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DTS as A Hydrostratigraphic Characterization Tool

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DTS AS A HYDROSTRATIGRAPHIC CHARACTERIZATION TOOL

Project Completion Report

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Project Summary

Title: DTS as a hydrostratigraphic characterization tool

Project ID: WR09R006

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Background/Need: Subsurface heterogeneity in hydraulic properties and processes is a fundamental challenge in hydrogeology. Most hydrogeologic problems are complicated by uncertainty in permeability, which is often difficult or impossible to fully characterize. The usefulness of heat as a tracer has been limited by thermometry that only records temporal changes in temperature at a single fixed or moving point. Distributed temperature sensing (DTS) is a powerful new method that allows for the nearly continuous measurement of temperature in time and space along fiber-optic cables. The fine spatial and temporal monitoring ability of DTS is creating new and unprecedented opportunities to study hydraulic heterogeneity at a wide range of scales. Despite numerous recent applications of DTS applications in surface water investigations, down-hole uses in hydrogeology have been limited. Recent studies on the Sandstone Aquifer system of Wisconsin have shown preferential flow through laterally continuous bedding plane fractures to be a defining characteristic of sandstone units that were traditionally assumed to be homogeneous and isotropic. The implication of these findings is that more detailed characterization efforts are necessary to adequately assess flow and transport problems in these units.

Objectives: The purposes of this study were to develop DTS as a down-hole groundwater monitoring and aquifer characterization tool, and to use its novel monitoring capabilities to gain new information on hydraulic heterogeneity in the Sandstone Aquifer system. This study builds on previous work by using DTS to monitor ambient and artificially-stimulated temperatures for the purpose of detailed hydraulic characterization at the borehole scale. In addition, DTS was used to investigate the effects of borehole flow processes on temperatures measured in wells. Finally, the novel monitoring capabilities of DTS allow hydraulic heterogeneity in the Sandstone Aquifer system to be studied at an unprecedented level of detail.

Methods: Investigations were conducted at three sites. At a former Aquifer Storage and Recovery (ASR) site in Oak Creek, WI, a 550 m deep monitoring well was instrumented with DTS. Temperatures were measured under ambient conditions, and during a week of pumping from an identical well located 55 m away. Subsequent geophysical logging and modeling studies were used to identify the processes affecting measured temperatures. Active, single-well thermal tracer experiments were conducted in two naturally flowing multi-aquifer wells near Madison, WI. Borehole water was circulated through an above-ground heat exchanger system, which was closed to the atmosphere. The system produced heating of up to 10 °C above ambient at flow rates of approximately 8 to 13 l/min. Heated water was returned to the wells using a depth-adjustable rubber garden hose outlet. The migration of the heated water in the borehole was monitored using DTS. Outlet depths and injection times were varied.

Results/Discussion

At Oak Creek, DTS data collected in the monitoring well recorded transient well-bore flow induced by pumping in the neighboring ASR well. Accompanying modeling studies showed that early-time decreases in temperatures signified downward flow, and that a reversal in this trend signified a transition to upward flow at steady-state. Geophysical logging provided an improved site conceptual model, and valuable information on the Sandstone Aquifer system under the Milwaukee area. In the two wells near Madison, WI, DTS data collected during active thermal tracer experiments characterized the ambient borehole flow regimes, revealing intervals of fracture-dominated and intergranular flow in the Sandstone Aquifer system. In comparison with geophysical logging, the DTS data showed diverging flow in both wells to be emanating from bedding plane fractures at stratigraphically similar locations in the Wonewoc sandstone.

The results of this study show wells to be complex conduits that are affected by, but do not necessarily represent, conditions in the aquifer, especially in hydraulically heterogeneous settings. Diverging flow in the Wonewoc Formation emanating from bedding plane fractures in stratigraphically similar positions suggests regional-scale fracture flow. This finding is significant in light of recent investigations that have characterized the Wonewoc as dominantly intergranular, and warrants further investigation

Conclusions/ Recommendations:

The active thermal tracer experiments demonstrated the effectiveness of DTS as a tool for detailed aquifer characterization. As a tool for measuring borehole flow, DTS has an effective operating range that exceeds that of conventional heat pulse and spinner flow meter techniques, which were previously unable to adequately characterize the ambient flow regime in DN-1440. In addition, DTS effectively integrates measurements over the entire width of the borehole, in contrast to heat pulse and spinner flow techniques, which may respectively be affected by leakage around the diverter or turbulence near the edge of the borehole. As a tool for measuring temperatures, DTS is superior to conventional wireline tools in its response time, which is on the order of seconds rather than minutes, and its ability to profile temperature synoptically without disturbing the fluid column.

Future work could use DTS methods to characterize aquifer heterogeneity in other wells open to the Sandstone Aquifer system. As shown respectively in the May 19 and May 28 experiments, both constant source and finite-pulse heating techniques can provide useful information. The latter provides the most unambiguous results as a stand-alone technique. An electric resister may provide a superior heat source in comparison to the heat exchanger used in this study.

Keywords: DTS, heat, temperature, tracers, hydrostratigraphy, Cambrian-Ordovician Aquifer System, Sandstone Aquifer, groundwater, Wisconsin

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Introduction

DTS is a powerful new method that allows for the rapid profiling of temperature along fiber optic cables. A thorough review of DTS theory can be found in Tyler et al. (2009), Selker et al. (2006a) and Hurtig et al. (1994). DTS is based on the transmission of pulsed laser light down an optical fiber and observation of the backscattered (reflected) signal. A small portion of the backscattering (Raman scattering) returns to the instrument at two characteristic wavelengths: one longer (anti-Stokes signal) and one shorter (Stokes signal) than the incident. The intensity ratio of the anti-Stokes and Stokes signals is an exponential function of the fiber temperature.

DTS was developed in the early 1980s (Dakin et al. 1985), and first applied to the Earth sciences in 1992 by Hurtig et al. (1993), who used it to profile ambient temperatures in shallow boreholes at the Grimsel Test Site in Switzerland. Following recent improvements in cost and instrument design (Selker et al. 2006a), the last several years have seen an explosion of DTS applications in hydrologic investigations. Most of these have been in surface water (e.g. Tyler et al. 2009; Mofffet et al. 2008; Westoff et al. 2007; Selker et al. 2006) and surface water/groundwater interactions (e.g Vogt et al. 2010, Henderson et al. 2009; Lowry et al. 2007; Selker et al. 2006b). Although DTS is now widely used by the oil and gas industry for down-hole production monitoring (e.g. Simonits and Franzen 2007), down-hole uses in hydrogeology have been limited.

This study builds on previous work by using DTS to monitor ambient and artificially-stimulated temperatures for the purpose of detailed hydraulic characterization at the borehole scale. In addition, DTS was used to investigate the effects of borehole flow processes on temperatures measured in wells. Finally, the novel monitoring capabilities of DTS allow hydraulic heterogeneity in the Sandstone Aquifer system to be studied at an unprecedented level of detail.

The Cambrian-Ordovician Aquifer System (hereafter referred to as the “Sandstone Aquifer system”) is an areally extensive, multi-aquifer sequence of mature, quartzose “sheet” (Runkel et al. 1998) sandstones, interbedded with dolomites, siltstones and shales.

At Oak Creek, WI, the Sandstone Aquifer system extends from approximately 180 m below ground surface (bgs) to more than 550 m bgs. In ascending order, the major units are the Mt. Simon, Eau Claire, Wonewoc, Tunnel City, St. Peter, and Sinnipee. The Sinnipee and overlying Maquoketa Shale act as a regional aquitard. Following extensive overpumping in the mid-twentieth century, Oak Creek and most other communities along Lake Michigan switched their water supply from the aquifer to the lake.

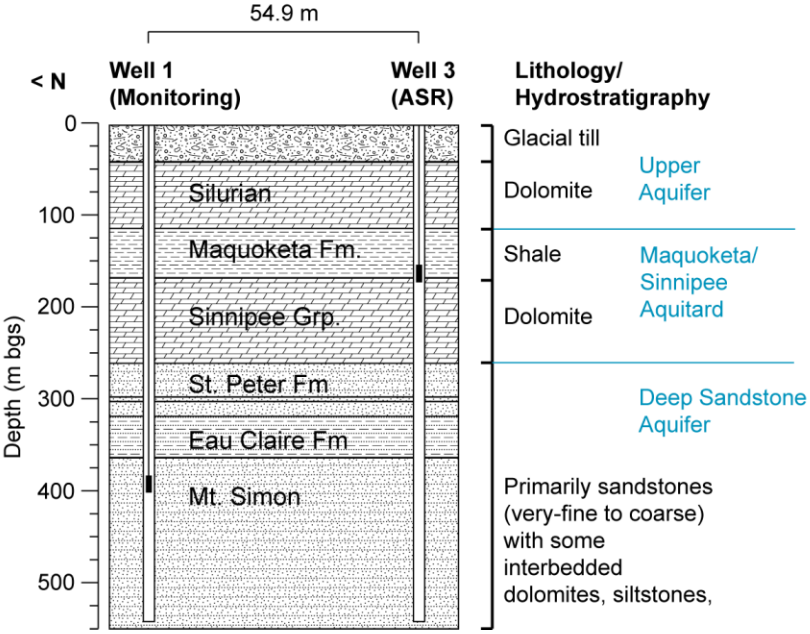

Figure 1: Schematic of the Oak Creek ASR site.

An Aquifer Storage and Recovery (ASR) operation at Oak Creek sought to use the Sandstone Aquifer system as a reservoir for the temporary storage of treated Lake

Michigan water, which would provide an auxiliary supply source of peak summer water demand, thereby reducing the necessary treatment plant design capacity. Two 550 m deep former municipal wells were retrofitted for ASR use (Figure 1). Well 3 was converted an ASR well, with the capability to inject or extract water at rates exceeding 3,800 l/min (1,000 gpm). Well 1, located 55 m away, was set up as a monitoring well, with a 57 l/min (15 gpm) sampling pump installed at a depth of 405 m bgs. Eight ASR "pilot" cycles were conducted between 1999 and 2007. Treated water from Lake Michigan was injected into Well 3, stored for a period of time, and then recovered (Miller 2001). An original objective of this study was to use DTS to monitor an injection cycle at Oak Creek. It was thought that DTS in Well 1 could potentially detect the breakthrough of the injection water, which was typically initially 10 °C colder than the native groundwater. Despite the cancelation of further ASR cycling due to water quality problems, the large open interval (370 m) and thermal history of ASR cycling at Oak Creek provided a unique opportunity for DTS in the Sandstone Aquifer system (Leaf 2010).

The bedrock units in the Madison area are the same as those at Oak Creek, but were less deeply eroded along the Cambrian-Ordovician unconformity. In addition to a thicker Tunnel City Group, the overlying Trempealeau and Prairie du Chien groups are also present. Hydrostratigraphically, the sequence can be divided into an upper and lower aquifer separated by the Eau Claire aquitard. Municipal pumping in the Madison metropolitan area has lowered water levels in both bedrock aquifers. This has substantially altered the natural flow system, creating vertical hydraulic gradients that are complex in both space and time. The Madison lakes, which previously received regional groundwater discharge, now lose water to the lower aquifer over much of their area (Bradbury et al. 1999). Although this has buffered declines in water levels, it presents a potential long-term threat to water quality in the lower aquifer. An exception to this reversal is the northern end of Lake Mendota, which lies near the margin of the cone of depression. In this area (which includes well DN-1440), vertical hydraulic gradients are sufficiently small to allow for periodic flow reversals in response to municipal pumping cycles (Bradbury et al. 1999; Anderson 2002).

Vertical hydraulic gradients in the Sandstone Aquifer system near Madison are also produced by natural phenomena. The unglaciated Driftless Area, which lies directly west of Madison, is characterized by a relatively high topographic relief and shallow depths to bedrock. This results in high rates of recharge (Hart et al. 2009) occurring at differing elevations. In the heterogeneous Sandstone Aquifer system, this produces vertical variations in head at downgradient locations. This is thought to be the primary reason for vertical hydraulic gradients at IW-512.

Several recent investigations have found laterally continuous bedding plane fractures to have a dominating effect on flow in the Tunnel City Group (e.g. Swanson 2007; Swanson et al. 2006; Runkel et al. 2006). This finding may also extend to other units in the Sandstone Aquifer system. In the initial characterization study of DN-1440, Anderson (2002) noted significant borehole flow from fractures in the Wonewoc Formation (see below). Similar investigations by Hart and Luczaj (2010) have observed fracture-dominated borehole flow in wells open to other units of the Sandstone Aquifer system. Some question remains as to the lateral continuity, and therefore regional significance, of these features.

Procedures and Methods

DTS measurements were collected in Well 1 at Oak Creek from November 13-16, 2009 under ambient conditions (using 30 min integrations) and from November 16-21 (using 15 min integrations) with Well 3 pumping at approximately 3,800 l/min (1,000 gpm). Pairs of reference coils at each end of the DTS cable were kept in icewater and circulating ambient temperature baths, which were also instrumented with Solinst Barologgers. The reference temperatures recorded by the Barologgers were used to calibrate the DTS data. A similar experiment was performed in June of 2008. A complete description of the 2008 experiment, and additional details on the 2009 experiment at Oak Creek can be found in Leaf (2010).

Following a hang-up of the DTS cable on the Well 1 sampling pump apparatus, the sampling pump and piping were removed from Well 1. This allowed for geophysical logging. In early February of 2010, natural gamma, caliper, normal resistivity, temperature, and fluid conductivity logs were collected. Heat-pulse logging of ambient well-bore flow was conducted in March of 2010. In addition to improving the conceptual model of the Oak Creek site, the geophysical logging results (Appendix B) provide a valuable addition to the limited pool of information on the Sandstone Aquifer system under the Milwaukee area.

Two numerical models were used to investigate the potential processes controlling the temperatures observed in Well 1 at Oak Creek. A three-dimensional transient MODFLOW (Harbaugh et al. 2000) simulation examined borehole flow in Well 1 induced by pumping in Well 3, by simulating Well 1 as a column of high conductivity (10^6 m/d) cells. An 11-year, two-dimensional transient simulation of radial groundwater flow and heat transport using the code HYDROTHERM (Kipp et al. 2009) examined the long-term thermal effects of ASR cycling on temperatures in the aquifer. A complete description of these models can be found in Leaf (2010).

Two research wells near Madison, WI were selected for active thermal tracer experiments. Well DN-1440 is situated in the Pheasant Branch Conservancy, which is located north of Middleton, WI near Lake Mendota. The open interval of DN-1440 intersects both the upper and lower aquifers, allowing for flow between the units in the presence of vertical hydraulic gradients. Packer head testing by Anderson (2002) showed a periodic reversal in the vertical gradient between the two aquifers that correlated with pumping schedules for Middleton Wells 4 and 5, which are located approximately 1.5 and 3 km from DN-1440, respectively.

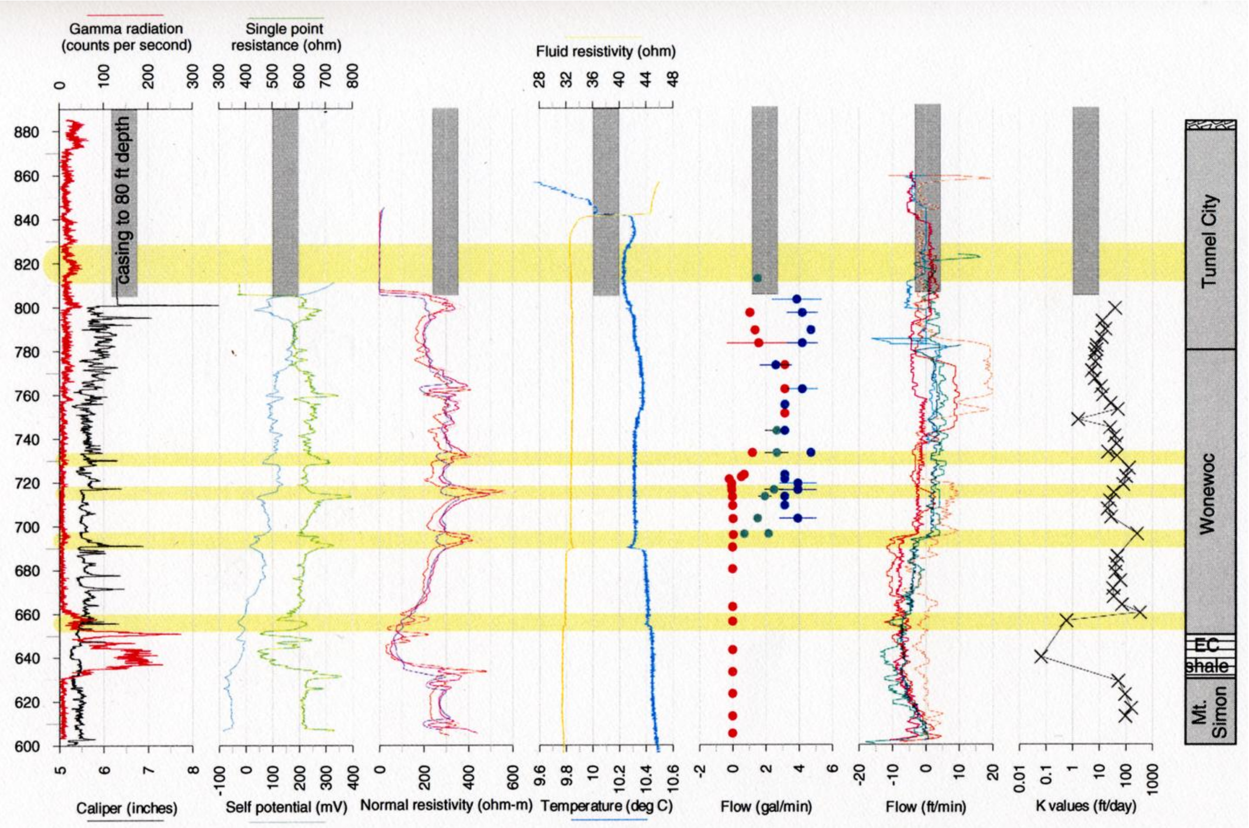

Figure 2: Borehole geophysics for DN-1440 (from Anderson 2002). Elevation is in ft. above sea level.

Figure 2 suggests that flow in DN-1440 is significantly influenced by fractures. Numerous secondary porosity features were detected in the Tunnel City and Wonewoc during the drilling of DN-1440, some of which correlate to anomalies in the geophysical logs (e.g. changes in resistivity, temperature and flow) that are consistent with hydraulically active bedding plane fractures. The locations of these features are denoted in Figure 2 by the yellow bands. The fractures at elevations of 657 and 693 feet (58.5 and 69.5 m bgs) appear to be important, as evidenced by abrupt transitions in temperature and flow, and high values of hydraulic conductivity, obtained through closed-interval packer testing (Anderson 2002). These features are also evident in a television log (Figure 3), which suggest that they represent clusters of bedding plane fractures.

Figure 3: Snapshot from downhole video log of DN-1440 showing hydraulically active fractures at 58 m depth.

Well IW-512 is located in a quarry off of Iowa County Highway A near Hollandale, WI. The well intersects at least three aquifers: the Mt. Simon, the Wonewoc/Tunnel City, and an upper aquifer consisting of a thin layer of sandstone (possibly the Jordan) and fractured dolomite in the Praire du Chein Group. As in DN-1440, there is significant hydrostratigraphic and hydraulic heterogeneity in portions of this well. Previous geophysical investigations by Hart and Luczaj (2010) have documented numerous fractures in the upper 100 m and diverging flow in the Wonewoc Formation.

In this well, heads in the Wonewoc/Tunnel City aquifer are above the land surface. Under ambient conditions, flow out of the casing can reach 180 l/min (45 gpm). This artesian flow can be stopped by installing a standpipe on the casing that allows the water level to rise to hydrostatic conditions (~1 to 2 m above the land surface). This causes all upward flow in the borehole to exit into the sandstone unit at about 45 m bgs, shown by the dark blue flowmeter curve in Figure 4. The normal configuration for IW-512 is with outflow stopped by a large PVC ball valve installed on the top of the casing. To ensure steady-state conditions with the well flowing, the valve was removed two days before the thermal tracer experiment.

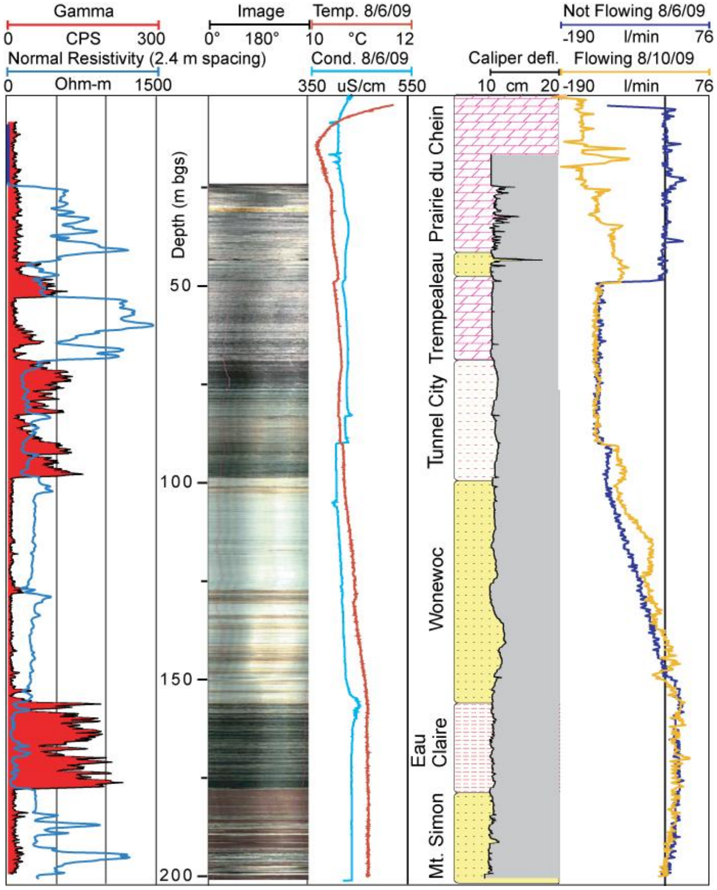

Figure 4: Borehole geophysics for IW-512.

A system was developed for heating groundwater with minimal disturbance (Figure 5). A low-flow, submersible Grundfos pump situated in the cased portion of the borehole delivers well water at adjustable rates of ~4 to 13 l/min (1-3.5 gpm) to a coil of 1.27 cm (0.5 inch) diameter copper pipe immersed in a cauldron heated by a high-pressure propane burner. The heated water is returned to the well via heavy-duty rubber garden hose. A short segment of pipe attached to the outlet keeps the hose taut in the well. A movable, high capacity hose reel allows for the outlet to be easily raised and lowered in the well, up to depths of more than 150 m (500 ft) bgs (Figures 6-7 and 6-8).

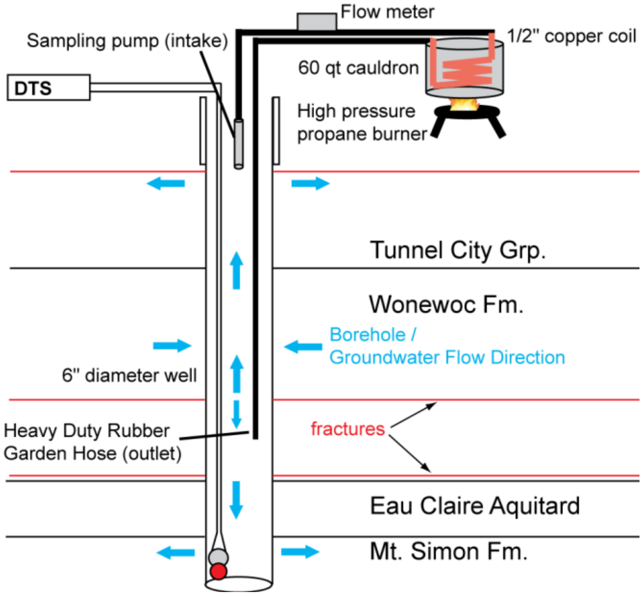

Figure 5: Heating system setup at DN-1440.

Flow is measured using an Omega piston-type, variable-area inline flowmeter. This device is not ideal for water with high concentrations of suspended solids, which inhibit the motion of the piston. Problems encountered during operation at DN-1440 suggest that the reported heating system flow rates may be underestimates. High flow rates in the well remove more heat from the outlet hose. Therefore, the overall output of the system ranges from approximately 1 to 4 kW. For a pumping rate of 8 l/min (2.1 gpm), this corresponds to a temperature increase of ~2 to 7 °C.

Three single-well tracer tests were conducted in DN-1440. On April 14, 2010, a pilot test was conducted using a conventional wireline temperature tool. The heating system was run at 8.7 l/min (2.3 gpm) for a period of two hours and forty minutes, with the outlet kept stationary at the bottom of the well while the wireline tool was continuously trolled up and down between the bottom of the well and the casing.

An experiment on May 19, 2010 was conducted in a similar manner using DTS. The heating system was run for two hours and forty minutes at ~10 l/min (2.7 gpm), with the outlet briefly at 73 m (240 ft.) bgs for the first 10 minutes and then lowered to just above the bottom of the well (87 m, 285 ft. bgs) for the remainder of the experiment. DTS measurements were collected every minute, at a spatial resolution of 2 m. On May 28, 2009, an additional experiment used the heating system in brief, 10-15 min. pulses with the outlet set at various depths. The migration of the heated water pulses in the well was monitored by DTS at one-minute intervals with a spatial resolution of 2 m. The results of both DTS experiments were calibrated to external reference temperatures collected by Solinst Baraloggers, which were co-located with reference coils of cable in known temperature baths.

At IW-512, the DTS system was configured and calibrated in the same manner. The heating system was run mostly continuously from 11:30 to 14:30 at ~13 l/m (3.4 gpm), with the outlet lowered in 12m increments. When the outlet reached ~160m, it was left stationary until 15:50, when it was shut off. The heating system was then pulsed in two 15 min increments at ~130 m bgs and ~95 m bgs, before being permanently shut off.

Results and Discussion

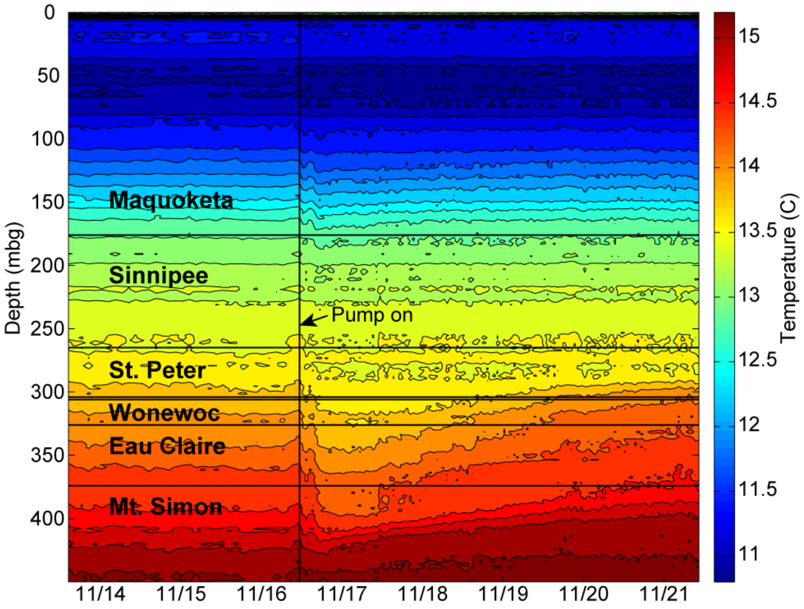

Figure 6: Contour plot of DTS data collected in Well 1 at Oak Creek. Contour interval is 0.2 °C.

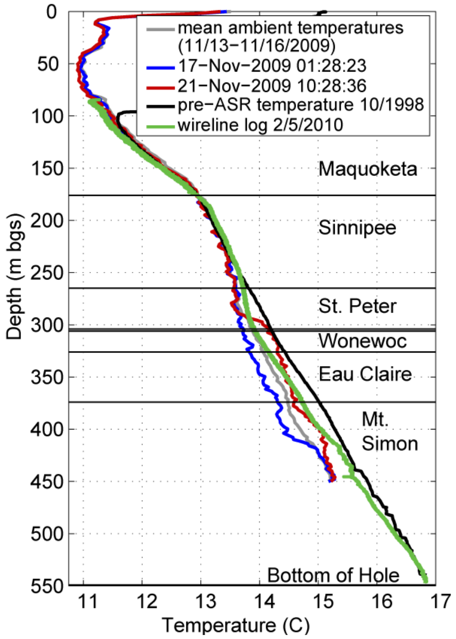

Figure 7: Temperature profiles comparing 2009 DTS data to pre-ASR

The results of the November 2009 DTS experiment at Oak Creek are shown in Figure 6. The temperature changes observed following activation of the pump in Well 3 are primarily caused by vertical borehole flow stimulated in Well 1. The results of the above-mentioned MODFLOW simulation (Leaf 2010) suggest that flow in Well 1 is initially downward, and then reverses after several hours to a steady-state configuration of upward flow from the Mt. Simon into the St Peter. This reversal in borehole flow direction is reflected in initial early-time decreases in temperatures in the Maquoketa and Eau Claire intervals, followed by overall warming at steady-state. The 2-D radial groundwater flow and heat transport modeling results (Leaf 2010) suggest that the ASR cycling produced some residual cooling that remained in 2010, as illustrated by the difference between the black and green curves in Figure . The modeling results also suggest that this cooling did not significantly contribute to the temperature changes observed in the DTS data (Leaf 2010).

Figure 8 shows a series of temperature profiles collected by trolling the wireline temperature tool during the April 14 heating experiment in well DN-1440. The timestamps in the legend indicate the times at which each run was completed. Individual runs (from the casing to the bottom) took between 15 and 25 min, depending on the trolling rate. The temperature/depth profiles therefore provide information that spans this amount of time.

At the beginning of the experiment, there is a relatively uniform rise in temperature along the length of the well caused by heat loss through the outlet hose. This is exemplified by the vertical segment of the black (56 minutes elapsed time) profile in Figure 8, which is warmer than the initial temperature (navy blue profile) by a uniform amount.

Operation of the shallow pump as described in the previous section imposes additional upward flow on the well. This upward flow is evident in the evolving slopes of the measured temperature profiles. Early in the experiment, heated water moving upward in the borehole loses heat to the surrounding rock. This creates a slope in the temperature profile, as seen in the portion of the 56 min. profile below the basal Tunnel City contact. As the rock warms, the rate of heat loss decreases, producing increasingly steeper temperature profiles. A near-vertical profile at 2:35 elapsed time suggests equilibrium has been reached between the flowing heated water and surrounding rock. Deviations from a straight vertical slope would then be expected to indicate the influx of formation water. This could be occurring in the upper Wonewoc.

The large decrease in temperatures between the outlet and the base of the Eau Claire indicates influx of cool water from the Mt. Simon. The linear character of this temperature change suggests that the influx is uniformly distributed (i.e. from porous media flow instead of fractures). Neglecting conduction, a simple mixing calculation (Leaf 2010) suggests that the cumulative flow over this interval is roughly 5.9 to 7.3 l/min (1.5 to 2 gpm). Following the shut-off of the heating system, influx from the Mt. Simon causes a rapid dissipation of heat. Within 15 minutes, temperatures near the bottom of the well are close to those measured prior to the experiment. The subsequent evolution of the temperature profiles following shut-off is similar to that observed at the start of the experiment. The movement of the inflection between the near-vertical and sloping segments of the profiles indicates upward flow velocity, which appears to be approximately 7 l/min, similar to the calculated influx from the Mt. Simon while the heating system was running.

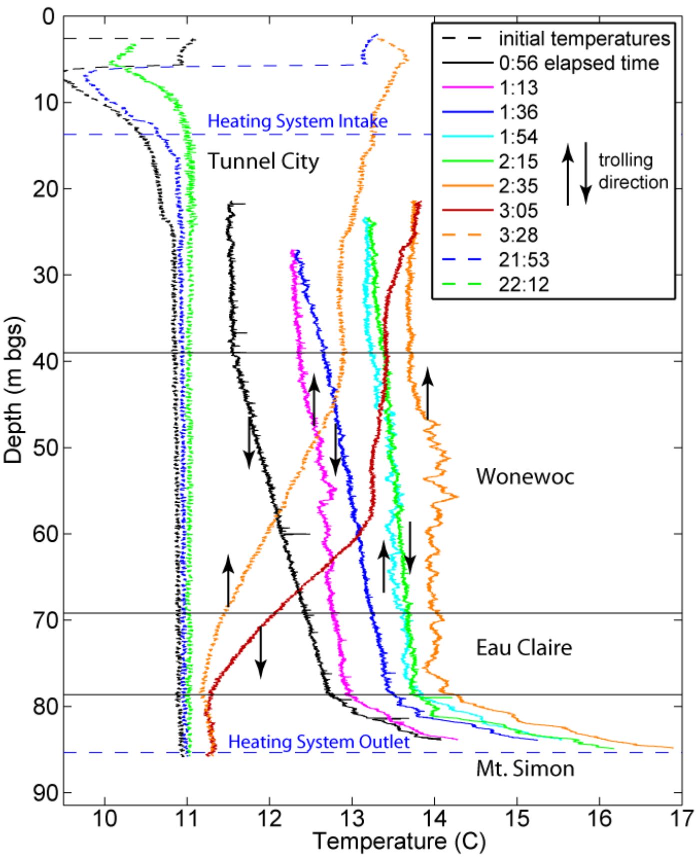

Figure 6: Wireline temperature results from the April 14 experiment in DN-1440.

Figure 9 shows a color-coded image of the results from the May 19 experiment, which used DTS to monitor the continuous operation of the heating system with the outlet fixed at the bottom of the well. Each pixel represents an individual measurement of temperature that is integrated over 2 m of cable and 1 min in time. The initial 50 minutes represent ambient temperatures, which are uniform due to vertical ambient flow. The heating system was activated at 11:55, first at a depth of 73 m and then at 90 m, as shown by the temperature pulse at 73 m bgs and constant temperature at 90 m. The

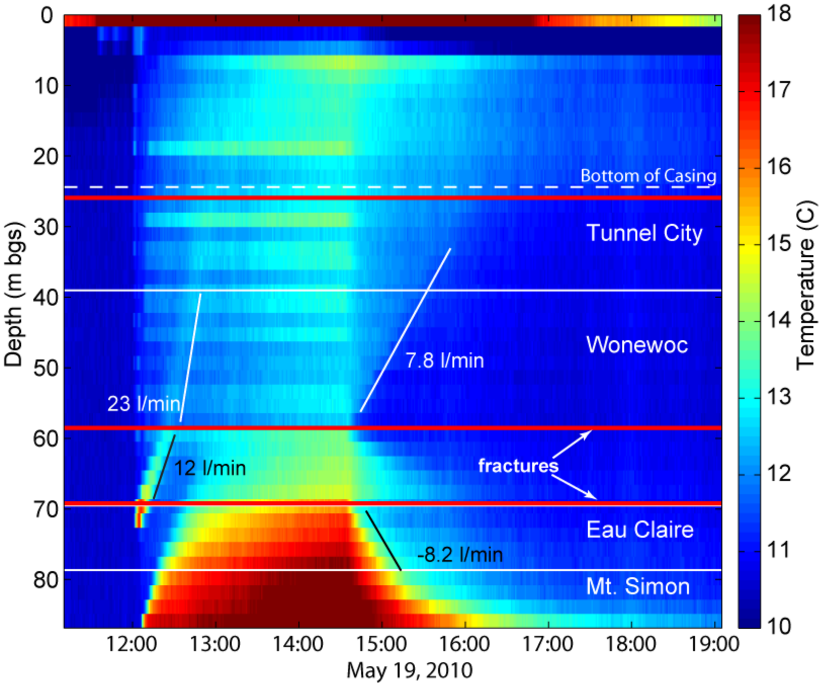

Figure 7: Image plot of DTS results from the May 19 thermal tracer experiment in DN-1440.

upward movement of the temperature disturbance under the influence of the sampling pump is indicated by the distance/time slope of the brighter (warmer) pixels. An abrupt increase in slope, shown by the white lines, above 58 m bgs indicates the influx of water from the above-mentioned fracture cluster. Closer to the outlet, the curved shape of the isotherms in the Mt. Simon and Eau Claire Formations is indicative of the thermal equilibration process between the borehole and the surrounding rock. The abrupt decrease in temperature at the top of the Eau Claire indicates inflow from the other hydraulically active fracture cluster. In the upper part of the profile, leakage of heat from the outlet hose is evident.

The evolution of temperatures following the shut-off of the heating system (at 14:32) provides detailed information on the ambient flow regime in the well. Immediate cooling occurs at the locations of the two important fracture clusters. Interestingly, the flow appears to diverge out of the cluster at 58 m bgs. Above this point, the linear shape of the migrating temperature front suggests uniform flow (i.e., no inputs or outputs). The flow appears to exit the well near the bottom of the casing, where a fracture is indicated in the geophysical logs (Figure 2). Curved isotherms in the bottom of the well reflect re-equilibration of the surrounding rock with the downward flowing cool water. They also suggest the gradual loss flow into the Mt. Simon.

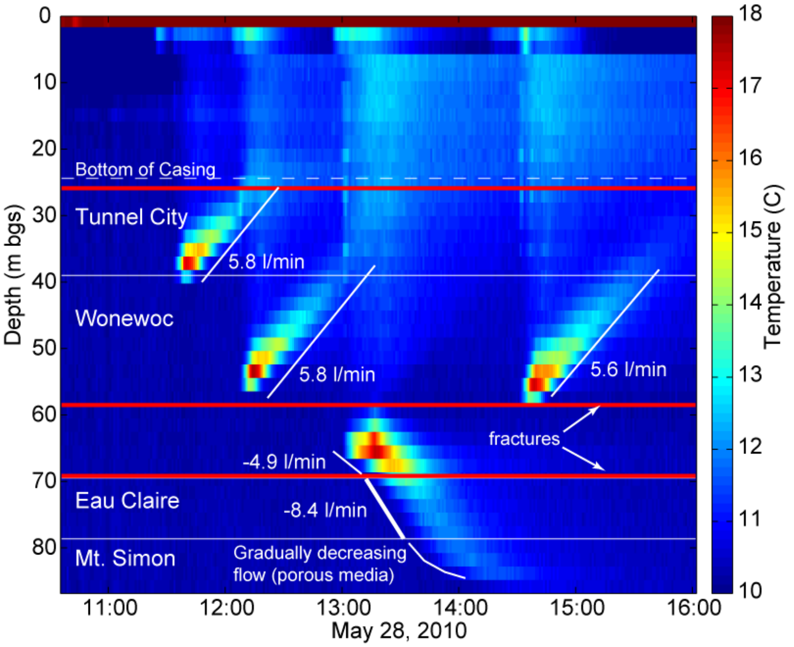

Figure 8: Image plot of DTS results from the May 28 thermal tracer experiment in DN-1440.

The ambient flow conditions observed during the May 28 experiment (Figure10) are similar to those observed on May 19. In the absence of large conduction effects, the curved shape of the temperature disturbance appears to confirm that flow in the Mt. Simon in this well is dominantly intergranular. This is consistent with the geophysical data and a smooth borehole wall texture observed in the downhole video log. In contrast, the linear slopes of the heat pulses migrating above the flow divide (which all agree closely) suggest that flow in the upper aquifer is dominated by fractures.

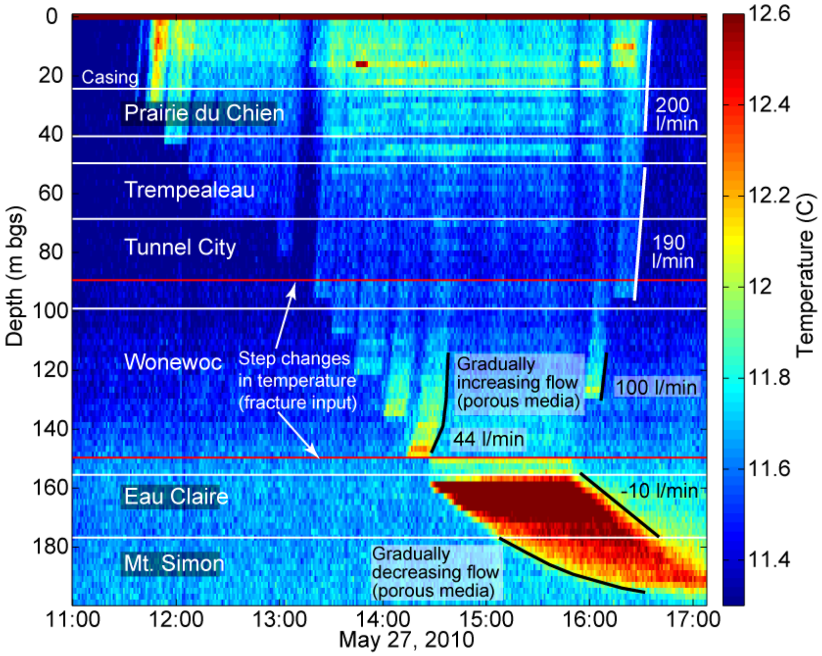

Figure 9: Image plot of DTS results from the May 27 thermal tracer experiment in IW-512.

The results of the IW-512 experiment are shown in Figure 11. High flow rates

(>100 l/min) in the upper part of the well are reflected by the steep distance/time slopes in the temperature changes. The high flow rates limited the effectiveness of the heating system, by removing additional heat from the outlet hose and mixing with the water leaving the outlet. This resulted in a lower temperature contrast. The abrupt changes in temperature at ~90 m and 150 m bgs indicate input from fractures. The latter of these two fractures appears to correspond to the flow divide in the Wonewoc, similar to the fracture cluster in DN-1440. Curved isotherms, indicating a gradual increase in upward flow in the Wonewoc and a gradual loss of flow in the Mt. Simon suggest porous media flow in the lower part of the well.

Conclusions/Recommendations

The DTS data collected at the Oak Creek ASR site helped characterize the evolving borehole flow regime in Well 1 while Well 3 is pumping. In comparison with transient groundwater flow modeling results, they show that samples collected in Well 1 do not discretely represent conditions in the Sandstone Aquifer at the location of the sampling pump. Rather, the samples represent a complex integration of conditions over a large section of the borehole, which is significantly affected by pumping in Well 3.

The DTS monitoring of active thermal tracer experiments elucidated the ambient flow regimes of wells DN-1440 and IW-512 in great detail, confirming previous observations of fracture-dominated flow in the Tunnel City Group and Wonewoc Formation. In the Mt. Simon Formation and other portions of the Wonewoc, they suggest flow to be dominantly intergranular. Diverging vertical flow in both wells appears to emanate from bedding plane fractures in the Wonewoc Formation. Stratigraphically similar positions and high heads in these fractures suggest that they may be regionally important. This finding is significant in light of recent investigations that have characterized the Wonewoc as dominantly intergranular, and warrants further investigation

In addition, the active thermal tracer experiments demonstrate an effective operating range for DTS that exceeds that of conventional heat pulse and spinner flow meter techniques. As a flow measurement tool, DTS effectively integrates measurements over the entire width of the borehole, in contrast to heat pulse and spinner flow techniques, which may be affected by leakage around the diverter or turbulence near the edge of the borehole. As a tool for measuring temperatures, DTS is superior to conventional wireline tools in its response time and its ability to profile temperature synoptically without disturbing the fluid column.

Future work could use DTS methods to characterize aquifer heterogeneity in other wells open to the Sandstone Aquifer system. As shown respectively in the May 19 and May 28 experiments, both constant source and finite-pulse heating techniques can provide useful information. The latter provides the most unambiguous results as a stand-alone technique. An electric resister may provide a superior heat source in comparison to the heat exchanger used in this study.

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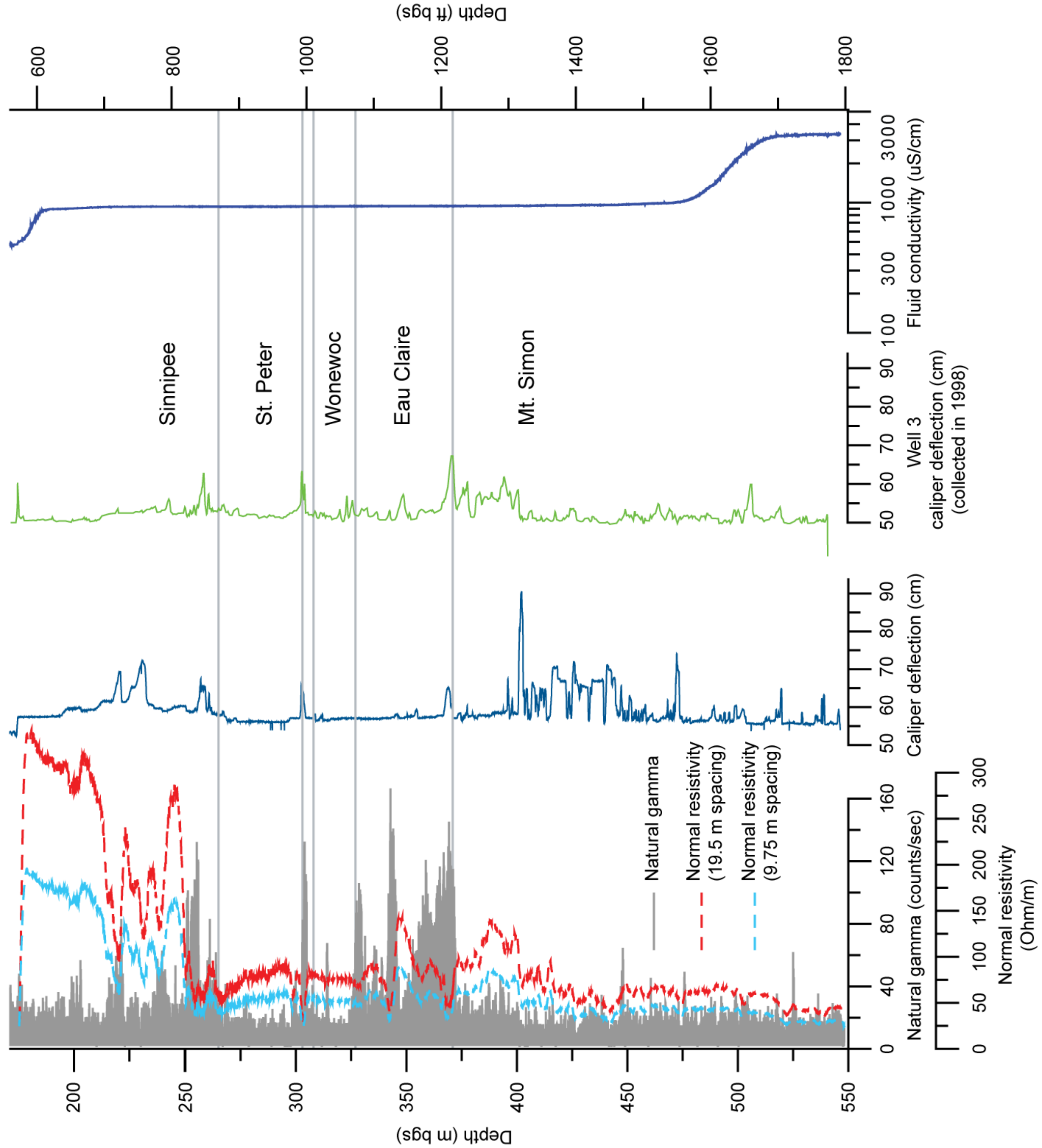
Appendix A: Conference presentations

Leaf, Andrew T., Jean M. Bahr, and David J. Hart 2009. Distributed temperature sensing as a hydrostratigraphic characterization tool. Paper presented at the annual meeting of the Geological Society of America, Portland, OR, October 18-21, 2009.

Leaf, Andrew T., Jean M. Bahr, and David J. Hart 2010. Distributed temperature sensing for characterizing vertical aquifer heterogeneity. Paper presented at the annual meeting of the American Water Resources Association-Wisconsin Section, Middleton, WI, March 4-5, 2010, and at the annual meeting of the Wisconsin Ground Water Association, Waukesha, WI, March 19, 2010.

Leaf, Andrew T., David J. Hart, and Jean M. Bahr 2010. Single-well thermal tracer tests using distributed temperature sensing. Paper presented at the annual meeting of the Geological Society of America, Denver, CO, October 31-November 3, 2010.

Appendix B: Oak Creek Well 1 geophysical logging results



Well 1 heat pulse flow logging results with confidence limits*
(upward flow is positive)

Depth	Stratigraphy	Pulse travel time (s)	Interpreted Flow		-95%	95%
244 m	Lower Sinnipee Group	10.95	6.20	l/min	13.64	-0.32
(800 ft.)		17.97	1.64	gpm	3.60	-0.09
		17.66				
		19.08				
305 m	Near the Tunnel City/ St. Peter contact	10.58	11.88	l/min	19.72	5.01
(1000 ft.)		13.48	3.14	gpm	5.21	1.32
		14.09				
366 m	Near the Eau Claire/ Mt. Simon contact	19.57	0.27	l/min	7.29	-5.88
(1200 ft.)		28.66	0.07	gpm	1.93	-1.55
		27.69				
		26.15				

*methods and additional description can be found in Leaf (2010)