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Pulse Interference Test (PIT) Conducted at Utah FORGE Enhanced Geothermal Site wells 16A(78)-32 and 16B(78)-32, Milford Utah

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ABSTRACT

The use of pulse interference tests (PITs) to measure reservoir hydraulic parameters has been explored for nearly five decades, with recent utilization in Enhanced Geothermal Systems (EGS). In a PIT, a finite volume of fluid is injected and either pumped back or flowed back under reservoir pressure. This process may be repeated multiple times with different volumes of fluid being introduced. PITs, therefore, have an advantage over recirculation tests for establishing hydraulic structure of formations, in that the volume of hydraulic interrogation can be varied with fluid volume. The test may be tuned, for instance, to evaluate formation near the injection wellbore or farther from the wellbore depending on the injection volume.

PITs were conducted immediately following a 30-day recirculation test at the Utah-FORGE site (Milford, Utah). Injection and backflow were induced in well 16A(78)-32 while pressures were measured in wells 16A(78)-32 and 16B(78)-32 (hereafter referred to as 16A and 16B) during a single day of testing. During the tests, 16B was shut in so variation in formation pressure was measured. The PITs included three pressure pulse periods of 20, 40, and 120 minutes repeated four times each. The recorded periodic hydraulic responses in 16B were miniscule but were resolved through filtering processes at known frequencies of pulses. The ability to extract hydraulic signals from noise using time-series analysis is a significant practical advantage of periodic PITs as small injection volumes can be used.

We used the generalized radial flow (GRF) model (Barker, 1988) to interpret the tests. The GRF allows for an interpretation of the hydraulic responses without assuming the dimensionality of flow within the fracture networks and can be readily adopted to periodic signals. In our presentation here, however, we assume only radial flow (two-dimensional flow) to and from the injection well. We found that the effective hydraulic diffusivity estimated from these tests decreased with increasing injection volume.

1. INTRODUCTION

Pulse interference tests (PITs) were introduced in the 1960s to measure hydraulic connection between injectors and producers in petroleum reservoirs (Kamal, 1983). These tests presented an advantage over a standard injection or pumping tests because multiple pulses could be used to create a diagnostic pressure signal that could be distinguished from trends or noise in pressure measurements (Johnson et al., 1966). Early efforts focused on tests in which wells underwent one or more cycles of pumping and recovery, or injection and flowback, but recently more attention has been given to methods that do not require cessation of operations. In this mode, sometimes referred to as oscillatory or harmonic pulse testing, injection or pumping rates are varied periodically but not entirely stopped (Ahn & Horne). Harmonic pulse testing has found application in geothermal reservoirs (Fokker et al., 2018; Salina Borello et al., 2019). However, more traditional injection backflow tests still have utility for diagnosing developing EGS reservoirs.

Here we present results from a series of periodic PITs conducted in a geothermal well field. In these tests, injection and backflow were alternated multiple times, for a variety of different periods. The period of injection and back flow was varied systematically. Consequently, although these tests were completed during a cessation in circulation, like harmonic tests they were designed to take advantage of processing in the frequency domain. The rationale for varying the hydraulic stress periods is that a range of injection volume, and therefore reservoir interrogation volume, can be applied (Guiltinan & Becker, 2015; Renner & Messar, 2006). This allows for spatial heterogeneity in the reservoir to be assessed as the well's radius of influence intersects features of contrasting permeability and compliance (Cardiff et al., 2013; Fokker et al., 2012).

These tests were carried out at the Utah Frontier Observatory for Research in Geothermal Energy (FORGE) site in Milford, Utah. The FORGE site was developed to conduct research and demonstration related to efficient operation of EGS. In the process of developing an EGS, hydraulic conductivity is increased between the injection and production wells through the use of hydraulic fracturing (reservoir stimulation). Hydraulic testing is a key method by which the success of stimulation efforts is evaluated. Our original intention was to perform periodic hydraulic pulse testing by injecting in well 16A and observing strain response in 16B using fiber optic distributed acoustic sensing (DAS) and distribute strain sensing (DSS). Unfortunately, the fibers installed in 16B were no longer functional by mid-August of 2024. Our tests, conducted in September of 2024, therefore, could be monitored only with hydraulic sensors (pressure transducers) at the wellhead. The work described here is part of a larger project (FOGMORE, Fiber Optic Geophysical Monitoring of Reservoir Evolution).

3. METHODS

3.1 FIELD SITE

The PIT was conducted on the FORGE site located in Utah's southwestern Basin and Range province, within the Milford valley. This extensional basin encompasses the Mineral mountains to the east and the San Franciscan mountains to the west. Stratigraphically, the FORGE site sits atop of basin-fill alluvium and a Miocene aged granitoid-gneiss basement (Simmons et al., 2018). Subsurface geothermal gradients reach temperatures of more than 200°C at the toe of deviated (65° from vertical) injection and production wells, 16A and 16B, respectively. Geothermal gradients narrow westward with respect to depth in proximity to the Opal Mound Fault just west of the FORGE site (Figure 2).

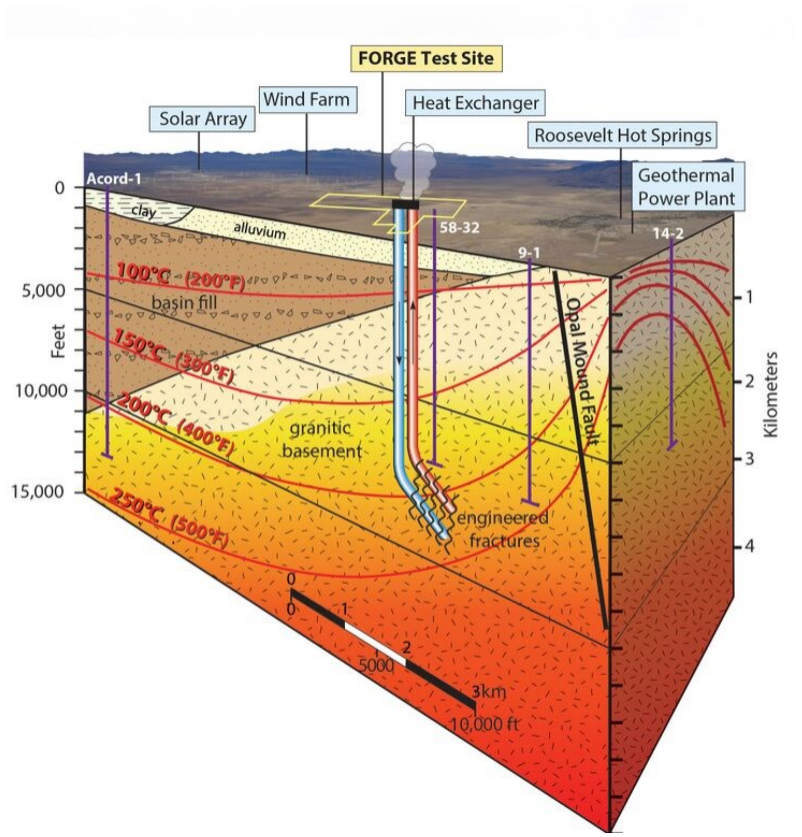

Figure 2: Block diagram of the Utah-FORGE site and its underlying stratigraphy (https://openei.org/wiki/UtahFORGE). The location of the FORGE site sits atop basin fill alluvium and granitoid-gneiss basement. The highly deviated injection and production wells, 16A(78)-32 and 16B(78)-32 are colored blue and red, respectively. Geothermal gradient narrow in proximity to the Opal Mound Fault and Roosevelt Hot Springs.

3.2 PIT EXCECUTION

The 16A-16B well pair underwent two procedures in 2024 including multistage fracture stimulation and a 30-day recirculation test completed in September 2024. Our PITs were conducted over a one-day period directly following the completion of the recirculation test. Execution of the PIT included injection/flowback periods of 20-minutes (10 min injection/10 min flowback), 40 min (20 min injection/20 min flowback) and 120 minutes (60 min injection/60 min flowback) to interrogate outward from the injection well, 16A, with 20-minute and 40-minute shut-in durations between each following period (Table. 1). Injection/flowback rates maintained constant at 105 GPM (2.5 bpm) with the hydraulic injections and manual flowback control being managed by Liberty Energy (Vernal, Utah). Injection parameters including wellhead pressure in both wells, pump side pressures and water injection rates (bbl/min) were monitored using a Pason system with Lime Instruments Software (Version 4.2.0.165 (c)) and flowback was controlled by means of a valve attached to a Nuflo MC-III EXP Flow Analyzer digitally displaying flow rates. To achieve flowback rates identical to injection rates, a manual diversion valve was used to divert flow from injection to backflow. Backflow rates were controlled manually using a ball valve in the discharge line. The intended production well, 16B, remained shut-in throughout the summation of the tests.

Table 1. Summary of the PIT tests conducted at Utah-FORGE. With each test being conducted a total of four times with a 20-minute and 40-minute shut-in period in between test 1-2 and test 2-3, respectively.

Test	Injection/Backflow Rate (gpm)	Period (min)
Test 1	105	20
Shut-In	0	20
Test 2	105	40
Shut-In	0	40
Test 3	105	120

The volume of a reservoir interrogated by a periodic hydraulic pulse increases with increasing period and hydraulic diffusivity. For the ideal case of a well of infinitesimally small radius without skin, fully penetrating a homogeneous reservoir of infinite extent, inducing perfectly radial flow about the injection well, a characteristic length can be defined as (Bakker, 2009):

$$\lambda = \sqrt{\frac{D}{\omega}} = \sqrt{\frac{KP}{2\pi S_s}} \tag{1}$$

where D is the hydraulic diffusivity, K is the hydraulic conductivity, S_s is the specific storage, ω is the frequency of oscillation, and P is the period of oscillation. Note that here we adopt terminology used commonly in hydrogeologic literature for hydraulic testing. From this characteristic length, a "radius of influence" can be defined by choosing the magnitude of hydraulic influence (which is theoretically infinite). For a pressure response that is 10% of the induced pressure, for example, the radius of influence is 1.8λ, for a pressure response that is 1% of the induced pressure, the radius of influence is 4.4λ (Bakker, 2009).

4. PROCESSING AND DATA FITTING

4.1 FILTERING OF PRESSURE RESPONSES

Because the test requires only variation in pressure, measured wellhead pressures were not corrected to bottom hole pressures. For ease in interpretation, pressure change was converted to hydraulic head using well head temperatures and the related density. Processing of the PIT data was achieved using outlier removal and filtering techniques in MATLAB. Wellhead pressure trends throughout the PIT tests decreased in 16A due to the reduction in injection rate, and increased in 16B as the pressure equalized following recirculation. The decreasing head trend in was removed using a first-order, linear detrending filter. The increasing wellhead pressure trend at 16B was removed using a Butterworth bandpass filter. To maintain phase characteristics, a zero-phase digital filter was applied to remove distortion within the signal in both the forward and reverse directions. Lastly, to smooth remaining noise, a moving average filter with varying window sizes was applied to the pressure responses of 16B, allowing increased visibility of the periodic signal.

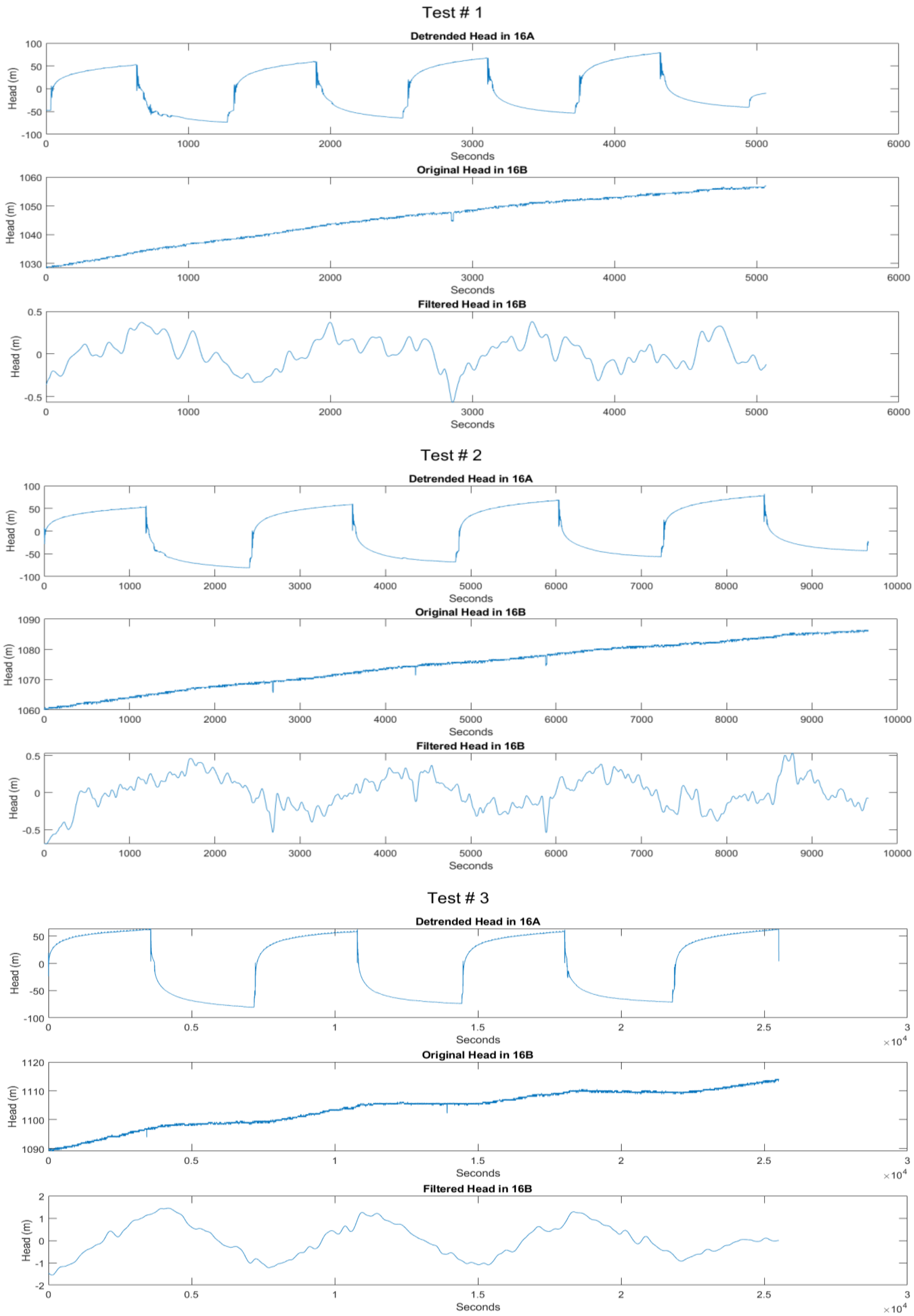

Figure 3: Head response to PIT vs. time of injection well 16A(78)-32 and observation well 16B(78)-32. Increasing hydraulic head drift visible in well 16B throughout all test periods: (a) 20-minutes, (b) 40-minutes, and (c) 120-min. Application of various filtration processes to 16A and 16B signal including detrending and bandpass filtering.

4.2 MODEL

The Generalized Radial Flow (GRF) model (Barker, 1988) was used to estimate hydraulic parameters from the hydraulic signal. The GRF assumes an infinite aquifer, zero well-bore storage, and instantaneous storage response for the formation, but does not pre-suppose the dimensionality of flow. This model was chosen because for later analysis we intend to examine the dimensionality of the flow field. For our initial analysis presented here, however, we assume radial flow which is expected due to the predominance of vertical in echelon fractures observed following stimulation (Niemz et al., 2025). The GRF is expressed in the Laplace domain, with s as the Laplace variable as (Barker eq. 31):

$$\bar{h}(r,s) = \frac{Q_0 r^{\nu} K_{\nu}(\lambda\, r)}{sKb^{3-n}\alpha_n \lambda^{\nu} 2^{-\nu}\Gamma(1-\nu)}, \qquad \text{where} \tag{2}$$

$$\lambda = \sqrt{\frac{S_s}{K}};\ \nu = 1 - \frac{n}{2};\ \alpha_n = \frac{2\pi^{\frac{n}{2}}}{\Gamma(^{n}/_{2})}.$$

where $K_{\nu}(z)$ is the modified Bessell Function of order, ν, and $\Gamma(z)$ is the gamma function. The parameter, K, is the hydraulic conductivity, S_s is specific storage, n is the flow dimension ($0 \leq n \leq 3$, but we assume $n = 2$), b is the extent of the flow dimension (here radial flow thickness), and $Q_0$is the injection rate amplitude. From this formulation in Laplace space, a hydraulic transfer function may be specified as:

$$\bar{g}(r,s) = \frac{r^{\nu} K_{\nu}(\lambda r)}{Kb^{3-n}\alpha_n \lambda^{\nu} 2^{-\nu}\Gamma(1-\nu)}\ . \tag{3}$$

A constant rate injection at a rate Q_0 has a source term $\overline{g_s}(\nu,r,s) = Q_0/s$, which recovers (2). For a sinusoidal input of amplitude, Q_0

$$\overline{g_s}(\nu,r,s) = \frac{Q_0 s}{\omega^2 + s^2} \tag{4}$$

where ω is the frequency of the sine wave. Then multiply in Laplace space to convolve the source term with the transfer function, to recover the head signal in Laplace domain:

$$\bar{h}(r,s) = \left[\frac{Q_0 s}{\omega^2 + s^2}\right]\left[\frac{r^{\nu} K_{\nu}(\lambda\, r)}{Kb^{3-n}\alpha_n \lambda^{\nu} 2^{-\nu}\Gamma(1-\nu)}\right] \tag{5}$$

The function (5) is inverted numerically to the time domain using an algorithm based on the Fast Fourier Transform (Becker & Charbeneau, 2000).

The GRF model allows flexibility in dimensionality of fluid flow, but here we assume radial flow, i.e. n = 2. Fixed inputs (Table 2) of the formation parameters including period length of each individual test were stored within the MATLAB modeling scripts to each test, maintaining consistency.

Table 2. Fixed parameters of PIT.

Parameter	Value	Description
r	100 m	Radial Distance Between Wells
b	20 m	Flow Region
P	Test 1: 1200 s (20 min) Test 2: 2400 s (40 min) Test 3: 7200 s (120 min)	Test Period
ω	2π / P	Frequency of Oscillation
Q_0	105 gpm	Injection Rate
n	2	GRF Dimension Value

Parameters were inverted by fitting the GRF model to the filtered head response. The best fit was obtained using a non-linear optimization algorithm (Levenberg-Marquardt) using the Mean Square Residual (MSR) as an objective function,

$$MSR = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \quad (6)$$

where n is the number of data points, y_i is the observed value and $\hat{y}_i$ is the model value. These best suited (lowest MSR) values were plotted in parameter space to assure global minima during optimization. Relinquishing low-computational cost, MSR paired with a grid search approach has advantages including identifying multiple local minima, avoiding local minima trapping, providing a clear visualization on a 2-D and/or 3-D grid, visually depicting any non-unique patterns within the model (Figure 4).

Utilization of the GRF model and the filtered hydraulic head response (Figure. 3) of all three test periods were applied to determine the unknown parameters, K and S_s. A widowed range of values were utilized individually to best identify our model fit line, removing noise and filtering artifacts associated with the very start and ends of our PIT tests. Figure 4 highlights the spatial computations of K and S_s in both two-dimensional and three-dimensional graphs. Warmer/high-elevation (z-axis) indicate disagreement between the model values and physically recorded parameters, whereas the cooler/lower-elevation values show greater alignment with the observed hydraulic parameter values. One recognizable valley location can be seen throughout all three test periods in the 3-D graphs indicating that a global minimum was found for each pair of best fitted K and S_s values.

5. RESULTS AND ANALYSIS

Optimized fits of the GRF model to the hydraulic responses measured in 16B produced unique best fit combinations of K and S_s for each test. Because the radius of influence is expected to change with increasing injection volume, these parameters are not expected to be consistent among tests, because the reservoir is assumed to be hydraulically heterogeneous. Figure 4 shows that the signal to noise improved from Test 1 to Test 3, as greater volumes were injected and, therefore, the hydraulic signal at 16B became stronger. Head oscillation with 10 min of injection (V_{inj}=4 m^3 or 25 bbl) was less than a meter but exceeded 4 meters with 60 min of injection (V_{inj}=24 m^3 or 150 bbl). Table 3 summarizes the best fit K and S_s as well as the calculated hydraulic diffusivity from these parameters and their MSR. The hydraulic diffusivity estimated through model fits decreases rapidly with an increase in injection volume (Figure 5).

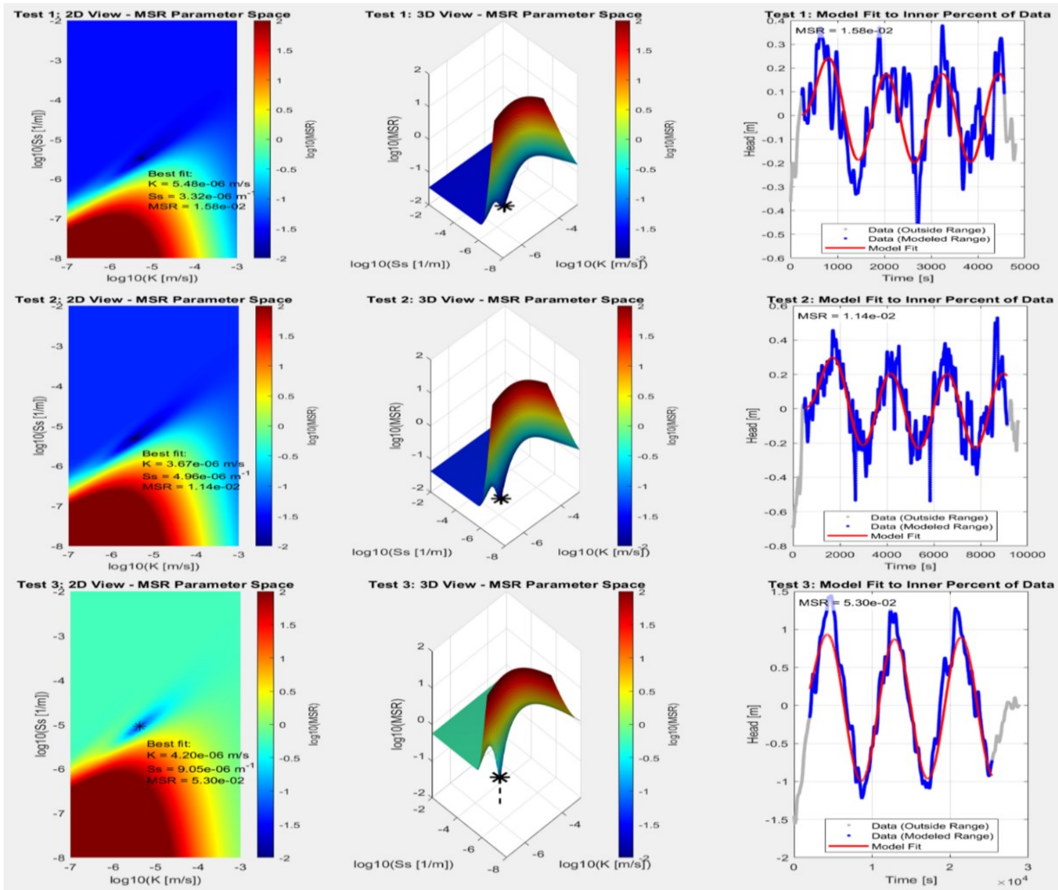

Figure 4. 2-D and 3-D representations of the best fit K and Ss values from the PIT and filtered hydraulic head response in blue, with the model-fit line in red. Graphs represent Test 1 (20 min periods), Test 2 (40 min periods) and Test 3 (120 min periods). 2-D and 3-D graphs visually depict spatial grid of values for K, Ss, and MSR in log scale. Asterisks indicate the lowest point (lowest MSR value) thus the "best fit" modeled value in accordance with the observed data.

Table 3. Summary of optimized hydraulic parameters from GRF model fit and an MSR objective function.

Test	Hydraulic Conductivity (K)	Specific Storage (S_s)	Hydraulic Diffusivity (D)	MSR
Test 1	5.48E-6 m/s	3.32E-6 m^{-1}	1.65 m^2/s	1.58E-2
Test 2	3.67E-6 m/s	4.96E-6 m^{-1}	7.41E-1 m^2/s	1.14E-2
Test 3	4.20E-6 m/s	9.05E-6 m^{-1}	4.64E-1 m^2/s	5.30E-2

A periodic injection/flowback suggests that there is a finite volume of the formation that is impacted by the test. Mathematically, there is no radial distance from the injection well in which there is zero hydraulic influence because the formation is assumed to be infinite. Consequently, in practice, a radius of influence is adopted to characterize the radial distance away from the injection well. Figure 5 provides plots of the radius of influence expressed where the head oscillation is expected to be 10% of the head at the injection well (1.8λ) and 1% of the head at the injection well (4.4λ) as expressed in (1). The radius of influence does not increase monotonically with injection volume and period because the apparent hydraulic diffusivity drops rapidly away from the well. The radius of influence calculation is more of a qualitative indication of the volume of reservoir interrogated by the PIT tests, however. The values expressed in Figure 5 suggest that the hydraulic responses were primarily weighted toward a volume 10s of meters from the injection well and were probably not heavily influenced by the stimulated hydraulic conductivity distribution about the observation well, 16B.

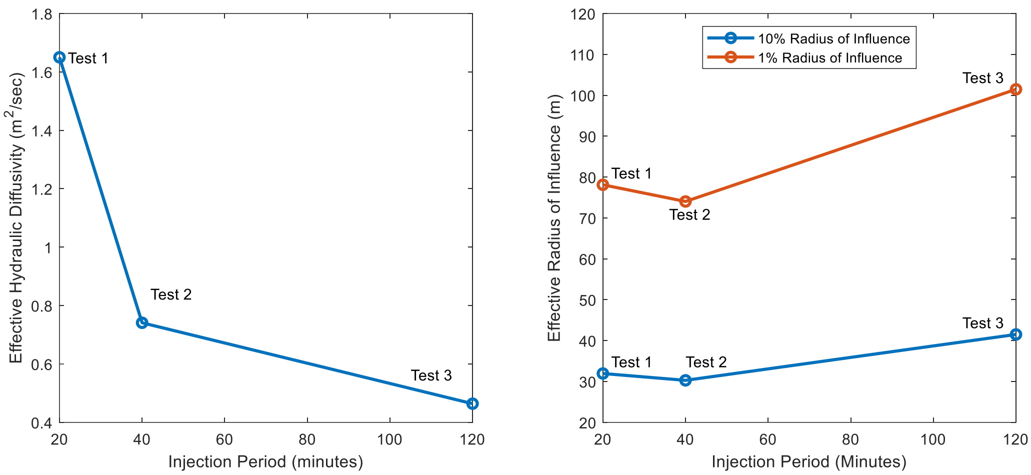

Figure 5. The relationship between hydraulic diffusivity (left) and radius of influence (right) versus the injection period. The radius of influence is calculated for 10% of the injection pressure and 1% of the injection pressure.

6. CONCLUSION

A series of Pulse Interference Tests (PITs) were conducted on a single day at Utah-FORGE using varying periods of injection/flowback at constant flow rates (105 GPM). Injection and backflow were conducted in well 16A and pressure response measure in 16B. The Generalized Radial Flow (GRF) semi-analytic model was used to interpret the pressure responses observed, removing the assumption of fluid flow dimensionality. The predicted hydraulic response from the GRF was fit to the observed hydraulic responses in 16B using a non-linear optimization routine which appeared to produce a global best fit to the combination of hydraulic conductivity and specific storage. The ratio of these two parameters, hydraulic diffusivity, was found to decrease rapidly with increasing injection period or, equivalently, injection volume.

The decrease in hydraulic diffusivity with increasing hydraulic interrogation volume is consistent with a greater permeability in the vicinity of the injection well. Such a decrease in hydraulic diffusivity might be expected given the limited distance over which proppant can be injected into a simulated formation and the expected greater fracture frequency in the vicinity of the well bore. Eight stages in 16A were stimulated in early Spring of 2024, with six stages using two proppant sizes (100 mesh and 40/70 mesh). Positive communication (frac hits) were observed between mid-stimulated stages of 16A to 16B. However, it is interesting to note that the radius of influence did not increase greatly with the increasing injection period, with a 90% reduction in pressure occurring with 25-40 meters in all three tests.

A decrease in hydraulic diffusivity with radial distance also agrees with the findings of previously published work in which no stimulation or proppant was used in bedrock formations (Guiltinan and Becker, 2015; Rabinovich et al., 2015; Becker and Guiltinan). A decrease in hydraulic diffusivity may occur because the effective storage becomes larger as fluid has longer time to migrate into tighter formations (Patterson and Cardiff, 2023). Thus, a heterogeneity in the simulated volume is not necessarily the only explanation for the range in inverted hydraulic diffusivity.

Given the time constraints we were only able to conduct these PITs at one injection/backflow rate. Using multiple rates would have been informative as it is thought that higher heads at the injection well may hydraulically prop open fractures and dynamically increase near well permeability. The simultaneous measurement of strain in fractures using fiber optic distributed acoustic or strain sensing in the injection and/or observation well would have provided confirmation of the effective fracture compliance on hydraulics, but the fiber in 16B was damaged prior our tests. Without additional information, it is difficult to separate the dynamics of fracture compliance and fluid hydraulic diffusion on the pressure response, as expressed by standard formation pressure response models as used here. However, these injection/backflow PITs conducted at the end of a 30-day recirculation tests, are the only hydraulic tests conducted to date that are spatially sensitive and indicate the variation in permeability as distance from the well bore. We are currently conducting hydromechanical simulations to better understand the formation properties interrogated using PITs.

7. ACKNOWLEDGEMENT

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