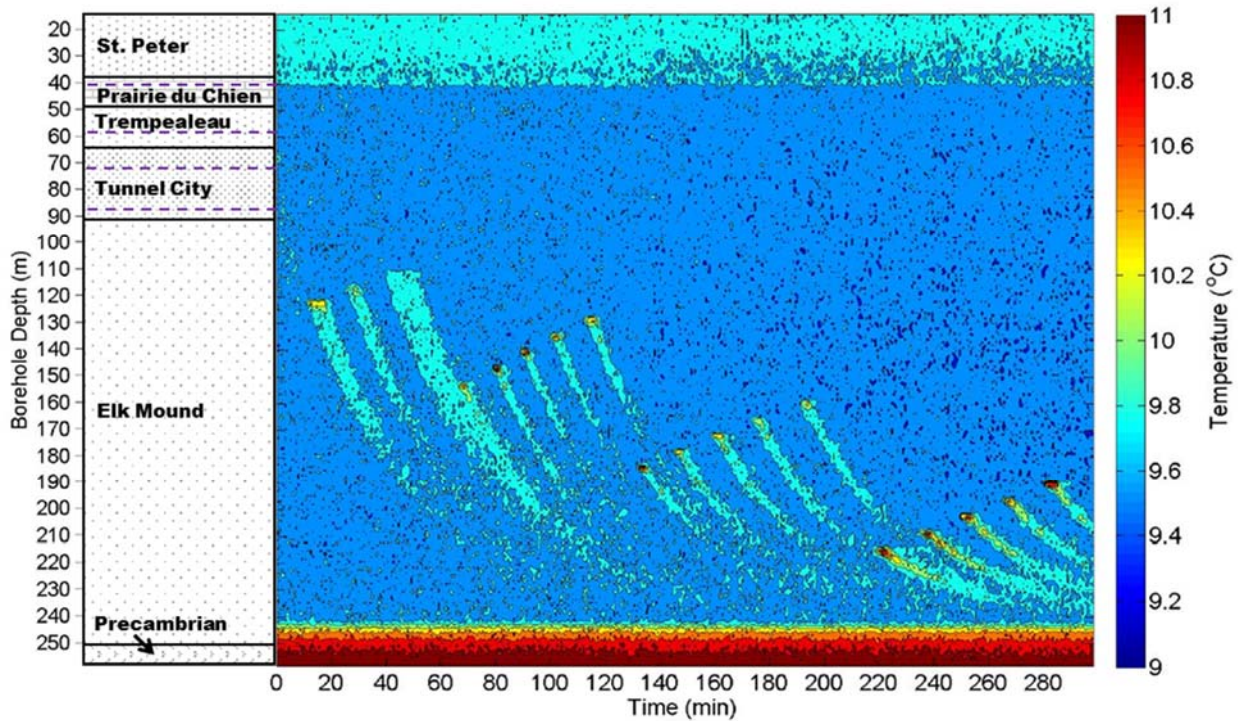


Figure 5 – Generalized stratigraphic column and plot of heat tracer test data for borehole CO-784. Dashed lines in the stratigraphic column indicate the depths of fractures observed in the OBI log.

Because the heat tracers for this borehole do not form linear features on the depth versus time plot, slopes were calculated for lines tangent to the heat tracers over specified intervals. Measured apparent flow rates show a continuous decrease in flow from 3.2 m/min (58 L/min) downward at a depth of 120 m to zero flow at a depth of approximately 240 m. Cessation of vertical borehole flow at a depth of approximately 240 m is supported by the background temperature profile in the borehole, which shows uniform background temperature to a depth of approximately 242 m, below which the temperature steeply increases (Figure 5). This steep increase in background fluid temperature is due to the geothermal gradient being compressed to the bottom of the borehole by the downward movement of water within the borehole. The fluid temperature begins to increase near the depth where downward flow ceases, in this case suggesting that the downward borehole flow rate reaches zero at a depth of approximately 242 m.

In-well heat tracer test results for this borehole indicate that a significant portion of the borehole, all within the Elk Mound Group sandstone, is dominated by porous media flow. In addition, the results indicate heat tracer migration can be monitored over significant vertical distances, allowing for changes in apparent flow rates with depth to be readily identified, even when those changes are gradual as is the case when the borehole flow regime is dominated by porous media flow.

CO-779

The CO-779 borehole is cased to the bottom of the Tunnel City Group sandstone and open to the entire thickness of undifferentiated Elk Mound Group sandstone and 40 m of the underlying Precambrian crystalline rock. As was the case for CO-784, the Elk Mound Group is undifferentiated at this location due to a lack of evidence within the borehole geophysical data for mudstone and siltstone facies that would indicate the presence of the Eau Claire aquitard.

Heat tracer tests were initiated at 22 depths in the CO-779 borehole. Each heat tracer signal remained at the same elevation for the entire time record indicating that there is no vertical migration of the induced heat in this borehole, i.e., there is no vertical borehole flow. Data from the first ten tracer tests are shown in Figure 6 as examples.

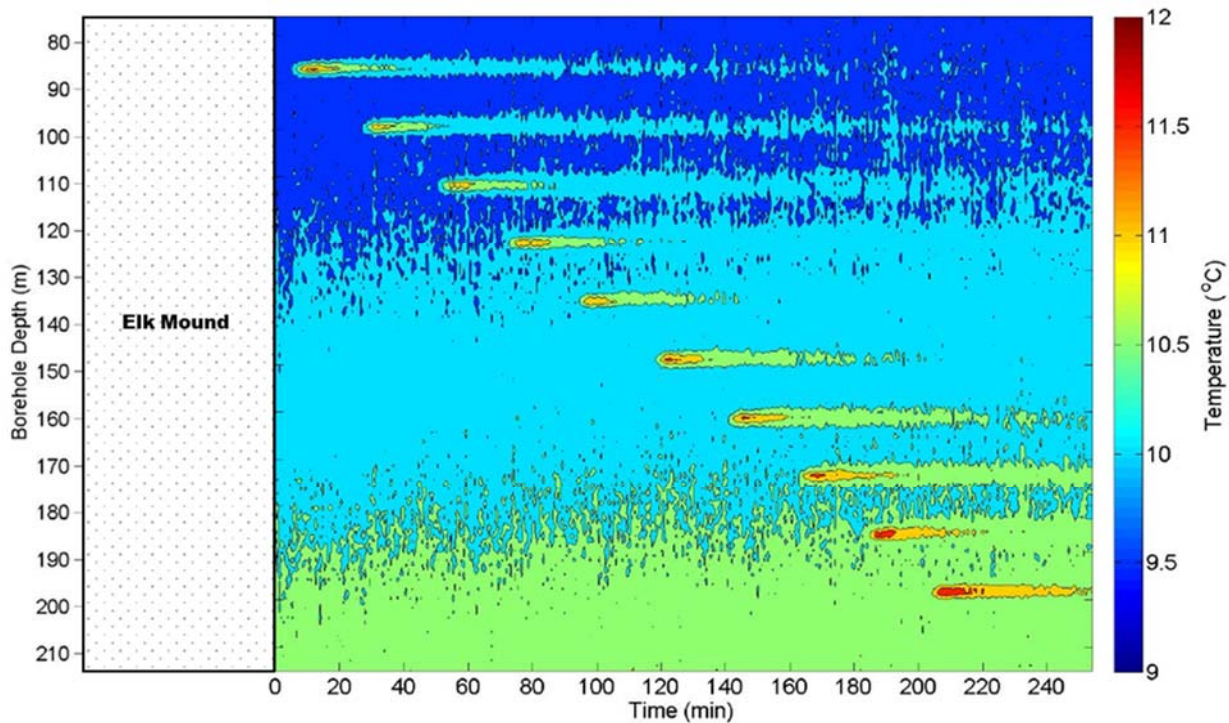


Figure 6 – Generalized stratigraphic column and plot of heat tracer test data for borehole CO-779 from 80 m to 210 m.

The lack of vertical borehole flow in CO-779 indicates there is no head gradient over the entire open length of the borehole, a length of 226 m, while all other tested boreholes had flows indicating the presence of vertical head gradients. Vertical gradients develop in recharge and discharge areas of flow systems and where vertical variations in formation hydraulic conductivity restrict the vertical movement of flow. Therefore, the absence of a vertical gradient could result from measuring heads at the hinge line of the regional flow system, between the regional recharge and regional discharge zones of the aquifer where flow is primarily horizontal, or from a lack of an interval with sufficiently low vertical hydraulic conductivity (i.e., no aquitard) to restrict vertical flow. The absence of a head gradient within the Elk

Mound at this location supports the conclusion from the geophysical data that the Eau Claire aquitard is absent at this site. However, CO-784 also lacked the Eau Claire aquitard but did have vertical flow within the Elk Mound. A key difference between the boreholes is that CO-784 was open to multiple formations above the Elk Mound while CO-779 was cased through the overlying formations. The downward flow observed at CO-784 is in response to a downward vertical head gradient between the Elk Mound and the overlying formations. This gradient likely exists at CO-779 as well, however, the borehole is cased into the Elk Mound Group and does not cross-connect formations with different heads, so there is no vertical borehole flow. Based on this comparison it appears the Tunnel City Group sandstone acts as an aquitard preventing significant flow into the Elk Mound from above. This is consistent with the findings of Meyer et al. (2008) who observed downward vertical gradients within the Tunnel City Group indicating poor hydraulic connection between subunits within the Tunnel City, and also consistent with the findings of Gellasch et al. (2013) who observed that fractured intervals within the Tunnel City and Wonewoc sandstones had significantly higher transmissivity than the unfractured sandstone, which caused the fractures to behave as aquifers and the unfractured sandstone to behave as an aquitard.

Conclusions

Our investigation of fluid flow in boreholes that intersect the Tunnel City Group and Wonewoc Formation sandstones confirms the findings of other researchers that these formations contain fractures that are hydraulically active under unstressed open borehole conditions, suggesting they have significant influence on the aquifer flow regime and great potential to act as conduits for preferential contaminant transport. Fracture flow was also found within the Jordan sandstone, indicating that fracture flow is not limited to the specific lithological or mineralogical conditions of the Tunnel City Group and Wonewoc Formation. Due to the potential for active fractures to act as preferential contaminant migration pathways, it is important to evaluate sandstone aquifers for fracture flow and incorporate fracture flow into conceptual and numerical models of sandstone aquifers when appropriate.

While the Wonewoc Formation (upper Elk Mound Group) was found to be dominated by fracture flow at DN-1440, the undifferentiated Elk Mound at CO-784 was found to be largely unfractured and dominated by porous medium flow. In addition, no borehole flow was observed over the entire thickness of the Elk Mound Group at CO-779. These results suggest there may be predictable differences in the amount of fracturing, and as a result, predictable differences in the flow regimes among the Cambrian sandstones in south-central Wisconsin. Additional research is needed to evaluate whether porous media flow is the rule in the Elk Mound when it is undifferentiated due to the absence of the Eau Claire aquitard.

The results of this study provide further evidence for the importance of fracture flow in sandstone aquifers. In addition, this study demonstrates the importance of using borehole flow logging or other hydrogeological characterization techniques to test for fracture flow because some fractures that are apparent in borehole geophysical logs are not hydraulically active. Borehole flow characterization is necessary to determine which fractures impact the flow system.

Finally, the predominance of borehole flow under unstressed conditions in the Cambrian aquifer system of south-central Wisconsin is an important finding of this study. Seven of the eight boreholes tested had measurable borehole flow under unstressed conditions. This suggests that borehole flow is common in layered sedimentary sequences where boreholes are likely to be open to multiple formations, resulting in cross-connection of layers or fractures with different heads. The occurrence of borehole flow has important implications for contaminant transport as the borehole can become a conduit through which contaminants can bypass aquitards and contaminate new aquifers. In addition, borehole flow causes mixing of groundwater chemistry and thermal conditions between formations, resulting in potentially ambiguous results from groundwater samples collected from such boreholes. For these reasons, it is important to evaluate boreholes for flow and take measures to prevent cross-contamination in boreholes that do cross-connect aquifers.

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Appendix A: Papers, Presentations, and Posters

Papers:

Sellwood, S.M., J.M. Bahr, and D.J. Hart (in review). Evaluation of a discrete-depth heat dissipation test for thermal characterization of the subsurface, GSA Special Paper, Geothermal Energy: An emerging resource.

Sellwood, S.M., D.J. Hart, and J.M. Bahr (in preparation). Evaluating flow regimes in siliciclastic aquifers using in-well heat tracer tests.

Presentations:

Sellwood, S.M., J.M. Bahr, and D.J. Hart, 2014. Discrete-depth heat dissipation tests as a potential tool for characterizing subsurface thermal conductivity variations, Geological Society of America annual meeting, Vancouver, British Columbia, October 2014.

Sellwood, S.M., D.J. Hart, and J.M. Bahr, 2014. Use of in-well heat tracer tests monitored by DTS to measure vertical borehole flow, 59th Annual Midwest Ground Water Conference, Lawrence, Kansas, October 2014.

Sellwood, S.M., J.M. Bahr, and D.J. Hart, 2014. Evaluating aquifer flow conditions using heat as an in-well tracer, American Water Resources Association Wisconsin Section annual meeting, Wisconsin Dells, Wisconsin, March 2014.

Sellwood, S.M., J.M. Bahr, and D.J. Hart, 2013. Identification of variations in heat exchange capacity with depth in a borehole using heat dilution tests, Geological Society of America annual meeting, Denver, Colorado, October 2013.

Sellwood, S.M., D.J. Hart, and J.M. Bahr, 2013. An update on development of new techniques for measuring borehole flow, Wisconsin Ground Water Association annual meeting, Waukesha, Wisconsin, April 2013.

Sellwood, S.M., D.J. Hart, and J.M. Bahr, 2013. Borehole flow characterization using discrete in-well heat tracer tests monitored by DTS, American Water Resources Association Wisconsin Section annual meeting, Brookfield, Wisconsin, March 2013.

Posters:

Sellwood, S.M., J.M. Bahr, and D.J. Hart, 2014. Evaluating aquifer flow conditions using heat as an in-well tracer, Minnesota Ground Water Association Spring Conference, St. Paul, Minnesota, April 2014.

Sellwood, S.M., D.J. Hart, and J.M. Bahr, 2012. Borehole flow characterization using DTS to monitor discrete in-well heat tracer tests, Geological Society of America Annual Meeting, Charlotte, North Carolina, November 2012.

Sellwood, S.M., D.J. Hart, and J.M. Bahr, 2012. A simple, low-cost downhole flow logging system, 57th Annual Midwest Ground Water Conference, Brooklyn Park, Minnesota, October 2012.