



Final Technical Report

Optimization and Validation of a Plug-and-Perf Stimulation Treatment Design at Utah FORGE

Award Recipient Organization: University of Utah (DOE Project DE-EE0007080)

Subrecipient Organization:

Fervo Energy

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Abstract

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Subrecipient Organization: Fervo Energy 4-2541

Principal Investigator: Dr. Jack H. Norbeck, CTO, Fervo Energy

This final technical report summarizes the work completed under Award No. 4-2541, a collaboration between the University of Utah and Fervo Energy to design, implement, and validate an optimized plug-and-perf stimulation strategy tailored to enhanced geothermal systems (EGS). The project pursued the development of a multistage, multicluster stimulation approach informed by a commercial-scale demonstration and refined for application at Utah FORGE.

Major milestones include drilling and completing a fully horizontal injection well and vertical monitoring well, both equipped with DAS/DTS fiber optics and permanent pressure/temperature sensors. The horizontal well was successfully stimulated with 16 plug-and-perf stages using proppant-laden slickwater, followed by a five-day injection test to characterize injectivity and reservoir response.

During 2024, Fervo supported Utah FORGE in the execution of landmark stimulation in Well 16A-32, contributing operational resources, fiber-connected data acquisition infrastructure, and expertise in microseismic interpretation. All technical milestones for Budget Periods 1 and 2 were achieved, and the results substantiate a path forward for commercial EGS deployment.

Keywords:

Enhanced Geothermal Systems (EGS), Plug-and-Perf, Multistage Hydraulic Stimulation, Utah FORGE, Horizontal Geothermal Well, DAS, DTS, Proppant

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Executive Summary

1.1 Background

This project addressed three primary technical barriers in commercial-scale EGS: achieving high injectivity, maintaining uniform flow distribution, and overcoming stress and fracture heterogeneity. The objective was to develop and validate a stimulation approach using plug-and-perf with proppant in high-temperature crystalline rock and translate those findings into practical design criteria for Utah FORGE operations.

1.2 Objectives

- Perform a multistage hydraulic stimulation at Fervo's site as a precursor to Utah FORGE implementation.
- Install permanent downhole monitoring tools (DAS/DTS and P/T sensors) for continuous data acquisition.
- Conduct injection testing and flow characterization.
- Support stimulation operations at Utah FORGE using refined designs and field-proven best practices.

1.3 Key Findings

- A total of **16 stimulation stages** were completed using **11.5 million gallons of slickwater** and **7.5 million pounds of proppant**.
- Instrumentation allowed real-time data acquisition including DAS, DTS, and microseismic data.
- The **first-ever geothermal horizontal well** drilled to 90° in a crystalline formation at **>350°F** was successfully completed and stimulated. In 2024, Fervo supported Utah FORGE in the stimulation of Well 16A-32, providing **field execution, high-quality proppant logistics, and real-time data support** via the Delano 1-OB well.
- All tasks and milestones from **Budget Period 1 and 2** were completed on schedule.

2. Introduction

2.1 Purpose of the Report

This report presents the full technical accomplishments of the Utah FORGE R&D subcontract titled *“Optimization and Validation of a Plug-and-Perf Stimulation Treatment Design”* awarded to Fervo Energy. It provides detailed documentation of planning, execution, results, and implications of the project work.

2.2 Scope of Work

- Drilling and characterization of a vertical monitoring well (Well 73-22) and horizontal injection well (Well 34A-22).
- Field-scale plug-and-perf stimulation with permanent monitoring.
- Single-well injection testing and history matching.
- Data analysis, modeling, and application of insights to Utah FORGE operations.

2.3 Organization of the Report

Structured according to DOE’s streamlined reporting framework, integrating project context, results, and references.

3. Methodology

3.1 Data Collection

- **Well 73-22 (Monitoring):** Equipped with quad-combo logging, acoustic/resistivity image logs, DAS/DTS fibers, and permanent P/T gauges.
- **Well 34A-22 (Injection):** Drilled to 11,220 ft MD; horizontal lateral ~3,250 ft; also instrumented with DAS/DTS fibers.
- **Stimulation Treatment:** 16 multicluster plug-and-perf stages with step-down tests and treatment pressure monitoring.
- **Microseismic Monitoring:** Acquired through Fervo's Delano 1-OB well and high-frequency DAS.

3.2 Analysis Techniques

- Diagnostic Fracture Injection Testing (DFIT)
- Step-down analysis for limited entry performance
- ResFrac reservoir modeling for history matching
- DTS temperature calibration with wireline surveys

3.3 Experimental Setup

- Slickwater hydraulic stimulation with a blend of **100 mesh and 40/70 mesh** proppants.
- High-resolution fiber-optic cables and P/T gauges deployed in both wells.
- Monitoring used for estimating **fracture surface area, SRV geometry, LEP friction, and cluster flow allocation.**

4. Results and Discussion

4.1 Key Results

- **Wellbore Schematics**

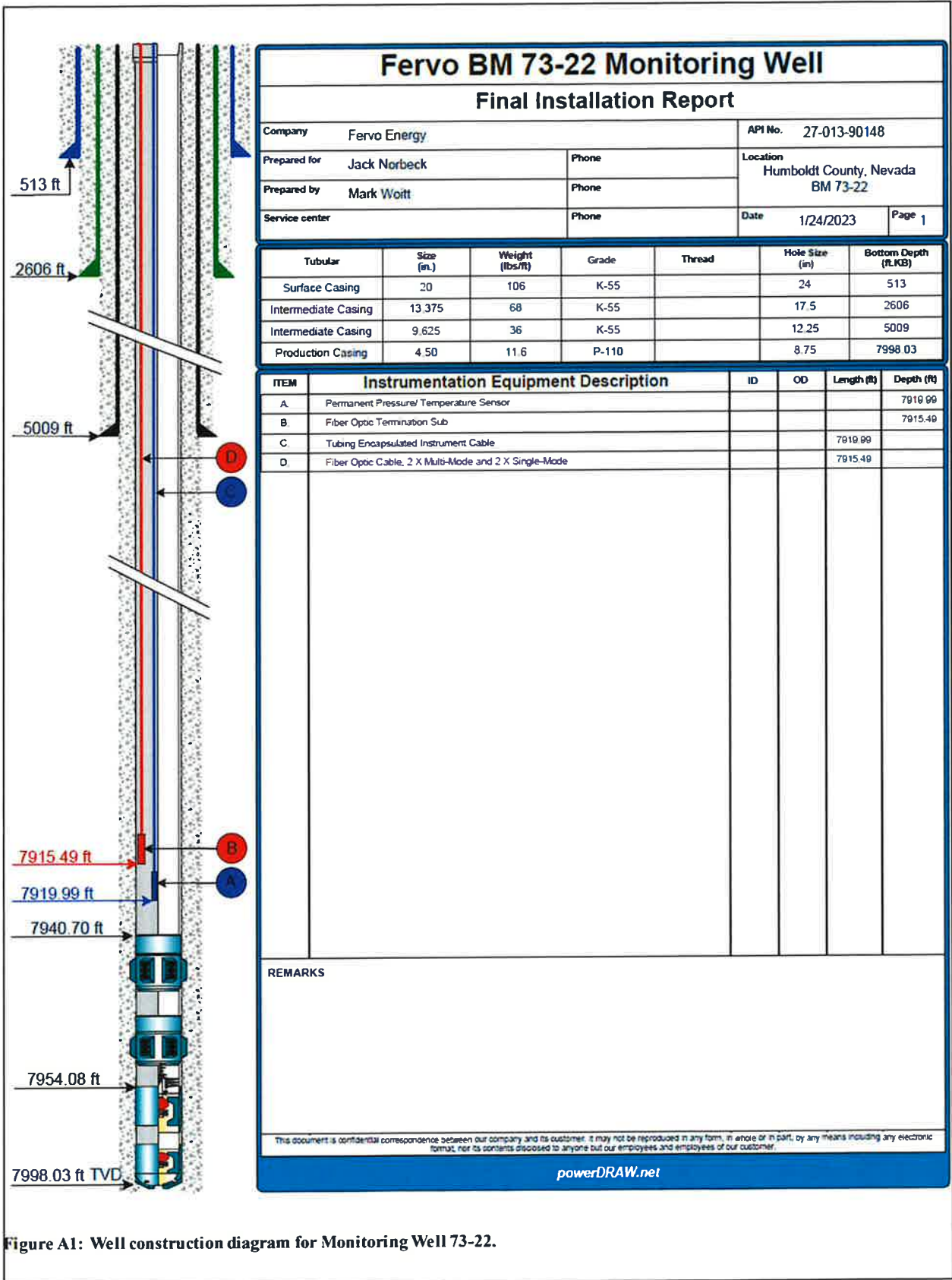


Figure A1: Well construction diagram for Monitoring Well 73-22.

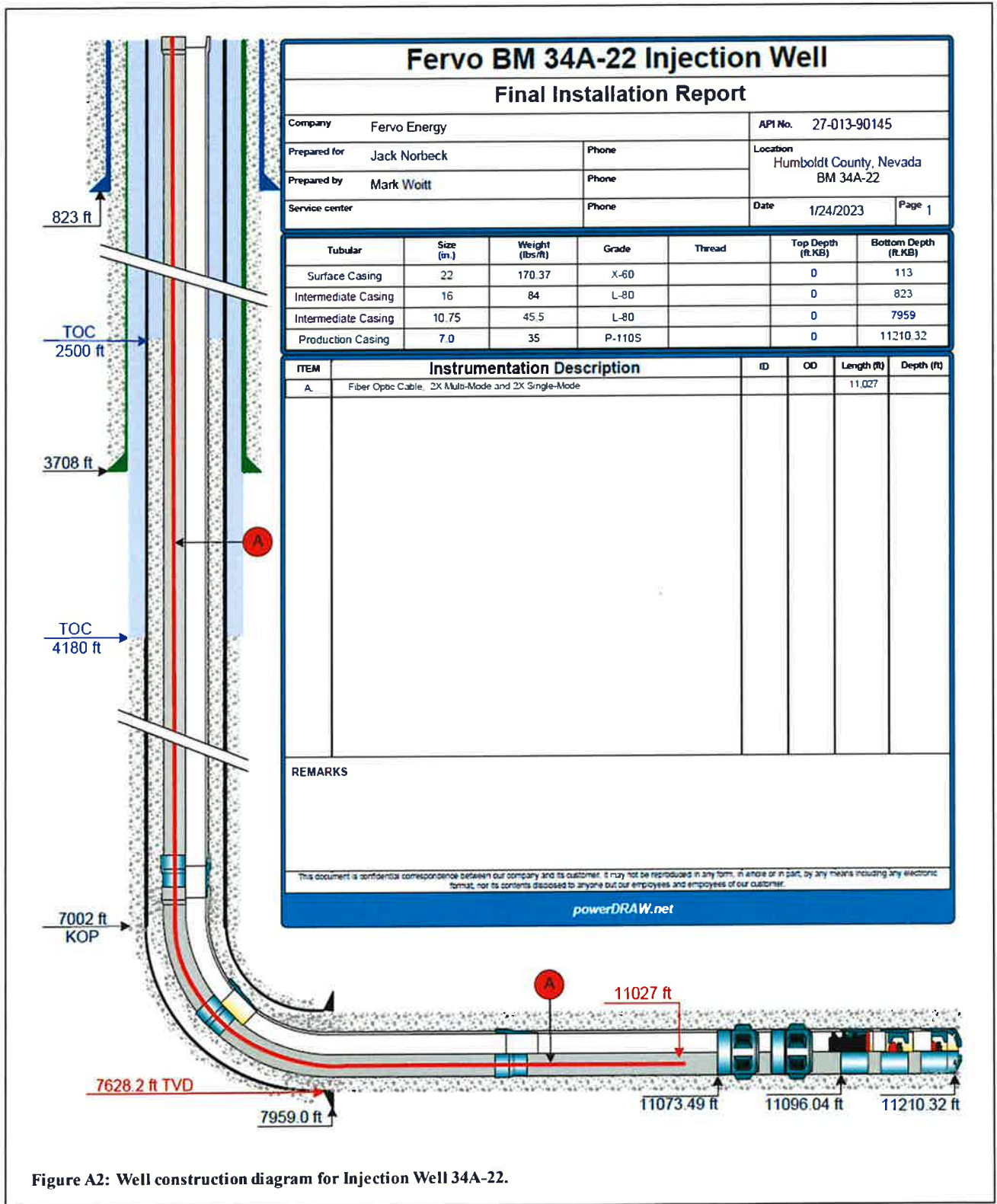


Figure A2: Well construction diagram for Injection Well 34A-22.

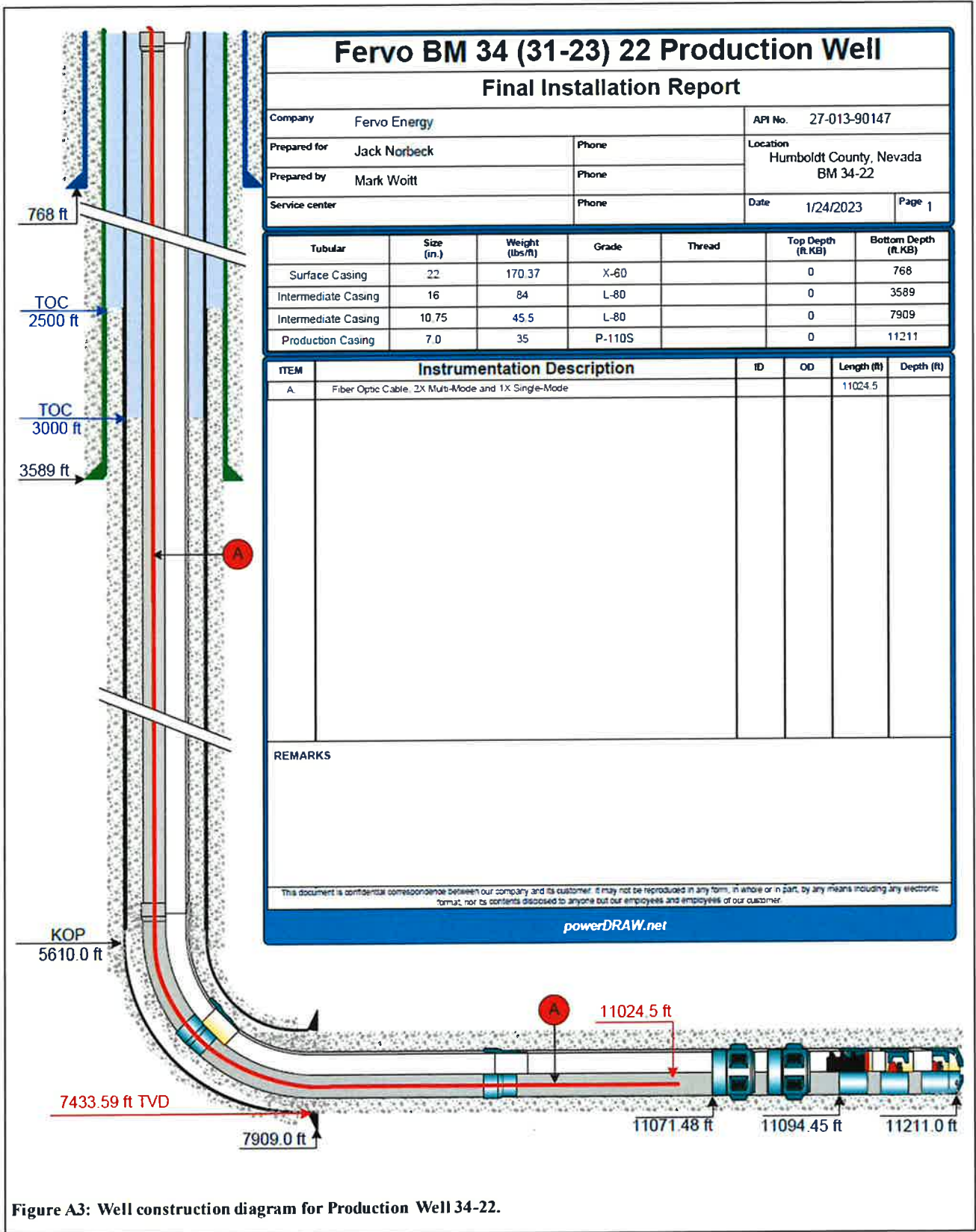


Figure A3: Well construction diagram for Production Well 34-22.

- **Drilling and Completion**

- **Monitoring Well 73-22** drilled with high-resolution DAS/DTS fiber optics and P/T sensors, no major operational delays.
- **Injection Well 34A-22** completed as a fully horizontal geothermal well at ~7,700 ft TVD, ~11,220 ft MD, with a lateral span of 3,250 ft—marking the first of its kind in high-temp, crystalline formation EGS.

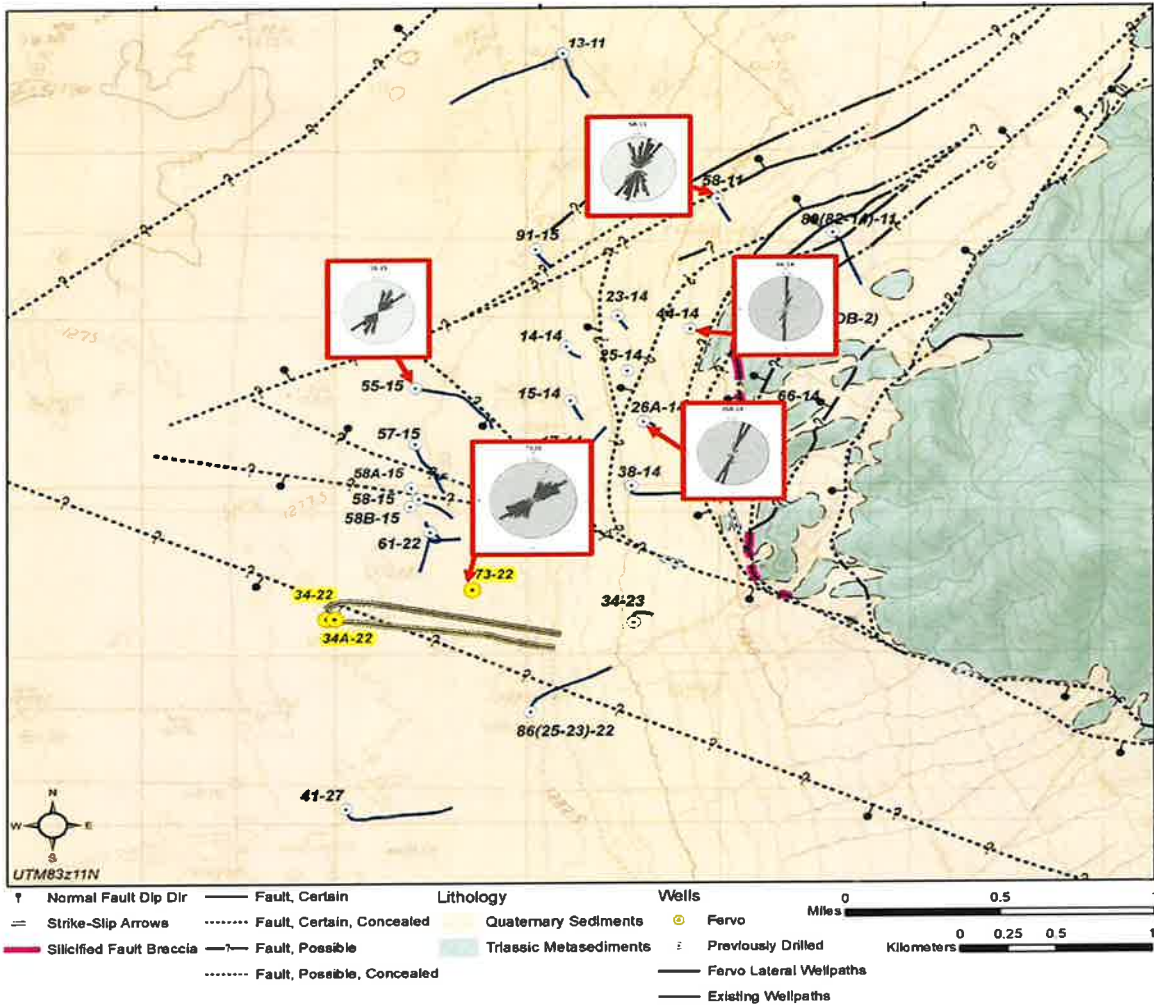


Figure 1: Map view of the Blue Mountain geothermal field located in northern Nevada. The rose diagrams overlaid on the wellfield represent the SHmax orientations interpreted from drilling induced fractures and borehole breakouts from several vertical and slightly deviated wells across the wellfield.

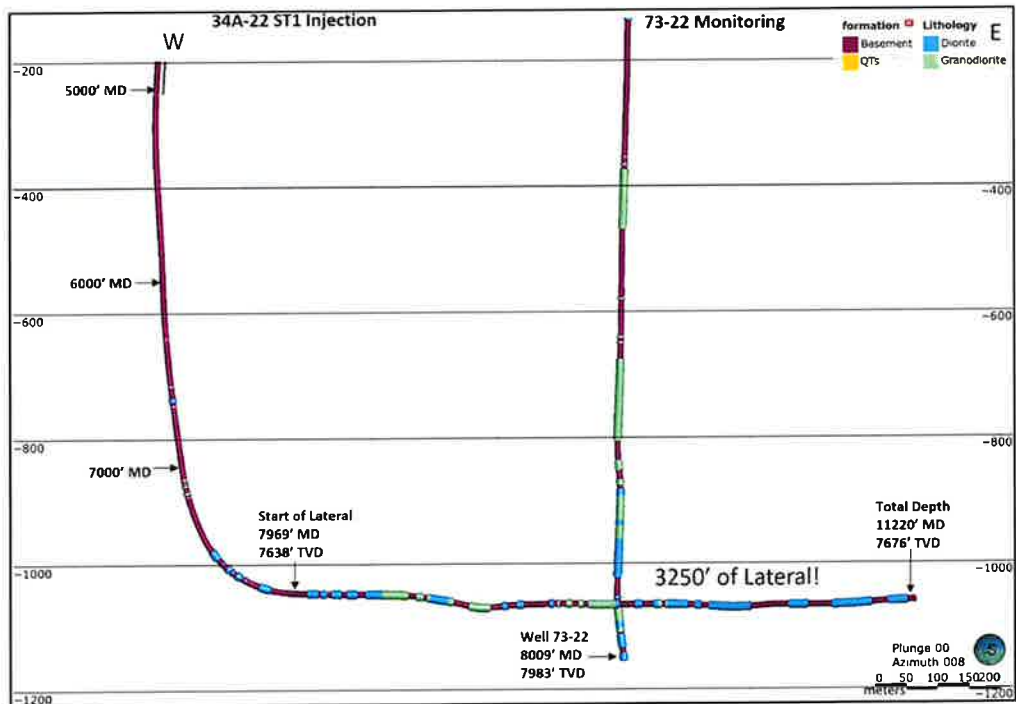
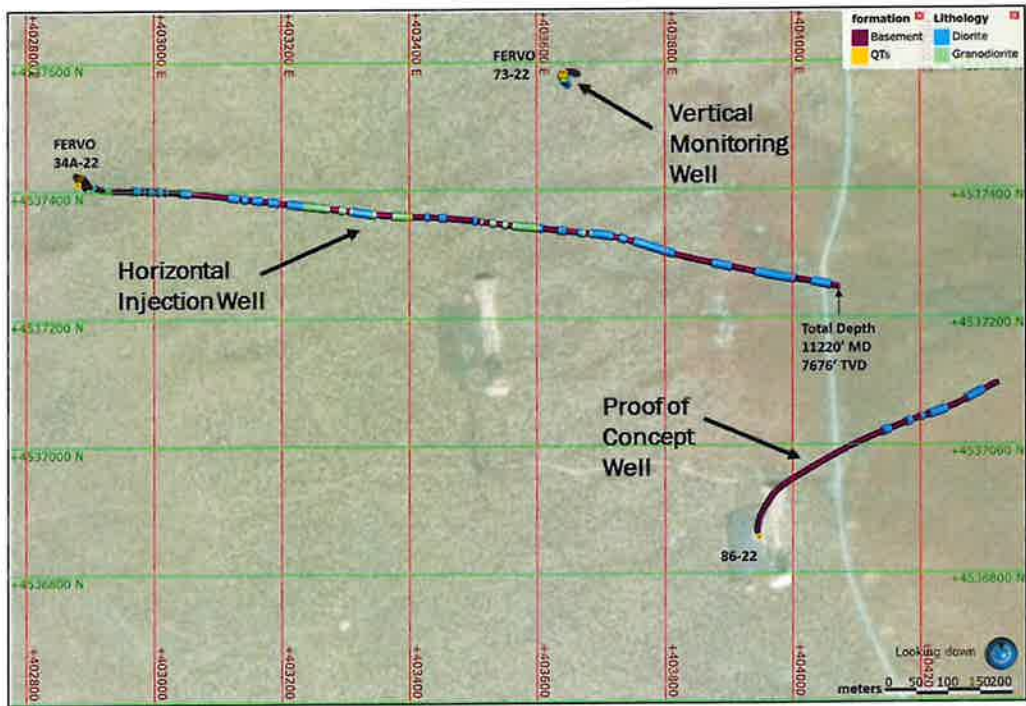


Figure 2: Map view and plan view of the project site. Injection Well 34A-22 is a horizontal EGS well and is the primary focus of this project. Monitoring Well 73-22 is located to the north and at approximately the mid-lateral position of Injection Well 34A-22. Both wells are instrumented with permanent fiber optic cables (DAS and DTS) cemented behind casing.

Fervo Blue Mountain 34A-22 As Completed

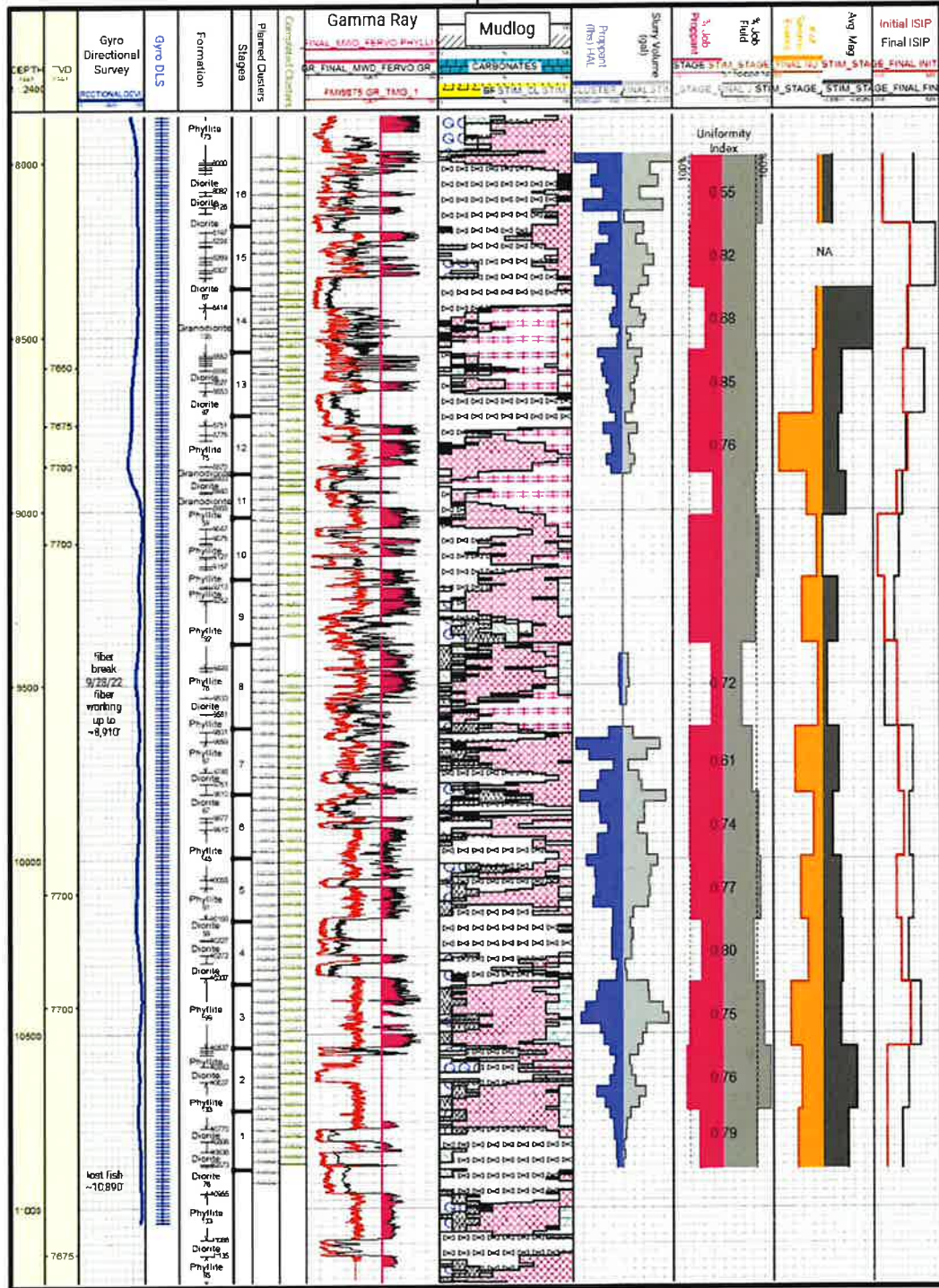


Figure 3: Injection Well 34A-22 petrophysical log summary.

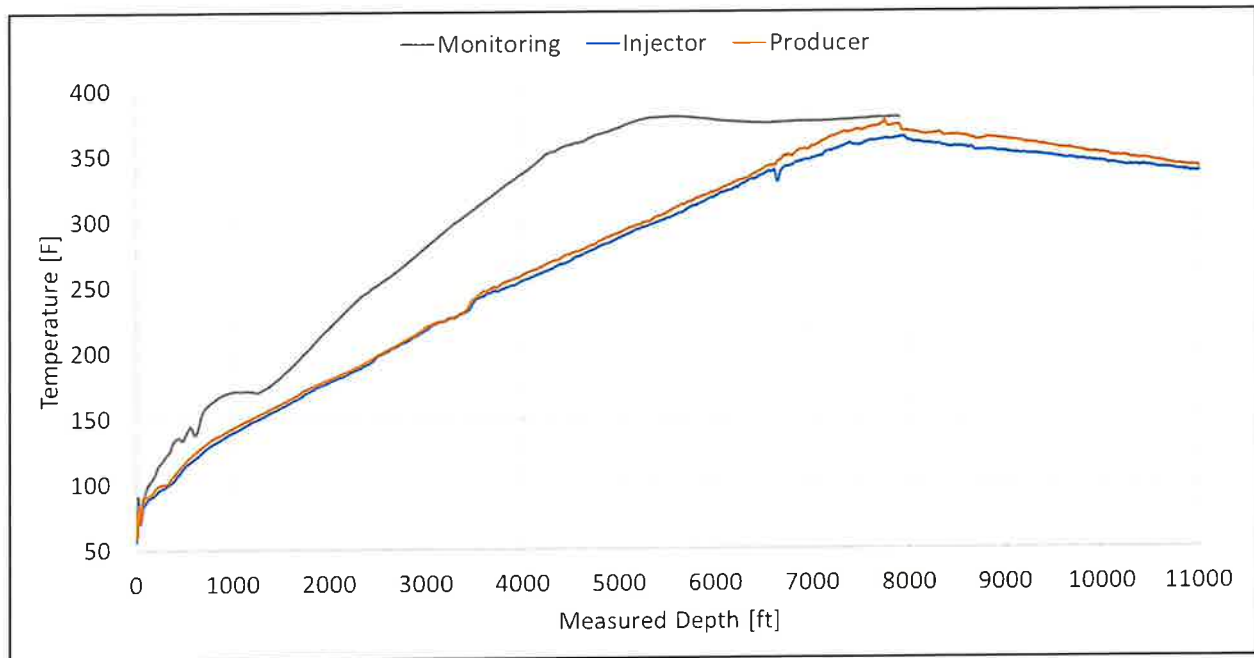


Figure 6: Equilibrated geothermal gradients in Injection Well 34A-22, Production Well 34-22, and Monitoring Well 73-22.



Figure 7: Fiber optic interrogator equipment.

- Stimulation Execution

Injector Well 34A-22 Pump Schedule							
Stage No.	Stage Name	Pump Rate (bbl/min)	Fluid Type	Clean Volume (bbl)	Well Head Prop Conc. (ppg)	Stage Prop (lbs.)	Stage Time (min)
1	Injection	10	Slickwater	95	0	0	10
2	Acidize	10	15% HCl	24	0	0	2
3	Displacement/Pad	100	Slickwater	1,071	0	0	11
4	100 mesh	100	Slickwater	1,429	0.25	15,000	14
5	100 mesh	100	Slickwater	1,429	0.5	30,000	14
6	100 mesh	100	Slickwater	1,429	1	60,000	14
7	100 mesh	100	Slickwater	1,310	1.25	68,750	11
8	100 mesh	100	Slickwater	1,310	1.5	74,250	13
9	100 mesh	100	Slickwater	1,248	1.45	76,002	12
10	Spacer	100	Slickwater	1,000	0	0	10
11	40/70 mesh	100	Slickwater	1,310	0.75	41,250	13
12	40/70 mesh	100	Slickwater	1,310	1	55,000	13
13	40/70 mesh	100	Slickwater	1,071	1.25	56,250	11
14	40/70 mesh	100	Slickwater	1,081	1.4	63,560	11
15	Flush + 70 bbbls	100	Slickwater	553	0	0	6
Total with Flush				15,668		540,062	167
Fluid Loading (bbl/cluster)		2,611		Total Proppant		540 k/lbs	
Proppant Loading (lb/cluster)		90,010		100 mesh		324 k/lbs	
Fluid Loading (bbl/ft)		87		40/70		216 k/lbs	
Proppant Loading (lb/ft)		2,984					
Total Proppant per Stage (lbs)						540,062	
Total Fluid (bbl/stage)						15,668	
Clusters per Stage (-)						6	

- 16 multistage plug-and-perf stimulation stages successfully executed in Q4Y22.
- Over 11.5 million gallons of slickwater and 7.5 million pounds of proppant deployed.
- Step-down tests in each stage confirmed limited entry perforation (LEP) effectiveness and near-well tortuosity control.
- Data acquisition enabled by permanent fiber optics (DAS/DTS) ensured real-time monitoring and cluster engagement validation.

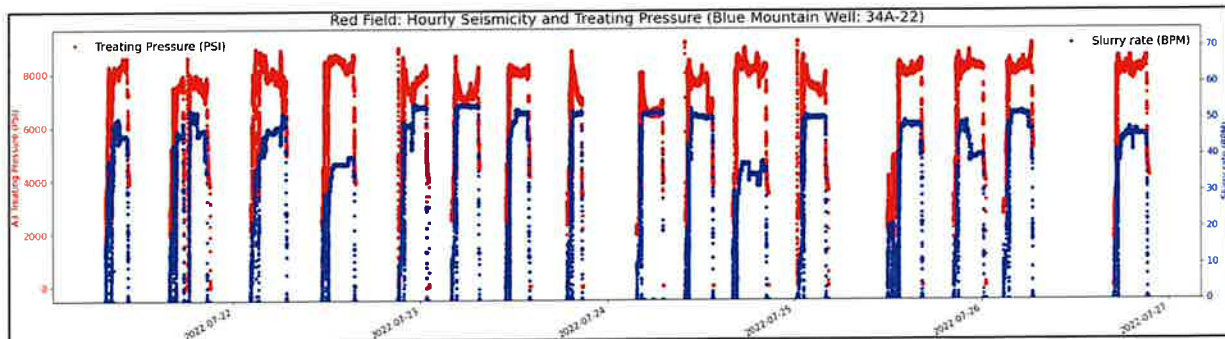


Figure 8: Treating pressure and slurry rate for the 16 individual hydraulic stimulation treatment stages performed on Injection Well 34A-22.

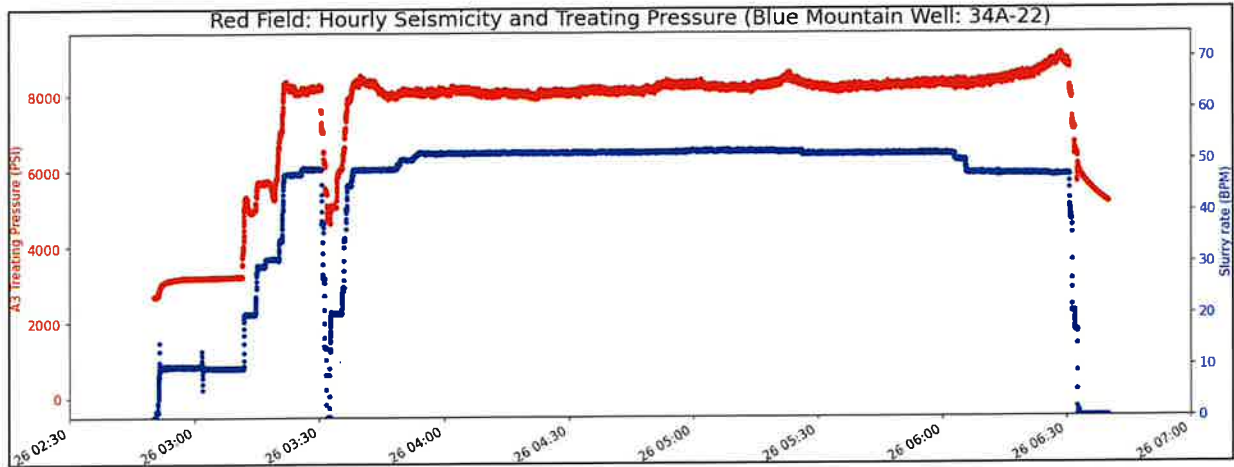


Figure 9: Treatment plot on typical stimulation treatment stage on Injection Well 34A-22.

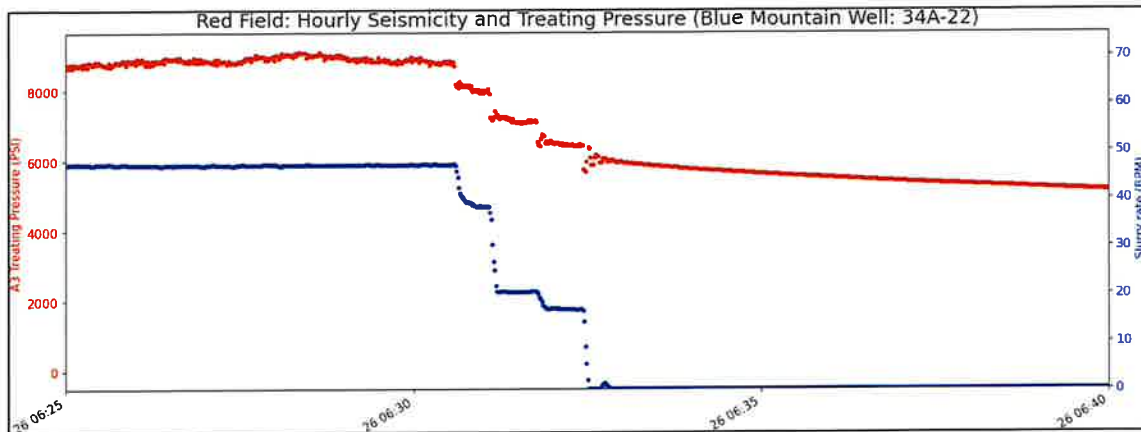


Figure 10: Example step-rate test performed at the end of a representative stimulation treatment stage. The rate and pressure response can be interpreted to determine the magnitude of limited entry perforation pressure drop and near-wellbore tortuosity.

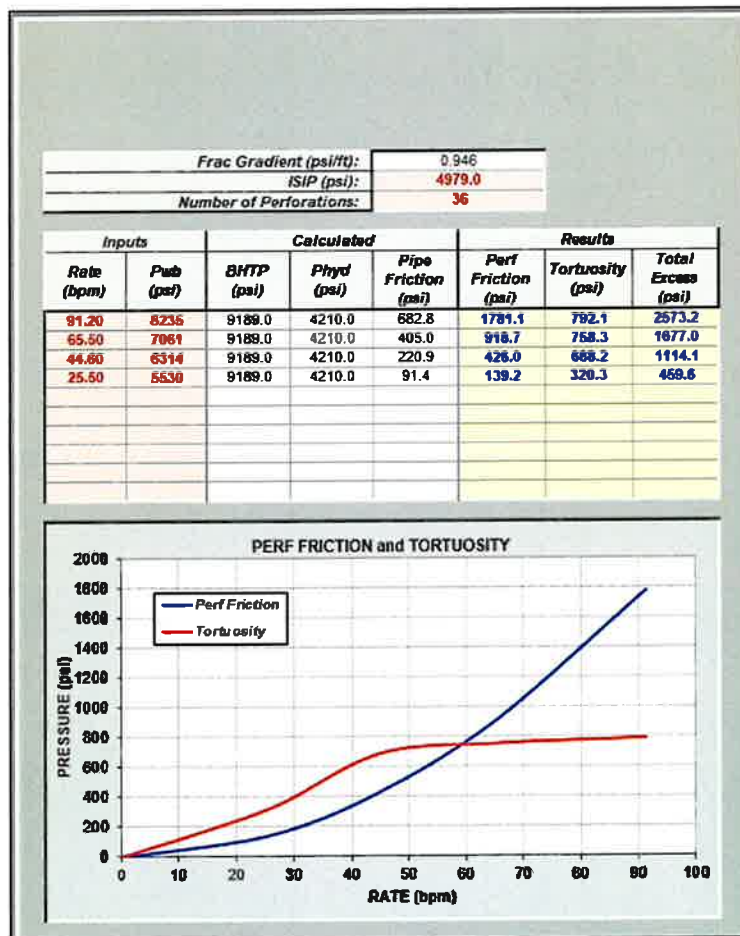


Figure 11: Post-stage step-rate test for a representative stimulation treatment stage on Injection Well 34A-22. The step-rate tests can be used to evaluate limited entry perforation friction and near-well tortuosity.

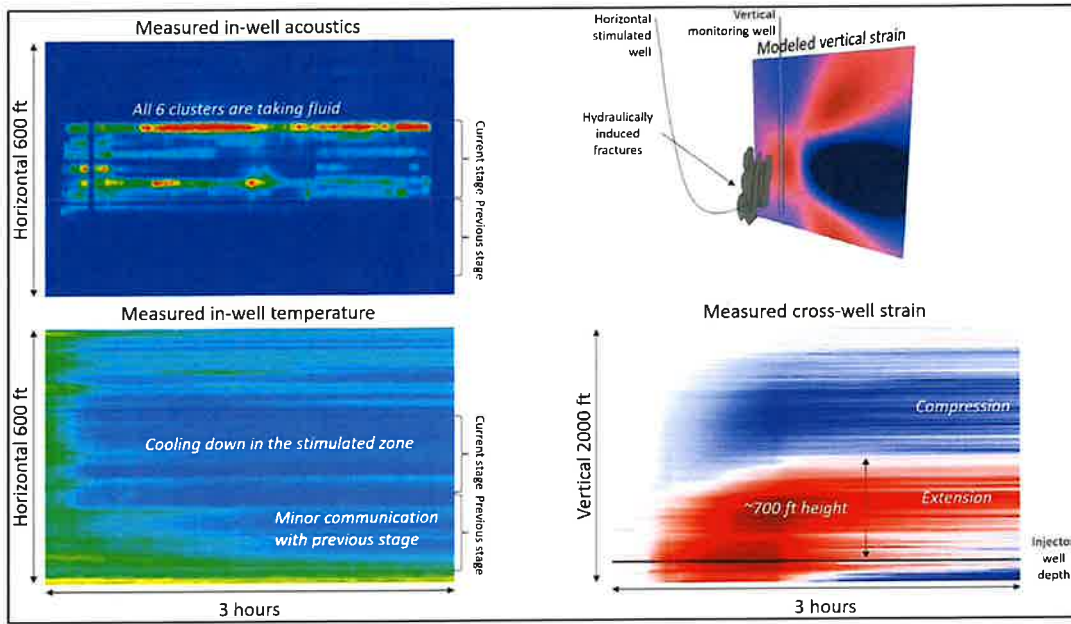


Figure 12: In-well DAS data (upper left) and in-well DTS data (lower left) from representative stimulation treatment stage on Injection Well 34A-22; modeled change in vertical strain in the reservoir (upper right) and measured cross-well strain from the low-frequency DAS measurements in Monitoring Well 73-22 during a representative stimulation treatment stage on Injection Well 34A-22.

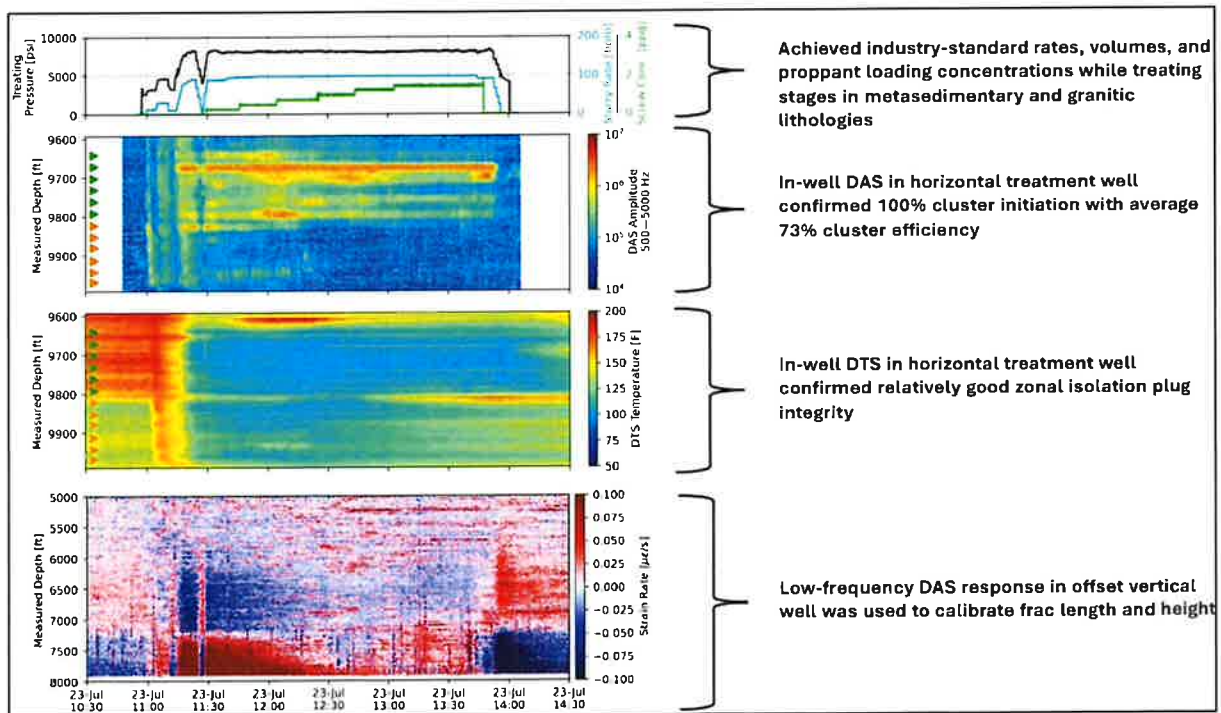


Figure 13: Treatment plot, in-well DAS, in-well DTS, and cross-well low-frequency DAS for a typical stimulation treatment stage on Injection Well 34A-22.

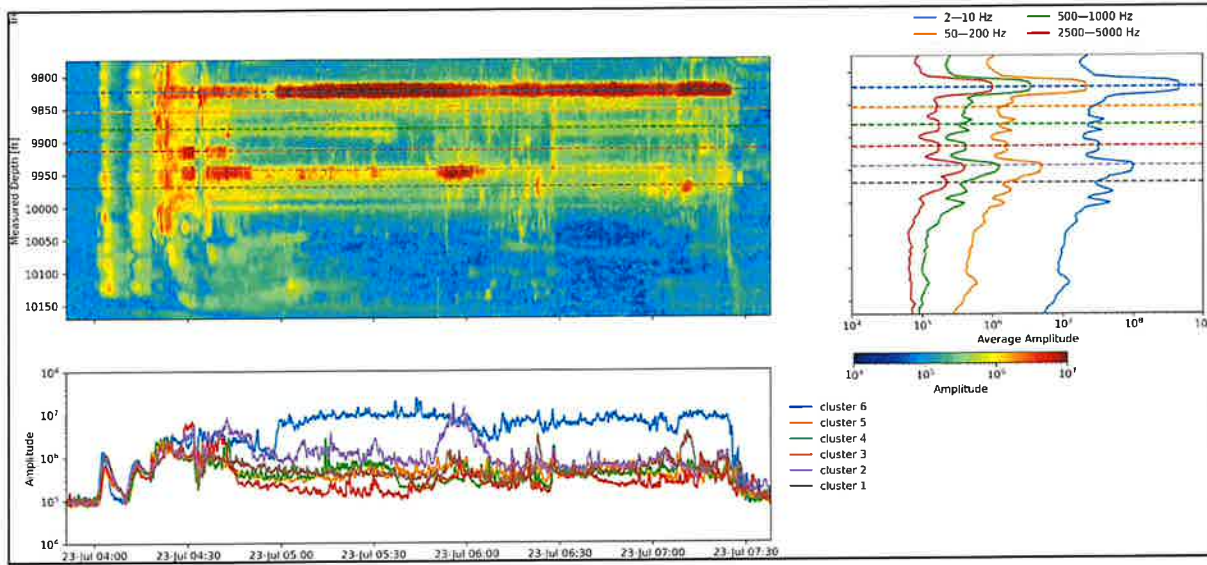


Figure 14: Example plot of the in-well DAS response during a representative stimulation treatment stage in Injection Well 34A-22. The amplitude of the DAS response at each perforation cluster is used to evaluate the **Uniformity Index (UI)**, sometimes referred to as the

flow allocation efficiency factor. The UI is defined as $UI = 1 - CV$, where $CV = \text{STD}(Q)/\text{Mean}(Q)$; Q represents flow per cluster, derived from DAS acoustic intensity proportional to flow rate during a pumping stage.

Stage	Slurry UI	Prop UI
1	0.787	0.750
2	0.769	0.656
3	0.751	0.730
4	0.778	0.759
5	0.773	0.735
6	0.740	0.696
7	0.606	0.547
8	0.735	0.712
9, 10, 11		
12	0.724	0.695
13	0.853	0.804
14	0.680	0.672
15	0.822	0.784
16	0.548	0.528

Figure 15: Uniformity Index (UI) or flow allocation efficiency factor based on the in-well DAS

measurements for all stages pumped on Injection Well 34A-22. Flow allocation was observed to be relatively uniform, with UI ranging from 55% to 85% across all stages.

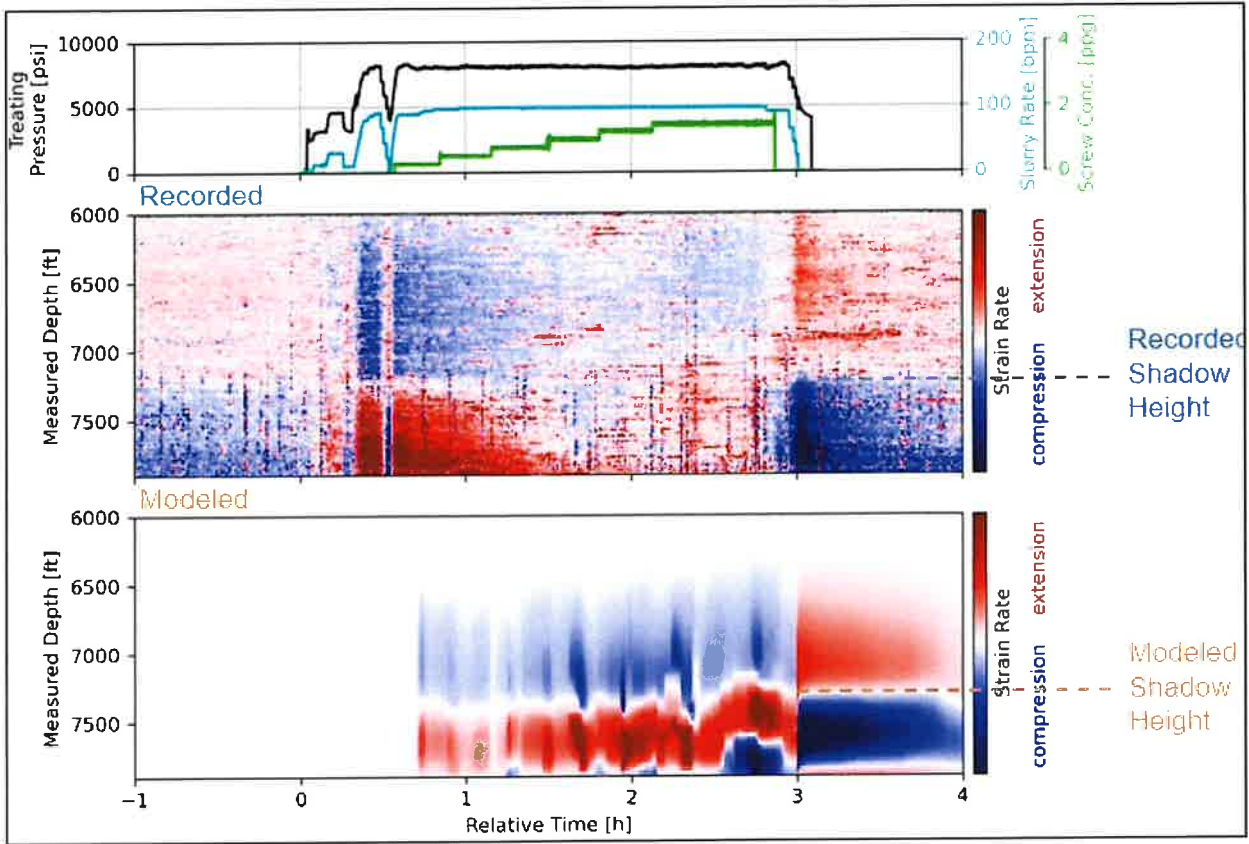


Figure 16: Treatment plot, in-well DAS, cross-well low-frequency DAS, and simulation of LF-DAS response for a typical stimulation treatment stage on Injection Well 34A-22.

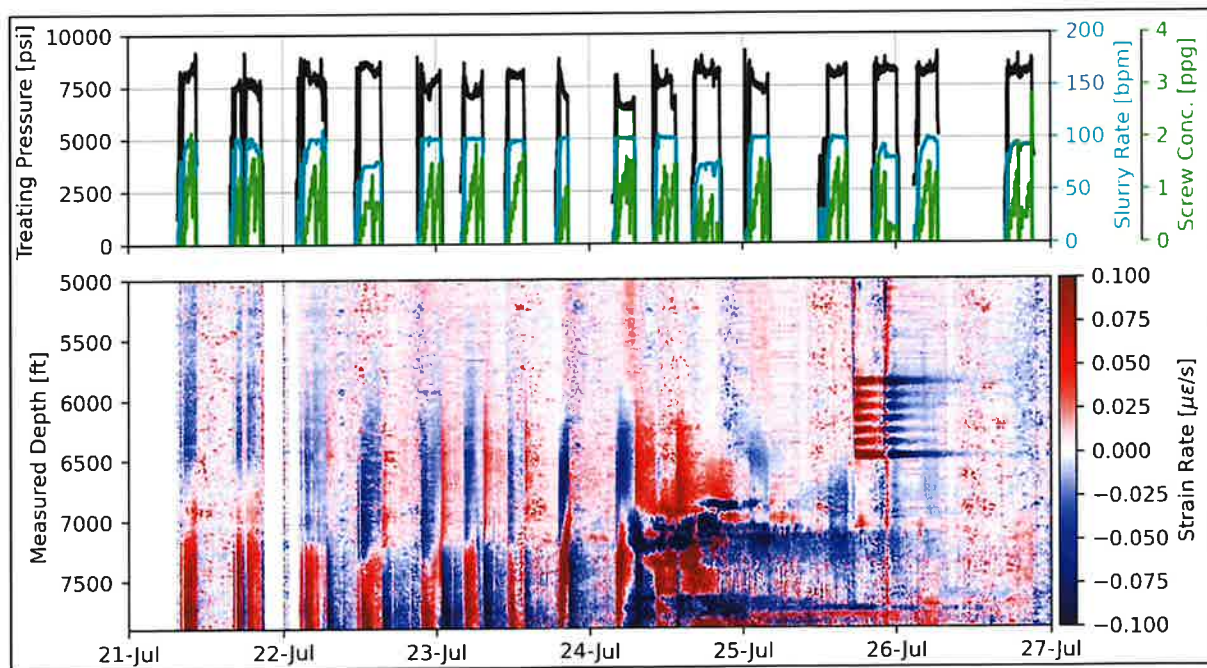


Figure 17: Cross-well low-frequency strain response measured at Monitoring Well 73-22 for each of the stimulation treatment stages performed on Injection Well 34A-22.

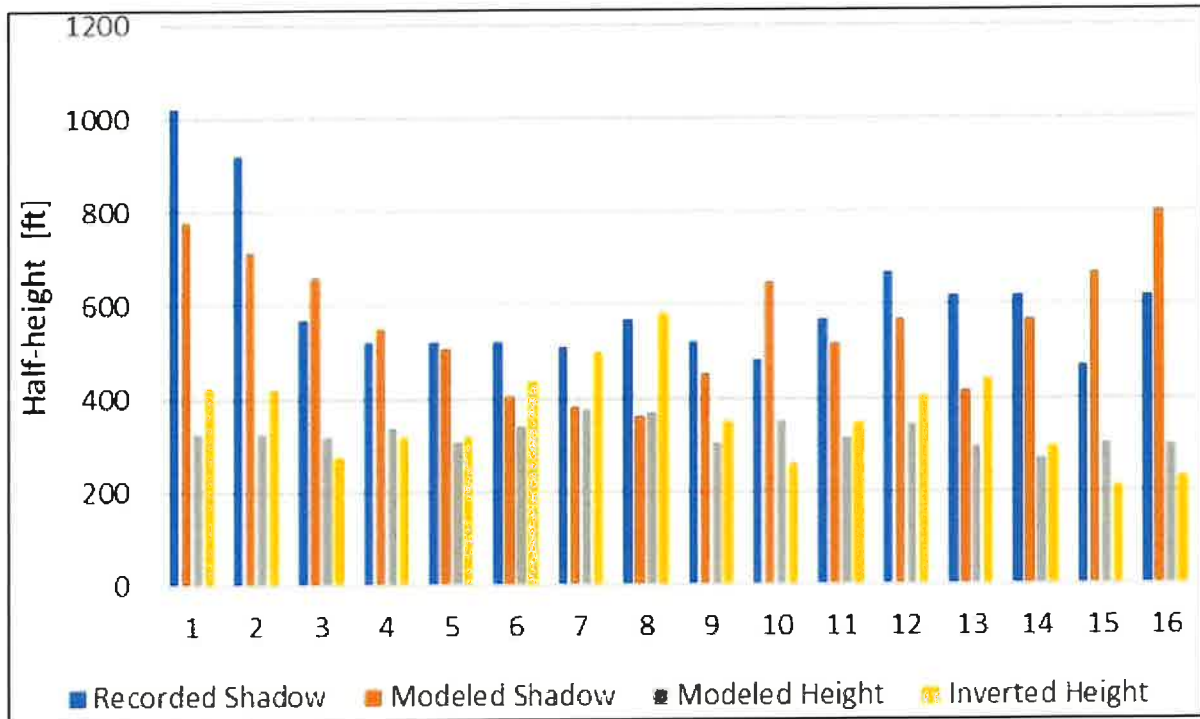


Figure 18: Stimulated reservoir volume half-heights interpreted from LF-DAS response recorded on Monitoring Well 73-22.

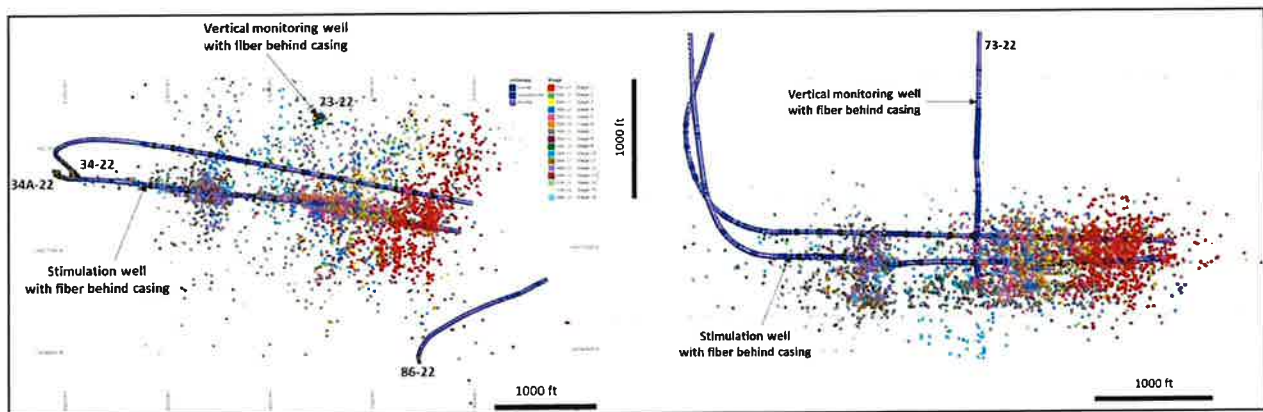


Figure 19: Microseismic event distributions from all treatment stages on Injection Well 34A-22.

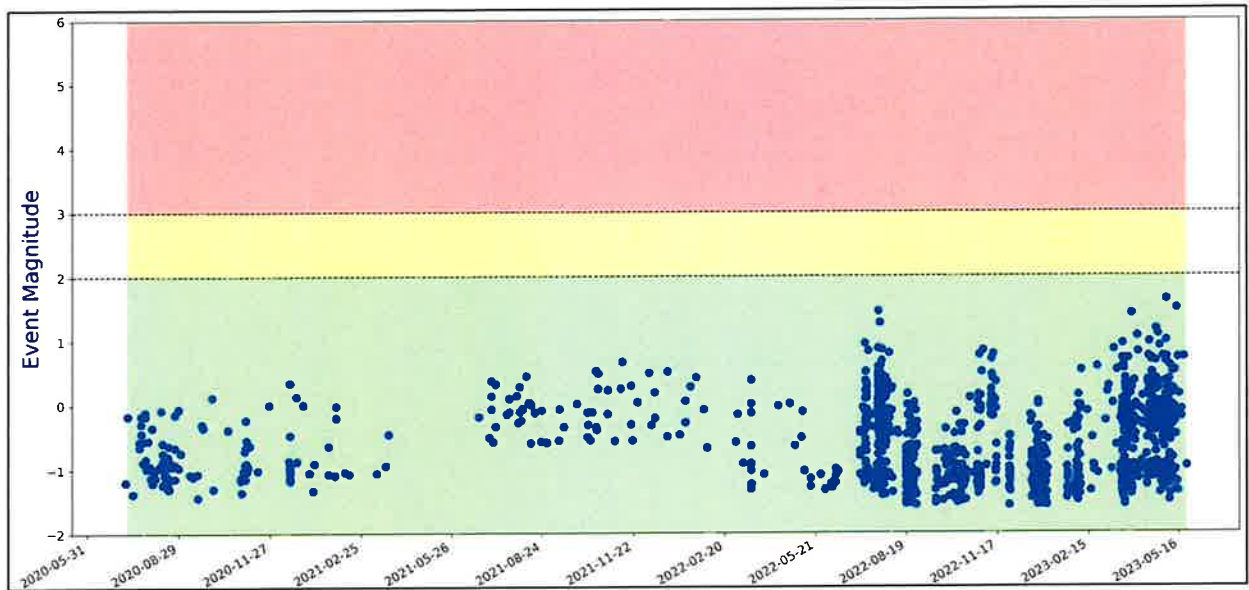


Figure 20: Seismicity observed from the surface seismic array over a 3-year period including the project duration including drilling, stimulation, and injection testing activities. The largest event recorded was approximately $M = 1.8$ in May 2023.

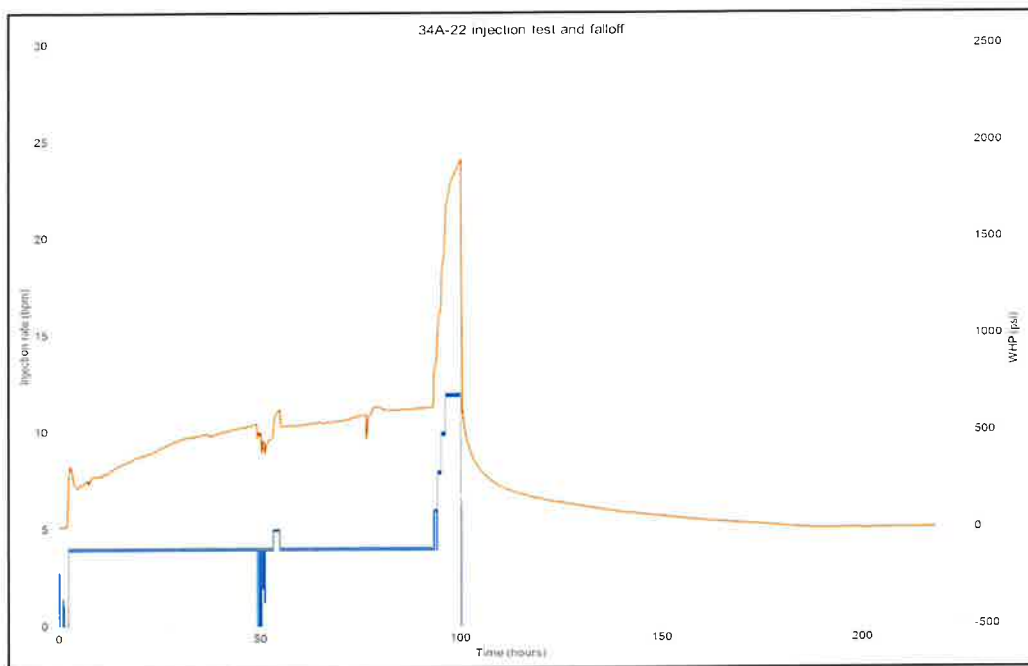


Figure 21: Injection rate and injection pressure from a constant-rate injection test, step-rate test, and pressure falloff test performed on Injection Well 34A-22. Water was injected at a relatively constant rate of 4 bpm for approximately four days, followed by a series of injection rate steps up to about 12 bpm, followed again by a hard shut-in and multi-day pressure falloff monitoring period. During this test, only the 7 heel-most stages on Injection Well 34A-22 were open to flow.

- **Post-Stimulation Injection Test:**

- Conducted in Q1Y23, the **5-day injection test** provided robust datasets for modeling near-well conductivity and total fracture surface area.
- Preliminary history matching using **ResFrac** was initiated in Q2Y23 and extended through Q3Y23.

- **Utah FORGE Collaboration (2024):**

- Fervo supported Utah FORGE’s Q2Y24 stimulation of **Well 16A-32** through:
 - Procurement, QA/QC, and logistics of **high-grade proppants** (both 100 mesh and 40/70).
 - Use of Fervo’s **Delano 1-OB** well as a high-frequency DAS microseismic monitoring platform.
 - Collaborative seismic data processing, aiding evaluation of SRV and induced seismicity risk mitigation.

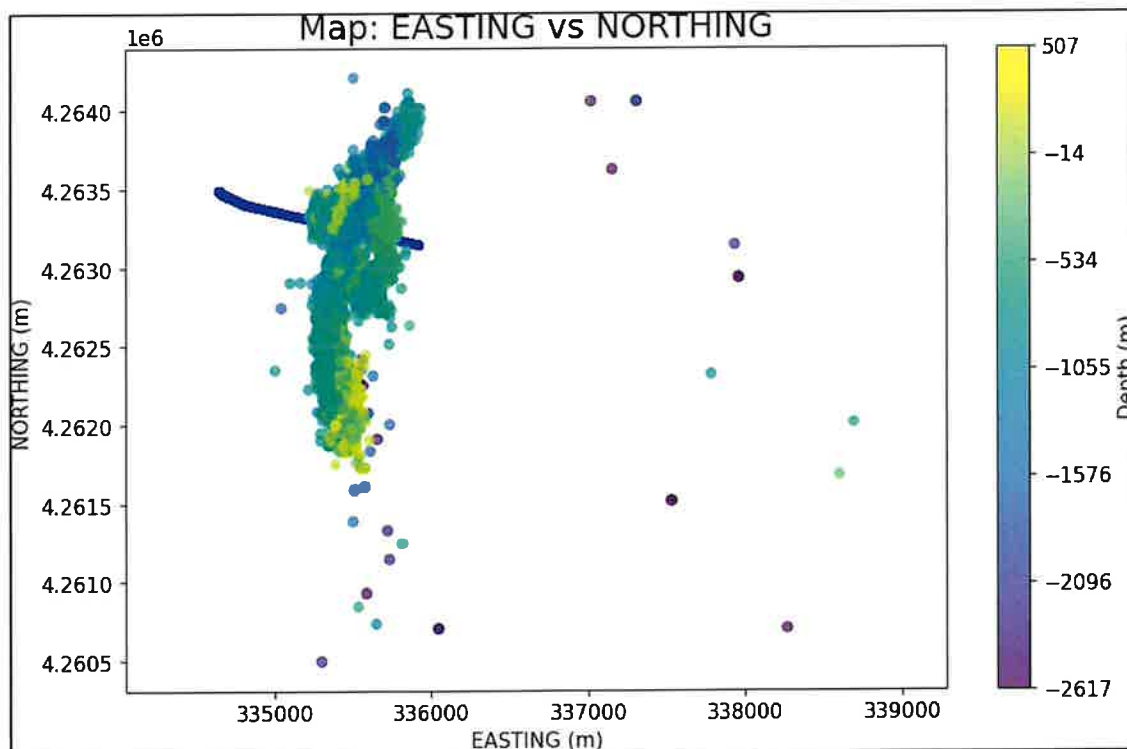


Figure 22: Microseismic catalog from the Utah FORGE circulation test augmented with event detections and locations from Fervo’s Delano 1-OB monitoring well.

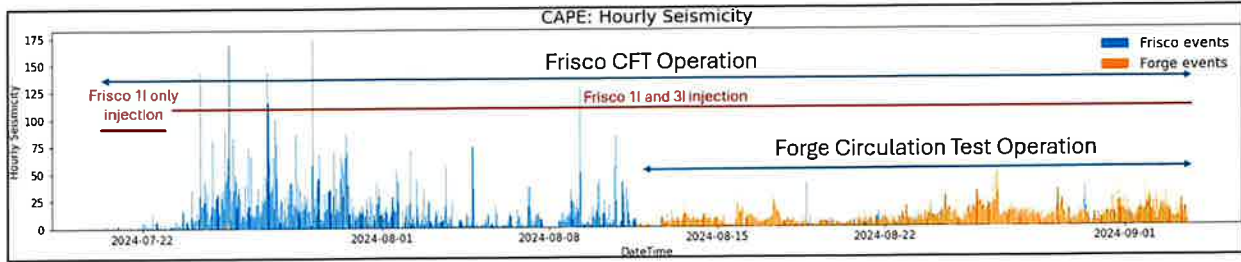


Figure 23: Microseismic event rate during Fervo and Utah FORGE circulation tests in August 2024.

4.2 Milestone Completion Analysis

From the cleaned **Milestone Table**, all planned milestones through **Q3 2024** were completed. Highlights include:

- **Milestone 1.5:** Reservoir characterization summary
- **Milestone 3.4:** Final cost estimate and reservoir analysis
- **Milestone 4.1:** Definition of teach/target/no-go metrics for FORGE design
- **Milestone 5.1:** Completion of Utah FORGE stimulation with data to evaluate technical objectives

This milestone traceability confirms full alignment with DOE’s R&D expectations for Budget Periods 1 and 2.

Table 1: Reservoir performance metrics for an economically viable EGS system outlined at the start of the project.

Reservoir Performance Metrics					
Limited Entry Perforation Friction: Designed vs. Actual			Near-well fracture conductivity		
No-Go Outcome	Target Outcome	Reach Outcome	No-Go Outcome	Target Outcome	Reach Outcome
Actual LEP is more than 1000 psi under designed LEP	Actual LEP is within +/- 750 psi of designed LEP	Actual LEP is within +/- 250 psi of designed LEP	< 50 md-ft	250 - 500 md-ft	> 1000 md-ft
Treatment Pressure			Fracture surface area		
No-Go Outcome	Target Outcome	Reach Outcome	No-Go Outcome	Target Outcome	Reach Outcome
> 9500 psi	6000 - 8000 psi	< 6000 psi	< 50,000 ft ² /cluster	200,000 ft ² /cluster	> 500,000 ft ² /cluster
Flow Allocation in a Multicluster Treatment Stage					
No-Go Outcome	Target Outcome	Reach Outcome			
Flow allocation efficiency factor < 30%	Flow allocation efficiency factor between 50% to 70%	Flow allocation efficiency factor > 80%			
SRV Size and Offset Well Spacing					
No-Go Outcome	Target Outcome	Reach Outcome			
Offset well spacing < 150 ft	500 ft - 750 ft	> 1000 ft			

Table 2: Achieved outcomes on key reservoir performance targets following execution of the field trial and interpretation of relevant datasets collected under this award.

Limited Entry Perforation Friction: Design vs. Actual			
	No-Go Outcome	Target Outcome	Reach Outcome
	Actual LEP is more than 1000 psi under designed LEP	Actual LEP is within +/- 750 psi of designed LEP	Actual LEP is within +/- 250 psi of designed LEP
Achieved Outcome			Within 100-200 psi of design
Treatment Pressure			
	No-Go Outcome	Target Outcome	Reach Outcome
	> 9500 psi	6000 - 8000 psi	< 6000 psi
Achieved Outcome		6000 - 8000 psi	
Flow Allocation in a Multicluster Treatment Stage			
	No-Go Outcome	Target Outcome	Reach Outcome
	Flow allocation efficiency factor < 30%	Flow allocation efficiency factor between 50% to 70%	Flow allocation efficiency factor > 80%
Achieved Outcome			58% - 85%
SRV Size and Offset Well Spacing			
	No-Go Outcome	Target Outcome	Reach Outcome
	Offset well spacing < 150 ft	500 ft - 750 ft	> 1000 ft
Achieved Outcome			500 - 1000 ft
Near-well Fracture Conductivity			
	No-Go Outcome	Target Outcome	Reach Outcome
	< 50 md-ft	250 - 500 md-ft	> 1000 md-ft
Achieved Outcome		300 - 400 md-ft	
Fracture Surface Area			
	No-Go Outcome	Target Outcome	Reach Outcome
	< 50,000 ft ² /cluster	200,000 ft ² /cluster	> 500,000 ft ² /cluster
Achieved Outcome			550,000 - 1,200,000 ft ² /cluster

4.3 Financial Execution Overview

The **Q13Y2 Quarterly Financial Report** (Prime Yr3) confirms disciplined execution of funds, with a concentration of spending aligned to high-value project phases:

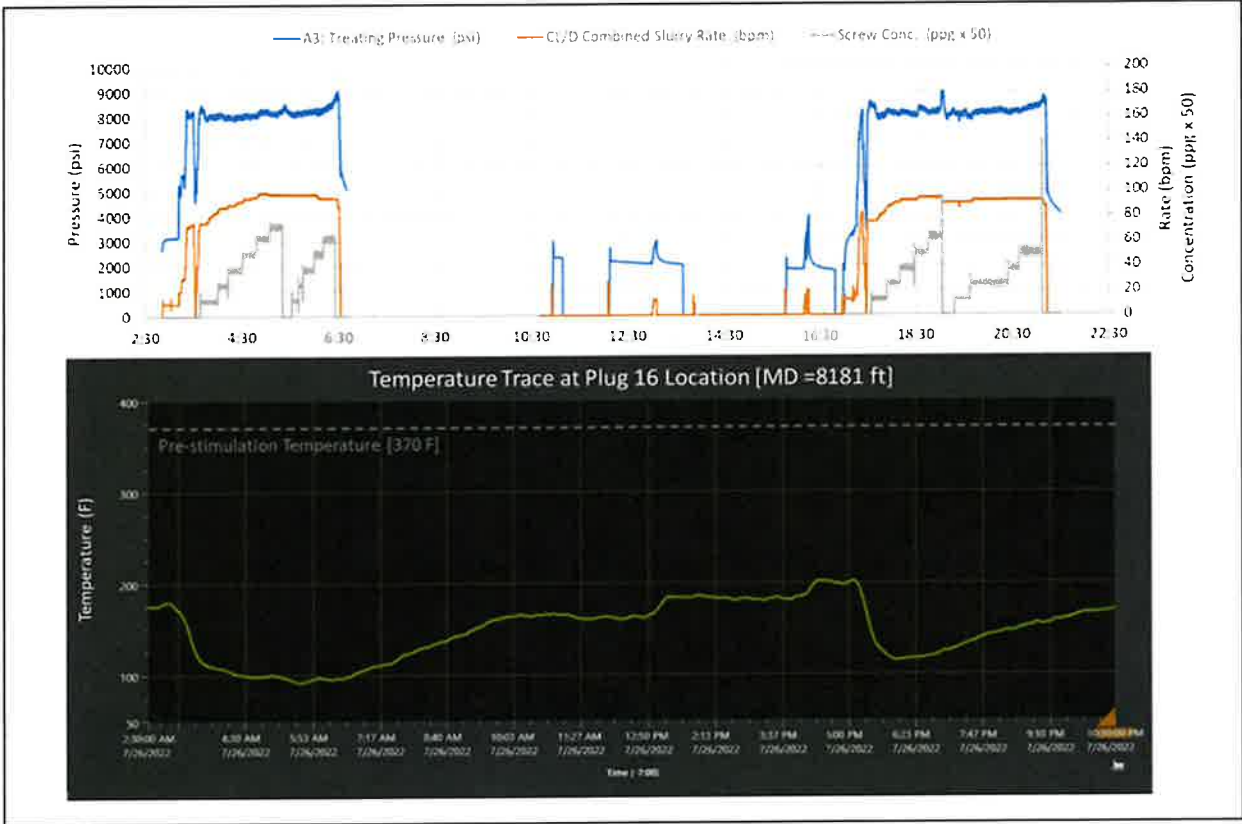
- Personnel investments were centered around **Reservoir Engineering, Supply Chain, and Geology**, supporting both technical planning and field execution.
- No significant cost overruns or unplanned budget reallocation occurred.
- All financial reports were submitted on time with blue-cell entry validation.

5. Conclusions and Recommendations

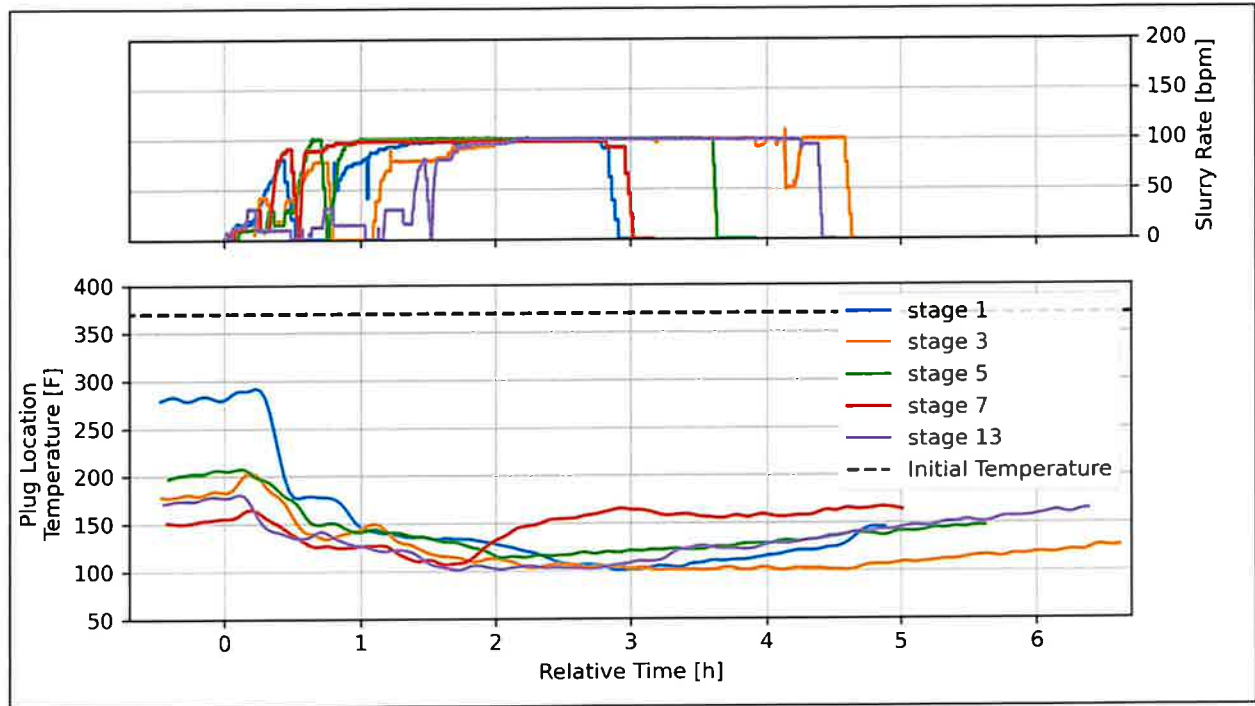
5.1 Summary of Conclusions

This project provided a rare opportunity to:

- Validate plug-and-perf designs under harsh geothermal conditions with success in all stimulation stage.



(a) Treating plots (top) and DTS temperature trace at the Stage 16 plug location (bottom) recorded while treating Stages 15 and 16. The temperature that the bridge plug was exposed to never exceeded 200 °F, well below its rated temperature limit. The results of this field trial indicate that it is possible to rely on significant amounts of wellbore cooldown due to wireline pumpdown operations and high-rate injection during the stimulation treatment.



(b) Typical treatment plots (top) and associated temperature traces at the plug locations (bottom) for several typical treatment stages. The plugs in the toe-most stages were exposed to the highest temperatures because they had not yet experienced as much cooldown. Later stages tended to be exposed to progressively lower temperature conditions.

We were able to take advantage of the permanent fiber optic cable to record continuous DTS measurements that allowed us to monitor temperature along the lateral throughout the stimulation treatment. In general, we found no evidence for plug failure on any stage based on downhole fiber optic data or surface pressure responses. To further understand the conditions that the plugs were actually exposed to, we analyzed the DTS measurements in greater detail. We expected to observe that the wellbore would experience significant cool down effects due to the high fluid injection rates during the treatment and during pump down activities. In (a), we show the treatment plots and the DTS temperature trace at the Stage 16 plug location (MD = 8,181 ft) over the duration of Stages 15 and 16. The static formation temperature at this location was 370 °F based on the equilibrated temperature profile measured after drilling the well and prior to the stimulation treatment (see Fig. 6). By the end of Stage 15, the wellbore had cooled down to approximately 100 °F. In between stages, the wellbore warmed back, however, the maximum temperature observed prior to beginning pumping operations on Stage 16 was only 200 °F, significantly below the rated temperature of any of the plugs trialed in this project. In (b), we show the temperature traces at the plug locations for several representative stages. We observed that the Stage 1 plug was subjected to the highest downhole temperature conditions, and all subsequent stages tended to be exposed to lower downhole temperature conditions. The Stage 1 plug experienced temperatures approaching 300 °F, having only been cooled down by relatively low-volume and low-rate injection while conveying the wireline assembly via pumpdown operations. However, even that minor amount of injection was sufficient to cool the wellbore below the temperature rating of Plug A, the lowest rated plug that was trialed.

Subsequent stages are generally exposed to lower temperatures because of the remnant cooling effects of prior stages. In this case, the modeling forecasts were able to predict the downhole temperature conditions during the stimulation treatment accurately. Based on real-time downhole measurements, we confirmed that bridge plugs do not need to be rated to the formation temperature because of the extreme cooling that occurs during wireline pumpdown and stimulation operations. In higher temperature formations, the rate of warmback in between stages will occur faster.

- Establish new **well construction benchmarks** for the geothermal industry.
- Apply the findings directly to **DOE's flagship Utah FORGE program** with measurable success in 2024 operations.
- Leverage commercial-scale project infrastructure to **de-risk DOE-funded R&D**.

5.2 Recommendations for Future Work

- **Expand DAS microseismic application** for high-resolution fracture propagation studies.
- **Embed commercial partnerships** early in DOE projects to leverage efficiencies (Fervo's integrated ops model proved critical).
- **Refine proppant and fluid design** strategies tailored to thermally stressed environments and maximize fracture conductivity.
- **Improve thermal resilience of downhole logging tools**, particularly for image logging in horizontal wells.
- Use SRV datasets from FORGE stimulation to calibrate next-gen well spacing and lateral geometry for future geothermal assets.

6. Tables

A. Uploaded GDR Datasets/Reports List

Submission Name	Resources	Id	Submitted	Status
Utah FORGE Project Red Microseismic Monitoring	1	1754	2025-08-07	In curation
Project Red Well 34-22 Stimulation Treatment Data - 2022	1	1753	2025-08-07	Publicly accessible
Utah FORGE Project Red Injection Well 34A-22	11	1752	2025-07-30	Awaiting curation
Project Red Monitoring Well 73-22 Geophysical and Mud Logging Data - 2022	11	1751	2025-07-30	In curation