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Fracture Tracer Injection Response to Pressure Perturbations at an Injection Well

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ABSTRACT

The EGS Collab project constructed an approximately ten-meter scale field site where fracture stimulation and flow/transport models can be validated against controlled, in-situ experiments. The first multi-well experimental site was established at the 4850 level of the Stanford Underground Research Facility (SURF) in the Homestake Mine located in South Dakota. Hydraulic fractures were created at an injection well drilled sub-horizontal from the drift. A flow system was established in one set of fractures by injection water at approximately 400 ml/min between a set of packers 164 feet from the drift wall in the injection well through a hydraulically stimulated fracture. Injected water was recovered from five locations in 4 nearby wells. From the end of October to the middle of November of 2018, a series of fracture characterization tests were conducted using a series of 10 tracer tests (7 which used C-dot and chloride as conservative solute tracers) to assess the flow pathway in the stimulated fracture. The injected tracers were detected in three of the five water production locations where the total water recovery ranged from approximately 50 to 80% of the injected water depending on the day the test was being conducted. Analysis of a series of tracers during this two-week period suggest a large change in the flow fracture field occurred during this testing period. A comparison of the tracer breakthrough curves at the production well showed a marked decrease in the initial and peak concentration over time, whereas the OB well exhibited an increase in the initial and peak concentration arrival during this fracture characterization testing period. These changes are believed to be in response to a number of higher-pressure short-term injections at the injection well in early November (2^{nd} to the 6^{th}). Results of this testing suggest that the fracture flow pathways can be altered as a result of the pressure perturbations in the injection well on the integrity of adjacent monitoring wells. Results from the EGS Collab project will support the DOE Geothermal Technology Office FORGE and other EGS development efforts.

1. Introduction

Enhanced or engineered geothermal systems (EGS) offer tremendous potential as a renewable energy resource supporting the energy security of the United States. The EGS Collab project was initiated by the DOE Geothermal Technologies Office (GTO) to facilitate the success of FORGE (https://www.energy.gov/eere/forge/forge-home). This project will utilize readily accessible underground facilities to refine our understanding of rock mass response to stimulation at the intermediate scale (on the order of 10 m) for the validation of thermal-hydrological-mechanical-chemical (THMC) modeling approaches as well as novel monitoring tools. The project is a collaborative multi-lab and university research endeavor bringing together a team of skilled and experienced researchers and engineers in the areas of subsurface process modeling, monitoring, and experimentation to focus on intermediate-scale EGS reservoir creation processes and related model validation at crystalline rock sites (Kneafsey et al., 2018).

The Sanford Underground Research Facility (SURF) in Lead, South Dakota hosting the EGS Collab project experimental site is located in the former Homestake gold mine and is operated by the South Dakota Science and Technology Authority. The SURF facility offered the EGS Collab project unique opportunities with respect to the accessibility of rock under relatively high in-situ stress conditions with supporting infrastructure, such as electrical power, water, working conditions, and internet. The Collab Experimental 1 testbed was located near the kISMET site on the 4850 level, providing the project with immediately available data on geomechanical stress conditions and thermal profiles around the drift. Two sub-horizontal boreholes were drilled in the direction of the minimum principal stress orientation and are being used as an injection (E1-I) and extraction (E1-P) wells nominally 10 meters apart (Figure 1). A notching technique was used in the injection well in an attempt to stimulate the fracture such that it would initiate and continue to propagate perpendicular to the injection well and eventually intersect the production well. The experiment designed called for a double packer to isolate the fracture intersection at both the injection and the production well (see Knox et al. 2017). It was anticipated that a continuous flow loop could be established through the hydraulically stimulated fracture between the injection and the production wells and that the fracture could be characterized using chemical tracers at a variety of flow rates and back pressure conditions (see Ingraham et al. 2018).

After hydraulic fracturing, three locations were connected to the injection well sufficiently to detect tracers injected in the influent. To initially characterize the fracture system, ten tracer tests were conducted between October 24 and November 14th, 2018. Mattson et al. (2019) discusses the injection and data analysis of these tracer tests. This paper discusses seven conservative solute tracer tests composed of C-dots and chloride and the inverse modeling results using the convective-dispersion model, CXTFIT2 (Toride et al., 1995) in the USDA's STANMOD version 2.2 package (Simunek et al.).

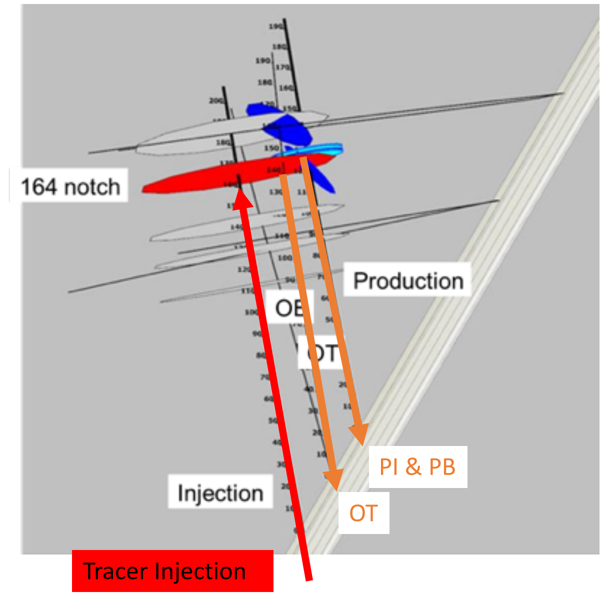

Figure 1: Plan view of the Collab experiment 1 site showing the drift tunnel, and location of the injection well, the 164 notch, and the three tracer sampling locations discussed in this paper.

2. Methods and Discussion

Seven conservative tracer tests using C-dots and chloride were conducted during the October/November fracture characterization campaign. Water was injected (constant rate of 0.4 L/min) at the 164 notch of the injection well and tracer was noted in the effluent at three locations in the drift. Mattson et al. (2019) discusses the variation in the tracer injection methods between tests. A standard tracer injection method has been used since the November 7th test. Effluent is generally taken as a grab sample in 12 ml vials and analyzed on site with a fluorometer. After hour samples were collected using fraction collectors and these samples were analyzed generally the next day. Ionic salt tracers were analyzed from samples brought from the field to a laboratory.

2.1 Conservative Tracer Comparison

These tracer test used both chloride and C-dots as conservative tracers. The C-dot nanoparticle tracer consists of a carbon core decorated with a highly fluorescent polymer 3-5 nm diameter particles. Since C-dots are detectable by a fluorometer at the Collab field site and they have been previously been used at the Altona field site in New York (Hawkins, 2016), they have been most often used in these tests. One question that comes up is are C-dots really conservative? Although other conservative solute tracers (e.g. bromide and iodide) have also been co-injected with the C-dots however these solutes have not completed analyses so a direct comparison of a single injection cannot be made at this time. Our best comparison for the Collab experiment are C-dot and chloride breakthrough curves for two Collab tracer tests that were conducted on consecutive days (Figure 2). Although not exactly perfect matches, the timing, shape are similar enough to suggest that the C-dots likely behave as conservative tracers at this field site.

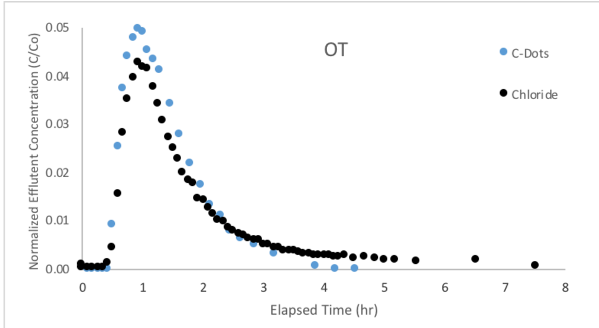

Figure 2: Comparison of the November 8th C-dot (blue) and the November 9th chloride (black) tracer breakthrough curves at the OT monitoring well.

2.2 Tracer Breakthrough Curves

Figures 3 and 4 show the tracer breakthrough curves for the three tracer producing sampling ports. Due to the high density of data, individual data points are not shown on these figures and the breakthrough curves are represented by colored lines. Figure 3 is the normalized concentration (i.e. the sample concentration divided by the injection concentration) as a function of time after injection. In general, the tracer breakthrough curves exhibit a fairly classical sharp rise to a peak followed by a long tail format. Some of the early tracer tests exhibit sharp peak attributed to a sampling interval that was not fine enough to clearly capture the initial breakthrough in detail. Revision to the sampling schedule assisted in better defining the initial breakthrough and peak concentration time.

Although these time series of tracers curves do not immediately display a trend, one interpretation of the data suggests a change in the curves after the November 2-6 pressure purges. These purge events were deemed necessary because the injection pressure at the injection well was increasing at a rate that would not allow for long-term steady state fracture characterization testing. A number of short-term injection well pressure (and flow) increases were performed in an attempt to clear the near well injection pathways of possible mineral/biological residue. This action was generally a success but the pressure appears to have altered the injection pathways for the post purge event tracer tests.

The effluent production rate from the wells varied between tests as well as between the sampling ports within each test. Figure 4 attempts to address these variable flowrates at the production intervals by plotting the tracer concentration as a function of the cumulative water recovered for each sampling port. During a single test the flow rate at any sampling port does not change significantly and has been assumed to be a constant value for these figures. OT (Figure 4 lowest plot) illustrates the greatest change in the position of the tracer breakthrough curve. Tracer breakthrough for test conducted before the purge events exhibit tracer breakthrough with a lower peak concentration (i.e. the blue, red, and black lines) than do the tracer breakthrough curves after the purge events (i.e. the yellow, magenta, green, and purple lines) at a lower volume. The flow rate from the OT monitoring well increased about 6-fold after the purge events (see Figure 5).

Figure 5 illustrates the flow rate that was produced at each production location that exhibited a tracer breakthrough curve. Prior to the purge event, most of the water was produced at PI and PB. After the purge event, most of the water was produced at the OT well.

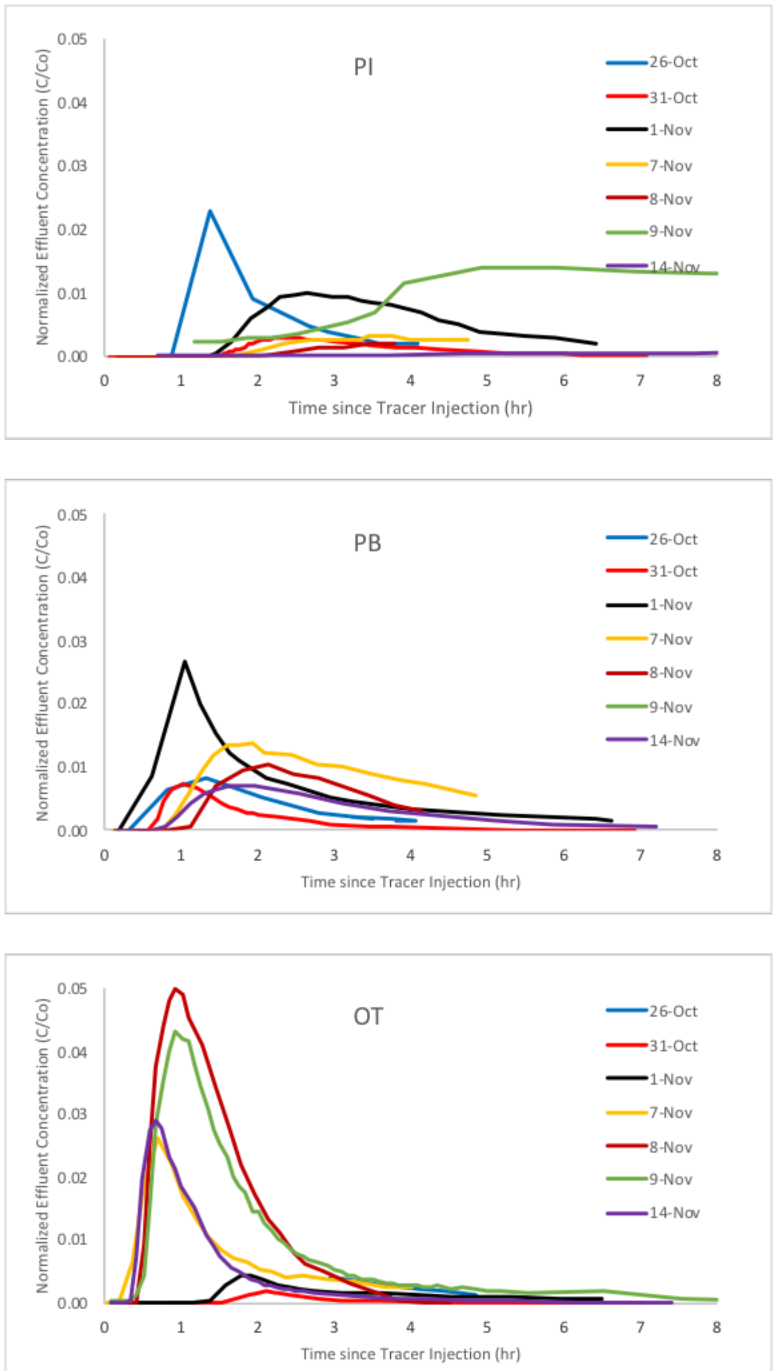

Figure 3: Tracer breakthrough curves for the first 8 hours after tracer injection at the production interval (PI), below the production interval packer (PB), and at the orthogonal top (OT) monitoring well for the seven tracer tests.

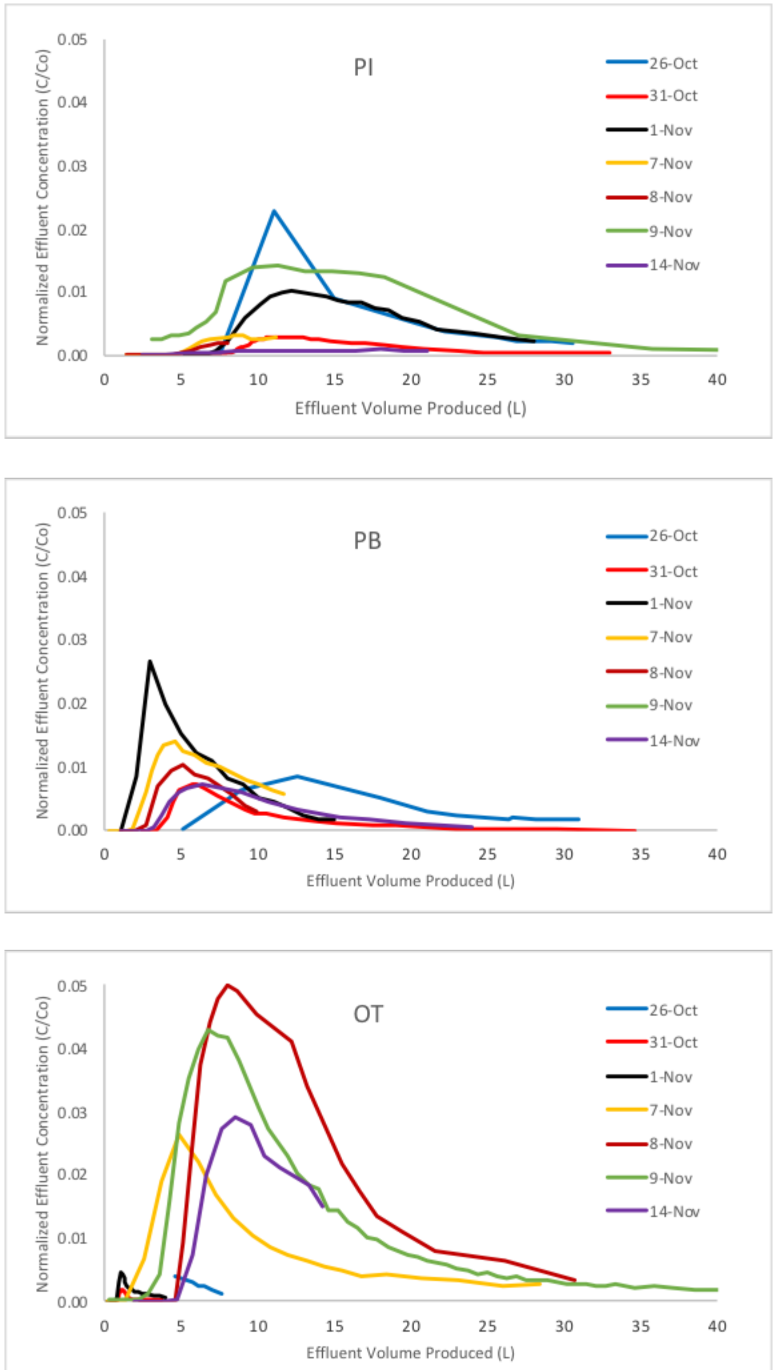

Figure 4: Tracer breakthrough curves as a function of effluent produced at the production interval (PI), below the production interval packer (PB), and at the orthogonal top (OT) monitoring well for the seven tracer tests.

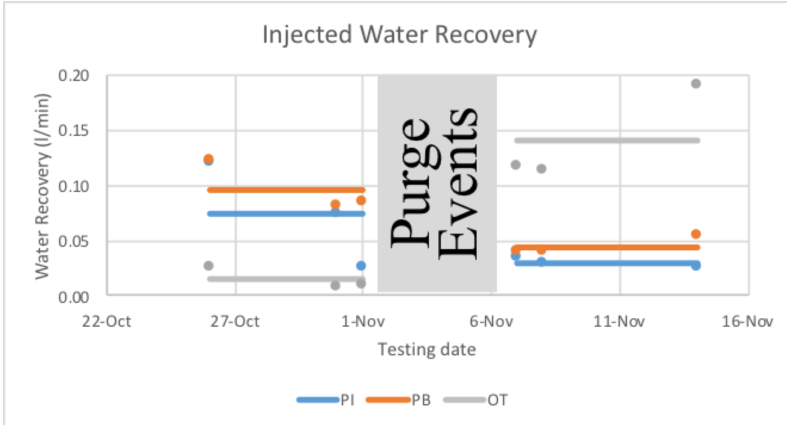

Figure 5: Water production rates for PI, PB and OT during the fracture characterization study using tracers.

2.3 Inverse Model

The CXTFIT software package used was a modified and updated version of the CXTFIT code of Toride et al. (1995) for estimating solute transport parameters using a nonlinear least-squares parameter optimization method and was used to solve the inverse problem by fitting the one-dimensional convection-dispersion equation (CDE), to experimental results. Velocity, dispersion and tracer mass were used as fitting variables to the tracer data. The shortest distances between the 164 notch in the injection well to the OT monitoring well (7.4 m) and production well (8.8 m for both PI and PB) were used. Injection time was set to 5 minutes for all injections. Some uncertainty in the injection time for the October tracer tests due to the piston operation sequence of the Quizex pump which likely made the injection time longer than 5 minutes and likely diluted the tracer injection concentration than used in these analyses.

Figure 6 illustrates the November 14th C-dot tracer breakthrough data at the OT monitoring well and the CXTFIT CDE curve fitted to this data. Most fits produced an r^2 greater than 0.94 whereas some of the more incomplete data sets (e.g. Nov 14th for PI) only had an r^2 equal to 0.74. The fit slightly underestimates the peak concentration and long tail of the data but this fit is generally good for such a simple model.

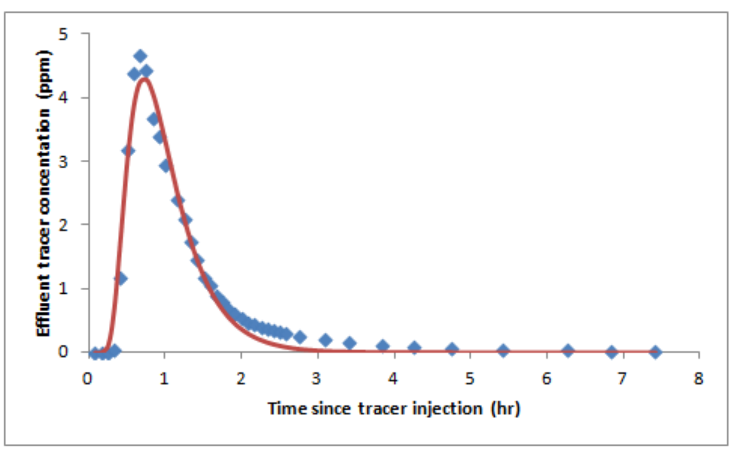

Figure 6: Example of the CXTFIT2 curve fit to the November 14th OT tracer breakthrough curve (blue is the sample data, red is the parameter estimation curve fit).

Table 1 lists the regressed transport parameters for all the October/November tracer test. General observations are: 1) a fairly linear decrease of the tracer velocity in PI during the tracer campaign, 2) a step function change after the purge events in the tracer velocity for PB and OT, 3) better tracer mass recovery for the post purge event tracer tests.

Table 1. Velocity, dispersion and tracer mass fraction inversion results from the CXTFIT analysis of the seven tracer tests (chloride samples were not collected for the PB well).

Date	Tracers	PI			PB			OT			Est. total Mass Recovered
		V (m/hr)	D (m2/hr)	Mass Fraction (-)	V (m/hr)	D (m2/hr)	Mass Fraction (-)	V (m/hr)	D (m2/hr)	Mass Fraction (-)	
October 26, 2018	C-Dots	5.8	1.2	0.22	4.2	7.8	0.21	2.2	1.8	0.16	0.59
October 31, 2018	C-Dots	3.0	1.3	0.07	6.5	4.5	0.09	3.2	0.5	0.02	0.19
November 1, 2018	C-Dots	2.4	0.7	0.37	5.8	7.2	0.38	3.0	1.4	0.08	0.84
November 7, 2018	C-Dots	2.0	1.4	0.14	2.5	4.3	0.58	6.2	9.4	0.33	1.05
November 8, 2018	C-Dots	2.2	0.8	0.06	3.2	2.4	0.28	5.6	4.4	0.74	1.09
November 9. 2018	Chloride	0.9	1.3	0.88	NA	NA	NA	5.3	5.0	0.31	1.19
November 14, 2018	C-Dots	0.0	1.5	0.46	3.1	4.1	0.24	7.8	6.8	0.29	0.99

2.4 Conclusion

Seven fracture characterization tracer tests were conducted at the Collab Experiment 1 field site with either C-dots or chloride as a tracer during the months of October and November 2018. Tracer breakthrough curves were analyzed using an analytical 1D convection-dispersion equation (CXTFIT2) to regress the tracer velocity, dispersion and fraction of tracer mass transport. Transport velocities are less than 10 m/hr and dispersion ranges from 0.7 to 9.4 m^2/hr.

Purging events during the November 2-6, appears to have altered the flow pathways in the experimental site. Flow rates (and tracer transport velocities) dramatically decrease for wells PI and PB whereas well OT increased after the purging events. When viewing the tracer breakthrough curves as a function of cumulative produced water, the fracture that connect the 164 notch to the OT well appears to have grown considerably in size as indicated by the later tracer breakthrough for the after purging characterization tests.

These results may suggest that short term pressurization at the injection well can change fracture flow pathways that may (or may not) be beneficial to heat extraction for EGS systems. These tracer test fracture characterization data is available in the GTO data repository for future model validation efforts and integration with geomechanical, flow and other monitoring data.

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