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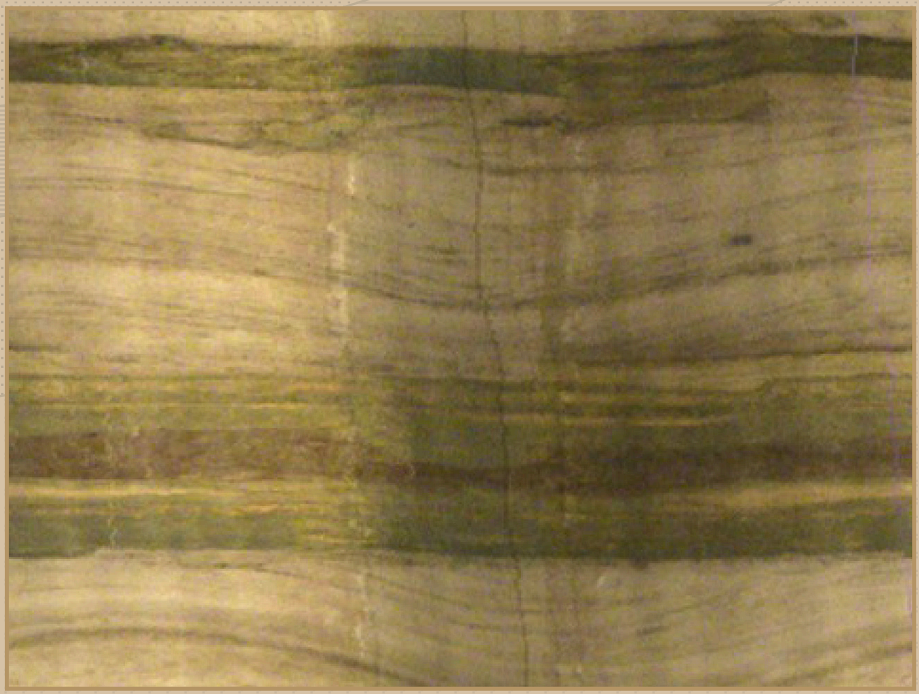
Hydrogeology of Fort McCoy Geothermal Test Well 5



Technical Report 3 • 2016

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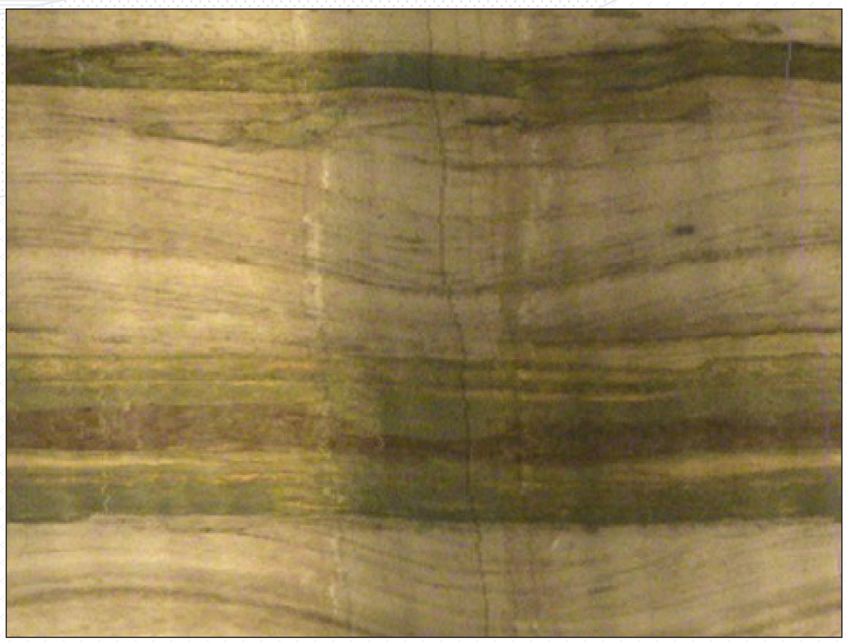

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Cover art, optical borehole images from Geothermal Test Well 5.

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Appendices are provided in separate files.

Introduction

As part of a statewide study of the geothermal gradient in Wisconsin and Fort McCoy's need to better characterize the aquifers at the base, a test hole was drilled on Fort McCoy property to a depth of 1,000 feet. Geothermal Test Well 5 was drilled and completed in May 2012. Personnel from the Wisconsin Geological and Natural History Survey (WGNHS) conducted the following activities during summer and fall 2012 to better characterize the hydrogeology and geothermal gradient at the site.

1. Collected and characterized rock cuttings every 5 feet during drilling of the well.
2. Collected geophysical logs of the well, including natural gamma, normal resistivity, single-point resistivity, spontaneous potential, spectral gamma, caliper, optical borehole image, fluid conductivity, and fluid temperature.
3. Conducted a 12-hour, constant-rate pumping test with recovery and an 8-hour, stepped-rate pumping test.
4. Collected borehole flow logs under ambient and pumping conditions.
5. Conducted packer testing at different depths in the borehole.
6. Collected groundwater samples that were submitted for analyses following the Safe Drinking Water Act guidelines.

The results of these tests are presented and discussed here. Results of groundwater sample analyses are available upon request from the Wisconsin Geological and Natural History Survey. The test results provide the necessary data for a better understanding of the geothermal gradient in Wisconsin and the hydrogeologic conditions found at Fort McCoy.

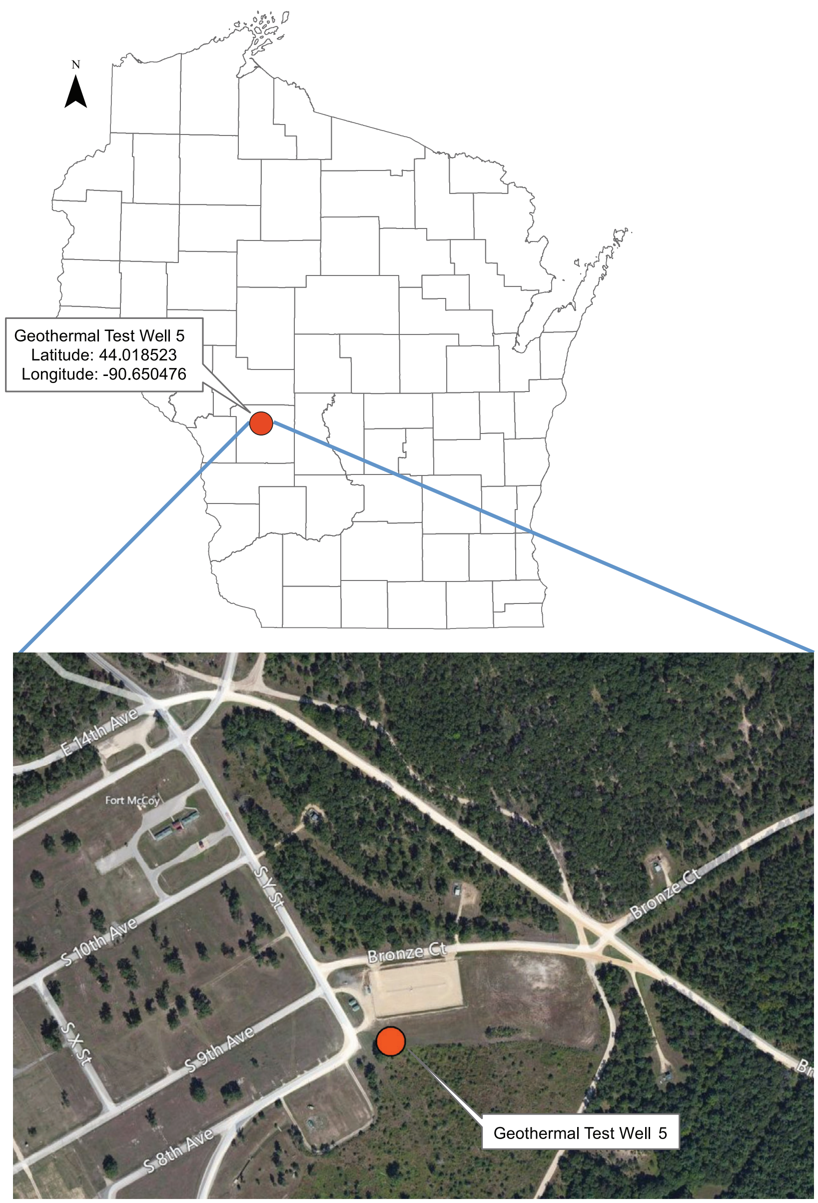

Figure 1. Location of Geothermal Test Well 5 (WGNHS Id 42000265).

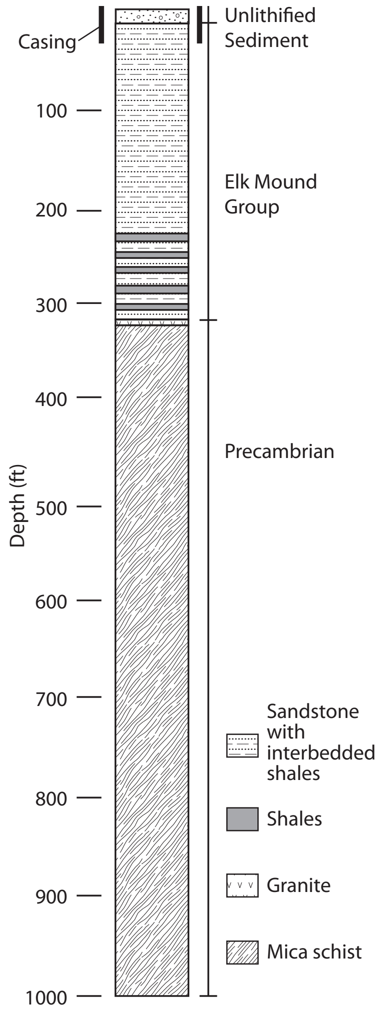

Figure 2. Lithology of Geothermal Test Well 5.

Drilling

Test Well 5 was drilled to a depth of approximately 1,000 feet from May 14 to May 18, 2012. An 8-inch-diameter boring was drilled to bedrock, which was encountered at 20 feet below ground surface, using mud rotary drilling. A 6-inch-diameter steel casing was set and grouted to a depth of 34 feet below ground surface with 3 feet of casing stickup above ground. Air-rotary drilling, using a 6-inch-diameter bit, was used from below the casing to the bottom of the boring at 1,000 feet. The drillers reported good circulation and return of cuttings during the entire drilling. The drill rate depended on the rock encountered. In the softer sandstone, the rate was more than 150 feet by hour; in the harder Precambrian rock, the rate was 20 to 40 feet per hour. Figure 1 shows the location of Geothermal Test Well 5. Field notes are available as appendix A.

Geology

The lithology and stratigraphy of the well is interpreted from cuttings collected during drilling and the geophysical logs. The cuttings are recovered during drilling and collected at 5-foot intervals. We used a 5-gallon bucket to collect the cuttings as air carried them out of the boring. This method offers a more effective way of sampling fine-grained material than a sieve. The cuttings were studied under a microscope and described. Figure 2 shows the geologic log constructed from cuttings.

The lithology of the test hole is similar to other wells located on Fort McCoy. In this well, about 15 feet of clay and gravel overlay 300 feet of Cambrian age sandstone, the Elk Mound Group, with some interbedded shale. Beneath the shale and sandstone is a thin 5-foot layer of granite. Mica schist lies beneath the granite from a depth of 320 feet to the bottom of the well at 1,000 feet. These crystalline rocks are Precambrian in age.

Borehole geophysics

We used borehole geophysics to better understand the well's geology. The data from borehole geophysics are complementary to the geologic cuttings and are often at a much higher resolution. We collected natural gamma, spectral gamma, normal resistivity, single-point resistivity, spontaneous potential, caliper, fluid temperature, fluid conductivity, and optical logs in this borehole. Figure 3 shows selected logs. The spontaneous potential and single-point resistivity data are not displayed because those logs did not add to our understanding of the geology and hydrogeology. The raw data are available on request.

Lithology from gamma and resistivity logs

The natural gamma and normal resistivity logs are most useful for identifying different lithologies. The natural gamma log responds to rocks with higher concentrations of potassium, uranium, and thorium. Rocks such as shales, granites, and schists have more potassium in their mineralogy, and, therefore, give high gamma readings. Sandstones composed of quartz grains generally have low gamma signals.

Normal resistivity is a measure of how well the rocks conduct electricity. Electricity flows easily through rocks with clay minerals and through water found in rocks with higher porosity. Shales are made of clay minerals; they conduct electricity well and have low normal resistivities. Sandstones have a fair amount of porosity; they conduct electricity moderately well. Crystalline rocks, such as schists and granites, have little porosity or clay minerals; they are usually poor conductors with a high resistivity.

We can differentiate between shales, sandstone, and crystalline rock using these two logs. The gamma log, shown in red in figure 3, is consistently low until a depth of 125 feet. The resistivity, shown in blue, is intermediate until a depth of 125 feet. The rock in this interval is a quartz sandstone. At 125 feet, the gamma has a spike and the normal resistivity has a trough. There is a shale bed at this depth. Similarly, shale is evident and interbedded with sandstone from 140 to 155 feet and from 195 feet to the base of the shales and sandstones at a depth of 310 feet. Where the shale is thicker, it is called out as shale on the geologic log (fig. 2). Below 310 feet, the gamma log generally remains high, as does the resistivity below 440 feet. Lower resistivities between 310 and 440 feet are associated with chlorite in the drill cuttings. These depths are all crystalline bedrock, identified from the drill cuttings as a mica schist. This metamorphic rock is most likely derived from feldspathic sandstones, shales, or conglomerates.

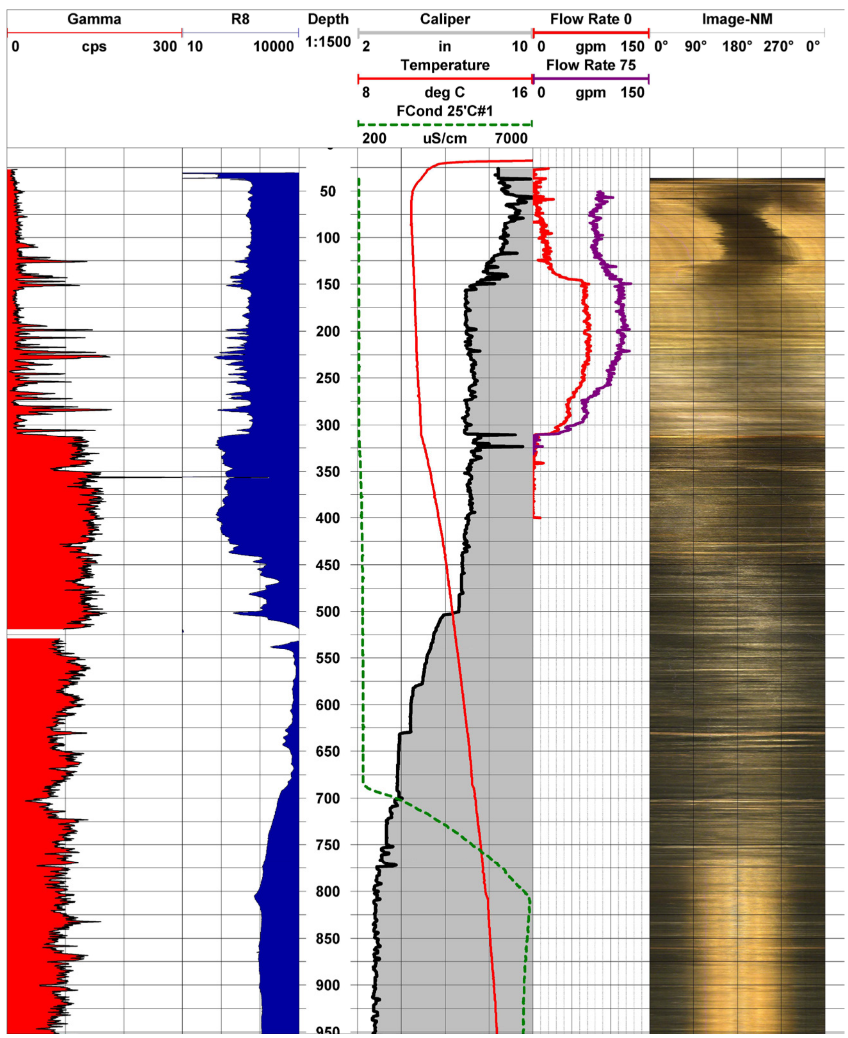

Figure 3. Borehole geophysical logs in Geothermal Test Well 5.

Temperature and fluid conductivity logs

The temperature log records the temperature of the borehole fluid with depth. This log is shown as the red line in figure 3. It starts out very high, due to higher surface temperatures during the date of measurement, and then slowly increases from around 10.5°C (50.9°F) at 50 feet to 10.9°C (51.6°F) at 310 feet, for a geothermal gradient of 0.27°F/100 feet (4.9°C/km). After 310 feet, the temperature change is more rapid with depth, increasing to 14.4°C (57.9°F) by 1,000 feet, for a geothermal gradient of 0.92°F/100 feet (16.7°C/km).

The geothermal gradient in the upper portion of the boring from 50 to 310 feet is not reliable; we know that cool water flow in the boring suppresses temperatures. The geothermal gradient in the lower portion of the borehole of 0.9°F/100 feet is in keeping with the value of 1°F/100 feet that we have found in similar wells in Marathon and Columbia Counties in Wisconsin.

We had expected to encounter granite at this location, based on well logs from nearby Sparta, Wisconsin. Granite has a higher radioactivity and heat production than mica schist; therefore, the geothermal gradient might have been higher had we encountered granite in this boring.

Fluid conductivity often provides a measure of water quality, given that it depends primarily on the concentration of ions in the fluid. Fluid conductivity seen in the upper portion of the borehole from 50 to 310 feet is less than 400 µS/cm. These values are usually associated with water that has lower-than-average ionic concentrations. The reason for the sharp increase in fluid conductivity in the lower portion of the boring, beginning around 685 feet, is unclear. Although it is not associated with a lithology change or fracture, the change might have been caused by water left in the boring just after drilling. Because the lower part of the boring would not have provided any water for drilling, fresh water would not have entered the bottom part of the boring. Water and cuttings may have been recycled and left at the end of drilling.

Although the water chemistry might not be in equilibrium with surrounding low-permeability rock, temperatures in the boring would have had time to come to equilibrium with the boring wall during the month between drilling and geophysical logging. This fluid conductivity may also be representative of the crystalline basement rock. The transmissivity of the lower portion of the boring was so low that it was not possible to completely purge the bottom part of the boring after drilling. This question will likely remain unanswered without further testing designed to measured fluid conductivities of the crystalline bedrock.

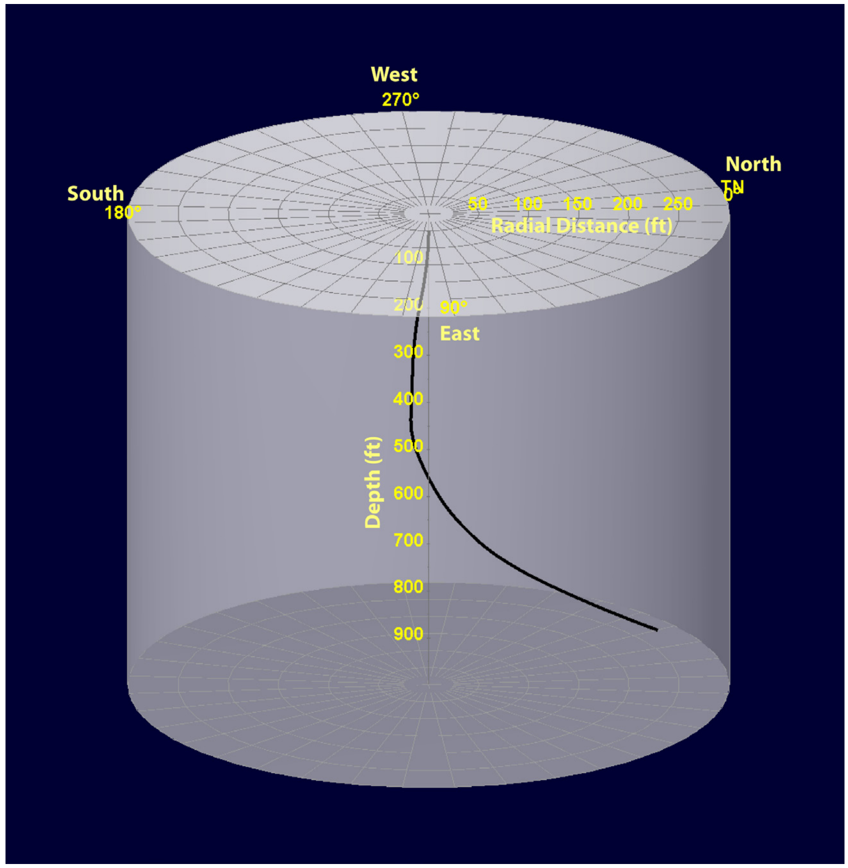

Figure 4. Deviation log of Geothermal Test Well 5.

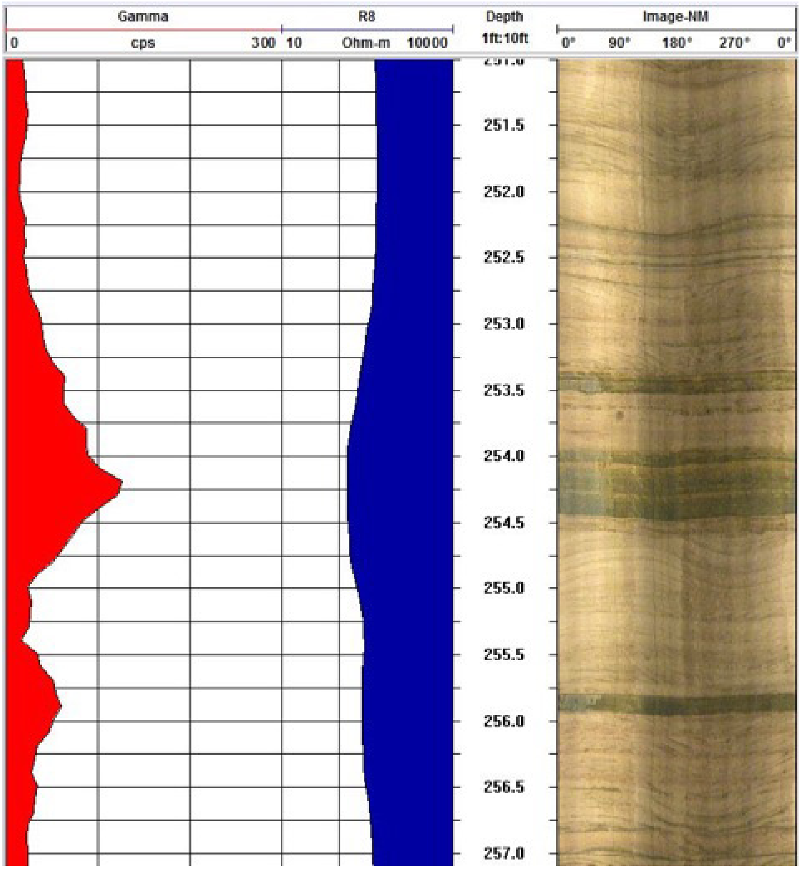

Figure 5. Gamma, normal resistivity, and optical log from 251 to 257 feet.

Caliper log

The caliper measures the borehole diameter, shown in gray in figure 3. It can show locations of rock fractures and widening of the borehole caused by drilling softer rocks. The caliper is reliable to a depth of around 500 feet. Below that depth, the hole is deviated from vertical because the tool is being pulled "sideways" up the boring, causing it to give a smaller reading than expected.

The caliper shows the boring has some horizontal fractures and soft sandstones from below the casing at 36 feet to 150 feet. The sharp "kicks" or spikes in the caliper log are due to fractures. The widened borehole from 50 to 150 feet is due to the softer nature of the sandstones to that depth. From 150 feet to near the base of the sandstone at 310 feet, there are fewer fractures and the sandstone is more competent. At the contact between the sandstone and the crystalline bedrock at 310 feet, the caliper log shows several large fractures. Below that, the caliper log shows several steps down in diameter at 500, 575, and 625 feet. These steps are likely due to the drillers pulling rod and changing bits. Although the boring is a nominal 6-inch diameter, the driller started with a 6.5-inch-diameter bit. As the larger bits wore down, the driller switched to smaller bits, ending with a bit about 5.5 inches in diameter. However, below 500 feet, the caliper reading is less than the bit diameter, leading us to conclude that the smaller caliper reading is due to the borehole being deviated. When the tool was pulled up the hole, the caliper arms were pulled up the boring at an angle to vertical, giving a smaller reading.

The borehole deviation is shown in figure 4. Although it may be surprising that the bottom of the well is located approximately 200 feet to the north of the well head, we have found that a 10 percent deviation is common in wells we have tested elsewhere in Wisconsin. In the figure, north is shown to the right (0°) to best show the deviation. The larger-than-usual deviation is due to drilling in the harder crystalline rock. A higher down-pressure is used, so the rod is more likely to bend.

Optical borehole image log

The optical image log uses a high-resolution color camera to record the borehole wall with depth. It produces an "unwrapped" image showing the entire circumference of the borehole going from 0 to 360 degrees. Figure 5 shows the optical, gamma, and normal resistivity logs from 251 to 257 feet. We can see three bands of darker shale layers at 253.4, 253.9 to 254.4, and 255.8 feet. These depths correspond to higher gamma and lower resistivities.

The optical log is also useful for identifying fractures. Figures 6a and 6b show fractures at varying depths. The caliper logs, shown to the right in the figures, show these fractures as increases in the well diameter. Figure 6a shows fractures at depths of 142.5, 145, and 150 feet. Figure 6b shows the fractures at the base of the sandstones at the contact with the crystalline rock. The fracture is evident as the dark line at 311 feet. The weathered portion of the crystalline rock can be seen from 311 to 313.5 feet. The flow log shows that the fractures noted in figures 6a and 6b contribute significant amounts of water to the well.

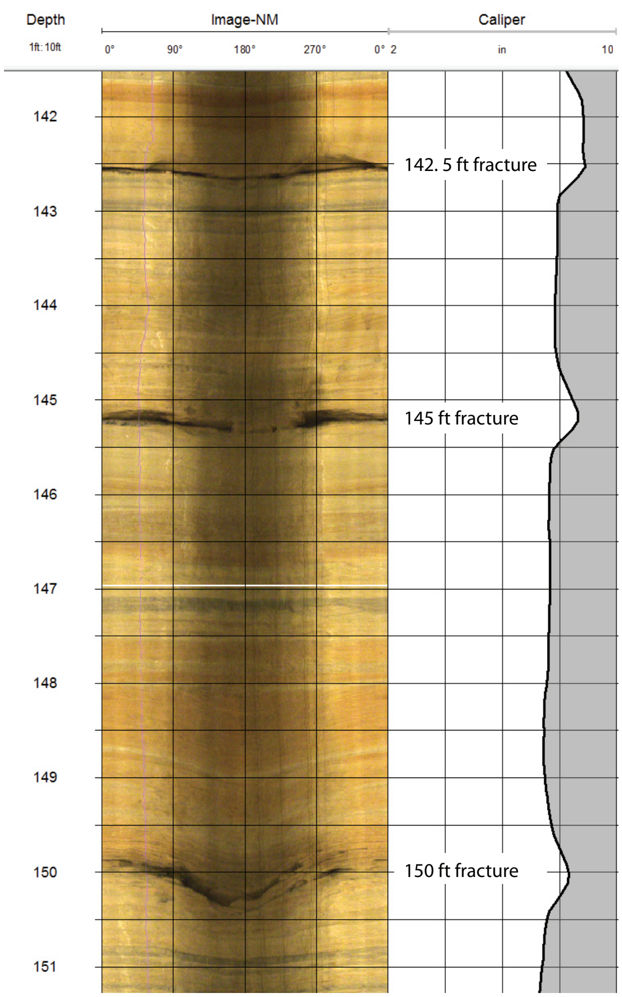

Figure 6a. Three fractures in the well at 142.5, 145, and 150 feet depth.

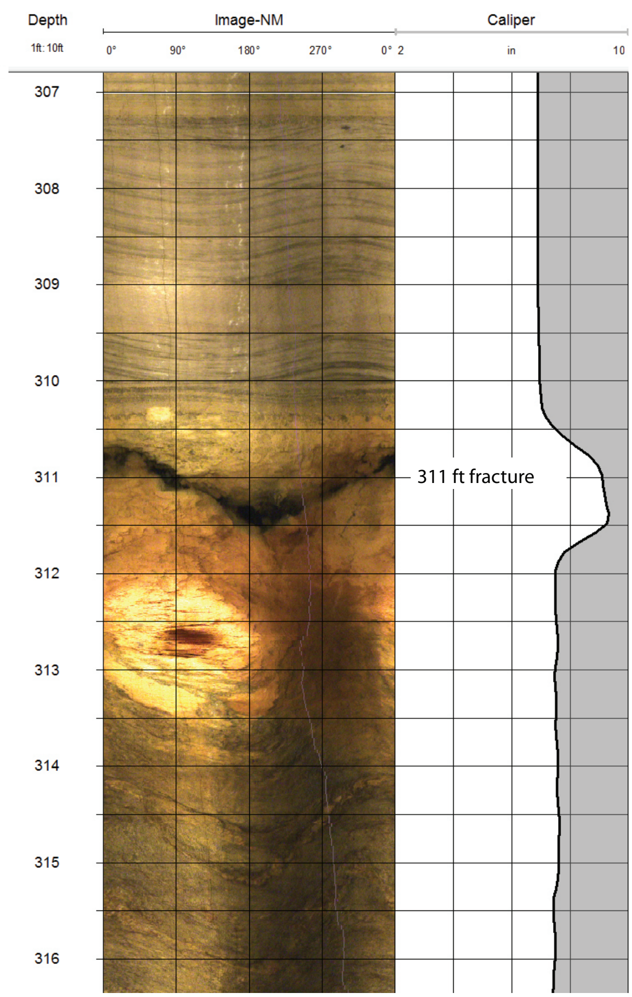

Figure 6b. Fracture at the contact between the sandstone and the crystalline rock at 311 feet.

Pumping tests

Pumping tests are a standard method used to measure aquifer properties, such as hydraulic conductivity, transmissivity, and storage. These properties are useful for managing well fields, and they can be used for estimating aquifer yields, zones of contribution, and potential for well interference.

Subsequent to the geophysical logging described above, we conducted a 12-hour, constant rate pumping test with recovery and an 8-hour, stepped drawdown test on Geothermal Test Well 5. The pump was set at a depth of approximately 40 feet, with the transducer at a depth of 45 feet. The entire open interval of the boring was tested from below the casing to the bottom of the boring. No interval of the boring was isolated with a packer.

The pumping tests give two important results. First, the aquifer properties at this well are similar to other wells at Fort McCoy. Second, we found significant interference from other supply wells at this site. We observed water level decreases in Geothermal 5 caused by those other wells. Figure 7 shows the water levels in the test well during the pumping tests. The times when pumping from the other wells is present in the record is shown on the x-axis. The 12-hour pumping test is shown in purple, the recovery in red, and the 8-hour, stepped drawdown test in blue, with the pumping rates listed beside the data.

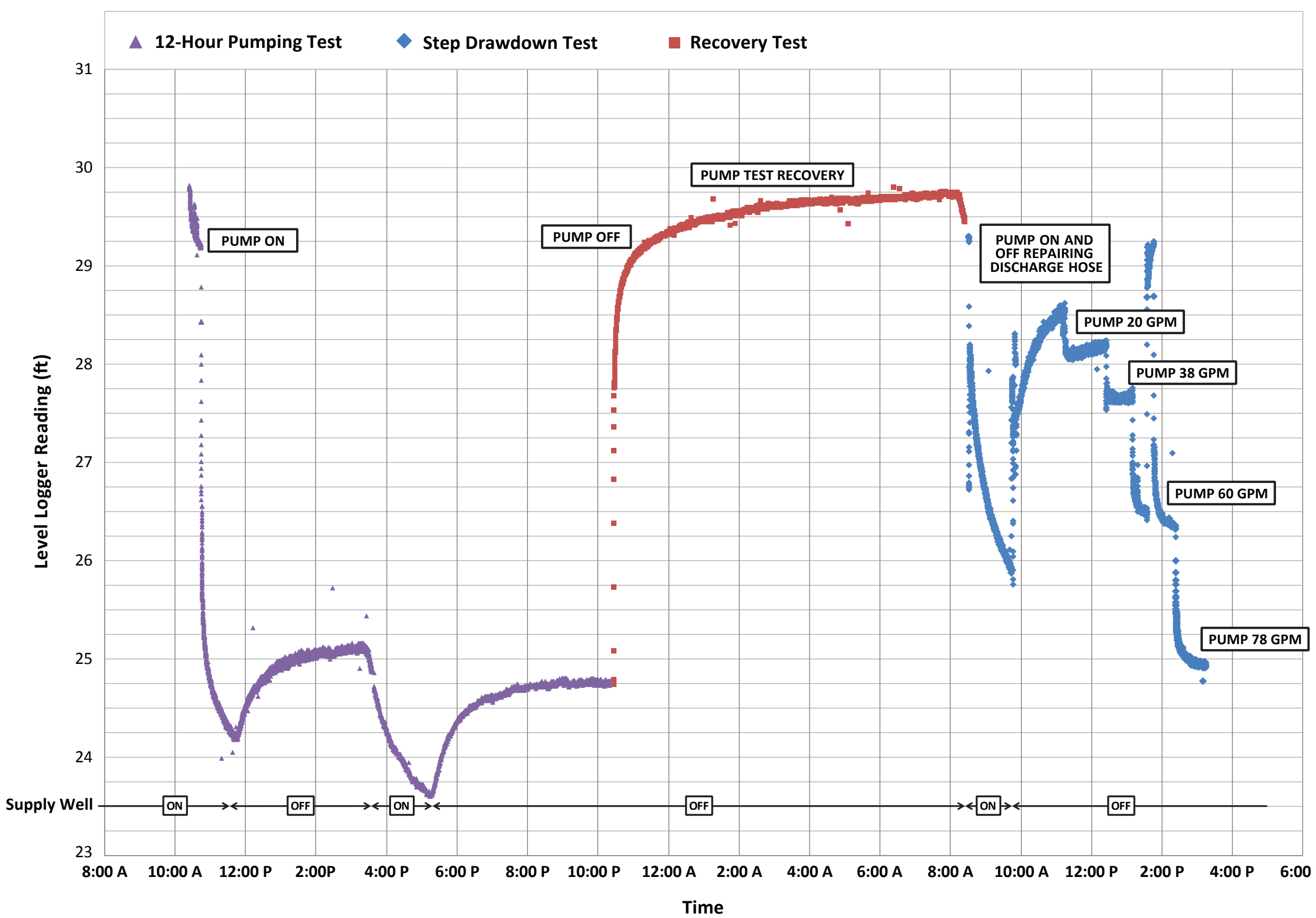

Figure 7. Water level data from 12-hour pumping test and recovery, and the 8-hour, stepped drawdown test. Periods when the data was affected by a supply well are shown above.

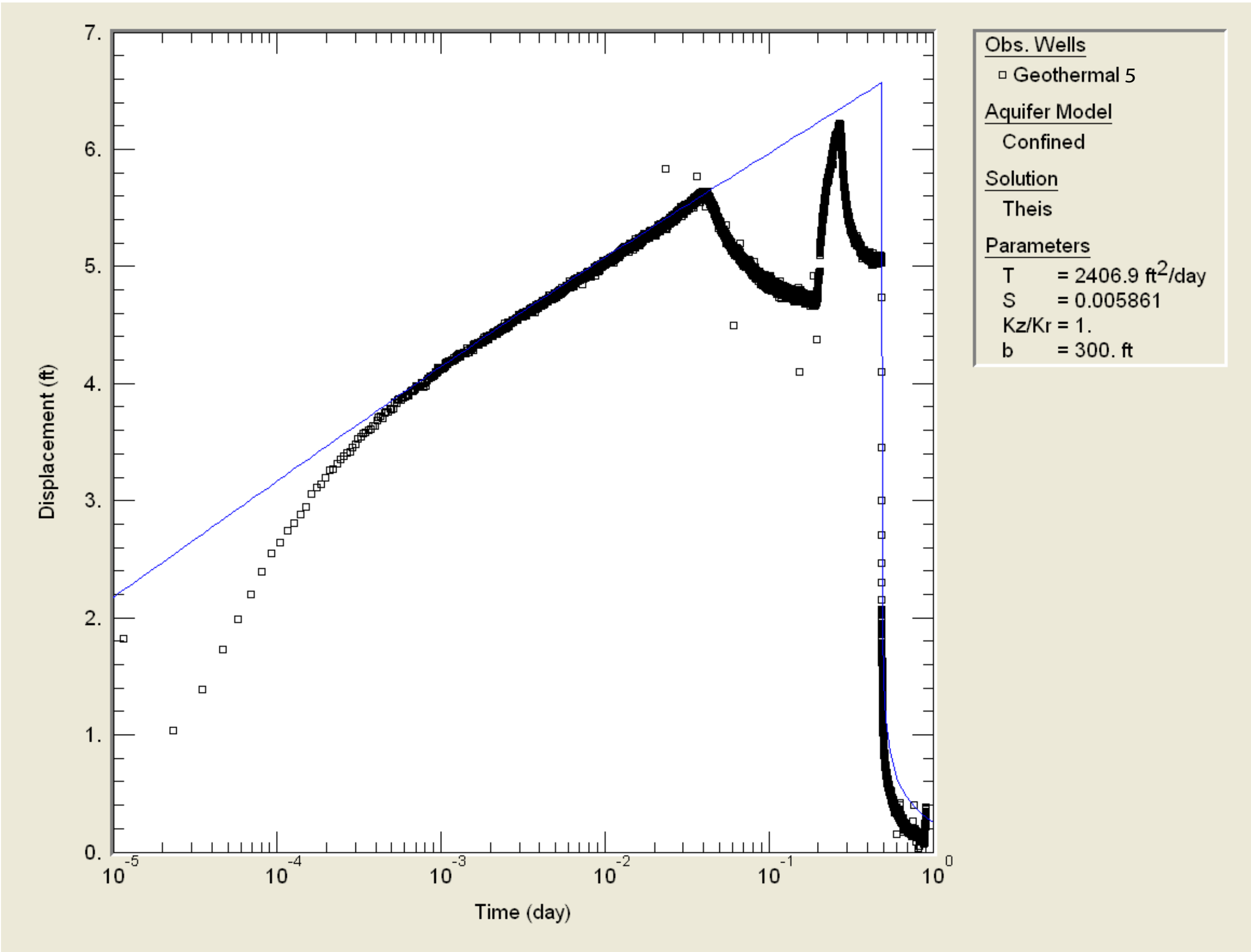

Figure 8. Results of 12-hour pumping test using Aqtesolv® and the Theis equation.

Analysis of the 12-hour pumping test

The 12-hour pumping test was conducted at a rate of 60 gallons per minute (gpm) and was run from about 10 a.m. to 10 p.m., followed by an overnight recovery period. A data logger was used to collect water levels at a 1-second interval for the entire test. We used Aqtesolv® (Duffield, 2007) and the Theis (1935) equation to analyze the pumping and recovery data. Figure 8 shows the data, the curve fit, and the estimated parameters.

The curve fit is relatively good after the initial drawdown. The well bore storage, which was not accounted for, is likely responsible for the deviation from the curve fit in the early time data before 4×10^{-4} days (30 seconds). The fit is very good from 4×10^{-4} to 3×10^{-3} days. At that time, the drawdown decreases, even though the pumping rate in the test well remained constant at 60 gpm. This change is likely due to a supply well turning off. That well appeared to start again at around 0.2 days and ran for several hours until around 0.3 days. The drawdowns approached the Theis curve solution at that time. The pump then turned off and remained off for the remainder of the pumping test and most of the recovery.

In addition to analyzing the drawdown and recovery data shown in figure 8, we could also analyze the recovery data alone, as there was no interference from the pumping well during the recovery phase. Figure 9 shows this analysis using Aqtesolv® and the Theis recovery equation.

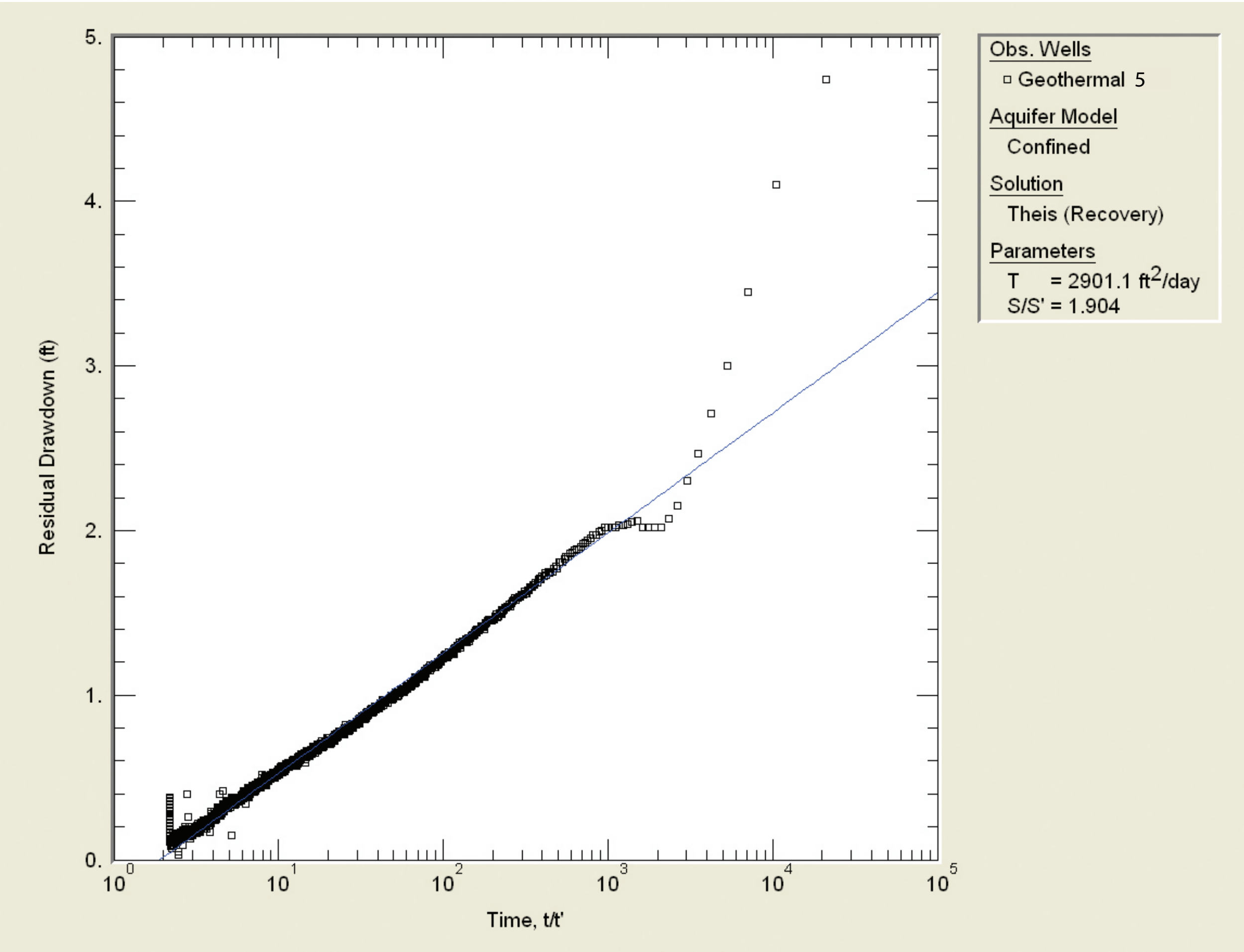

Figure 9. Results of 12-hour recovery test data using Aqtesolv® and the Theis recovery equation.

The fit to the data is much better, mostly because there was no interference from other supply wells during most of the recovery period. Table 1 lists the fitted parameters, transmissivity (T) and storage (S). The hydraulic conductivity (K) and specific storage (Ss) for the aquifer are calculated from the transmissivity, storage, and aquifer thickness (b):

$$K = \frac{T}{b} \quad Ss = \frac{S}{b}$$

We used an aquifer thickness of 300 feet, eliminating the cased interval and the crystalline bedrock. The flow logs, described below, showed no contribution to flow from the crystalline bedrock, so that could be eliminated from the total thickness of the aquifer.

These values, which are similar to previous estimates from other wells at Fort McCoy in this aquifer, are reasonable for those sandstones.

Table 1. Results of the 12-hour pumping test and recovery

Analysis	Transmissivity, T (ft^2/day)	Storage, S (ft/ft)	Hydraulic conductivity, K (ft/day)	Specific storage, Ss (ft^{-1})
Theis	2406.9	0.005861	8.0	2.0×10^{-5}
Theis recovery	2901.1	0.0112*	9.7	3.7×10^{-5}

**Calculated by multiplying the storage from the Theis analysis by the recovery/drawdown ratio, S/S', in figure 9 (1.904).*

Analysis of the 8-hour, stepped drawdown test

In addition to the 12-hour pumping test, we also conducted a stepped drawdown test. These tests are used to determine the efficiency of a well. Well efficiency is defined as the ratio of the expected drawdown, provided there are no frictional losses near or in the well bore to actual drawdowns. As the pumping rate increases in a well, the frictional losses due to turbulent flow increase with the square of pumping. This is expressed in equation form as

$$s = BQ + CQ^2$$

where s is the drawdown and Q is the pumping rate (Jacob, 1947). B and C are coefficients determined by fitting a curve to pumping rate drawdown data. Figure 10 shows the approximate steady-state drawdowns for several pumping rates. These rates and the well efficiency at the different rates are listed in table 2. Using the best fit curve, we find $B=5.02\text{x}10^{-2}$ feet/gpm and $C=1.78\text{x}10^{-4}$ feet/gpm^2. This aquifer is very prolific. Few 6-inch wells can produce 75 gpm with less than 5 feet of drawdown.

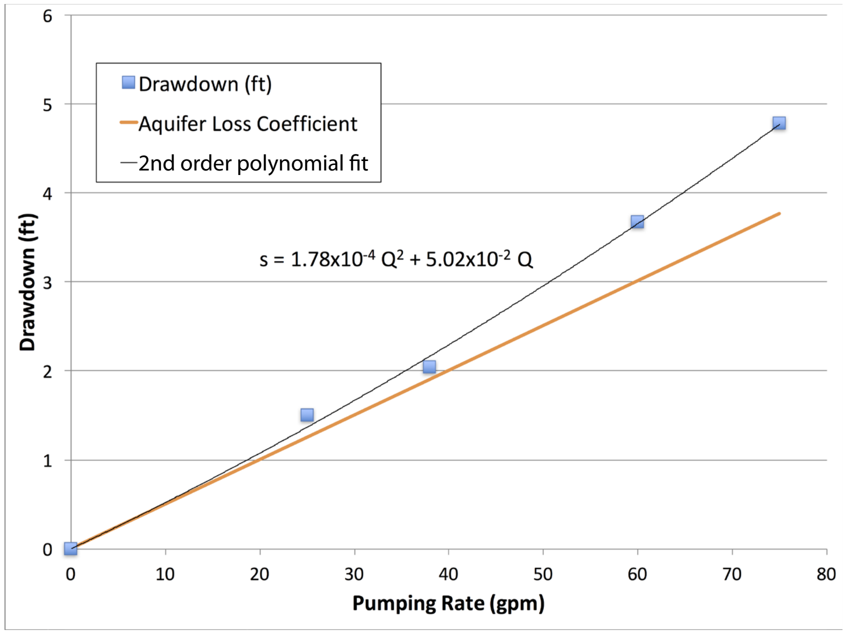

Figure 10. Stepped drawdown test.

Flow logging and packer testing

In addition to pumping tests that give results averaged over the entire boring, we also conducted flow log and packer testing. These tests give data on flows, heads, and transmissivities of intervals within the aquifer, rather than a lumped average. The flow logging was conducted during the stepped drawdown test; the packer testing was done at a later time.

Flow logging

The spinner flow meter measures vertical flow in the borehole. It is a relatively simple instrument consisting of a propeller at the end of the tool. As the tool is trolled down and up the boring, it records fluid velocity. The measured flow rates are shown in figure 11 for ambient conditions during which there was no pumping and the well was pumped at 75 gpm.

The ambient flow log, shown as the red line in the center of figure 11, provides a great deal of information about the borehole and the site hydrogeology. Starting at the base of the flow log at 310 feet, we noted a sharp increase in upward flow from 0 gpm to about 30 gpm at 300 feet. This inflow to the borehole is from the larger fracture at 311 feet shown in figure 6b. The flow gradually increases to 65 gpm as we move up the boring to 250 feet. Inflow at this zone is distributed across the sandstone and not through fractures. The upward flow remains fairly constant from 250 to 150 feet, indicating little flow into or out of the borehole in this zone. From 150 feet to 140 feet, the flow rate decreases rapidly. This decrease is due to flow moving out of the borehole into the fractures from 150 to 140 feet, shown in figure 6a. Finally, the flow gradually decreases from 140 feet to the base of the casing at 36 feet. The flow in the borehole and direction and magnitude of flow to and from the aquifers is shown in figure 11.

We used a spinner flow meter to determine flow in the borehole during ambient (Q=0 gpm, shown as the red line in fig. 11) and pumping (Q=75 gpm, shown as the purple line in fig. 11) conditions. By stressing the aquifer at two pumping rates and by assuming that we have reached steady state, we can look at the change in flow in an interval and apply the Theis equation in each interval (Paillet, 1998). Appendix B shows the spreadsheet used for this analysis, which provides estimates of the far-field aquifer heads and the hydraulic conductivities of each interval. Those heads and conductivities (Ki) are shown in blue and purple on the right side of figure 11. Based on the spinner log, we can see that the heads at the base of the sandstone are about 20 feet higher than those near the surface. We can also see that the intervals with fractures have

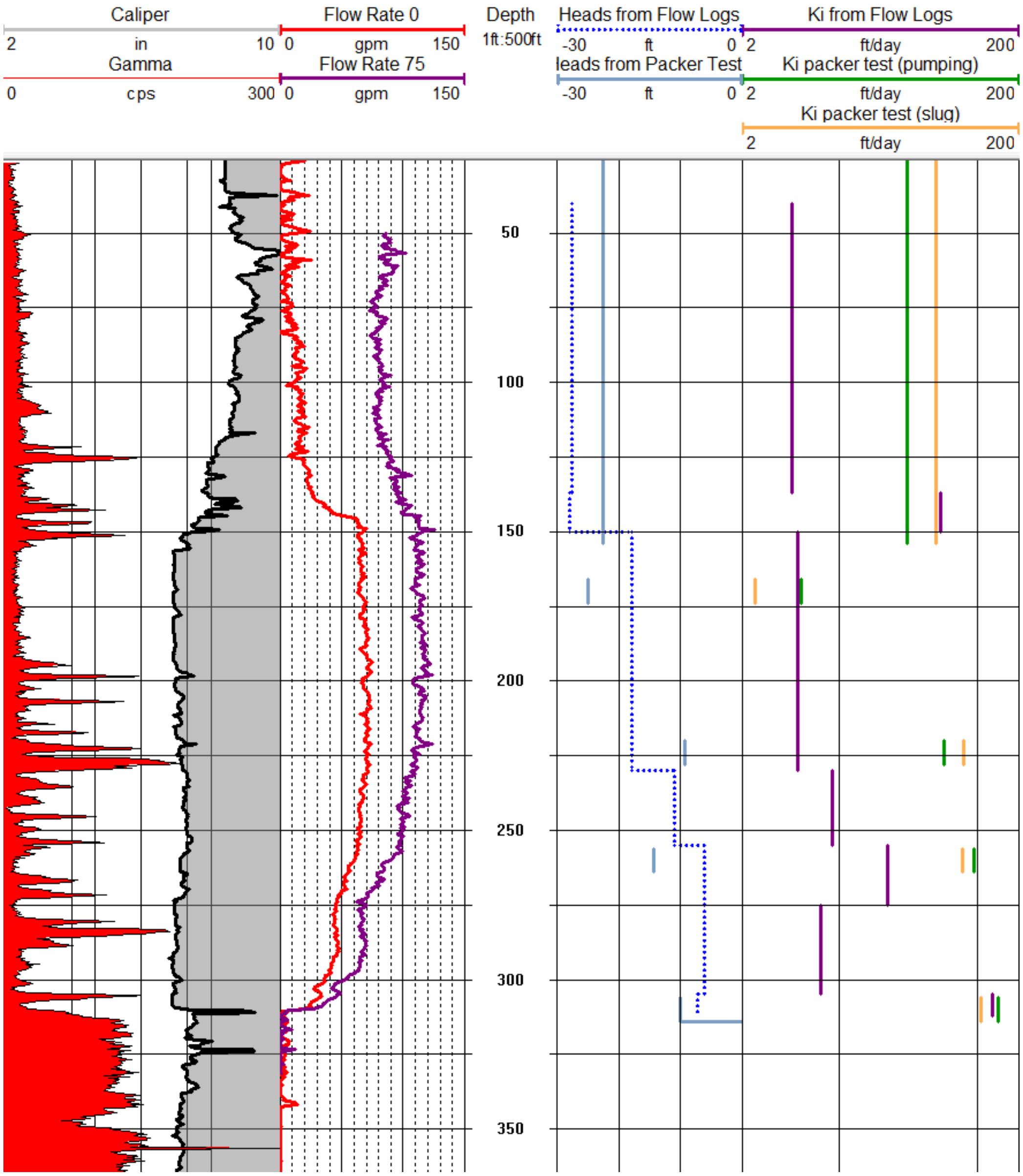

Figure 11. Flow logging and packer testing results. Flow is upward.

Table 2. Stepped drawdown test results

Pumping rate (gpm)	Measured drawdown (ft)	Calculated drawdown (ft)	Aquifer loss coefficient (ft)	Well efficiency BQ/(BQ+CQ²)
0	0	0	0	1
25	1.50	1.41	1.26	0.89
38	2.04	2.21	1.91	0.86
60	3.67	3.68	3.02	0.82
75	4.78	4.76	3.77	0.79

larger hydraulic conductivities than the sandstone without fractures. The results of the flow logging are listed in table 3.

Table 3. Flow logging results

Interval depth (ft)		Hydraulic conductivity (ft/day)	Interval head below top of casing (ft/day)
Top	Bottom		
36	137	4.6	-27.6
137	150	54.6	-27.9
150	230	5.0	-17.8
230	255	8.9	-10.9
255	275	22.2	-6.1
275	305	7.4	-6.1
305	312	126.8	-7.3

Packer testing

We used a straddle packer system to record heads and conduct hydraulic testing of specific intervals in the borehole. The straddle packer has two inflatable packers separated by 8.3 feet of screened interval. When the packers are inflated, they expand to the borehole wall and provide seals that separate the screen interval from the rest of the borehole. This allows measurement of the head and hydraulic properties of the screened interval. We measured heads in the screened interval with a hand tape and electronic pressure transducer. Figure 12 shows the changes in water levels in the screened interval centered on a depth of 170 feet during the test and the steps taken to collect the data for that interval. The water levels shown in figure 12 are relative to the top of casing. A hand tape was used to check and provide a backup to the pressure transducer readings.

We conducted these tests at five different intervals. The results are listed in table 4. We did not have a good seal with the borehole with the upper packer at the uppermost interval, centered at 150 feet. Those results are for the entire upper part of the borehole from 154 to 36 feet.

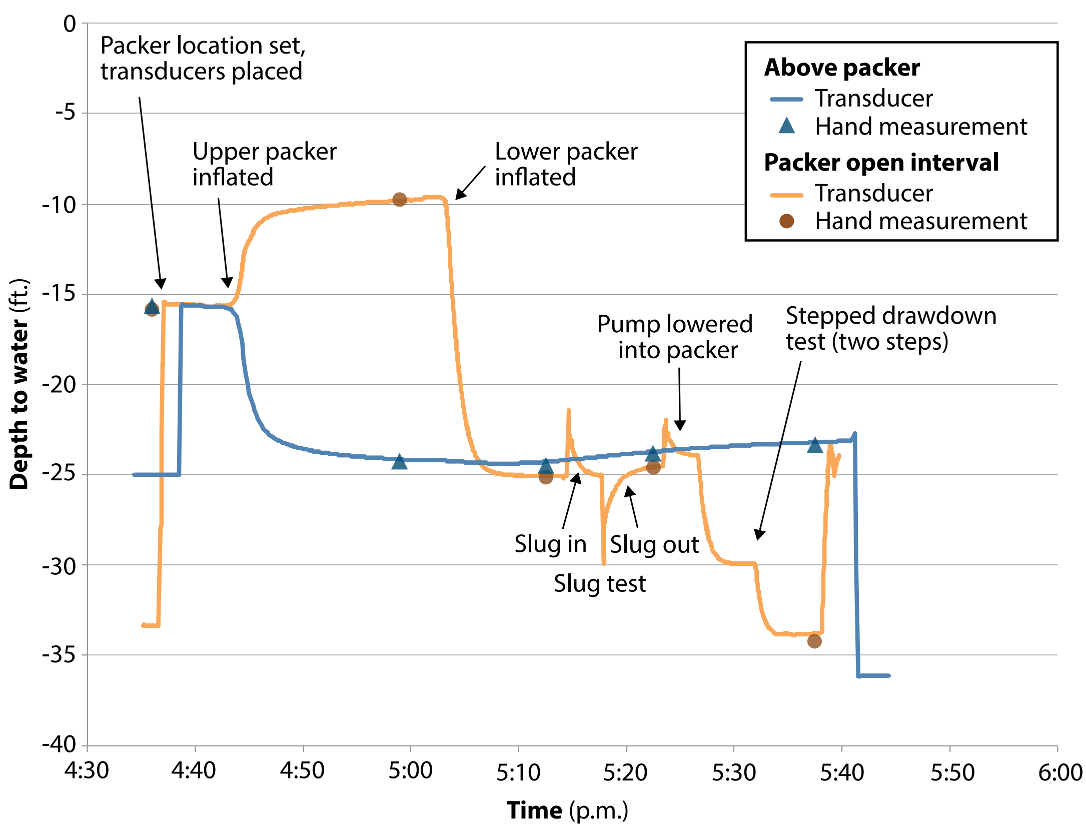

Figure 12. Straddle packer data for testing at 170 feet.

Table 4. Packer testing results

Interval depth (ft)		Hydraulic conductivity		
Top	Bottom	Slug test (ft/day)	Pumping test (ft/day)	Interval head below top of casing (ft)
36	154	50	31	-22.6
166	174	2.5	5.3	-25.0
220	228	80	57	-9.4
256	264	77	94	-14.3
306	314	105	140	-10.0

The slug tests were analyzed using Aqtesolv (Duffield, 2007) and the Hvorslev (1951) solution. The pumping tests were analyzed using TGUESS (Bradbury and Rothschild, 1985). Appendix C shows the Aqtesolv curves and TGUESS Excel worksheet. As with the flow logging, the hydraulic conductivities across zones with fractures (for example, between 306 and 314 feet), are much higher. The packer tests also show higher heads in the deeper sandstone versus the shallow. The head decrease from deep sandstone to shallow sandstone as measured by the packer is approximately 15 feet. This value, although less than that estimated by the flow logging, is still in reasonable agreement, and it represents an unexpected and strong vertical gradient.

The presence of the strong vertical gradient has implications for the flow system. A possible explanation for this observation—that heads are higher with depth into the sandstone—is shown in figure 13. The elevation of the recharge area for the deep aquifer would be at a higher elevation than the water table at the site. The shales seen in the geologic and geophysical logs would confine those higher heads. The potential implication is that the water in the deeper part of the sandstone is older and has traveled far from its recharge zone, most likely miles away beyond the location of the expected shale subcrop. In contrast, the water in the upper part of the sandstone would have been recharged locally, likely from within Fort McCoy boundaries. To accept this possibility, the continuity of the shale aquitard up-gradient along the flow path would need to be confirmed and the subcrop of the shale located.

Another alternative is that the upper aquifer has been lowered 15 feet by pumping in the nearby supply wells. The depth to water in Geothermal Test Well 5 after drilling was 92.87 feet below the top of casing (approximately 91 feet below the ground surface). We also know that pumping by one of the supply wells lowered heads in Geothermal 5 by over 1 foot during the 12-hour pumping test, as shown in figure 7. If the overall water use at Fort McCoy was large enough, this alternative would also be a possibility. Pumping schedules and rates would determine whether this possibility should be accepted or eliminated.

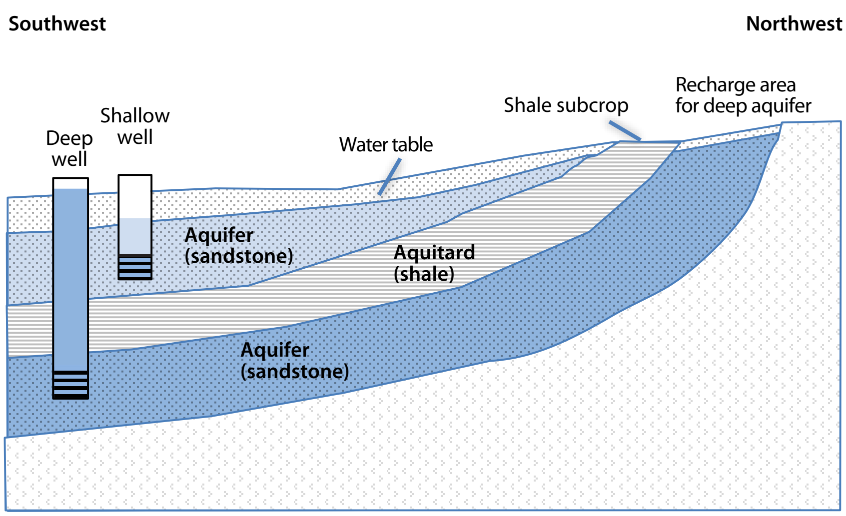

Figure 13. Conceptual model of regional flow.

Conclusions

From spring 2012 to fall 2012, we conducted field investigations at a geothermal test boring at Fort McCoy. These activities included drilling and logging the well, describing the well cuttings, collecting geophysical logs, conducting flow logging, pump testing and packer testing, and collecting groundwater samples.

The following observations may be useful for hydrogeologic and geothermal practice at Fort McCoy.

1. There was significant interference drawdown at the test well from one or more production wells located 500 and 1,100 feet from the test well. Well interference should be taken into account when new production wells are brought online.

2. There is ambient upward flow in wells that connect the entire section of sandstone. This has implications for water supply, the hydrogeology of the site, and geothermal testing.

    a. The deeper part of the sandstone aquifer is not connected to the shallow aquifer, so water quality in one may not reflect the water quality in the other.

    b. Water in the shallow sandstone is from local recharge and would be younger (months or years); water in the deep sandstone would have likely traveled farther and would be older (by years or decades). The deeper aquifer would be less susceptible to contamination from the surface.

    c. If a thermal loop test is conducted in a well that is open to the entire sandstone, the test will overestimate the thermal conductivity and heat production of the boring. In addition to thermal conduction, heat will be carried away by the water flowing in the boring during the test. However, the boring will be filled with grout during installation of the final system, with a much lower heat exchange because the water will no longer be carrying heat. Only thermal conduction will transport heat in that case.

3. The aquifer has a high production capacity, more than 75 gpm in a 6-inch-diameter well, with a tested hydraulic conductivity of around 9 feet/day.

    a. That production is through both fractures and porous media flow in the sandstones.

    b. The upper part of the aquifer, above 150 feet, has a very high hydraulic conductivity (K), as does the deeper part of the sandstone below 250 feet. The middle portion between 150 and 200 feet has a moderate K.

    c. No measureable flows were detected in the crystalline bedrock.

4. There is little variation in the crystalline bedrock, a mica schist, from 300 to 1,000 feet, with the exception of a couple of zones of more granitic rock, including one just below the sandstone.

5. The geothermal gradient 0.92°F/100 feet (16.7°C/km) in this well is similar to other values around Wisconsin.

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