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MEASUREMENT OF THE SPATIAL DISTRIBUTION OF HEAT EXCHANGE IN A GEOTHERMAL ANALOG BEDROCK SITE USING FIBER OPTIC DISTRIBUTED TEMPERATURE SENSING

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ABSTRACT

Highly channelized flow in fractured geologic systems has been credited with early thermal breakthrough and poor performance of geothermal circulation systems. An experiment is presented here in which the effect of channelized flow on fluid/rock heat transfer is measured. Hot water was circulated between two wells in a single bedding plane fracture and the elevation of rock matrix temperature was measured using fiber optic Distributed Temperature Sensing (DTS). Between wells with good hydraulic connection, heat transfer appeared to follow a classic dipole sweep pattern. Between wells with poor hydraulic connection, heat transfer was skewed toward apparent regions of higher transmissivity (or larger aperture). These results are consistent with hydraulic and tracer tests, as well as ground penetrating radar imaging, that shows a heterogeneous distribution of transmissivity. Although these results are preliminary and still qualitative, they suggest that flow channeling can have a significant impact on heat transfer efficiency even in single planar fractures.

INTRODUCTION

Enhanced Geothermal Systems (EGS) are heavily dependent on creating a sufficient surface area through which heat may be exchanged between flowing fluid in fractures and the surrounding hot rock matrix. In geothermal reservoirs characterized by tight interconnected fractures, water flows unevenly in response to injection and pumping. Uneven flow or flow “channeling” can lead to premature thermal breakthrough and, therefore, is a critical design parameter for effective EGS.

Tracer testing has become a standard tool for the prediction of early breakthrough. Over 100 tests have been conducted in geothermal reservoirs [*Shook and Forsmann*, 2005]. The vast majority of these tests have utilized conservative (non-reactive) tracers to measure residence time among well pairs. Recent advancements have produced "smart" tracers which can provide more detailed characterization of fractures, including surface area [*Tester and others*, 2006]. While theoretically viable and numerically validated, tracer tests have not been compared to independent measurements of effective surface area in field experiments. Here, an experiment is conducted in which heat exchange between circulated water in fractures and the bulk rock matrix is measured independently from the water temperature. These tests will be used to validate tracer measurements that will be presented elsewhere.

EXPERIMENTAL METHOD

The field site is located in Altona Flat Rocks, in northern New York, USA about 4 miles northwest of West Chazy, New York. Altona Flat Rocks is highly unique in the Northeastern United States, because a glacial flood stripped soil overburden off of bedrock, exposing an expanse of sandstone with shallow groundwater in bedrock fractures [*Rayburn et al.*, 2005]. The natural flow of groundwater is to the Southeast and occurs only in fractures due to the low porosity of the well cemented Cambrian-aged Potsdam Sandstone formation. The proximity of the water table to the bare rock surface permitted imaging of fracture planes and saline tracer migration with ground penetrating radar (GPR) [*Becker and Tsoflias*, 2010; *Talley et al.*, 2005; *Tsoflias and Becker*, 2008]. A five-spot 15 cm diameter well pattern penetrates a conductive sub-horizontal fracture 7.6 m meters below the surface. For this project, an additional ten 15 cm diameter boreholes were drilled to a depth 60 cm above the conductive fracture for temperature monitoring of the dry rock matrix.

Temperature in the rock matrix above the fracture was measured using a fiber optic Raman scattering Distributed Temperature Sensing (DTS) system. Raman DTS measures temperature by measuring photon backscatter from laser transmission along a standard fiber optic cable. The ratio of Stokes and Anti-Stokes backscatter wavelengths is used to measure temperature while time of flight is used to position the temperature along the cable [*Tyler et al.*, 2009]. The system used at Flat Rock is a Sensornet Oryx, which records temperature every 1 m along the cable with a stated accuracy of 0.02 C when backscatter is integrated over a period of 10 minutes as in our experiments.

Because the native spatial resolution of 1 m along the fiber optic cable, the cable was wrapped around a threaded 5.71 cm outer diameter schedule-80 PVC pipe to increase the spatial resolution to 2.1 cm. Our laboratory tests indicate the instrument is not capable of distinguishing between strong temperature contrasts less than 5 cm apart, however. A special high numerical aperture cable was used for this purpose to reduce attenuation of signal due to the fiber curvature. Wrapping was facilitated using a standard machine tool lathe fitted with a retaining adapter (Figure 1). During the winding process, the fiber was wrapped with electrical tape to hold the fiber in place and protect it during installation (Figure 2). Five 3-meter long sensors and five 1.5-meter long sensors were created and tested on the campus of CSU Long Beach then shipped to the Flat Rock field site.

Figure 1: Process of wrapping fiber optic cable around a threaded PVC pipe assisted by a lathe.

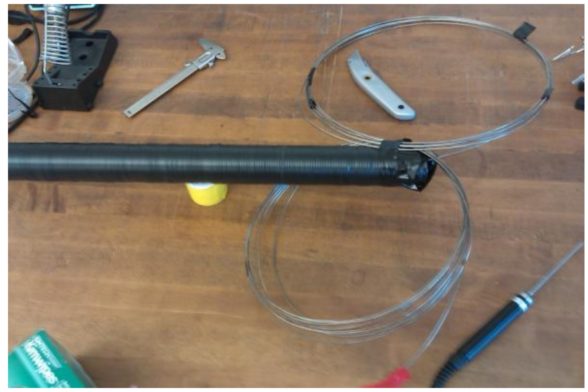

Figure 2: Close up of threaded PVC pipe wrapped with fiber optic cable and secured with electrical tape.

During July, 2011, all ten Sensor rods were installed into each of the ten boreholes. The ends of each sensor rod were fused to an adjacent borehole’s sensor rod, creating a network that could be used to measure temperature along one continuous cable. The 8.26 cm annulus created between the sensor rods and the borehole wall was filled with a mixture of sand and water to create thermal coupling with similar thermal conductivity as the low porosity sandstone. A 3 cm horizontal layer of clay was added every 76 cm during backfilling to diminish the potential for pore water convection in the annulus. Unfortunately, two of the sensors were damaged by vandals during the team’s absence from the field and could not be repaired in time for the experiments.

The thermal experiments were conducted by circulating heated water between the center and a corner well in the five spot (Figure 3). Two circulation experiments were conducted: (1) injection in 404 and pumping from 304 and (2) injection in 404 and pumping from 104. These wells were chosen because they were adequately covered by the partially crippled temperature sensor network. Fortunately, these wells allowed us to compare circulation with wells that were well-connected (304) and poorly-connected (104) hydraulically

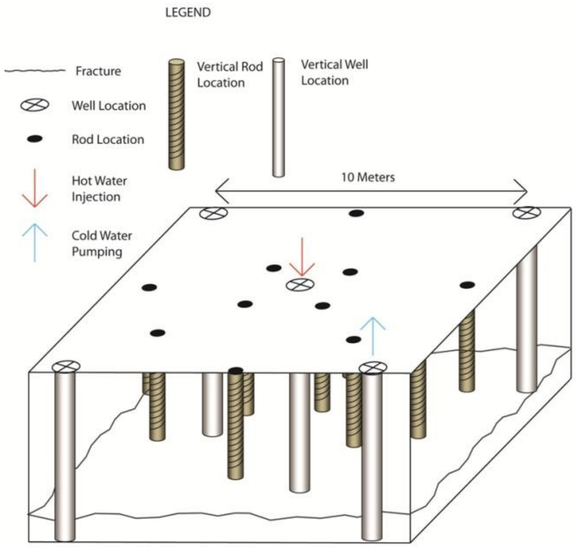

Figure 3: A schematic of the thermal experiments conducted in fractured bedrock.

Water for the experiments was heated using a propane-fired spa heater that maintained a constant 40ºC temperature in an 800 L source tank (Figure 4). This water temperature was approximately 30ºC warmer than temperature of the sandstone prior to the experiment. Water was circulated by gravity drainage into well 404 and return pumping from well 304 or 104 using a Grundfos MP1 adjustable speed pump. All wells were hydraulically isolated to the target fracture using inflatable straddle packers that limited fluid movement within 15 cm above or below the fracture. Temperature and head were monitored using self-contained loggers (Solnst, Waterloo, Ontario) in all wells within the straddled intervals.

Figure 4: A photograph of the experimental site. The DTS instrument, spa-heater, and storage tank are visible near well 404.

The two (404-304, 404-104) thermal experiments were conducted from October 4th to October 8th, 2011. The circulation between well 404 and 304 ran with an injection/pumping rate of 4 liters per minute for 46.5 hours and then the rate was increased to 8 liters per minute for an additional 7 hours to reduce the duration of the experiment. Circulation between well 404 and 104 ran with an injection/pumping rate of 8 liters per minute for 22.2 hours. During the 404-304 experiment, temperature in the pumped water raised 4 ºC and in the 404-104 experiment, only 1 ºC.

PRELIMINARY RESULTS

Because experiments were completed in October, 2011, at this writing only preliminary interpretations are available. It is clear, however, that heat exchange between the warm circulated water and the rock matrix was measured by the DTS sensor system. DTS measurements show heat propagating vertically above the fracture for both the 404-304 experiment (Figure 5) and 404-104 experiment (Figure 6). The maximum temperature rise in the rock matrix was approximately 6ºC during the 404-304 experiment and approximately 3ºC during the 404-104 experiment.

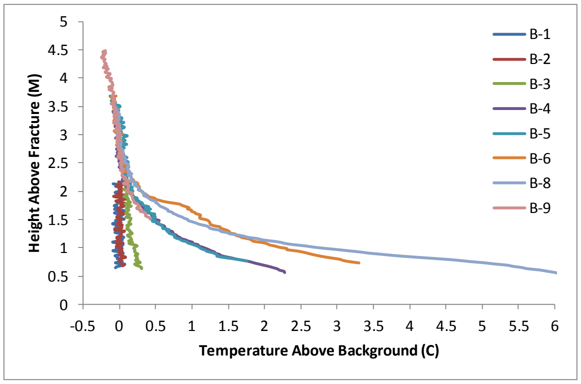

Figure 5: Temperature increase above background measured in the rock matrix during the 404-304 test using the DTS sensor.

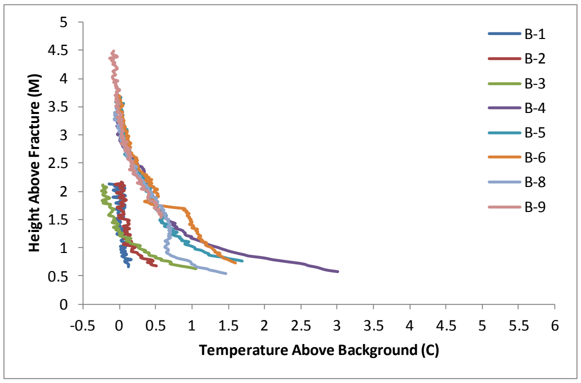

Figure 6: Temperature increase above background measured in the rock matrix during the 404-104 test using the DTS sensor.

DISCUSSION

The temperature profiles show the expected shape due to diffusion of heat from a constant heat source. The profiles are not predicted exactly by such a simple theoretical model, however, because (1) the temperature of circulated water in the fracture was not constant in time or space and (2) at the initiation of the second test the rock matrix temperatures had not returned entirely to background temperature. Analytical modeling is underway to assess the rate of heat transfer between the fracture and matrix. In the meantime, we offer a qualitative presentation of the heat exchange observed during the experiments.

Warm water circulation between well 404 and 304 elevated the rock matrix temperature in a manner consistent with a “dipole” circulation flow pattern. The greatest increase was measured just upstream (B-8) and just downstream (B-6) of well 404 (Figure 7). A lesser increase was observed in the next nearest lateral boreholes (B-4 and B-9). Wells intercepted by the longest theoretical dipole flow paths, (B-1, B-2, B-3) showed little or no increase in temperature.

The circulation between well 404 and 104 elevated the rock matrix temperature in a manner inconsistent with a “dipole” circulation flow pattern. This experiment showed an asymmetric distribution of temperature about the imaginary line connecting wells 404 and 104. The greatest temperature increase was again measured just downstream (B-4) of well 404, but the next well in direct path to 104 showed little temperature change. Both the proximate lateral wells, B-8 and B-6 showed an increase in temperature but the more distal wells to the East (B-3, B-5) also showed an increase. The propagation of the thermal front, therefore, appears to be skewed eastward in the 404-104 experiment.

The asymmetric distribution of heat about the circulating wells 404 and 104 is consistent with other studies from the site. Pump testing shows a relatively poor hydraulic connection between well 104 and the remaining wells [*Castagna et al.*, 2011]. GPR imaging of saline tracer suggested more efficient transport between wells 204-304 than wells 504-104 [*Talley et al.*, 2005]. A GPR measured tracer experiment, in which saline water was circulated between well 204 and 304 and imaged with stationary antennae place between 404 and 304, showed strong breakthrough consistent with a direct flowpath [*Becker and Tsoflias*, 2010]. Finally, recent GPR imaging of the target fracture without saline tracer suggests that apertures are generally larger in the region between wells 404 and 304 than they are between 404 and 104 [*Tsoflias et al.*, 2011].

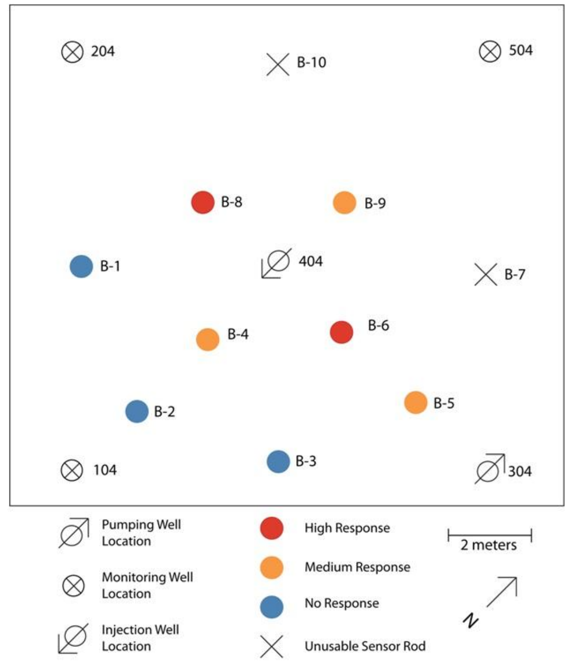

Figure 7: Classification of temperature response realized in the rock matrix during the 404-304 circulation experiment.

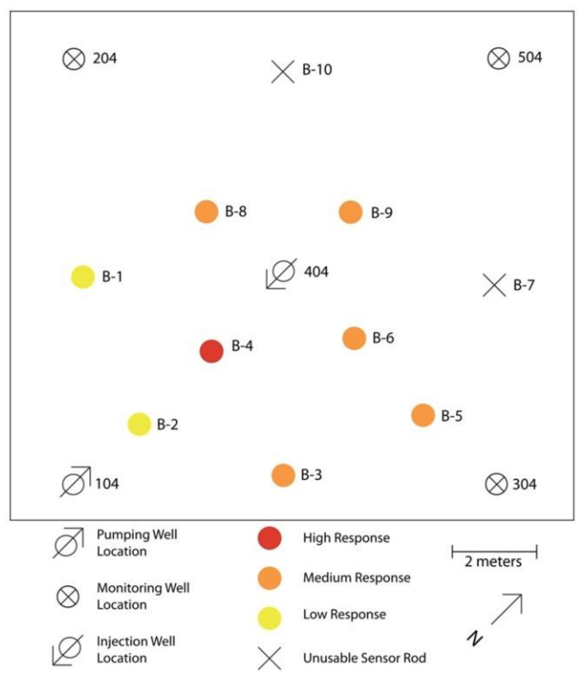

Figure 8: Classification of temperature response realized in the rock matrix during the 404-104 circulation experiment.

CONCLUSIONS

The heat transfer experiment produced useful results in spite of the loss of some equipment due to vandalism. Elevated temperatures in the sandstone matrix were measured in response to hot water circulated through the single bedding plane fracture. Heat transfer from the fracture to the rock matrix was highly symmetrical between two wells situated in a well-connected region of the study fracture, suggesting a classic dipole water sweep. Heat transfer was less symmetrical between two wells known to have poorer hydraulic connection. In this experiment, heat transfer appears to have been diverted to a more conductive region of the study area due to flow channeling. The experiment appears to lend support to the impact of channelized flow, even in single planar fractures. These results are only preliminary and qualitative, however. Modeling is underway to better constrain the results and interpretation.

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