Final Technical Report

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Signature______________________________________ Date___________________

***The Prime Recipient certifies that the information provided in this report is accurate and complete as of the date shown.**

EXECUTIVE SUMMARY

The extraction of heat from hot rock requires circulation of fluid through fracture networks. Because the geometry and connectivity of these fractures determines the efficiency of fluid circulation, many tools are used to characterize fractures before and after development of the reservoir. Under this project, a new tool was developed that allows hydraulic connectivity between geothermal boreholes to be identified. Nanostrain in rock fractures is measured using fiber optic distributed acoustic sensing (DAS). This strain is measured in one borehole in response to periodic pressure pulses induced in another borehole. The strain in the fractures represents hydraulic connectivity between wells. DAS is typically used at frequencies of Hz to kHz, but strain at mHz frequencies were measured for this project.

The tool was demonstrated in the laboratory and in the field. In the laboratory, strain in fiber optic cables was measured in response to compression due to oscillating fluid pressure. DAS recorded strains as small as 10 picometer/m in response to 1 cm of water level change. At a fractured crystalline rock field site, strain was measured in boreholes. Fiber-optic cable was mechanically coupled borehole walls using pressured flexible liners. In one borehole 30 m from the oscillating pumping source, pressure and strain were measured simultaneously. The DAS system measured fracture displacement at frequencies of less than 1 mHz (18 min periods) and amplitudes of less than 1 nm, in response to fluid pressure changes of less 20 Pa (2 mm of water). The attenuation and phase shift of the monitored strain signal is indicative of the permeability and storage (compliance) of the fracture network that connects the two wells. The strain response as a function of oscillation frequency is characteristic of the hydraulic structure of the formation.

This is the first application of DAS to the measurement of low frequency strain in boreholes. It has enormous potential for monitoring geothermal reservoirs for purposes of understanding reservoir compliance and for assuring security of injection fluids. Periodic pressure pulses can be induced by oscillating injection or pumping during operation so the system could provide real time reservoir data. DAS cable may already be installed at a site as it is becoming increasingly used for seismic observation. Simulations conducted for this project indicate that strain should be propagated through borehole cements, so observations can be made outside of well casing. In uncased holes, the cable would need to be mechanically coupled to the borehole wall to provide measurements. One option would be to install fiber into cemented and abandoned boreholes to extend their utility.

Contents

INTRODUCTION

As a preface to the technical content described by task, a background in periodic hydraulic testing and fiber optic distributed acoustic sensing is provided.

Periodic Hydraulic Testing and Hydrogeomechanics

Cross-well periodic hydraulic testing has been used in the oil industry since the 1960's [*Hollaender et al.*, 2002] but has received renewed attention in the literature [*Cardiff et al.*, 2013; *Cardiff and Sayler*, 2016; *Fokker and Verga*, 2011; *Fokker et al.*, 2012; *Guiltinan and Becker*, 2015; *Rosa and Horne*, 1991]. The general approach is to create a periodic hydraulic signal in one well and observe the responding signal in one or more monitoring wells. This may be done purposefully or oscillating hydraulic signals from ongoing injection/pumping operations may be utilized in some cases. Repeated injection followed by shut-in periods, for example, can create an analyzable hydraulic signature.

The frequency of the pressure signal does not change as it propagates through the formation, only the amplitude and phase. The attenuation and phase lag of the responding signal measured at a monitoring well may be used to estimate effective hydraulic parameters in the formation, such as transmissivity and storativity. Because the interrogated volume increases with oscillation period, the test can be tuned to investigate hydraulic connections near or far from the source well. The method works particularly well in fractured rock because small storativity reduces attenuation of the pressure signal [*Renner and Messar*, 2006].

In fractured rock, oscillating pressure will cause fractures to dilate and contract as the effective stress varies. This creates a measurable strain at fracture affected by pressure response. In general, rock strain in response to fluid stress is known as hydromechnical response [*Rutqvist and Stephansson*, 2003]. Hydromechanical response is critical to geothermal systems and EGS systems in particular. Hydromechanical behavior in rock fractures is known to be non-local, that is, is not a function of the fluid pressure and rock mechanical properties at a particular location, but can be influenced by the heterogeneity of fluid flow and rock structure. As a simplification, however, an apparent fracture compliance can be defined as the ratio of the strain amplitude and the pressure amplitude observed at the same location. Fracture compliance measured in this way can be compared to laboratory measurements on fractured rock cores.

The key to the advancements explained here is this hydromechanical coupling of pressure and strain. We use distributed acoustic sensing to measure strain in rock fractures. Although the geomechnics of the rock are important, our focus in this project was to use strain as a proxy for fluid pressure. We do this because strain can be measured at extremely small values using distributed acoustic sensing, provided the hydraulic signal is periodic (oscillatory).

Fiber Optic Distributed Acoustic Sensing

The principles of DAS used for monitoring borehole seismic and acoustic signals are widely available in the literature [*Daley et al.*, 2015; *Johannessen et al.*, 2012; *Molenaar et al.*, 2012; *Parker et al.*, 2014]. DAS systems consist of an interrogator unit attached to a fiber optic cable. In practice, the technology is similar to fiber optic (FO) distributed temperature sensing (DTS). However, while DTS measures temperature along the length of the fiber, DAS measures acoustic signals in the form of an oscillating strain rate. Laser optical phase demodulation is used to obtain strain rate along the cable [*Daley*, 2013]. The strain rate is measured over a specified gauge length along the cable, and recorded at the center location along this distance. For our experiments, measurement channels were every 0.25 m along the cable and the gauge length was 10 m. Conversion to strain was is accomplished by integration over time. The instrument used for these tests was a Silixa iDAS^{TM} system.

The low frequency response of DAS systems has received considerable attention during the past several years. To our knowledge, this project was the first to demonstrate the lowest measurable frequency recordable by a commercial DAS system. Since that time, low-frequency response (<1 Hz) has been equated to strain due to hydraulic response during hydraulic fracturing [*Jin and Roy*, 2017]. The distinction between strain and acoustic response is somewhat arbitrary in this application, however. DAS is capable of measuring only the rate of longitudinal strain in the glass fiber regardless of frequency. Low frequency DAS response is considered “hydraulic strain” only because frequencies of < 1 Hz suggest that whole body inertial strain is less important than strain caused by hydraulic diffusion. One aspect that distinguishes our project from these other approaches is that we focus strain measurement to individual fractures and measure a known frequency response. In this way we can assure we are measuring hydraulic connections rather than a combined rock/fracture strain.

SUMMARY OF RESULTS BY TASK

Task 1. Laboratory Experimental

The purpose of the laboratory experiments was to (1) test the ability of the iDAS instrument to measure and process signals at ultra-low frequencies and (2) to test potential for measuring fluid pressure through longitudinal strain on a fiber. For the applications discussed here, pressure-induced compressional strain along the cable, which is essentially radial, is measured as longitudinal (elongation) strain in the glass fiber. The relationship between pressure and strain is a function of the transfer of fluid pressure to the optical fiber; strain is transferred through the cable's outer coating to the fiber glass. The elongation is related to the compression on the glass via the Poisson ratio and Young's Modulus of the glass fiber itself. The complexity of this relationship suggests that absolute pressure measurements made with DAS would need to be calibrated downhole using an electronic sensor. However, for pressure interference tests, it may be sufficient to have relative pressure measurements to complete a required analysis.

Laboratory tests were conducted by inducing sinusoidally varying pressure on a tight buffered optical fiber, and monitoring the response using the DAS system. Pressure oscillation was induced by tethering a solid cylinder to a rotating disc, and placing that cylinder in a water reservoir. As the disc was rotated by a computer-controlled stepper motor, the cylinder displaced water in the reservoir as a perfect sinusoid. Water pressure oscillation was measured with a high resolution electronic transducer connected to a laptop. About 200 m of tight-buffered optical fiber was wrapped about a 10 cm (4 in) diameter PVC pipe and submerged in the water reservoir. Sinusoid periods of 10, 100, 500, and 720 seconds for water level oscillation amplitudes of 40, 100, 500, and 1000 Pa (~4, 10, 50, 100 mm of water head) were tested.

These tests were published in the journal in a special DAS issue of the Society of Petroleum Engineer's journal, *The Leading Edge* [*Becker et al.*, 2017a]. Readers are referred to that publication for details. Only the main findings are summarized here. Examples of fast Fourier transform (FFT) spectra of selected tests are shown in Figure 1. In these results, 300 channels (75 m of cable) have been stacked, but for most tests 40 stacked channels (10 m cable) produced acceptable results (Figure 2). The FFT was taken for the entire unfiltered signal but only the lowest frequencies are shown. For short periods and large hydraulic amplitudes, the strain response is well above noise. As period increases or pressure amplitude decreases, signal to noise ratio is reduced, thereby degrading the signal to a point where the induced frequency is no longer dominant. This is because the native measurement of DAS is strain rate along the fiber optic (FO) cable. Longer oscillation periods imply smaller strain rate.

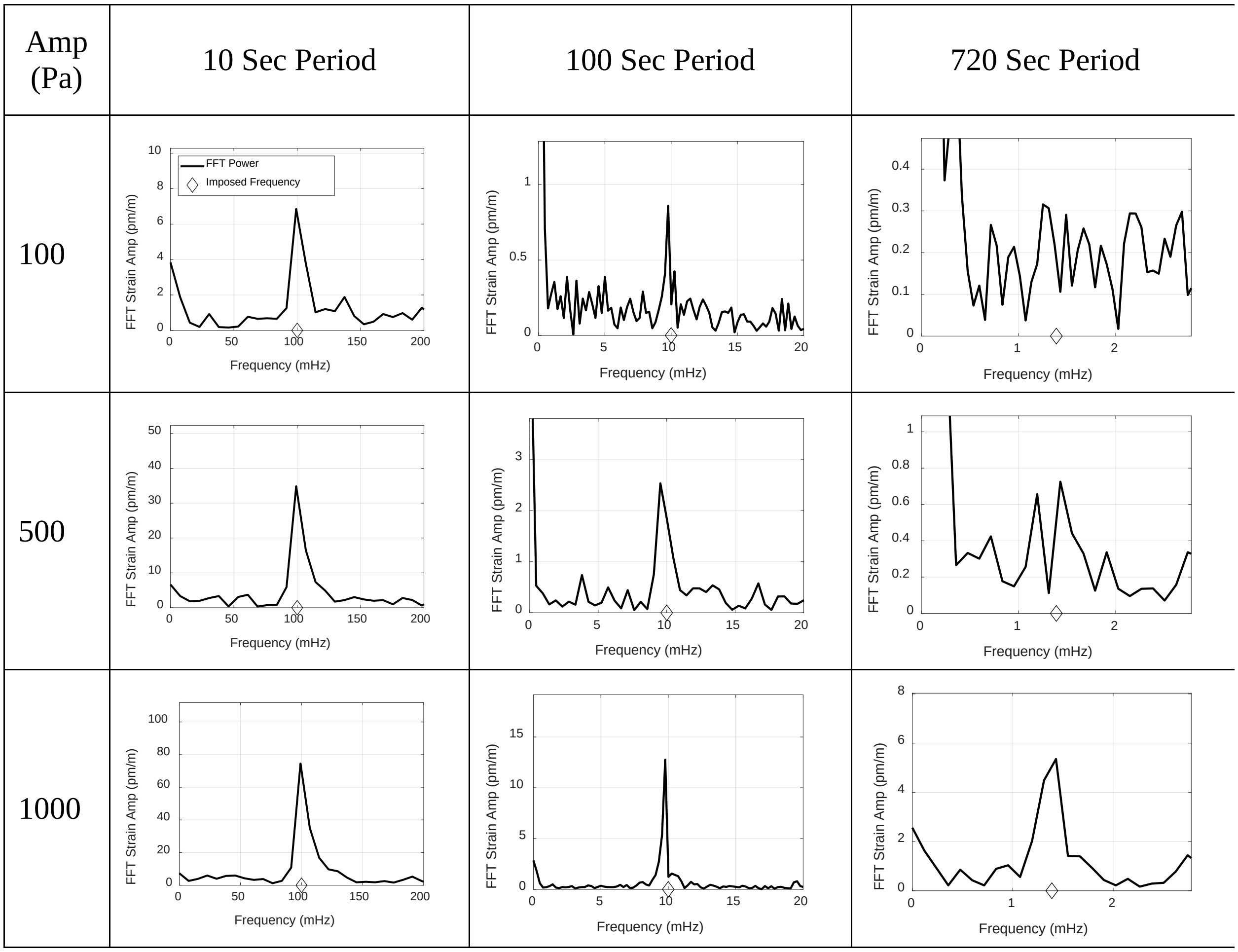


Figure 1 Selected FFT spectra from laboratory tests.

A summary of all the tests conducted is shown in Figure 2. Strain amplitude is plotted against pressure in the reservoir. Solid symbols represent DAS signals that displayed a strong FFT peak and a sinusoidal filtered strain response (e.g. 1000 Pa, 10 sec). Open symbols represent DAS signals that displayed a strong FFT peak and a noisy sinusoidal filtered strain response (e.g. 100 Pa, 100 sec). Open grey symbols represent DAS signals that showed no discernable periodic response (e.g. 100 Pa, 720 sec). Linear regression trend lines display the strength of the correlation between the strain and the pressure amplitude. A strong linear relationship between strain amplitude and pressure amplitude is observed at short (10 second period) oscillation periods. At longer periods DAS is less sensitive to pressure changes and linear regression shows a poorer correlation between strain amplitude and pressure amplitude. At the longest period tested (720 sec) only the 1000 Pa pressure oscillation resulted in a clear response from DAS.

These tests

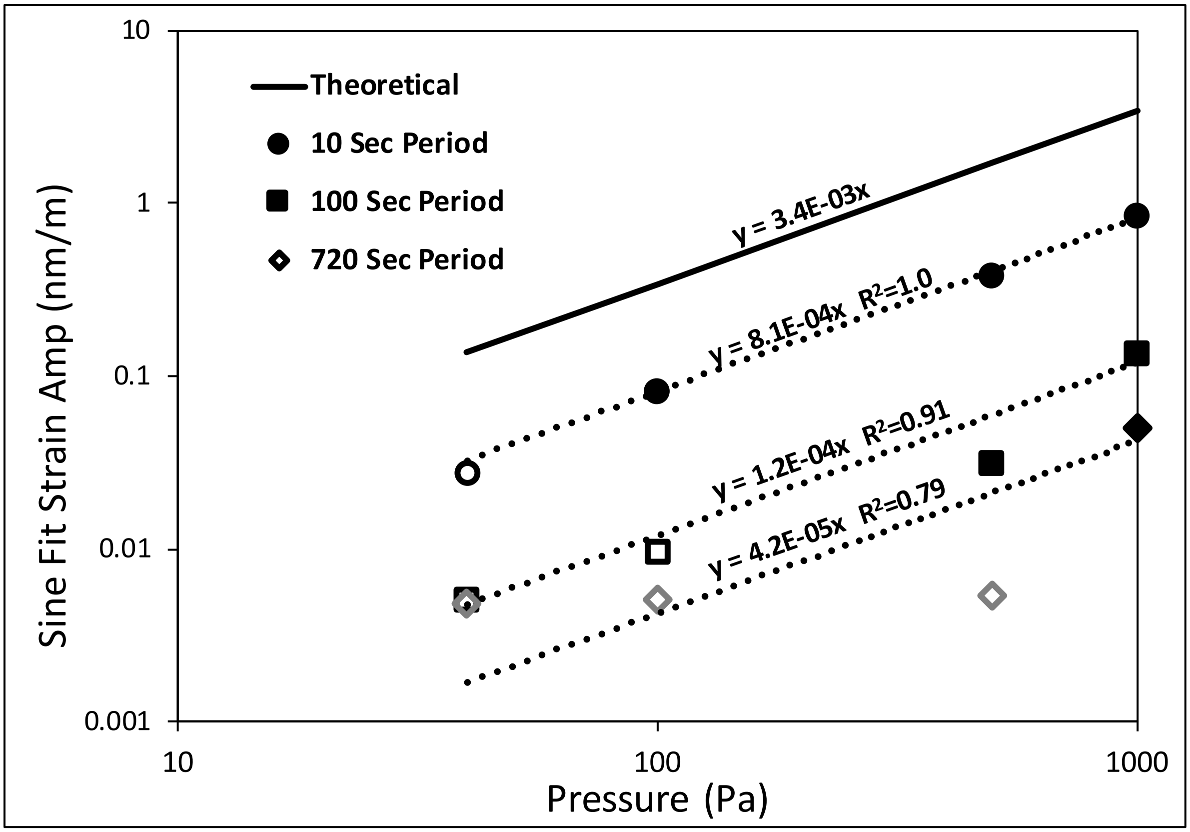


Figure 2 Summary of responses from laboratory tests. Open symbols produced poor sinusoid responses and are suspect. Open grey symbols produce no discernable sinusoidal signal. Linear trend lines are shown as dashed lines.

These tests demonstrated

1. Static fluid pressure can be sensed using DAS through longitudinal strain in response to compressional strain on the fiber cable
2. DAS can measure strain rate at very low frequencies but is less sensitive at lower frequencies and smaller strains
3. Strain measurements are linearly related to pressure only for good stain rate signals (i.e. shorter periods and larger strain)
4. For these tests, the instrument could measure strain amplitudes as small as 10 picometer/m (picostrain) in response to pressure oscillation periods of less than 100 seconds and pressures less than 100 Pa (10 mm H_2O).

The distributed nature of DAS would not seem to lend itself to fluid pressure measurements. In a well, for example, an oscillatory pressure response would be distributed evenly over the entire fluid column. However, DAS may be already installed in a well for purposes of measuring microseismic. In addition, electron sensors cannot withstand the pressure and temperature regimes in deep geothermal wells. DAS may present a useful method for measuring cross-hole hydraulic connections in geothermal wells. In addition, these laboratory tests demonstrated the ultra-low frequency response possible in DAS systems, opening up possibilities for other ultra-low-frequency strain measurements as discussed next.

Task 2. Field Experiments

The field experiments consisted of (1) solute and heat tracer experiments and (2) oscillatory hydraulic tests with strain measurement. The tracer tests were conducted in collaboration with Cornell University. The research group at Cornell lead by Adam Hawkins and Jeff Tester developed thermal reactive tracers (DE-EE0006764). As a result, we collaborated with them on the tracer aspect of the project. The strain tests were completed just prior to the solute tracer tests.

Field tests were conducted at the Mirror Lake Fractured Rock Hydrology Site, within the Hubbard Brook Experimental Forest Figure 3. The Mirror Lake Site was established by the U.S. Geological Survey's Toxic Substances Hydrology program to investigate contamination issues in fractured bedrock. The site itself is free of any contamination and the wells are on U.S. Forest Service property. The many prior investigations conducted in the Forest Service East (FSE) well field provided an important baseline for the hydraulic studies conducted for this work [*Shapiro et al.*, 1995]. Bedrock at the FSE well field is composed primarily of granitoids that have intruded the pelitic schist country rock [*Johnson and Dunstan*, 1998]. A combination of tectonic and unloading stresses have resulted in the formation of a complex fracture network throughout the crystalline bedrock to a depth of at least 300 meters. Individual fractures tend to extend about 1-5 m in length [*Barton et al.*, 1997], so permeability within the well field is assumed to occur along interconnected fractures and fracture zones [*Becker and Shapiro*, 2000a; *Becker et al.*, 2003; *Becker and Shapiro*, 2003; *Tiedeman et al.*, 1997]

Solute and Heat Tracer Experiments

The purpose of this phase of the field experiments was to establish transport connectivity between wells as a comparison to the hydraulic connectivity established through periodic hydraulic tests. Transport is more germane to geothermal systems as heat transports through fractures in a similar manner to solutes. Heat transport was also tested through the circulation of heated water between wells FSE 6 and FSE 9.

Methods

FSE 6 was used as the pumping well and injection was in FSE9 for all solute and heat tracer tests (Figure 3). FSE 6 and 9 are separated by a distance of 36 m. FSE 6 was pumped with a variable speed pump at a rate of ~8 lpm while injection at FSE 9 was at the same rate. This produced a flow "dipole" through which tracer was transported from FSE 6 to 9.

The tracers used in the tests were bromide, lithium, and C-dots. Lithium and bromide were introduced as the salt LiBr. Bromide was intended to act as a non-reactive tracer while lithium was expected to undergo ion exchange with cations in the rock surface. The separation in breakthrough between lithium and bromide, therefore, was used to arrive at an estimate of available (wetted) surface area [*Hawkins et al.*, under revision]. C-dots are a silica nanosphere tracer developed at Cornell [*Hawkins et al.*, 2016]. Aside from their lower rates of diffusion, the transport in a similar manner to solute tracers.

The heat tracer test was conducted by circulating water pumped from FSE 6 through an on-demand propane fired water heater and then reinjecting that water into FSE 9. The test was initiated on July 29, 2015 and ended on August 5, 2015. Injected water was at a temperature of 74 C while the water in the formation was initially at about 10 C. Fiber optic distributed temperature sensing (DTS) cable was deployed in FSE 6, 9, 10, 11,12, and 13 to monitor temperatures during the experiment (Figure 4). An Ultima XT DTS instrument manufactured by Silixa was used to interrogate the FO cable. DTS cable in FSE 10, 11, 12, and 13 were used to monitor temperature in fractures due to heat flow and the DTS cable in FSE 6 was used to monitor thermal breakthrough as this was the pumping well.

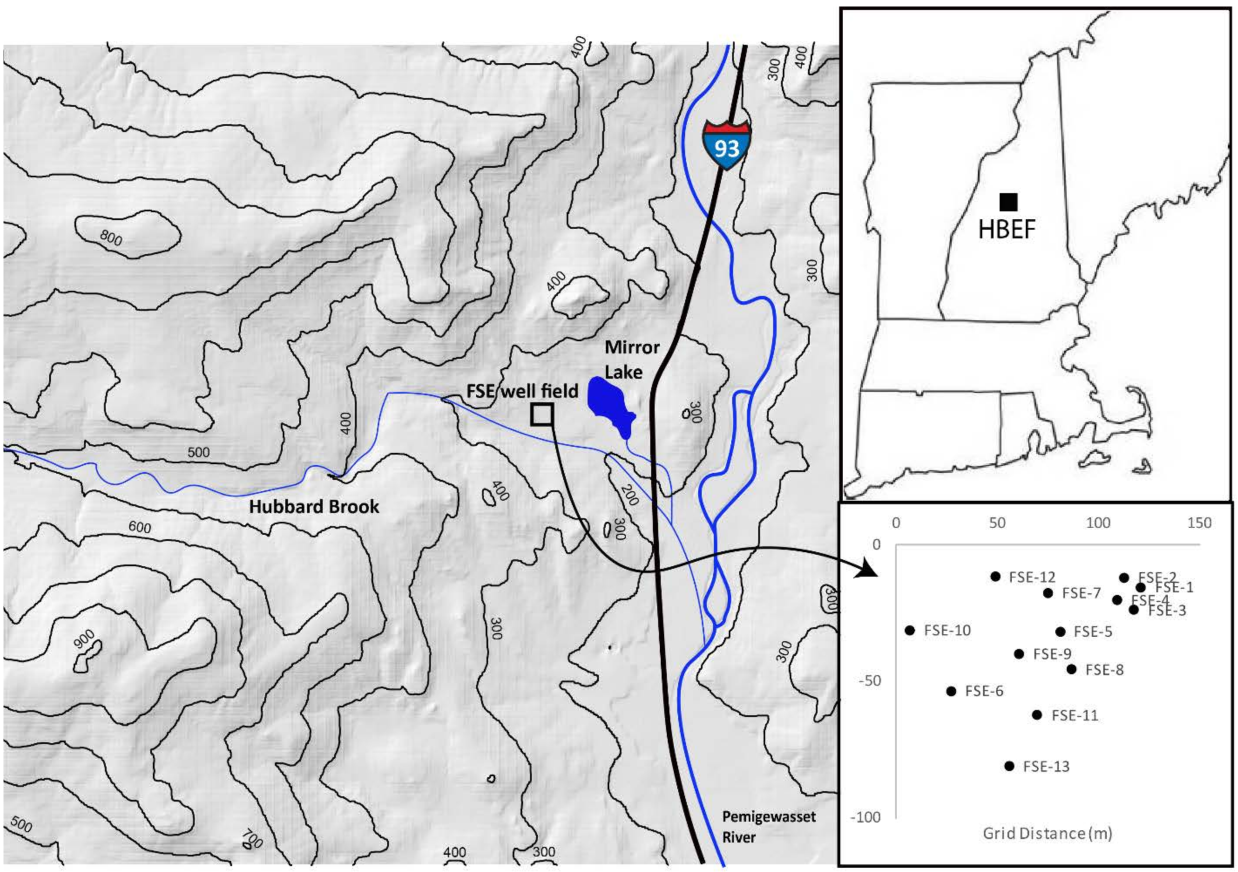


Figure 3 Location map of the Mirror Lake Experiments Field Site.

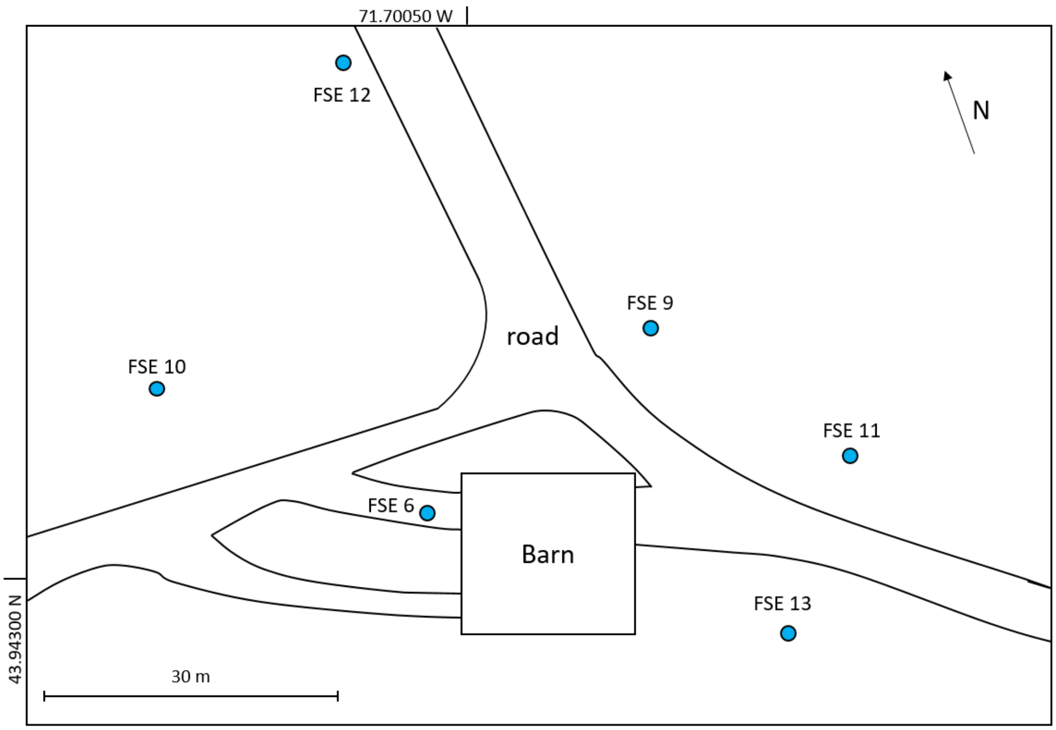


Figure 4 Map view of the well field at Mirror Lake.

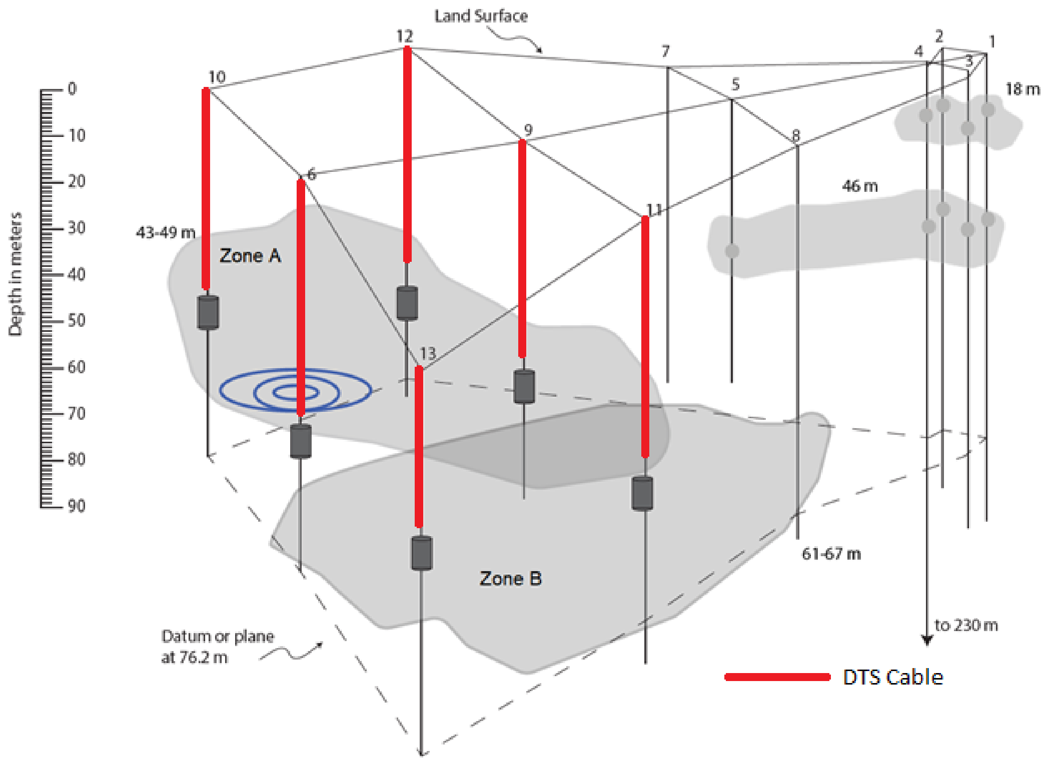


Figure 5 Perspective view of DTS cables in FSE well field.

Results

A separation in breakthrough of the non-reactive tracers, C-Dots and Bromide, and the ion-exchange tracer, Lithium, is clearly observed in the breakthrough curves (Figure 5). A rise in divalent cations calcium, magnesium, and strontium were was observed in the breakthrough but monovalent cation sodium did not change. Monovalent cation lithium, therefore, appears to exchange with divalent cations available on the rock surface.

Temperature rise in the observation wells (FSE 10, 11, 12, 13) was not discernable during the experiment. DTS is a high sensitive to temperature change. For the 10-minute sampling interval used by the Ultima DTS instrument has an RMS of about 0.04 C. Temperature rose about 0.1 C in FSE 6 over the experimental period (Figure 6). There was an initial increase in temperature that coincided with the arrival of the tracer that is interpreted to be “thermal breakthrough”. Subsequent to this initial increase temperature rose very slowly.

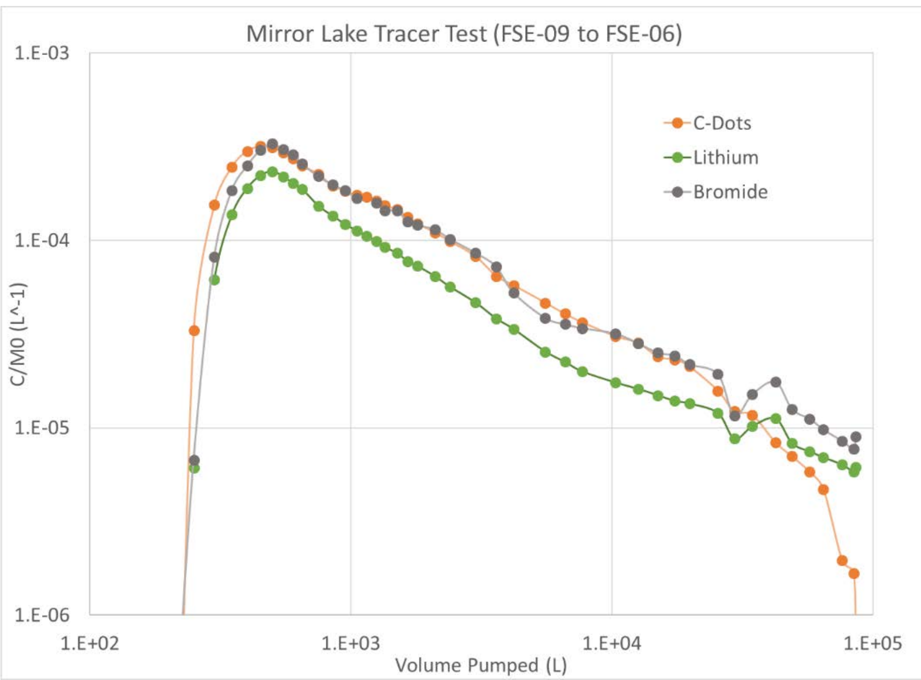


Figure 6 Breakthrough of solute tracer at FSE 6

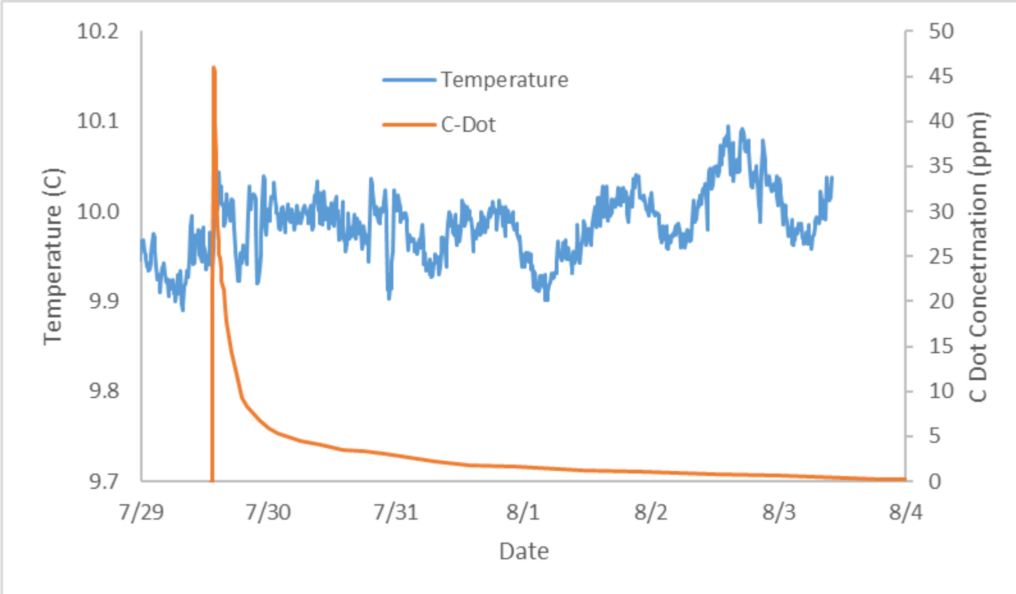


Figure 7 Temperature recorded by DTS in FSE 6 compared with C-Dot tracer breakthrough.

Interpretation

Interpretation of the solute and heat tracer experiments is ongoing. Similar tests were performed during the same summer at Altona Flat Rock, in collaboration with Cornell University. Modeling tools developed for the Altona project [*Hawkins et al.*, under revision] are being used to estimate available surface area. At this time, we are still working with the ion exchange model which is more complicated than that at Altona.

The heat tracer experiment yielded disappointing results. The loss of heat to the formation was so large that temperature increase at the monitoring wells was too small to model. Thermal breakthrough at the pumping well may be interpretable but the temperature measurement made by the DTS show influence of the air temperature on the instrument. We are using a Matlab® script to correct for this influence by integrating calibration bath data collected during the experiments. At this time, it is not clear if the increase in temperature is sufficient to warrant thermal modeling as originally proposed. Modeling effort has been refocused to understand the geomechanical measurements and proposed in the quarterly reports. These efforts are described in the next section.

Oscillatory Hydraulic Tests with Strain Measurement

Laboratory tests completed in Task 1 indicated that oscillatory strain could be measured using the DAS system. The strain measured in the laboratory experiments was induced by changing static pressure fluid pressure surrounding 200 m of tight buffered fiber optic cable. In the field experiments, similar measurements were made of oscillating water levels in wells in response to pumping and injection in a companion well. In three wells, rock strain was measured by coupling the fiber to the borehole wall. This latter measurement is particularly promising and became the focus of the research project. The experiment and results have been described in an article presented at the *Stanford Geothermal Meeting* [*Becker et al.*, 2016] and published in *Geophysical Research Letters* [*Becker et al.*, 2017b]. The methods and results are described here briefly. More detail can be found in these two articles.

Methods

Hydraulics in the FSE well field are dominated by an upper and lower set of transmissive fractures (Figure 5). Inflatable packers were installed in the open 15 cm diameter boreholes (FSE 6, 9, 10, 11, 12, 13) to limit hydraulic connections in this experiment to the upper zone only. Packers were inflated just below the conductive fracture zones (30-60 m depth) as located through previous testing and geophysical logging [*Johnson and Dunstan*, 1998]. For the periodic hydraulic tests discussed here, FSE6 was subjected to alternating pumping and injection to create square-wave hydraulic signal. This was accomplished using two variable speed pumps (Grundfos RediFlo2) controlled by two programmable variable speed controllers. A tank located near the wellhead was used to store water for reinjection. Flow meters up hole and down hole were used to ensure that the injection and pumping rates were kept equivalent during the tests. Injection and pumping rates of 20 L/min were programmed to alternate automatically to create oscillation periods of 2, 4, 8, 12, and 18 minutes, with the first half-period pumping and the second half-period injecting. The difference between maximum and minimum head in FSE6 ranged from about 2 m for the short period (2 min) tests to about 7 m for the long period (18 min) tests. Although the flow signal was a square-wave shaped time series, responses all appeared to be sinusoidal due to diffusion of the hydraulic pulse during propagation through the well field. During the oscillation of flow in FSE6, heads were recorded in FSE6 and the 5 monitoring wells using pressure transducers. For sake of brevity, only the hydraulic and strain response in FSE10 is discussed here. FSE 10 is located 30 m from FSE 6.

A single FO circuit was routed through all of the monitoring wells such that measurements from FO DTS and DAS could be recorded simultaneously during periodic testing (Figure 5). A fiber-in-metal-tube (FIMT) cable containing multimode fiber for DTS and single mode fiber for DAS was used. The cable was constructed with an outer jacket of high density polyethylene, a stainless-steel tube, two 50/125 micron (core/cladding diameter) multimode and two 9/125 micron single mode fibers surrounded by a hydrogen scavenging gel (AFL, Spartanburg, South Carolina, USA, DNS-10628). This kind of FO construction is referred to as “loose tube” as it allows the glass fiber to move within the gel-filled stainless steel tubing. We also deployed a separate cable designed specifically for strain sensing in FSE10 which is of “tight-buffered” construction, in which the glass fiber is surrounded by a stiff filling material rather than gel. We focus here on the loose-tube FO construction because it is more typically used for borehole deployments.

FO cable was mechanically coupled to the borehole wall using an overpressure flexible (FLUTe^{TM}) liner as described by *Munn et al.[2017]* for seismic DAS monitoring. These liners were originally developed to prevent cross-connection and allow discrete-level monitoring in bedrock wells [*Cherry et al.*, 2007]. The liner is made from an impermeable, tubular, flexible nylon fabric that extends from the top of the well (anchored at the well casing) into the borehole. During installation, about 3 m of overpressure head was maintained to evert the liner down the well and simultaneously coupled the FO cable to the borehole wall past the target fracture depth. The overpressure head in the liner is more than an order-of-magnitude greater than any head response from oscillatory pumping tests in the well, ensuring that the FO cable remains coupled to the rock wall. The liner was fitted with a permeable mesh woven into the fabric at the depth of the transmissive fracture (28 m). A pressure transducer at the surface was connected to a tube in communication with the permeable mesh. Because the tube is filled with both water and air, pressure transducer measurements had to be compensated for compression of air in the tubing [*Keller*, 2016].

The position along the FO cable was converted to well depth using reference temperature pulses at the top of the well casing. Because the DTS measurements have a spatial resolution of 25 cm, and the DTS and standard DAS FO cable are co-located, the depth control on the DAS cable was within 25 cm. Strain rate was converted to strain by integrating with respect to time [*Daley et al.*, 2015].

Results

Figure 8 shows the Fast Fourier transform (FFT) amplitude spectrum for the mean strain measured over the 40 channels (10 m) straddling the transmissive fracture. The DAS strain response was well above noise for all tested frequencies. Taking the mean of 40 channels (stacking) increases the signal to noise ratio, but the signal was measurable even for one channel.

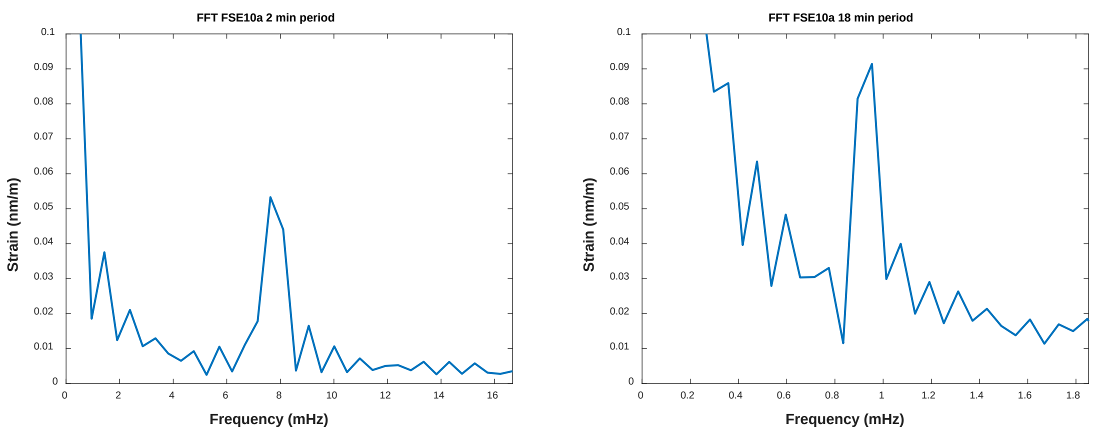


Figure 8 Fast Fourier Transform of strain signal recorded in FSE10.

The time-varying strain response measured by DAS is compared with pressure response measured in the same fracture in Figure 9. Only the shortest and longest experimental periods are shown for brevity (other period responses and their corresponding FFT spectrum are shown as supplement to [*Becker et al.*, 2017b]). The response in each of the bottom 40 channels (10 m) are shown in the left column. The response from 5 m above and below the target fracture are stacked. This range for stacking was selected because the gauge length used for strain measurement was 10 m. After stacking, the signal is filtered using a low-pass Butterworth digital filter to remove noise 20% above the imposed frequency, followed by a second Butterworth filter to remove signal with frequency 20% below the imposed frequency. In this way both high frequency noise and low frequency trends are removed from the DAS signal. The filtered signal remained sinusoidal even when using a broader filter window (e.g. 40% above and below). Heads measured in FSE10 had amplitudes ranging between 2 mm for the 2-min period, and 6 cm for the 18-min period (Figure 2).

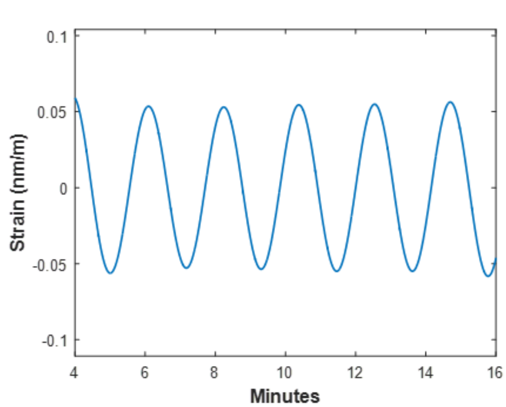
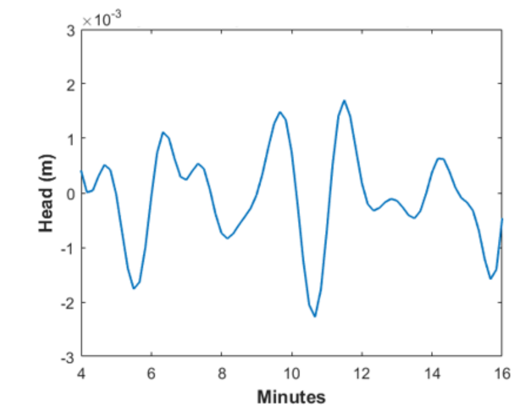
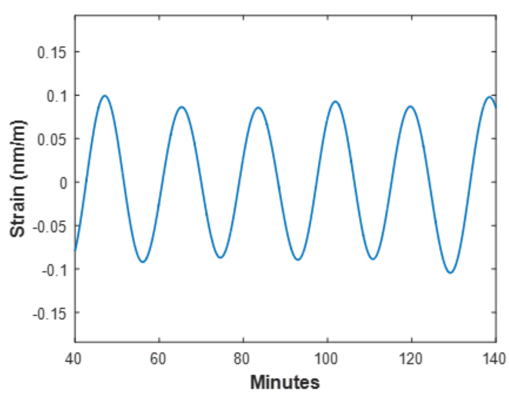
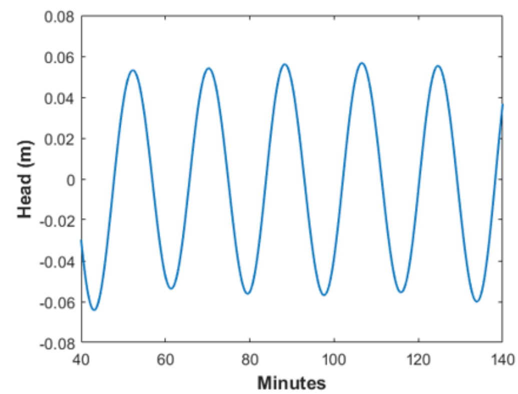
Period (min)	Filtered DAS Strain Response (mean of lowest 40 channels or 10 m)	Filtered Head Response Measured at Stressed Fracture
2		
18		

Figure 9 Shortest and longest period (filtered) strain and head response in FSE 10.

Figure 10 summarizes the relationship between DAS strain amplitude and the pressure amplitude measured in the same fracture. Amplitude of strain and pressure were evaluated by fitting a sine curve to the data using non-linear optimization. Nanostrain (nm/m) was converted to displacement (nm) by multiplying by the gauge length used in the DAS measurement (10 m). Fracture displacement amplitude shows a strong logarithmic relationship with fluid pressure with an R^2 value of 0.99.

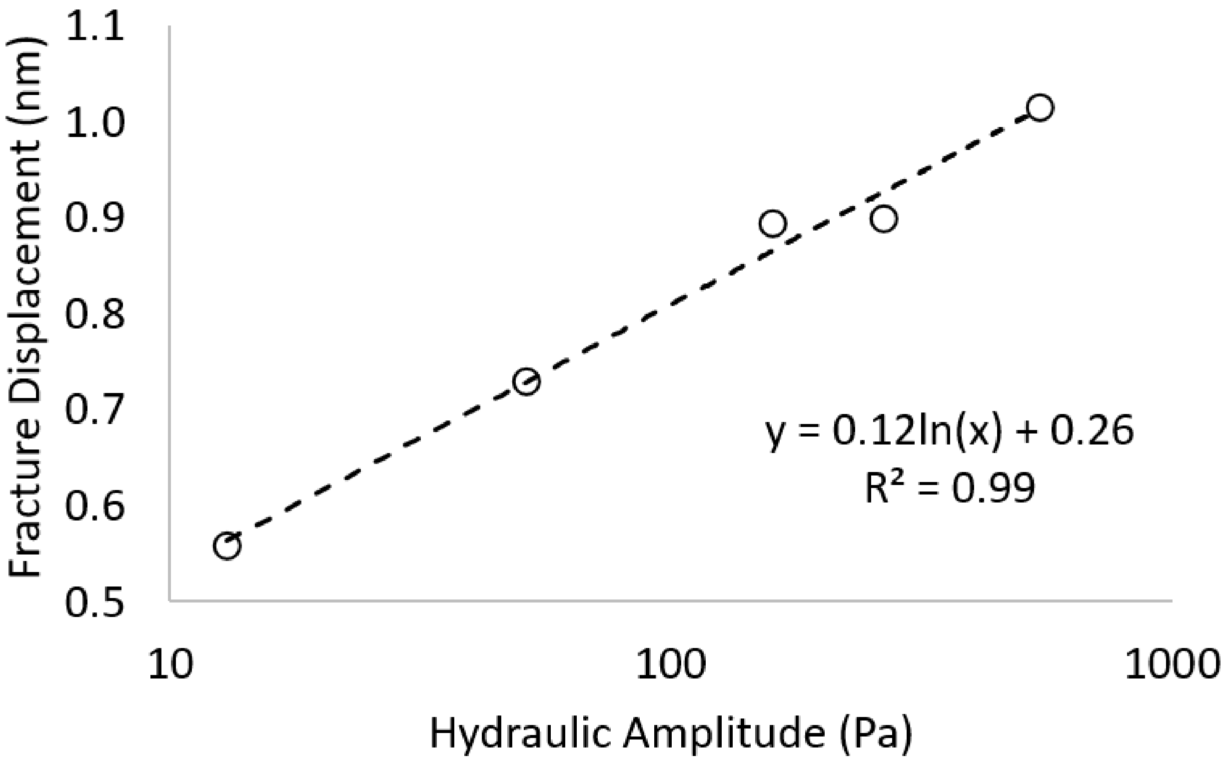


Figure 10 Fracture displacement amplitude measured by DAS at fracture (28.25 m depth) versus fluid pressure measured in the same fracture for oscillation periods ranging between 2 and 18 minutes.

An important result of this research is that, unlike other strain measurements methods such as Fiber Bragg Grating, DAS-based strain measurement is distributed. This means that the point of strain can be both indicated and measured. As an illustration, Figure 11 shows the amplitude of strain measured every 25 cm along two FO cables deployed in FSE 10. For comparison, the borehole logs for these wells are shown to the right. The zone of fracturing known from these logs and previous studies is shown with the green bar. The increase in measured strain in both in the vicinity of the pressurized fracture zone is obvious. The reason the strain increase is gradual and not a point at the fractures is because strain is actually measured between two points separated by a “gauge length” of 10 m. Strain is measured then as a moving window every 25 cm along the cable. Two strain features separated by a distance of less than 10 m cannot be distinguished.

Strain measurement is compared in two classes of cable design: a standard “loose tube” design and a strain sensitive “tight buffered” design. In a loose tube cable, the fiber glass is surrounded by a gel inside of a stainless steel tube. In a tight buffered cable, the fiber glass is surrounded by a solid plastic buffering material. Tight buffered cable would be expected to better transfer strain from the outside of the cable to the glass. This seems to be the case in the field experiments.

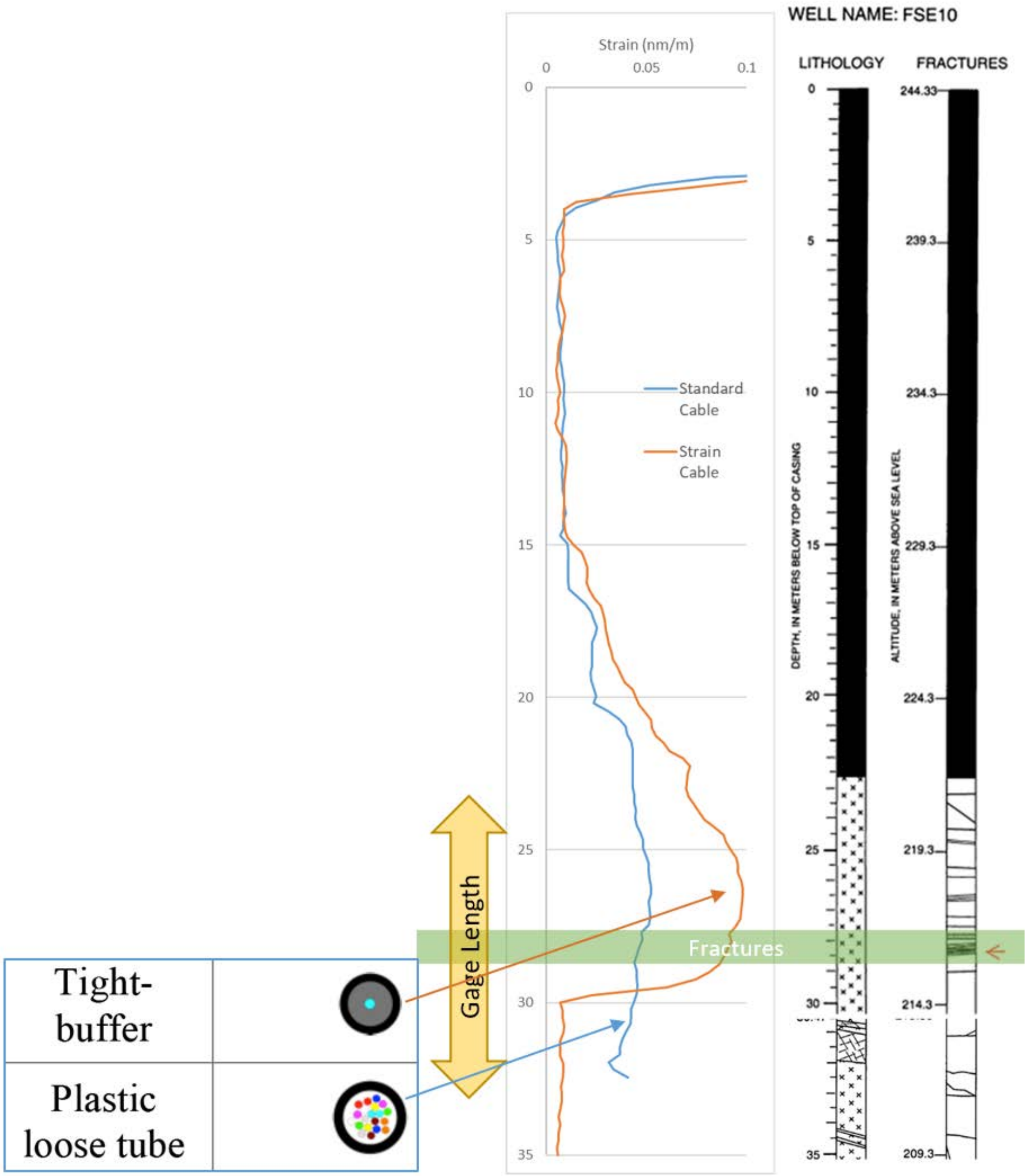


Figure 11 Amplitude of strain plotted against depth in borehole FSE 10. Borehole logs are shown for comparison.

Strain measured in wells not coupled to be borehole by a flexible liner was mostly below noise. In these wells, the FO cable was strained due to an increase in the water level in the well which was measured simultaneously by a pressure transducer. In FSE 11, for example, a significant signal was observed during the 18 min oscillation period when water levels in the well oscillated with an amplitude of 10 cm. Based upon the very similar experiments conducted in the laboratory, we expected a periodic strain in response to a periodic water level oscillation. This occurs as fluid pressure compresses the fiber, thereby causing a longitudinal strain. However, it is possible that the variation in water level also caused a change in the longitudinal strain through the variation in buoyancy as the submerged length of cable also varied periodically. We are still doing signal processing to determine if both influences are significant in the observed oscillating strain.

Interpretation

The field experiments were highly successful, far exceeding expectations. By mechanically coupling the FO cable to the borehole wall using a flexible liner, fracture displacements of less than 1 nm were measured in response to less than 2 mm of change in hydraulic head (Figure 10). These measurements were distributed, which allows the source of the strain to be localized within a 10 m gauge length (for our measurement configurations). Consequently, we have demonstrated a tool capable of locating and measuring formation strain provided the cable can be mechanically coupled to the formation and a periodic pressure signal can be created in the formation.

Task 3. Numerical Modeling of Periodic Testing

This task was initial oriented toward combined simulation of hydraulics, heat transport, and solute tracer transport at Mirror Lake. However, heat was not detected in the observation well and thermal breakthrough in the pumping well was much smaller than anticipated. At the same time, as described above, the geomechanical strain measurements performed much better than anticipated. In response to these developments during the course of the project we decided to realign the simulation with an emphasis toward understanding hydrogeomechanics. Unlike heat and solute transport, for which we already had appropriate simulation tools, hydromechanical modeling require development of new simulation approaches. In addition, simulations were conducted to understand the transfer of strain from a formation undergoing strain to a fiber optic cable embedded in borehole cement.

Modeling a Fractured Formation

After some experimentation, we developed a hybrid method of simulating flow in fractures and the responding strain on the rock formation. This was performed in COMSOL by calculating Darcy flow in a planar fracture and then using the pressure resulting from this flow as a boundary condition on strain in the surrounding block matrix. This is much more efficient than trying to refine a computation mesh to the scale of a fracture as is done in most poroelastic models.

One of the objectives of the hydromechanical modeling was to understand how periodic hydraulic signals are propagated through a heterogeneous fracture. In particular, we were interested in understanding the apparent phase lag between pressure and strain observed in FSE10. Flow channels are known to develop in fractured systems through the hydraulic interconnection of anomalously larger apertures in fractures. Channeled flow has been inferred in the FSE well field through tracer experiments performed in the past [*Becker and Shapiro*, 2000b; *Becker and Shapiro*, 2003]. We wanted to test the hypothesis that flow channeling could create a characteristic phase lag between pressure and strain in a fractured rock.

Methods

For simplicity, we considered a single fracture in a granite block (Figure 12). Within this fracture we created a rectangular "channel" of higher hydraulic conductivity. A periodic pressure pulse was applied along one edge of the fracture (blue line) and pressure and strain response were observed both inside and outside of the flow channel imposed on the fracture. The pressure and displacement are plotted for a plane parallel to the fracture located 0.1 m above the fracture. Notice that pressure propagates more rapidly in the channel while displacement propagation lags behind.

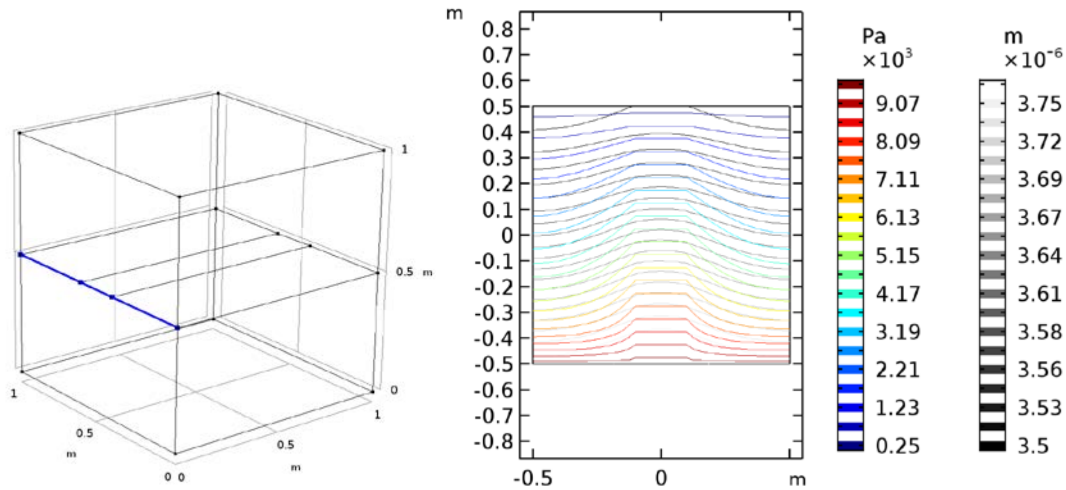


Figure 12 Left: Simulation design of a periodic pressure pulse applied at one edge of a fracture that splits a granite block (blue line). Right: Pressure response and displacement plotted just above the fracture.

Results

The response that would be measured in boreholes situated inside and outside of the channel are shown in Figure 13. Both pressure and displacement response outside of the channel lag pressure and displacement response within the channel. However, notice that pressure lags displacement much more significantly outside of the flow flow channel. From this result, we infer that the phase difference between pressure and displacement may be a diagnostic of the flow condition in the borehole. If strain and pressure arrive contemporaneously in a field cross-hole hydraulic test, for example, it could be an indication of flow short circuiting between the two wells.

We have performed many similar hypothetical simulations to examine the relative behavior of pressure and stress in heterogeneous systems. Current efforts focus on representing the responses observed at Mirror Lake. During the processing of the DAS data, however, we noticed that the integration algorithm being used by our DAS subcontractor, Silixa, caused erroneous phase shifts when converting between strain rate and strain. As a result, we no longer entirely trust the phase lags between pressure and strain observed in our early analysis of the field results. As part of a DOE STTR (Small Business Technology Transfer) project we are developing laboratory tests that well help verify the algorithms used to process low frequency DAS responses.

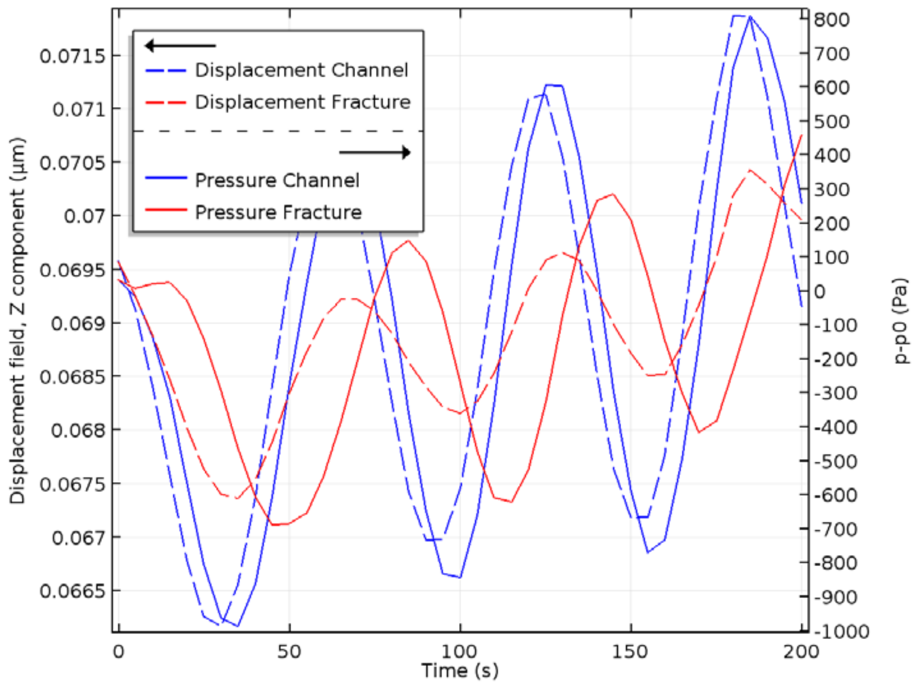


Figure 13 Simulated response of pressure and displacement measured at boreholes situated inside (blue) and adjacent to (red) the flow channel.

Interpretation

These simulations demonstrate that the coupling of fluid flow in rock fractures and strain in the surrounding rock mass is observable at boreholes outfitted with the DAS technology. Important information regarding the geomechanical characteristics of the rock as well as the heterogeneity of flow in rock fractures can be obtained through the interpretation of field data with hydromechanical simulations. The geomechanical interactions will be even more critical under the influence of thermal gradients imposed during heat extraction.

Most of the effort expended under this task was involved with developing the capability of efficiently simulating coupled fracture/rock interaction. Simulations thus far have focused on sensitivity studies and hypothetical models. However, because of the efficacy of the computation method, we will be able scale these results to account for more realistic formation characteristics and heterogeneity. Heterogeneity within fracture plane has already been demonstrated. We have simulated simple channels as well as correlated random fields of varying permeability within fracture planes. More recently we have attempted to create interconnected fracture networks and this has proved to be more challenging beyond simple orthogonal geometries. However, the simulations as tested are capable of exploring the diagnostic capability of combined pressure/strain measurements.

Once we confirm that the integration of the strain rate signal does not create an artificial phase shift in the strain data, we will perform a series of simulations to mimic the field experiments. These experiments will involve estimated geomechanical properties of the Mirror Lake rock and fractures, as well as the accurate representations of the pumping and injection during the periodic hydraulic tests. Simulations will be conducted assuming a single fracture, however, for simplicity. We currently have draft simulations that follow this description so we anticipate a submission by late spring, 2018.

Modeling Borehole Strain

The DAS system measured strain rate in a FO cable. The strain rate is actually measured in a glass fiber that is protected by multiple layers of protective casing. In addition, we anticipate that FO cable would be cemented into a well in practice. Consequently, COMSOL was used to simulate strain from formation to the FO cable. In particular, we simulated strain transfer from a dilating/contracting fracture to a FO cable cemented in the center of a slimhole.

Methods

Unlike the COMSOL models of fracture reservoirs, this modeling was relatively straightforward. We used a radially symmetric model rotated about the axis of the borehole. A prescribed displacement boundary was induced at the perimeter of the borehole to represent the opening of a fracture (at z =0). The fracture walls were assumed to displace upward and downward by 1 micron (2 micron opening). The borehole was assumed to be filled with cement and a fiber optic cable. The cable was assumed to be steel as the stainless steel tubing will be the stiffest aspect in most cables. All materials were assumed to be linear elastic.

The simulations are limited for both loose tube and tight buffered FO cable designs. In a loose tube construction, the glass fiber is “overstuffed” in the metal tube. This slack is used to prevent breakage during installation in the case that the cable is overly tensioned. In addition, between the glass fiber and the metal tube is a gel material. Because we model here only solid mechanics, we cannot represent fluids. This can be done in COMSOL, but fluid/solid interactions are difficult to represent with confidence. Tight-buffered construction can be represented with solid mechanics because the glass fiber is not over stuffed and the filling material is a plastic solid. However, the buffering materials using in FO cable construction are proprietary and we have not been able to obtain information about their mechanical properties. Consequently, we are not able to model the transfer of strain through the cable, only through the cement filled borehole to the cable exterior.

Results

The displacement realized in the borehole in response to a 2 micron dilation of a fracture is shown in Figure 14. The color shading represents displacement response in the borehole. It is clear that strain is focused at the fracture and at about 1 borehole diameter from the fracture the displacement has become entirely longitudinal. At this distance from the fracture, displacement in the borehole is equal to the displacement of the rock mass outside the borehole.

Interpretation

These simulations demonstrate that the gauge length of measurement employed by DAS (e.g. 10 m) is much larger than the 3-D stress behavior localized at a fracture. Consequently, we can assume that the strain in the borehole cement away from the fracture is equal to the strain in the formation at the same distance from the fracture. However, we are not yet able to model strain transfer through the cable itself. Given that different cable designs produced different strain measurements, by about a factor of 2 (Figure 11), we know that this strain transfer is important. We are still working to get mechanical properties of the tight buffering materials so we can simulate strain transfer through cables under similar circumstances. The model shown here can easily be modified to make these calculations once the linear elastic properties become available.

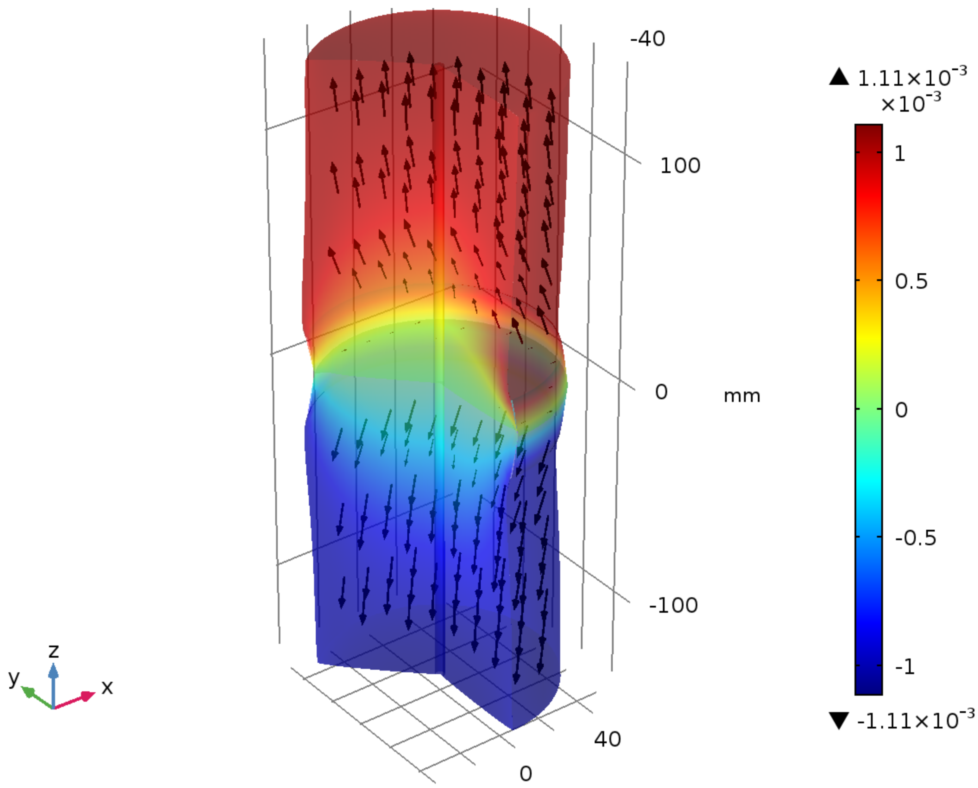


Figure 14 COMSOL solid mechanics simulation of displacement in a cement filled borehole. A fiber is cemented at the center of the borehole.

Task 4. Reporting and Publication

This task is non-technical in nature. Here are listed report presentations and papers published under this project. Note that under this task falls publications written in collaboration with the Cornell Group, whose project (DE-EE0006764) was funded at the same time as our own, under the same GTO Funding Opportunity Announcement. Much of the field demonstration for the Cornell project was conducted at Altona Flat Rock, a site that PI Becker established in 2004. Adam Hawkins, the lead PhD student for the Cornell project, performed his MS research at this site under a previous GTP project (DE-EE0002767). Consequently, for some publications the prior project (DE-EE0002767) is credited for support and others the current project (DE-EE0006764) is credited for support. All the publications listed below were supported by DE-EE0006764.

Peer Reviewed Publications:

Becker, M., et al. (2017a), Fluid pressure sensing with fiber-optic distributed acoustic sensing, *The Leading Edge*, 36(12), 1018-1023.

Becker, M. W., et al. (2017b), Fracture hydromechanical response measured by fiber optic distributed acoustic sensing at milliHertz frequencies, *Geophysical Research Letters*, 44(14), 7295-7302.

Hawkins, A. J., M. W. Becker, and G. P. Tsoflias (2017), Evaluation of inert tracers in a bedrock fracture using ground penetrating radar and thermal sensors, *Geothermics*, 67, 86-94, doi:https://doi.org/10.1016/j.geothermics.2017.01.006.

Hawkins, A. J., D. B. Fox, M. W. Becker, and J. W. Tester (2017), Measurement and simulation of heat exchange in fractured bedrock using inert and thermally degrading tracers, *Water Resources Research*, doi:10.1002/2016WR019617.

Hawkins, A. J., M. W. Becker, and J. W. Tester (under revision), Inert and adsorptive tracer tests for field measurement of flow-wetted surface area, *Water Resources Research*.

Published Workshop Papers:

Becker, M. W., Cole, M., Ciervo, C., Coleman, T., and Mondanos, M. J., 2016, Measuring Hydraulic Connection in Fractured Bedrock with Periodic Hydraulic Tests and Distributed Acoustic Sensing: *41st Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California v. SGP-TR-209.

Hawkins, A., D. B. Fox, M. W. Becker, and J. Tester (2017), An inverse model for predicting structure and thermal lifetime using inert and adsorbing tracers, paper presented at *42nd Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, February 13-15, 2017.

Hawkins, A., D. B. Fox, M. W. Becker, and J. Tester (2016), Meso-Scale Field Testing of Reactive Tracers in a Model Geothermal Reservoir, paper presented at *41st Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, February 22-24.

Published Abstracts:

Becker, M. W., T. Le Borgne, O. Bour, N. Guiheneuf, and M. Cole (2015), H51C-1378 Periodic Hydraulic Testing for Discerning Fracture Network Connections, paper presented at 2015 Fall Meeting, AGU, San Francisco, Calif., 14-18.

Ciervo, C., M. W. Becker, M. Cole, T. I. Coleman, and M. J. Mondanos (2016), Using Fiber Optic Distributed Acoustic Sensing to Measure Hydromechanics in a Crystalline Rock Aquifer, Abstract H51C-1494, presented at 2016 Fall Meeting, AGU, paper presented at American Geophysical Union Fall Meeting.

Cole, M., M. W. Becker, and C. Ciervo (2016), Periodic Hydraulic Tests in a Bedrock Fracture Network, Abstract H13I-1532, presented at 2016 Fall Meeting, AGU, paper presented at American Geophysical Union Fall Meeting.

Published Theses:

Cole, M. (2018), Periodic Hydraulic Tests in a Fractured Crystalline Bedrock, Mirror Lake Fractured Rock Research Site, Hubbard Brook Experimental Forest, New Hampshire, USA, Master of Science Thesis, California State University Long Beach, Long Beach, CA.

Digital Data:

Also included under this task is the digital archiving of data at the Geothermal Data Repository (https://gdr.openei.org/home). The data are archived and may be searched under three separate titles:

DAS for Periodic Hydraulic Tests: Laboratory Data
DAS for Periodic Hydraulic Tests: Hydraulic Data
DAS for Periodic Hydraulic Tests: DAS Data

The first dataset was described under Task 1. The second and third under Task 2.

POTENTIAL APPLICATIONS AND NEXT STEPS

This project has demonstrated the use of distributed acoustic sensing (DAS) for geomechanical monitoring in bedrock. This technology can be employed in geothermal fields for multiple purposes. As an illustration, Figure 15 shows a cross-section through a portion of the Brady Hot Springs geothermal field in Nevada [*Feigl and Team*, 2017]. Wells 18D-31 and 18B-31 are injection wells. The blue arrows show potential conduits of flow in the reservoir. Note that well bores indicated in grey are idle. These wells could potentially be cemented with fiber optic cable installed. Pulsed injection would be measured by the DAS system at any interval hydraulically connected with the injection wells. Multiple connected fractures, and their relative connectivity, would be measured simultaneously. Currently, because the deep wells are open-hole, it is not clear how the reservoir is connected hydraulically. Furthermore, the presence of these open holes creates artificial conduits of flow that may alter the natural hydraulic and thermal state of the reservoir. Because these idle wells will need to be plugged and abandoned, the incremental cost of included fiber optic cable is almost negligible. Consequently, extremely valuable data on reservoir hydraulics could be obtained for a relatively low cost. These data are dynamic. Cross-hole measurements can be made whenever the field injection scheme is altered to verify reservoir conformance.

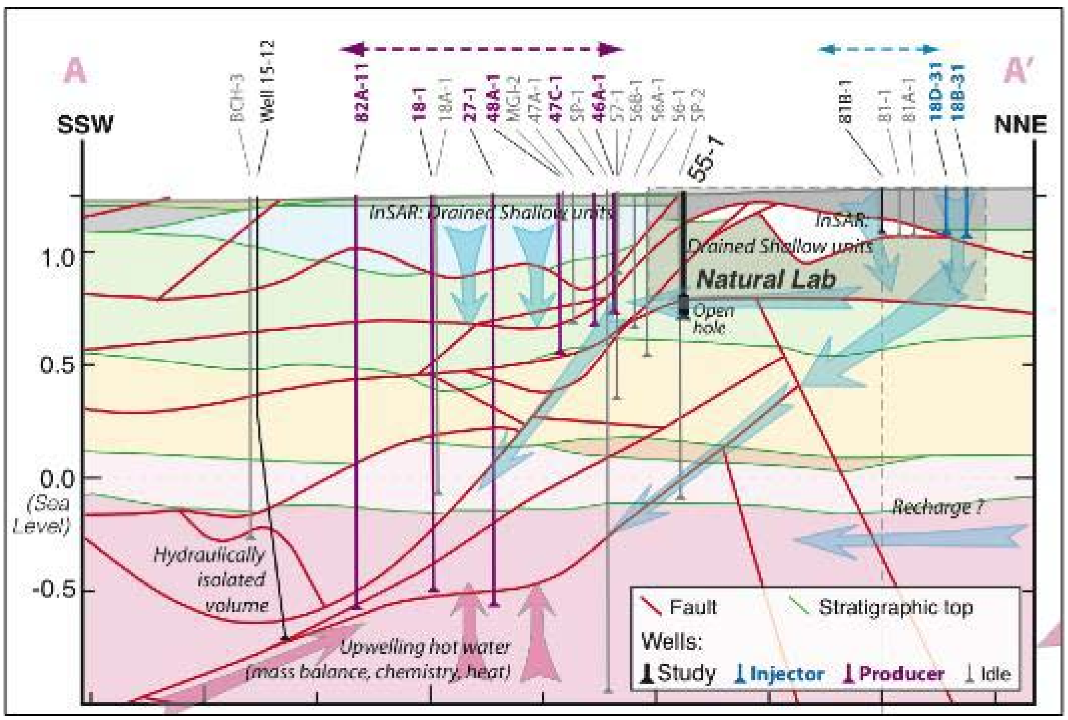


Figure 15. Vertical cross through the Brady Hot Springs geothermal field illustrating faults and potential fluid connections [*Feigl and Team*, 2017].

Another potential application is monitoring of shallow aquifers. The shallow units currently drained by operations are indicated in light blue in Figure 15. DAS fiber could be installed in these wells outside of casing, in the cemented annulus, or in idle open holes. Because the period of the pulsing in injection wells would be known, any response with that same frequency would be a strong indicator that the injection fluids are escaping to shallow units. Such detection is often difficult to note with confidence because many competing influences can cause pressure changes in shallow formations [*Sun et al.*, 2015]. A characteristic frequency is something of a "smoking gun," indicating that geothermal injection is not contained. DAS, consequently, has potential for monitoring reservoir security in addition to its potential for monitoring reservoir conformance.

There remains some gaps between the results of this work and confident application in geothermal fields. First, the strain measured by DAS has not yet been calibrated against standard strain measurements. We are currently constructing laboratory tests to evaluate DAS strain against differential variable reluctance transducer (DVRT) strain meters as part of a DOE Small Business Technology Transfer (STTR) project. Second, the influence of cable construction was found to affect strain measurement but the magnitude is not known. We are testing various cable constructions in these STTR tests. Third, we have not yet tested the potential influence of borehole cementing on sensing. We have performed simulations to address this (e.g. Figure 14) but a field test is required to understand the strain transfer from formation to cable. We will propose such tests for a follow on Phase II STTR project, to be conducted also in at the Mirror Lake site. In general, however, the technology is ready for deployment in an operating geothermal field.

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