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A Slimhole Approach to Measuring Distributed Hydromechanical Strain in Fractured Geothermal Reservoirs

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ABSTRACT

Because many fiber optic sensors are fully functional when cemented into boreholes, they are obvious candidates for deployment in boreholes that need to be sealed and/or abandoned. Exploration slimholes that are not converted to production wells, and production wells that are to be abandoned, are obvious candidates for such installations. Many new fiber optic sensors are coming online but in this article the focus is low-frequency dynamic strain sensing through the use of distributed acoustic sensing (DAS). The transfer of strain between formation and borehole is investigated through geomechanical simulations and DAS strain sensing tested in a shallow crystalline bedrock. Simulations indicate that strain transfer between hydraulically impacted fracture zones are localized below the spatial resolution (gauge length) of DAS systems. Field tests demonstrate that strain in a fracture zone can be localized and measured in a fiber optic cable so long as it is mechanically coupled to the formation. The method requires an oscillatory hydraulic forcing to strain the fracture for it to be measured by DAS. In the field experiments, this was accomplished by alternating pumping and injection at a companion borehole 30 m distant from the borehole equipped with the DAS fiber. Strain signals were reliably measured above a noise of 10 picostrain in response to head changes less than 2 mm of water. These results suggest that DAS sensing of a fiber optic cable cemented into a geothermal borehole would be capable of measuring periodic hydraulic responses from an injection or pumping system a great distance from the monitoring borehole, dependent upon the magnitude and frequency of the hydraulic oscillation. Using a slimhole, reservoir connectivity could be imaged over many depths. This could be accomplished using the same fiber-optic cable installed for DAS seismic monitoring or distributed temperature sensing (DTS).

1. INTRODUCTION

Establishing sufficient hydraulic circulation is fundamental to enhanced geothermal systems (EGS). Hydraulic connectivity among injection and pumping wells may be accomplished through pulse interference or tracer tests, but neither of these methods can localize the geologic structures (e.g. fracture zones) that are responsible for the connectivity. Hydraulic structure is usually derived from hydraulic connectivity by applying independent mapping of geologic structure from borehole logging to observed hydraulic response. The perceived permeability may be divided into some number of potentially permeable zones using fracture frequency and orientation analysis, for instance. More recently, microseismic imaging during stimulation has been used to map connective structures. However, fracture zones that are stimulated do not necessarily flow during circulation between injection and pumping.

The strategy proposed here is to make use of former exploratory holes (slimholes) or idled production wells, by cementing in fiber optic (FO) sensors along the entire borehole. Because the sensors can be utilized in sealed boreholes, they extend the utility of otherwise idled boreholes while minimizing risk to cross-contamination and regulatory actions. For example, temperature can be monitored using distributed temperature sensing (DTS), strain using localized or distributed fiber-based methods [*Bremer et al.*, 2010] and seismic energy through distributed acoustic sensing (DAS) [*Daley et al.*, 2015; *Parker et al.*, 2014] all in the same borehole.

Here, we focus on distributed strain sensing through the use of DAS. Although there are other FO-based methods of strain sensing, we utilize DAS because of its proven value as a seismic/acoustic sensor and its ability to provide monitoring over the entire borehole length. Concerns with seismic activity associated with EGS makes it highly likely that DAS will be utilized more commonly as a downhole geophone in EGS systems. Additionally, we have demonstrated that DAS systems can measure extremely small periodic strains in rock. Strains of less than one nanometer/m have been measured in the laboratory and in field tests [*Becker et al.*, 2017a; *Becker et al.*, 2016; *Becker et al.*, 2017b] .

In this article we investigate the transfer of strain from a fracture in a rock formation to a FO cable embedded in a cemented wellbore, and demonstrate in the field how strain can be localized and measured using DAS. It is important to note that DAS can readily quantify only periodic strains. Consequently, the reservoir needs to be strained through oscillating injection or pumping. This can be done during normal operation of a reservoir, however [*Sun and Nicot*, 2012; *Sun et al.*, 2015]. The measurement of DAS strain in slimholes can, therefore, serve as a real-time measurement of hydraulic response during geothermal operation.

2. BACKGROUND

The principals of DAS are well documented in the published literature [*Daley et al.*, 2015; *Johannessen et al.*, 2012; *Li et al.*, 2015]. The system consists of a FO cable, usually with single mode fiber, connected to an interrogator unit. The interrogator uses phase demodulation of a laser signal to measure strain rate along the cable. This is accomplished over a specified gauge length (e.g. 10 m). Time of flight is used to position the signal along the cable. Typically, sampling is made at a frequency of 1 kHz or greater to sample vibrations of frequencies between Hz and kHz. More recently, greater attention has been paid to the low frequency component of this signal which represents diffusive strain rather than inertial energy transport [*Jin and Roy*, 2017]. Low frequency (<1 Hz) components suggest the movement of fluid in fractured rock systems, for example.

Multiple field studies have demonstrated the application of DAS in boreholes for seismic applications [*Daley et al.*, 2015; *Ghahfarokhi et al.*, 2018; *Jin and Roy*, 2017; *Parker et al.*, 2014]. The key to data quality is to couple the dynamic strain in the formation and the cable [*Daley et al.*, 2015]. For example, the cable can be run within a production well cemented behind casing, clamped to production tubing, or run along a wireline, for example [*Li et al.*, 2015]. Of these methods, however, only cementing behind casing seems to produce good data quality for seismic applications [*Munn et al.*, 2017]. Cement provides a strong inertial and strain coupling that transmits formation behaviors to the cable.

Geothermal systems present particular challenges for FO sensing in general, and DAS in particular. The extreme temperatures and pressures of geothermal systems pose a problem for fiber longevity. Advancements in FO construction appear to be overcoming some of these limitations, however [*Paulsson et al.*, 2014]. The construction of the cable, which protects the glass fiber, is an important consideration. The glass fiber must be protected from water because hydrogen tends to break down the refractive index profile of optical fibers, resulting in “hydrogen darkening”. Glass fiber is, therefore, always protected by at least one stainless steel tube and, for deep applications, sometimes multiple steel tubes. In addition to the sealed steel tubing, a hermetic carbon layer, and hydrogen scavenging gel are often used to protect the fiber from darkening. This gel is a poor transmitter of strain. Field tests have shown that a tight buffered design, which uses a solid material to surround the glass fiber, produces better strain transmission for both high [*Munn et al.*, 2017] and low frequency [*Becker et al.*, 2017b] sensing. In general, there is a potential trade-off between efficient strain transmission and cable design. Fiber is typically overstuffed in metal tubing to prevent damaging strain during deployment and to compensate for the thermal expansion coefficient differential between steel and glass. While the excess fiber length (EFL) may reduce the risk of damage, it may also reduce measurement sensitivity to strain. Nevertheless, as we show here strain can be measured in less than optimal cable design.

Geothermal exploration can involve the drilling of slimholes prior to or in addition to large-diameter production sized wells. Slimholes are often preferred in the early stages of exploration and development because of reduced rig size, reduced cost, and reduced loss of drilling circulation [*Combs et al.*, 1999; *Nielson and Garg*, 2016]. Estimates of cost savings vary by site of course, but the cost of a slimhole can be only 60% of the cost of a full production well and substantially reduces the surface footprint due to reduced mud volumes [*Combs et al.*, 1999]. After coring and borehole geophysics, slimholes are often abandoned. Production wells that do not produce are either abandoned or left open and unused. With FO sensing, these boreholes have tremendous potential for long term temperature, strain, and seismic monitoring even after they are cemented.

3. METHODS

3.1 Simulations

Geomechanical simulations were conducted to understand strain transfer from a rock formation to a FO cable cemented into a slimhole. These simulations were conducted in COMSOL™, a multiphysics finite element simulator. The simulation was radially symmetric, i.e. 2-D in the radial dimension. The construction of the fiber optic cable itself was not simulated because there was insufficient information regarding the material properties of cable construction. All of the materials were assumed to behave linearly elastic because of the small strains and long time periods involved. The cement was assigned a Young’s Modulus of 25 GPa, a Poisson ratio of 0.33, and a density of 2300 kg/m^3.

The influence of a dilating fracture on a vertical cement-filled borehole was simulated by displacing the outer boundary 1 nm vertically upward and 1 nm vertically downward. The scenario simulates two blocks of rock parted by an increase in pressure in a horizontal cross-cutting fracture (Figure 2). Corresponding displacement was measured at the center of the borehole to represent displacement that would be induced on a FO cable centered in the borehole. For simplicity, the cable diameter is considered to be zero.

3.2 Field Tests

Field tests were conducted at the Mirror Lake Fractured Rock Hydrology site, within the Hubbard Brook Experimental Forest. 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 peletic 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 less than 10 meters in length, so permeability and transport is along interconnected fractures and fracture zones [*Becker and Shapiro*, 2000; 2003; *Hsieh and Shapiro*, 1994].

To conduct periodic hydraulic tests, FSE 6 was subjected to alternating pumping and injection to create either periodic step or sinusoidal hydraulic signals. This was accomplished using two variable speed pumps (Grundfos RediFlo2) controlled by two programmable variable speed controllers. *Rasmussen et al*. [2003] used a similar setup to conduct periodic hydraulic tests in unconsolidated sediments. A tank located near the wellhead was used to store water for reinjection. Flow meters up hole and down hole were used to assure that the injection and pumping rates were kept equivalent during the tests. For the results discussed here, periodic step tests were used. In the periodic step tests, pumping and injection were alternated at a constant rate of about 15 L/min. Period step tests were conducted with oscillation periods of 2, 4, 8, 12, and 18 minutes, with the first half-period pumping and the second half-period injecting. During the oscillation of flow in

FSE 6, heads were recorded in FSE 6 and the 5 monitoring wells using pressure transducers. The difference between maximum and minimum head in FSE 6 ranged from about 2 m for the short period (2 min) tests to about 7 m for the long period (18 min) tests.

In FSE6, FO cable was mechanically coupled to the borehole wall using an overpressured flexible (FLUTe^{TM}) liner used also 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 (Figure 1). 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].

Two FO cable designs were used in the lined FSE10 borehole, hung side-by-side. The first was a fiber-in-metal-tube (FIMT) cable containing multimode fiber for DTS and single mode fiber for DAS. 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 solid filling material rather than gel.

The position along the FO cables were converted to well depth using reference temperature pulses at the top of the well casing. Because the DTS measurements have a spatial resolution of 29 cm, and the DTS and standard DAS FO cable are co-located, the depth control on the DAS cable was within 29 cm. Strain rate was converted to strain by integrating with respect to time [*Daley et al.*, 2015]. For our data, this conversion resulted in a nearly constant multiplier such that strain could be obtained from strain rate without signal degradation. Overall, the process path followed was to (1) clip the data to the well of interest, (2) convert strain rate to strain, (3) perform a digital Fast Fourier Transform (FFT) to inspect the frequency response for the entire signal and for each channel, (4) calculate the mean response for a 5 channel (+/- 0.5 m) window about the fracture depth, (5) perform a high pass then a low pass IIR filter to remove drift and high frequency vibration noise, respectively, (6) fit a sine function to the filtered response to obtain DAS strain amplitude. Originally, we used the FFT to obtain amplitude magnitudes, but this approach was affected by spectral leakage and was abandoned in favor of the sine fitting. The final result is a time-series measurement of strain at each recorded channel along the FO cable.

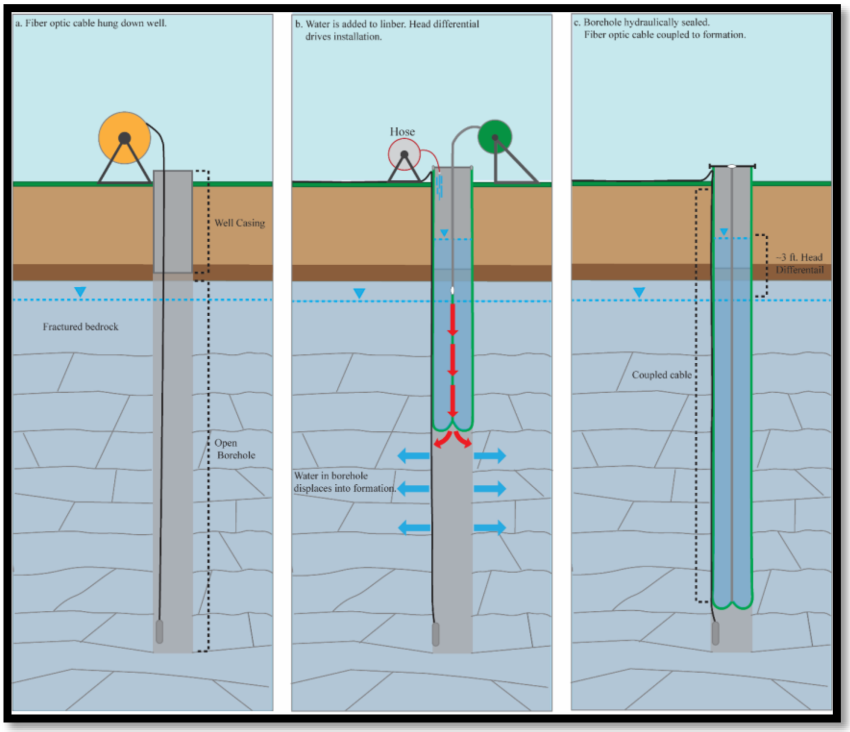

Figure 1 Sequence illustration of how fiber optic cable was mechanically coupled to the borehole walls.

4. RESULTS

4.1 Simulations

A geomechanical simulation of strain transfer between a fractured formation and a cement-filled borehole is shown in perspective in Figure 2 . The displacement magnitude in the z-direction (vertical) is shown by the rainbow color scale. For the example shown, the borehole is assumed to be 50 cm (20 in) in diameter. A strain shadow is clearly evident at the location of the fracture. Displacement of the top and bottom of the rock blocks 1 nm up and down, respectively causes a strain on the cement in the borehole. Borehole diameters of 10 to 50 cm were tested and the strain shadow width increased linearly with diameter (Figure 3). If the width of the strain shadow is defined as the height above and below the fracture at which displacement is 90% of the induced displacement (0.9 nm) then the strain shadow was consistently 2.8 times the diameter of the borehole. This suggests that the zone of straining in response to a single fracture dilation is about 3 times the diameter of the borehole.

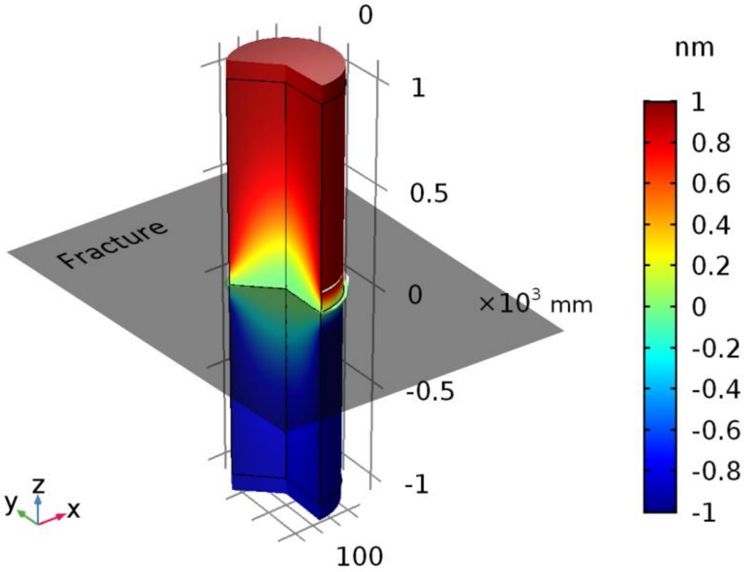

Figure 2 Simulation of displacement in a 50 cm diameter cemented borehole strained by +/- 1 nm fracture displacement at Z = 0

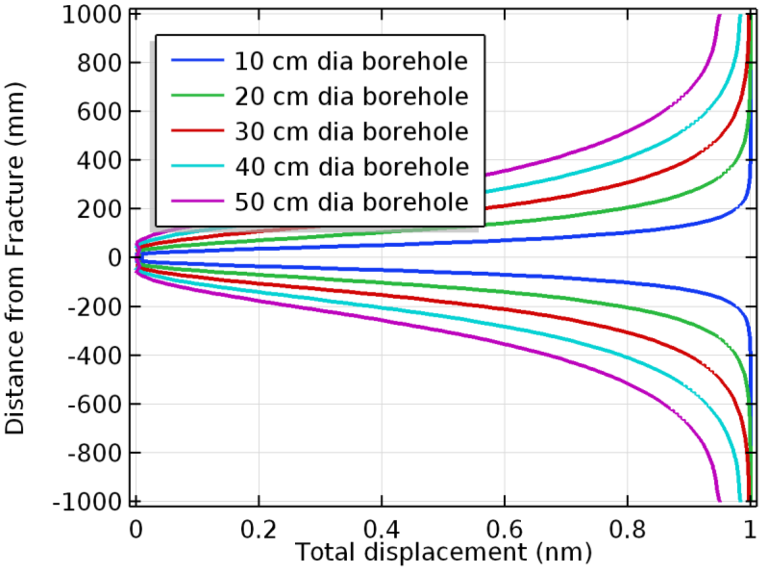

Figure 3 Displacement measured at the center of the simulated cement-filled borehole.

4.2 Field Tests

The head response measured at the fracture and corresponding strain measured by DAS in the standard loose-tube cable are shown for the 18 min pumping period in Figure 4. The deepest 30 channels (7.5 m) were stacked to enhance signal to noise. Additional stacking did not produce a markedly better response. The stacked response was processed using a low-pass Butterworth digital filter to remove noise 20% above the imposed frequency. Strain was measurable in all tests conducted. Heads measured in FSE 10 with a pressure transducer had amplitudes ranging between 1.3 mm (2 min period) and 56 mm (18 min period) [*Becker et al.*, 2017b].

The period-specific amplitude of the strain response was computed for all channels corresponding to depths within the lined FSE10 borehole. A sine function was fitted to each of the responses to obtain amplitude and phase. The exercise was completed on both the standard and strain cables. Amplitudes are plotted versus depth in Figure 5. Note that the amplitudes are very high above the water level in the liner because the DAS is picking up acoustic noise where it hangs freely in the wellbore. The strain response increases in the vicinity of the hydraulically strained fracture as indicated by the acoustic televiewer log at right [*Johnson and Dunstan*, 1998]. Strain responses begin when the straining fracture is within the gauge length of measurement (10 m) and peak when strain is centered within the gauge length. Note the asymmetry in the strain response due to the bottom of the liner at 30 m. Below this depth the cable is not mechanically coupled to the borehole wall and, therefore, does not sense strain.

Both cables showed an increase in strain response near the fracture zone but the tight buffered (strain) cable produced about 2x the magnitude in strain response of the loose-tube (standard) cable (Figure 5). Both cables produced similar noise levels of about 10 picostrain 10 m above the fracture zone. The strain in the tight-buffered cable appears to be more localized than that in the loose-tube construction. This is expected as the loose-tube construction is designed to allow the fiber to slip with in the metal tube to prevent damage. Although both cables provide acceptable signal to noise, better results are obviously obtained with the tight-buffered construction.

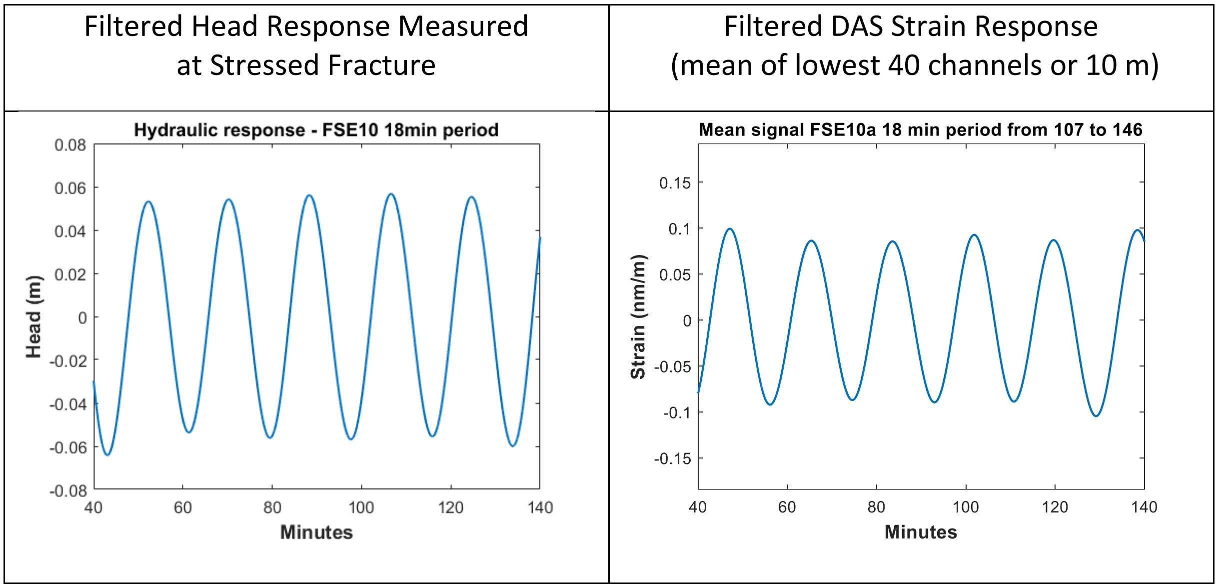

Figure 4 Sample response of pressure at the fracture and DAS measured strain for an 18 in period pumping oscillation.

5. DISCUSSION

Simple geomechanical simulations conducted in COMSOL showed that strain is readily transferred through cement in a borehole, with a strain shadow that is about three times the diameter of the borehole. Given that the gauge length of DAS systems is about 10 m, this localized strain will not be significant. The DAS will sense the opposite displacement of rock blocks above and below the fracture (assuming a vertical borehole) rather than strain in the fracture itself. There is not reduction in strain between the fracture and the fiber. The outside of the FO cable, if coupled to the cement in the borehole, will receive the same strain as the rock.

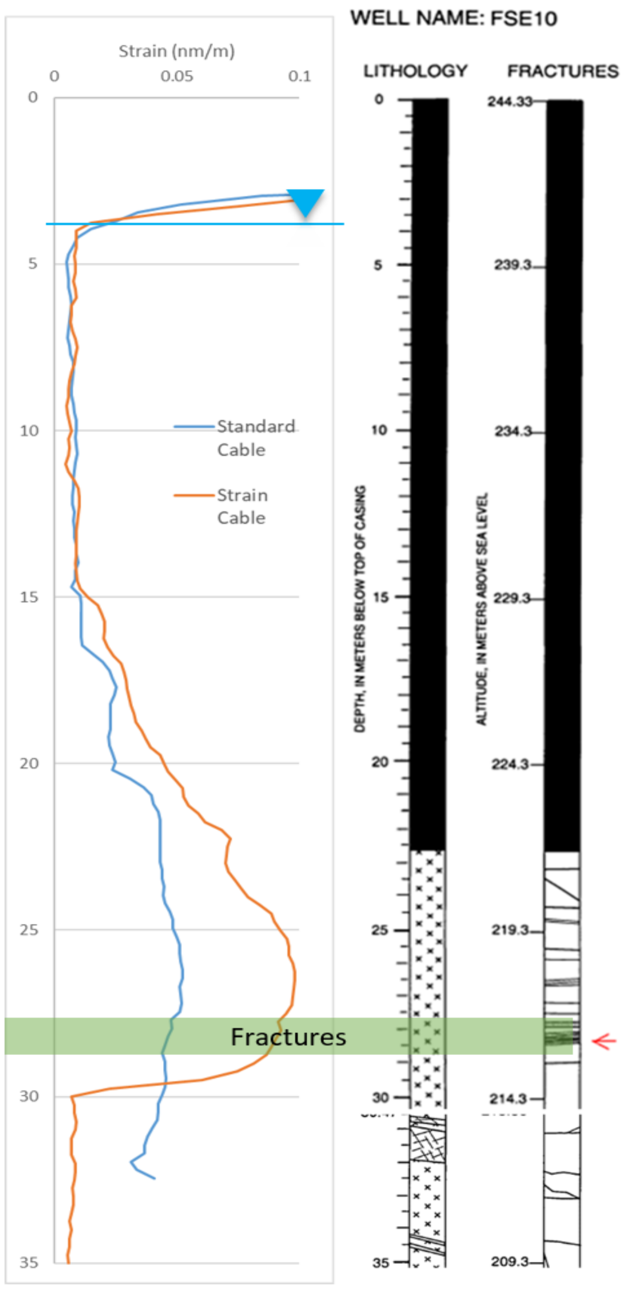

Figure 5 DAS strain amplitude measured along loose tube (standard) and tight buffered (strain) FO cable. The known depth of fracture communication is indicated in green.

These field experiment demonstrate that strain can be sensed at extremely small magnitudes, provided the strain signal is periodic. The noise level in this shallow environment was about 10 picostrain. Strong signals in strains were measured at about 50 picostrain. These measurements were made in a near surface environment and the fiber was coupled to the formation only with a flexible membrane liner. Fibers coupled to the borehole through cement in deep environments may result in an improved signal to noise ratio.

It is important to note that these strains are measureable only when they are periodic. DAS is designed to measure periodic acoustic strains and its native measurement is strain rate. For this reason, longer periods result in reduced sensitivity. The longest period tested in these field experiments was 18 min. Strains resulting from longer periods could certainly have been measured, but the maximum measurable period has yet to be determined. We are currently performing laboratory tests to determine the performance at periods of ½ day. At these periods, earth tides can be sensed which would offer an enormous advantage for DAS strain sensing.

The measured strain response is clearly a function of cable design. This relationship is demonstrated by the fact that a tight-buffered cable was twice as sensitive to strain as a loose-tube cable. However, it is interesting to note that the loose-tube fiber is still sensitive to strain, even though the glass fiber moves within the metal tube. In addition, the strain response in the loose-tube construction seems more distributed than that in the tight-buffered construction. It may be that similar strains would can be sensed in both cables but the strain is distributed over a longer distance in the loose-tube cable. Unfortunately, our 25 m of sensing was small compared to the 10 m gauge length so the ultimate distribution of strain in the FO cable could not be evaluated. It is worth noting that new DAS systems have been tested to be 100 times more sensitive to dynamic strain (e.g. Silixa Carina system) than the iDAS system used in our experiments. With the improved system we might have been able to sense at much longer periods and lower strains.

Clearly more work is necessary to understand the coupling of strain between formation and FO cable. Laboratory studies have looked at this coupling in seismic frequency range by comparing accelerations inferred from DAS and measured by seismic point receivers [*Papp et al.*, 2016]. Similar studies are needed in the low-frequency (<1 Hz) range. Coupling between cement and FO cable, and through the cable to the glass optical fiber need to be quantified at various frequencies. Laboratory experiments of strain in DAS FO cable in response to fluid pressure suggest that strain response may be frequency dependent [*Becker et al.*, 2017a]. Frequency dependency may occur if buffering material behaves plastically at slower strains.

6. CONCLUSIONS

Instrumentation of cemented slimholes or production wells with fiber optic sensors is an attractive way to add value to boreholes drilled in geothermal fields. Installation of cable for distributed temperature sensing (DTS) seems like an obvious minimum installation before cementing and abandoning a borehole. This same cable can be used for DAS if it is constructed such that strain can be transferred from the cement to the glass fiber. In addition, DAS systems are typically optimized for single-mode fiber while DTS is optimized for multi-mode fiber. However, both types of fiber are readily incorporated into the same FO cable construction. Other fiber sensor systems are coming on line which can also be included in cemented slimholes or production wells. These include Fiber Bragg Grating strain sensors for which high temperature versions have already been demonstrated [*Bremer et al.*, 2010; *Paulsson et al.*, 2014].

The DAS technology discussed here responds to periodic strains. The need to impose a periodic strain is an obvious disadvantage to the method, which may or may not be offset by its extremely low signal to noise. Periodic hydraulic signals have been suggested as of late for a variety of applications. It has long been used for pulse interference test in the petroleum industry operations [*Hollaender et al.*, 2002] and has become increasingly popular for characterizing the hydraulics of freshwater bedrock systems [*Guiltinan and Becker*, 2015]. Because a periodic hydraulic signal is characteristic of a source, periodic hydraulic tests have been suggested for use in leak detection at for both borehole construction and geologic confinement [*Sun et al.*, 2015]. If DAS technology continues to improve, periodic strain in response to earth tides may be measurable. In fact, it may already be possible with more recent systems on the market but this has yet to be field tested.

Because DAS measurement of low-frequency rock strain has only so recently been demonstrated [*Becker et al.*, 2017b] , more work is required to make it a reliably quantitative tool. The field tests described here make clear that cable construction has an impact on the strain sensitivity. The more the glass fiber slips within the construction, the less the strain transfer from the surrounding environment, and the more difficult the localization of strain in the cable. Because excess fiber length (EFL) is commonly built into a FO cable designs to prevent fiber breakage, there may be a trade-off between strain sensitivity and the robustness of the cable. For high-temperature geothermal systems, additional casing and protection may exasperate this problem. Based upon simulations discussed here, strain transfer through borehole cement should not be a problem.

The discussion here focuses on fiber optic DAS strain sensing. If distributed temperature sensing is combined with DAS seismic and DAS strain sensing, then reservoir temperature, hydraulic-connectivity, and seismic activity could be monitored in a single borehole. Because this borehole could be cemented it may be considered permanently abandoned and, therefore, removed from regulatory consideration. Cemented boreholes also eliminate concerns of cross-contamination with shallow aquifers. Demonstration of such a system at a geothermal reservoir is currently feasible and certainly seems warranted.

7. ACKNOWLEDGEMENTS AND DATA AVAILABILITY

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