Welcome!

The program will begin soon.
You will not hear audio until we begin.

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Webinars

Utah FORGE: Engineering an Enhanced Geothermal System

John McLennan

October 17, 2022

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Funding for this work was provided by the U.S. DOE under grant DE-EE0007080 "Enhanced Geothermal System Concept Testing and Development at the Milford City, Utah FORGE Site"

We thank the many stakeholders who are supporting this project, including Smithfield, the Utah School and Institutional Trust Lands Administration, and Beaver County as well as the Utah Governor's Office of Energy Development and Utah's Congressional Delegation.

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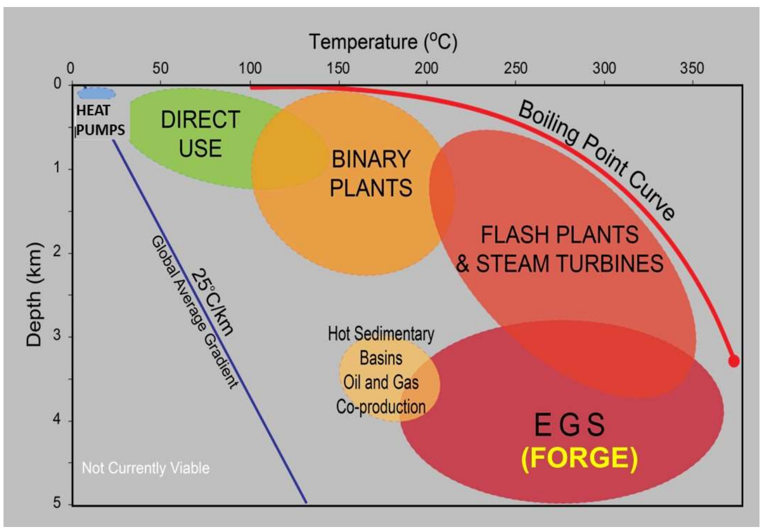
Geothermal Systems

Webinars



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Moore and Simmons, 2013

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Renewed Interest in Geothermal

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Drivers

- Changing Temperatures
- Increasing Heating/Cooling Costs
- Shortages of Critical Minerals (Li, Rare Earth Elements, Metals, Hydrogen)
- Reducing Water Loss (Boilers)
- DOE Goal of Increasing U.S. Electric Generation from 3,700 Mwe To 60,000 Mwe By 2050

Approach

- Geothermal, Enhanced Geothermal Systems (EGS)
- Stimulate Low Productivity Geothermal Wells
- Abandoned Oil and Gas Wells
- Closed Loop Systems (Conduction Dominated)
- More Efficient Working Fluids (CO_2, Organic Fluids) and Binary Power Plant Designs
- Supercritical (Magma) Systems

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Benefits of Geothermal Energy: Electric Generation

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- Low Emissions
- Base Load Power
- Peaking
- Renewable
- Vast Resource
- Low Cost Once Established
- Small Geographic Footprint

In Utah

- 73 MWe installed
- 1300 MWe potential

PacifiCorp's 38 MWe
Blundell Plant
Compare footprints of geothermal plant and wind farm

ENEL Green Power's 25 MWe
Cove Fort Plant

Cyrq Energy's 10 MWe
Thermo Plant

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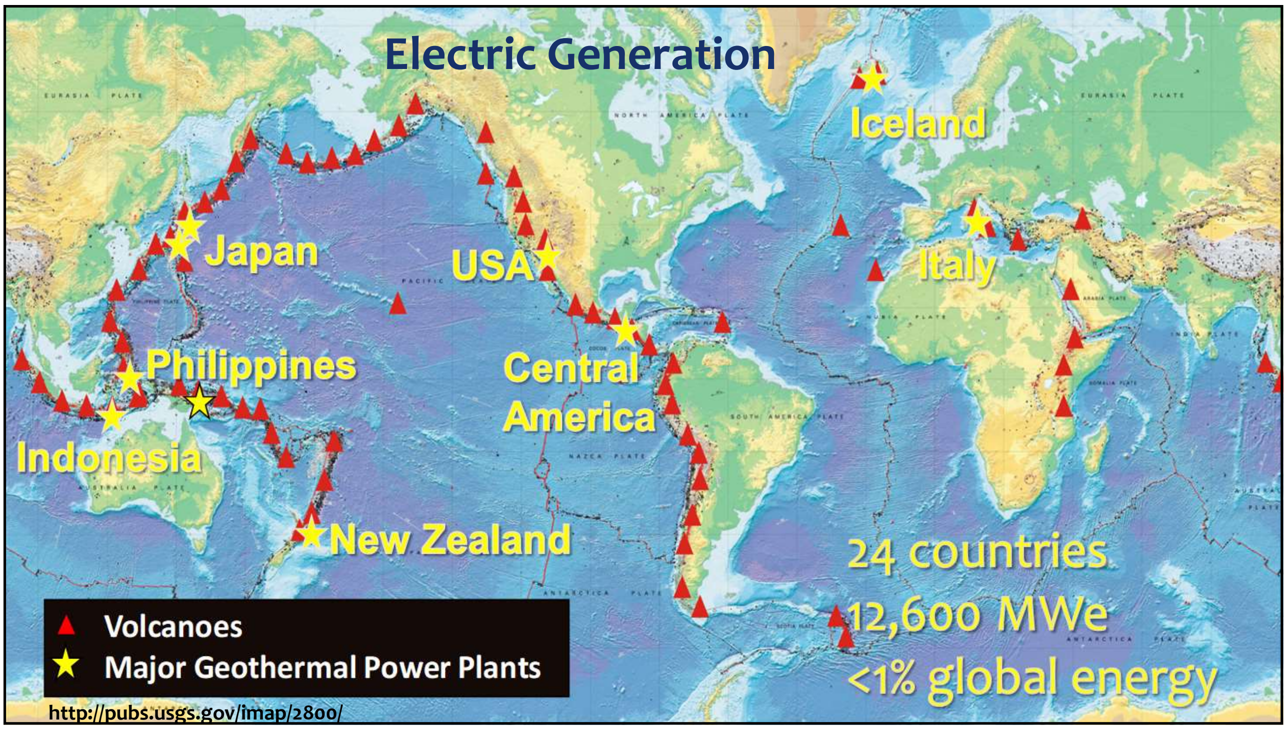
Electric Generation
Iceland
Japan
USA
Italy
Philippines
Central America
Indonesia
New Zealand
24 countries
12,600 MWe
<1% global energy
Volcanoes
Major Geothermal Power Plants
http://pubs.usgs.gov/imap/2800/

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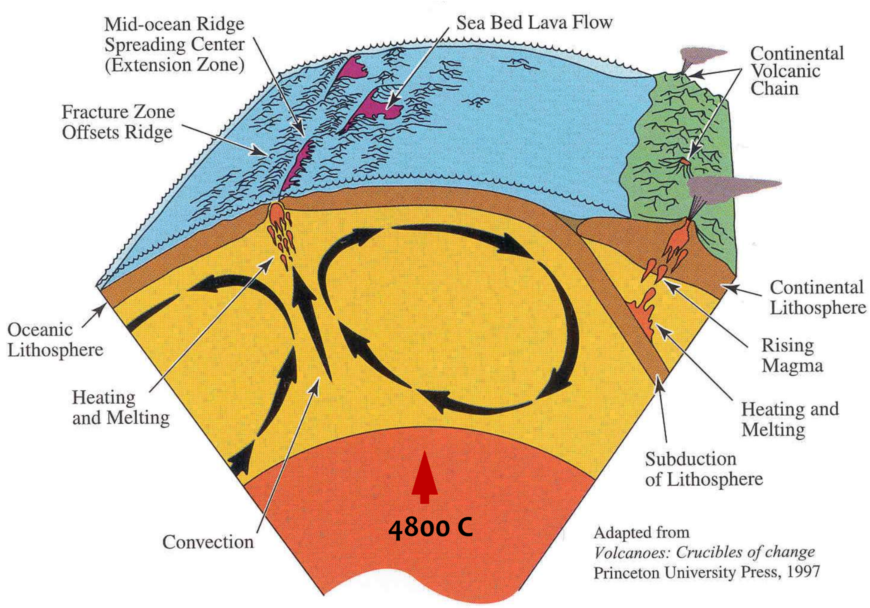
The Earth's Dynamics



Adapted from
Volcanoes: Crucibles of change
Princeton University Press, 1997

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Liquid-Dominated (Conventional) Geothermal Systems

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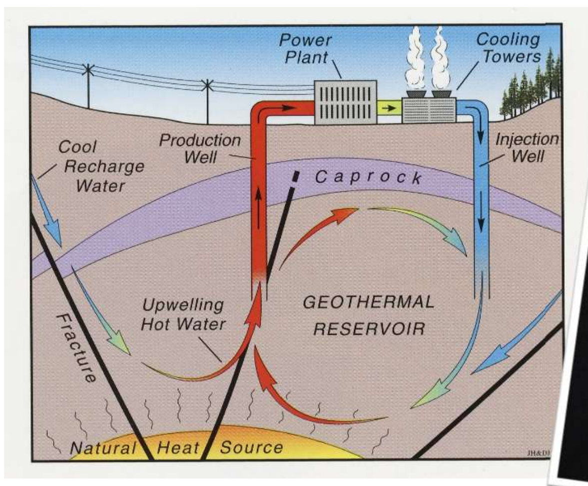
1. Heat Source
2. Water to Transport Heat
3. Conductive Fractures



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Characteristics of Conventional Systems

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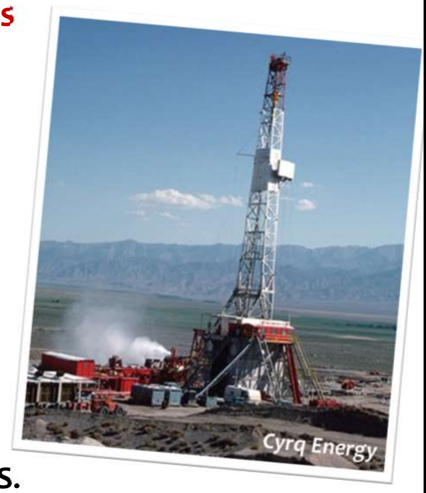
Generic Characteristics of Hydrothermal Systems

- Large *in situ* fluid volumes
- Convective heat transfer
- Extensive natural fracture systems
- Production from high permeability fractures
- Production from a few plants to ~800 MWe

Rules of Thumb

- Average well .... 6 MWe
- Largest wells .... 50 MWe
- At 392°F (200°C) .... 1 MWe from flow rate of 365 gpm which could service 750 to 1,000 homes in U.S.



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Enhanced Geothermal Systems

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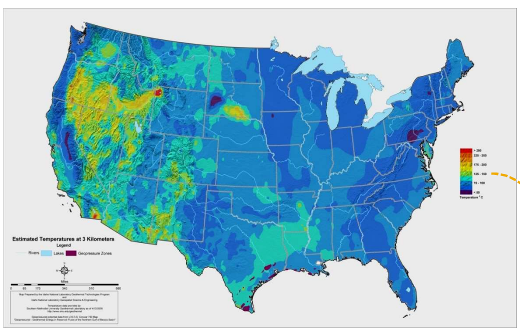
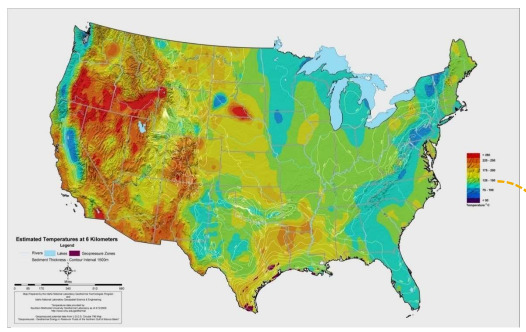
Resource Base:

USGS Estimated Potential in Western States is 518,000 MWe



150°C

Temperatures at 3 km



150°C

Temperatures at 6 km

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Data from SMU and Tester and others, 2006

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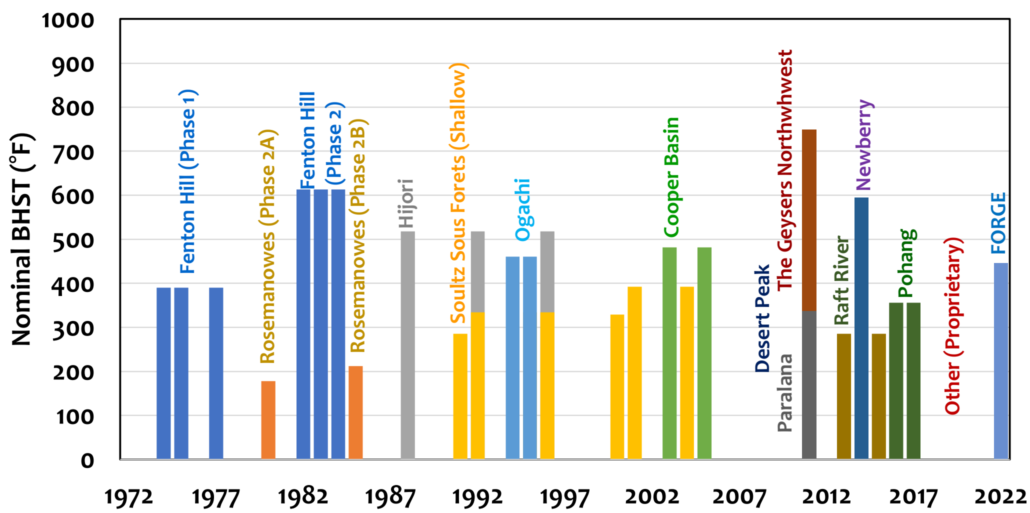
Nearly 50 Years of EGS Stimulations



Compiled from Tester et al., 2006 and Breede et al., 2013

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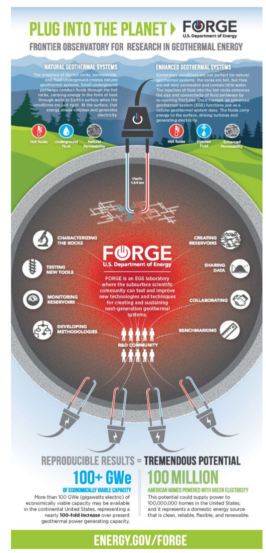
The DOE FORGE Program

Phase 1
- Five sites selected; $400,000 awarded to Utah for "desktop" characterization (Completed)

Phase 2 (2016-2019)
- 2A/B: $10M awarded for permitting and proving resource (Completed)
- 2C: Milford chosen for the laboratory ($10,000,000 available)

Phase 3 (2019-2024)
- Drill, stimulate and flow test two deep wells; ~ $220 million over the five years for testing and research



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Frontier Observatory for Research in Geothermal Energy

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New Technologies? Revitalizing Classical EGS

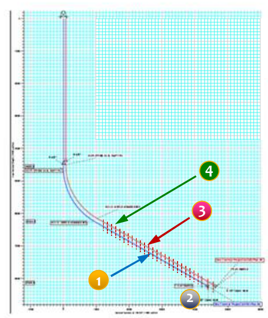
Conceptual Reservoir Development

1. Drill Injection Well
2. Hydraulically Fracture (Multiple Stages)
3. Drill Production Well to Intersect Fractures
4. Populate Well with Frac Stages

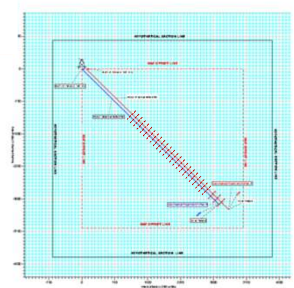
Conceptual Commercial Agenda

- Injected Cold Water Circulates Through Hydraulic Fractures
- Hot Water Brought to Surface Through Production Well
- Flashed to Steam and/or Run Through Organic Rankine Cycle Binary Plant

Classical EGS Conceptual Schematic



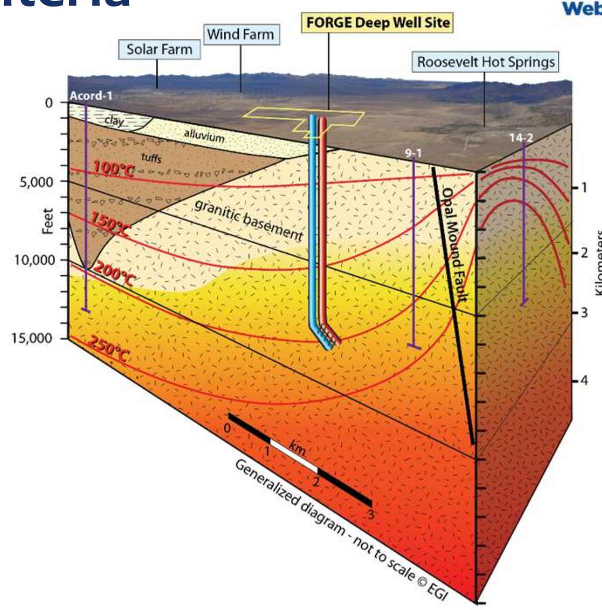
Elevation (Side) View



Plan (Map) View

FORGE Criteria

- Temperature >350°F at depths >5000 ft
- Low permeability rocks (granite)
- Low risk from induced seismicity
- Low environmental risks
- No connection to hydrothermal system



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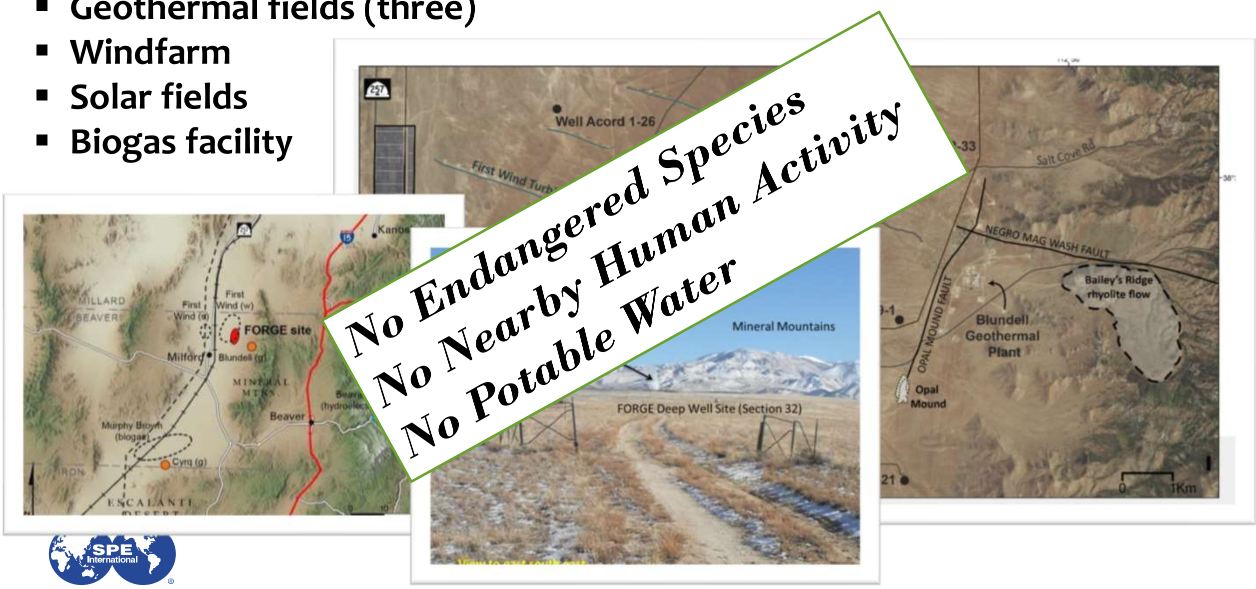
Utah's Renewable Energy Corridor

- Geothermal fields (three)
- Windfarm
- Solar fields
- Biogas facility



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Recent Activities and Plans

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- **Drill two highly deviated wells into granitic rocks with a temperature of ~175 to 235°C in the 1.5 to 4 km depth range.**
- **Connect wells with hydraulic fracturing**
- **Circulate**

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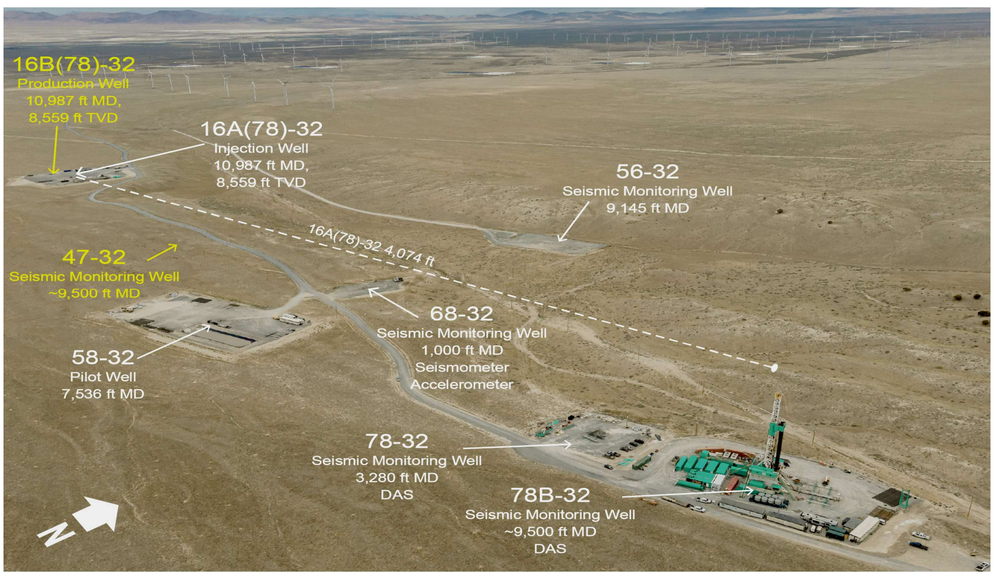
Directional Well 16A(78)-32



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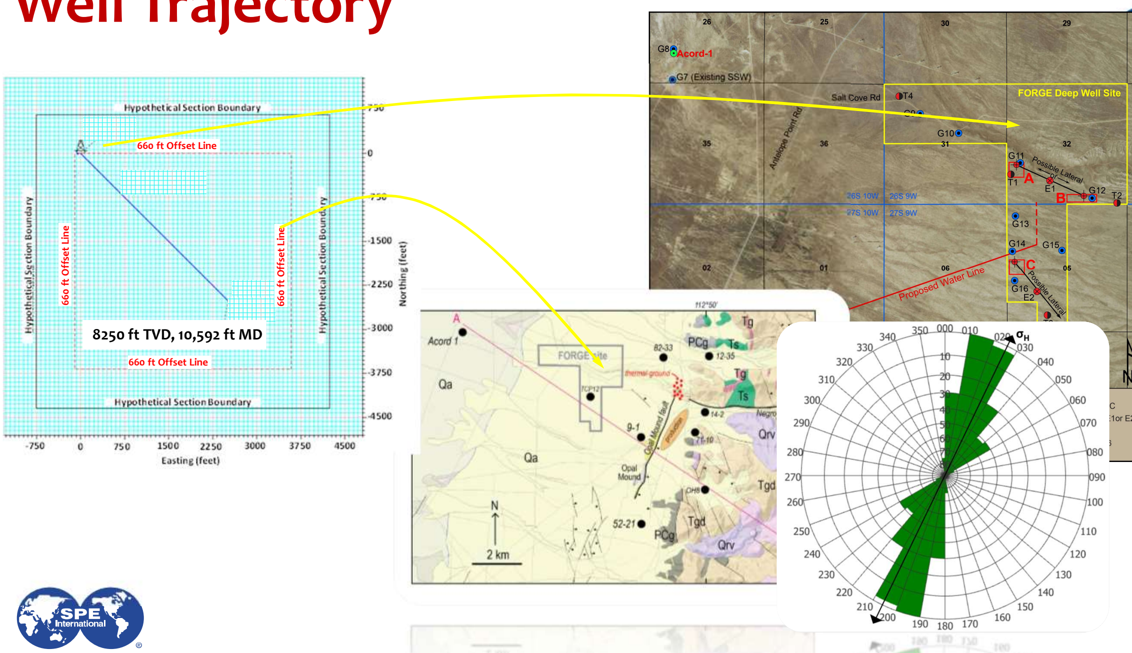
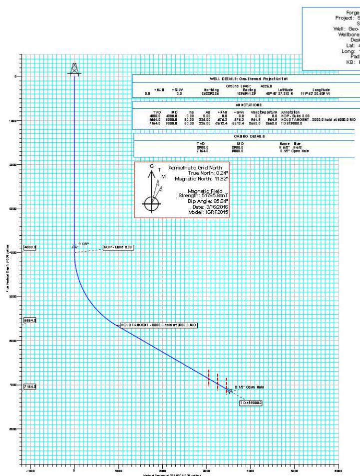
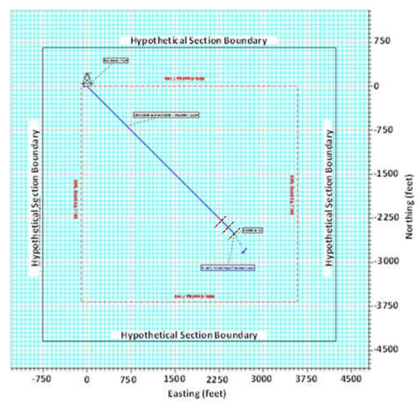
Well Trajectory



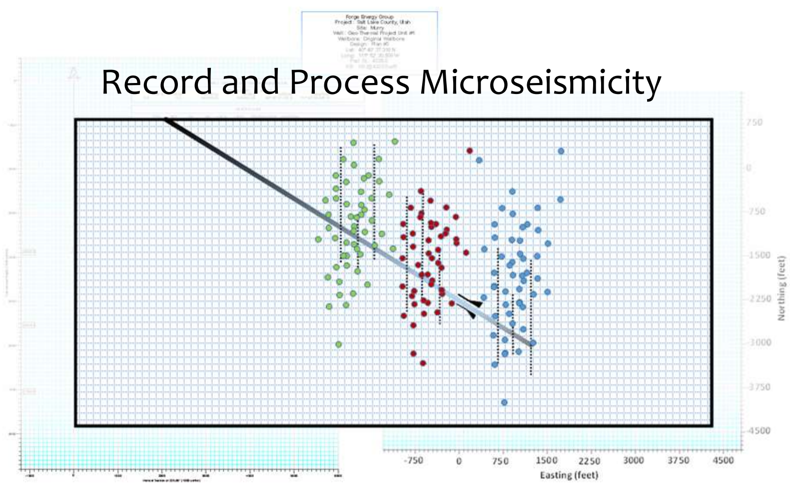
Stimulate Active Well at Toe





Stimulate Active Well at Toe

Record and Process Microseismicity



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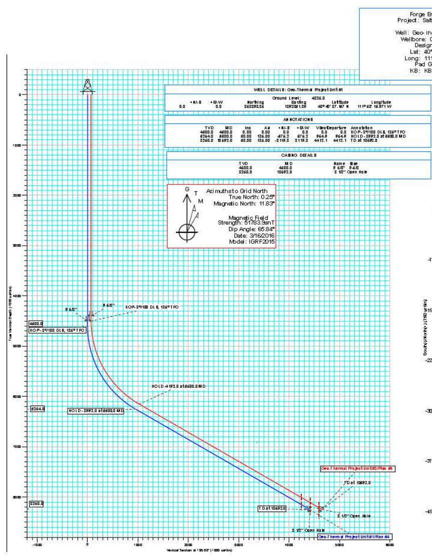
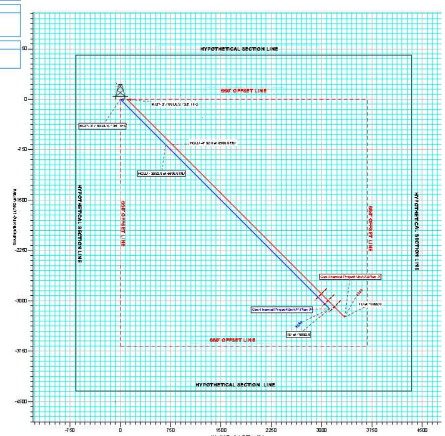
Steer Passive Well to Intersect Fractures





Why Problematic? Operational Considerations

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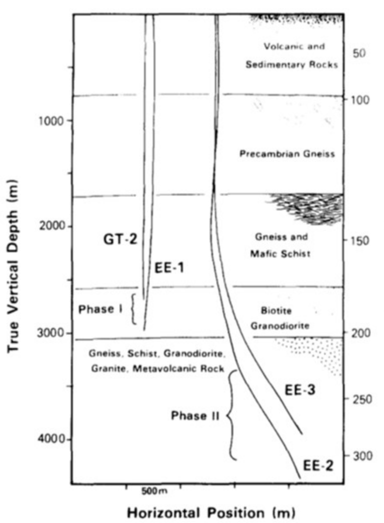

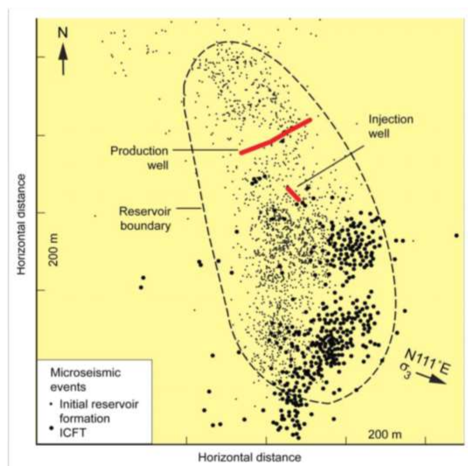

- Jemez Caldera, Fenton Hill
- Phase II Injection Program
- EE-2 and EE-3
- Sub-vertical
- Significant Stimulation

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How Are Geothermal Operations Different?

Temperature:

- Average temperature greater (production intervals from 160°C to above 300°C+)

Mechanical Characteristics:

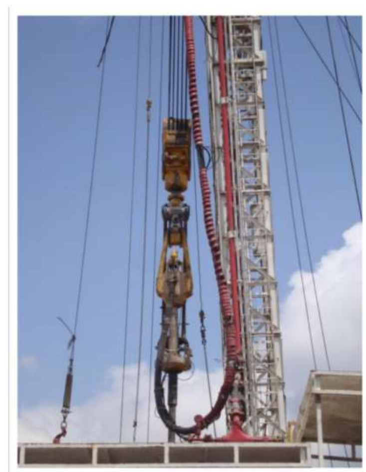
- High strength (35,000 psi (240+ MPa) compressive strength), high modulus, abrasive (quartz often above 50%)

Natural Fractures:

- Highly fractured

Formation Fluids:

- Often contain corrosive fluids
- Some have very high solids content [total dissolved solids (TDS) [in some Imperial Valley brines is above 250,000 ppm]



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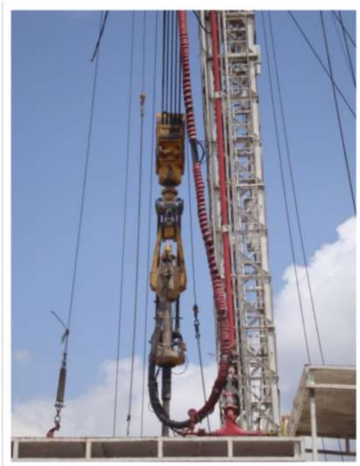
How Are Geothermal Operations Different?

Temperature
Mechanical Characteristics
Natural Fractures
Formation Fluids
High Production Rates Required
- Large Diameter Casing

May Need to Reach Significant TVD
- Extensive and Hot Drilling and Completion

Often Underpressured
- Lost Circulation (Also Natural Fractures)



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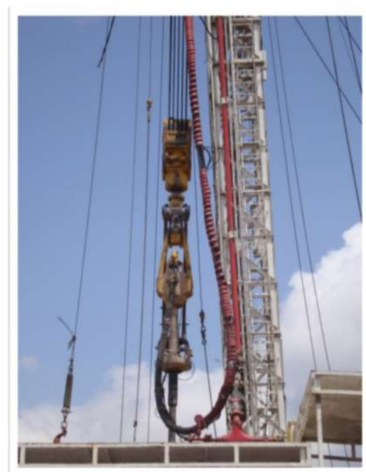
Well Cost Drivers

1. Tools and techniques required for harsh downhole conditions.
2. Large diameters: produced fluid (hot water or steam) intrinsically low energy density, large flow rates and large casing required.
3. May require more casing strings to achieve a given depth in a geothermal well
4. Uniqueness: even in same field, wells more different than oil and gas wells in same field, learning curve from experience is less useful



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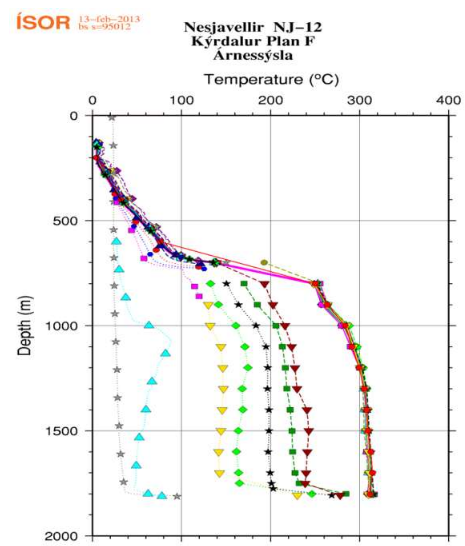
Temperature

- Depth and temperature of geothermal resources vary considerably
- Several power plants, (e.g., Steamboat Hills, Nevada and Mammoth Lakes, California) operate on lower-temperature fluid (below 200°C) produced from depths of approximately 330 m
- The Geysers produce dry steam (above 240°C) and are typically 2,500 to 3,000 m deep.
- Extreme cases - exploratory well with a bottomhole temperature of 500°C at approximately 3,350 m in Japan
- Experimental holes into molten rock (above 980°C) in Hawaii and Iceland



https://orkustofnun.is/gogn/unu-gtp-sc/UNU-GTP-SC-16-21.pdf

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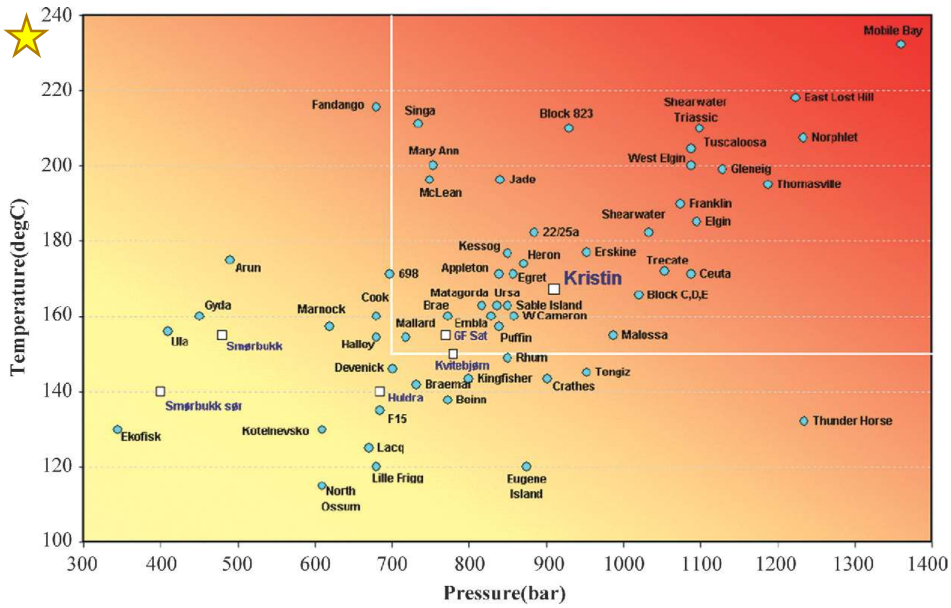

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https://assets.geoexpro.com/legacy-files/articles/Kristin%20a%20tough%20lady.pdf

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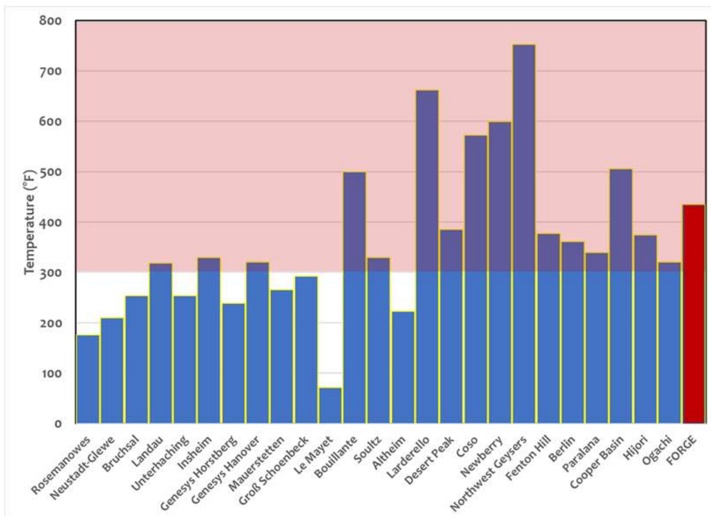
Why Problematic? Temperature

Need and motivation for products and services that can perform successfully at elevated temperature/time required

And – multiple stimulation stages envisioned



Why Problematic? Reservoir Characteristics?

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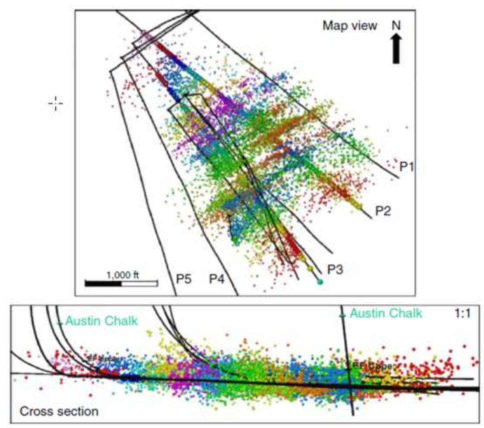
Courtesy Bartley 2019



Raterman et al. 2018. Sampling a Stimulated Rock Volume : An Eagle Ford Example, SPE 191375, SPE Reservoir Evaluation & Engineering

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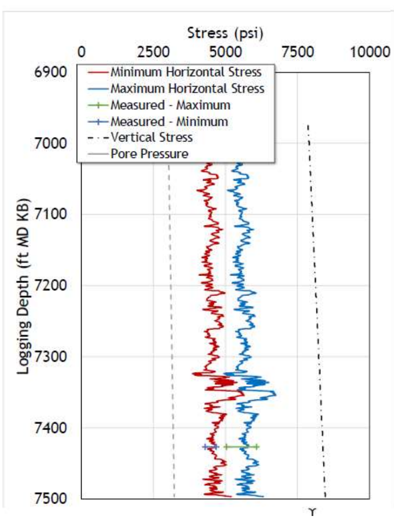
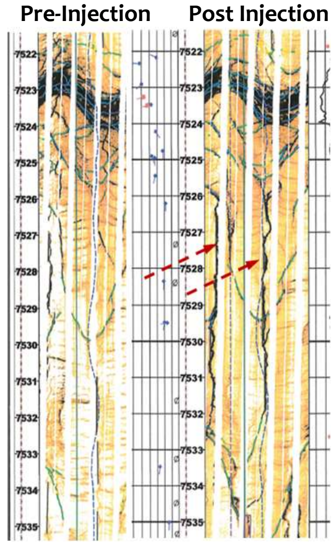
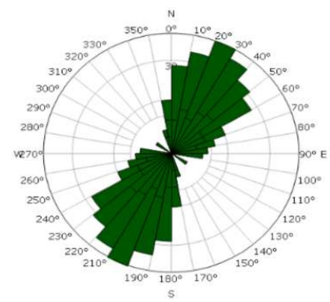
In Situ Stress and Fractures

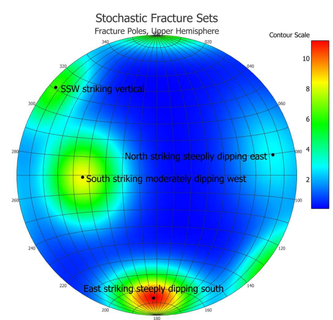


Pre-Injection Post Injection



Azimuth Induced Fractures: Well 58-32





Reservoir Surveillance: Logging Programs

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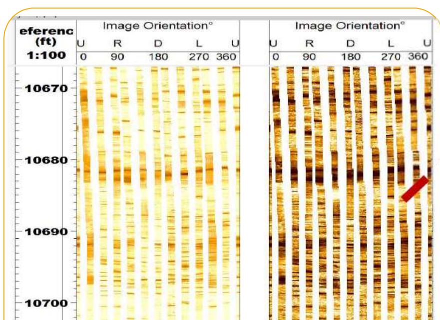
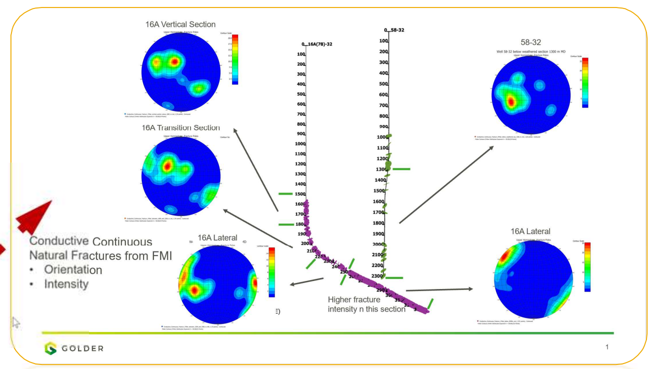
- Run FMI successfully from 10, 923 to 4,851 ft MD through tubing



PRELIMINARY PROCESSED IMAGE



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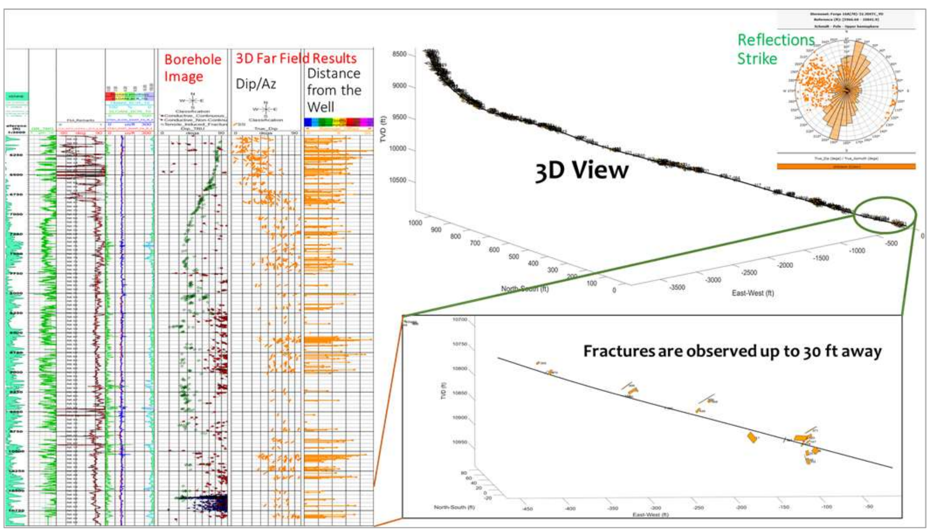
Far-Field Sonic Processing: Image and 3D Far-Field Results



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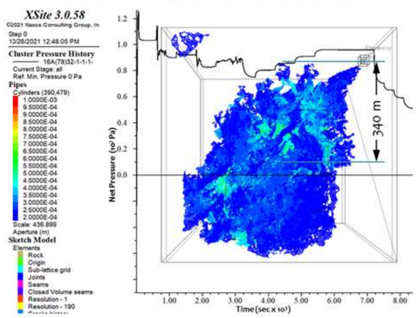
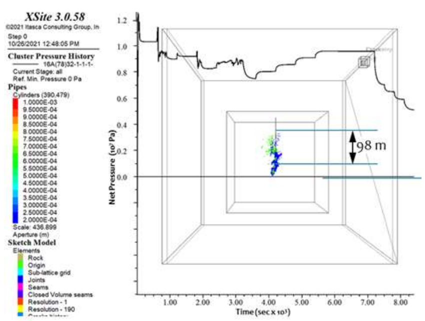
Permeable, Frictional DFN

Fractures Opened to More than 0.2 mm in Shear



Fractures opened to more than 0.2 mm in Sliding

Hydraulically Opened Fractures



Hydraulically Opened Fractures

Courtesy FORGE Simulation Team and Itasca Consulting Group

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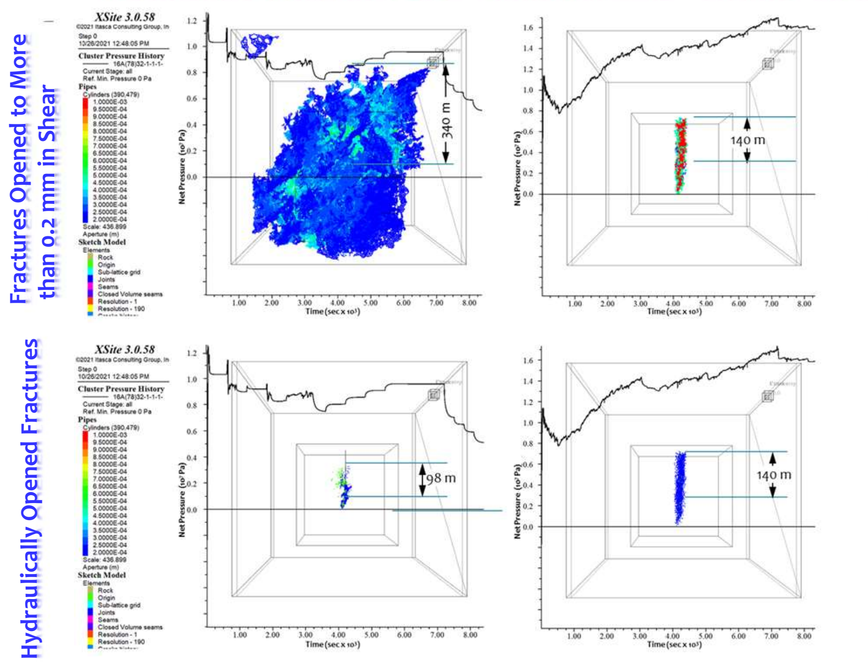
Permeable, Frictional DFN **Impermeable, "Strong" DFN**



Fractures opened to more than 0.2 mm in Sliding

Hydraulically Opened Fractures

Courtesy FORGE Simulation Team and Itasca Consulting Group

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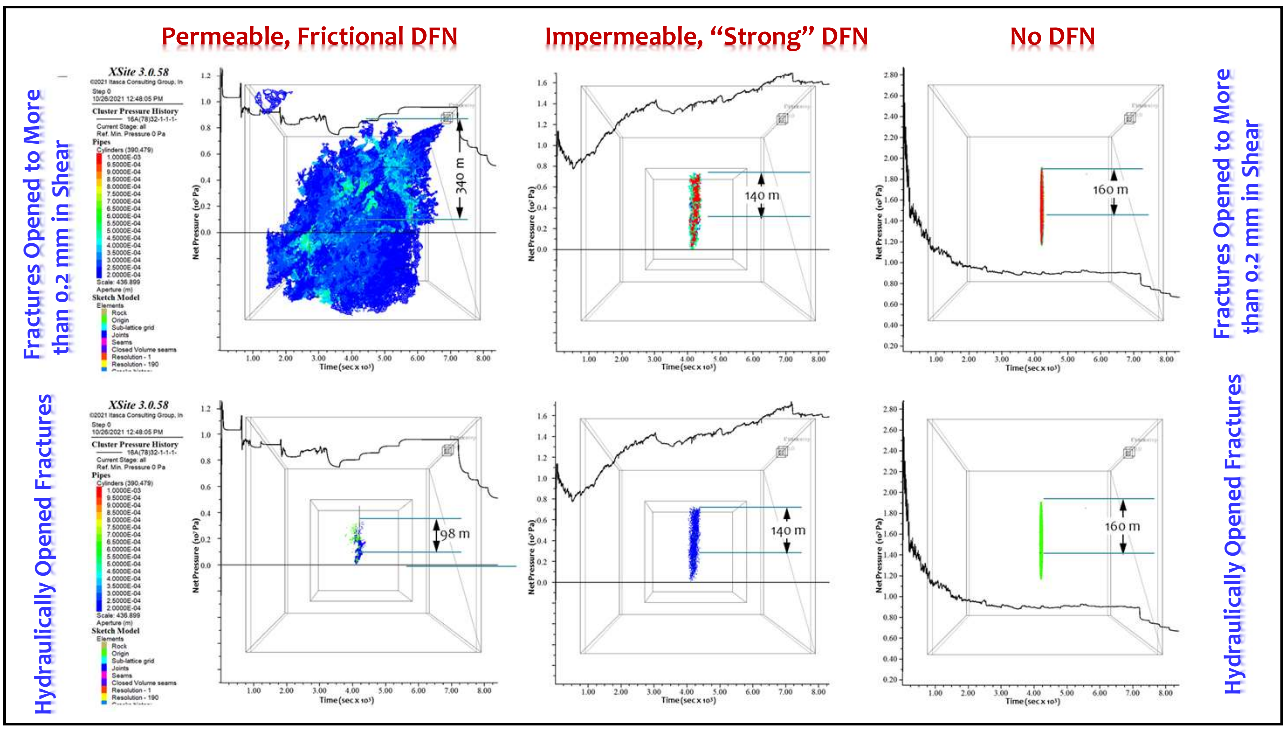
Permeable, Frictional DFN
Impermeable, "Strong" DFN
No DFN
Fractures Opened to More than 0.2 mm in Shear
Hydraulically Opened Fractures
XSite 3.0.58
Cluster Pressure History
Sketch Model
340 m
140 m
160 m
98 m
Net Pressure (10⁷ Pa)
Time (sec x 10³)

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Isolation Tools … Problematic Previously

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Zone 2 Packer Failure

a

Zc

Zone 3 Packer. Rings and slips caused significant drag

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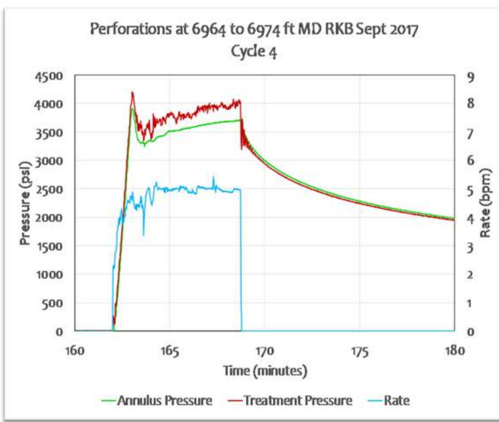
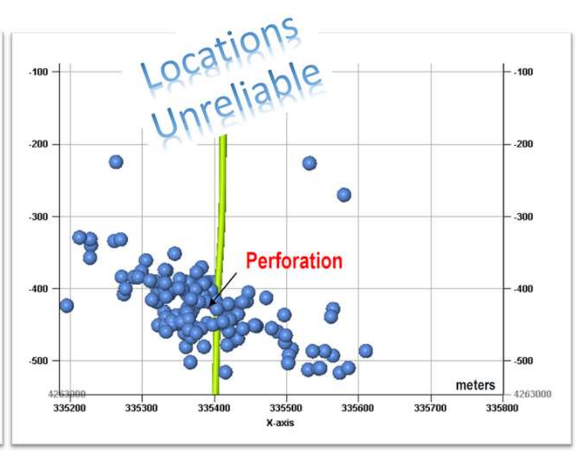
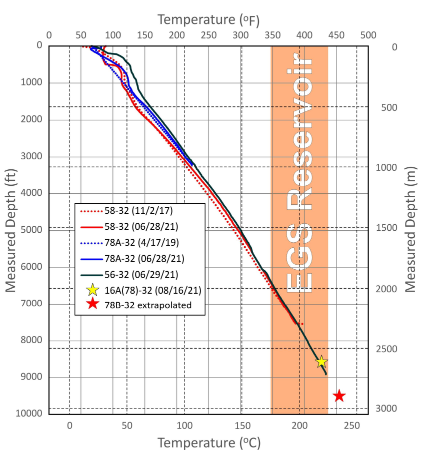
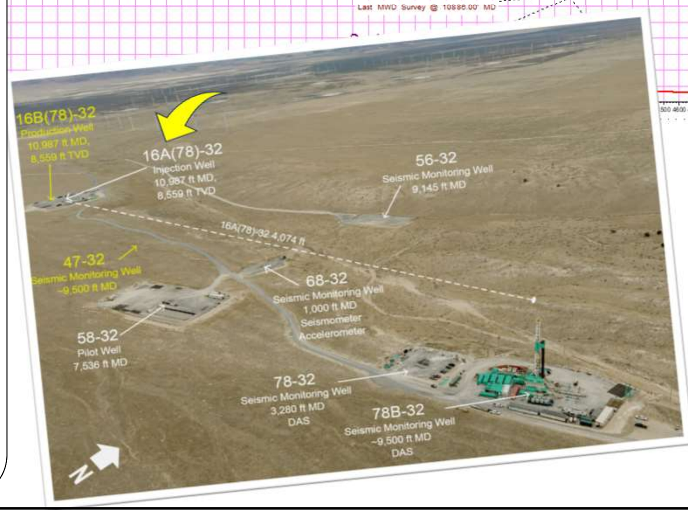
Questions/Considerations …





Well 16A(78)-32





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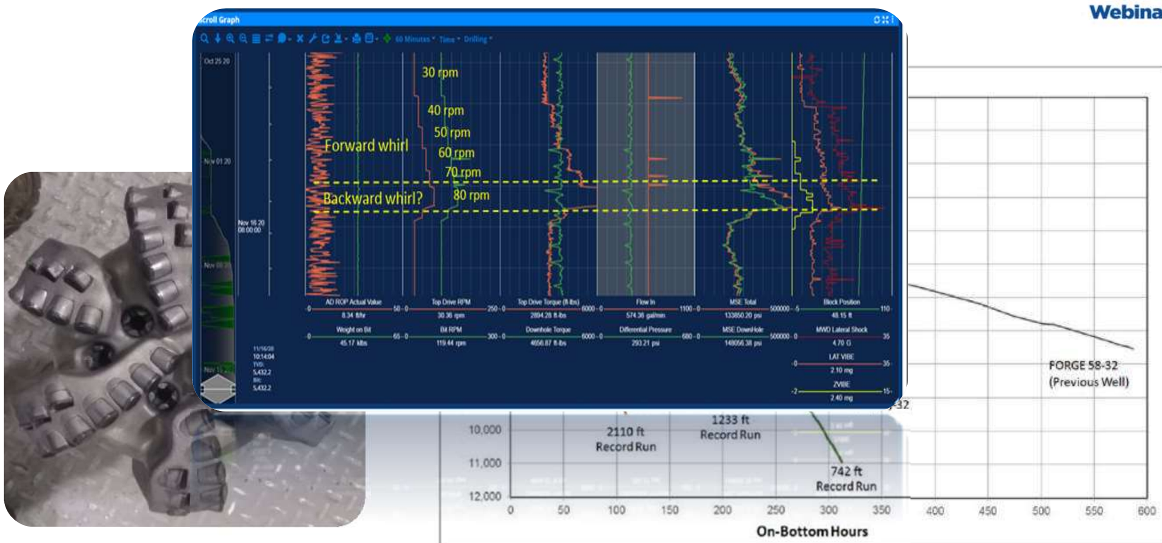
Improvements In Drilling Rates Over Time



(Dupriest and Noynaert 2022)

Mechanics of Drilling: Evolution of PDC Bit Designs

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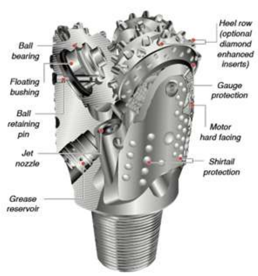

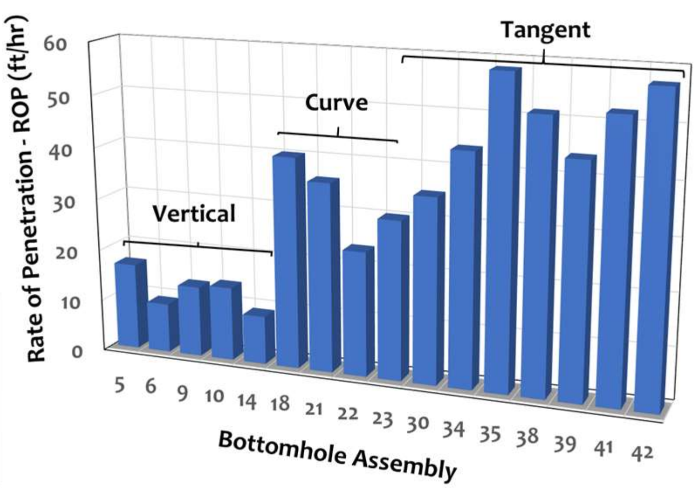

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How To Improve?

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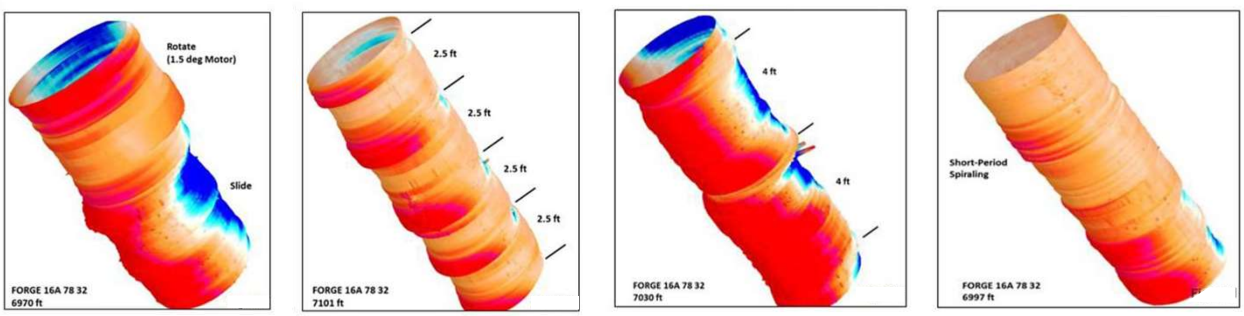
Eliminate Drilling-Related Rugosity



Images Courtesy of Dupriest and Noynaert
IADC/SPE-208798-MS, 2022

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Well 16A(78)-32

Three failed openhole XLOTs, One failed DFIT Packer

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Reservoir Surveillance: DFIT

DFIT (Diagnostic Fracture Injection Test)

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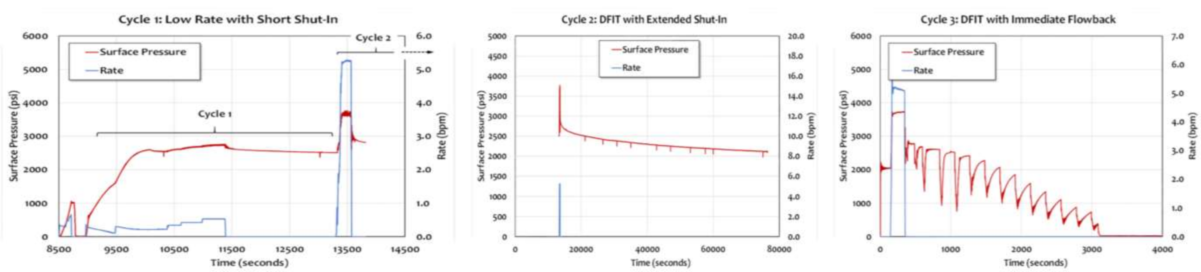

- Acquired quality injection data
- Applicable for calibrating logging predictions of in-situ stress
- Easily treatable (at least in openhole) consistent with previous experience
- Permeability lower than in offset well
- Further demonstration of the viability of flowback data

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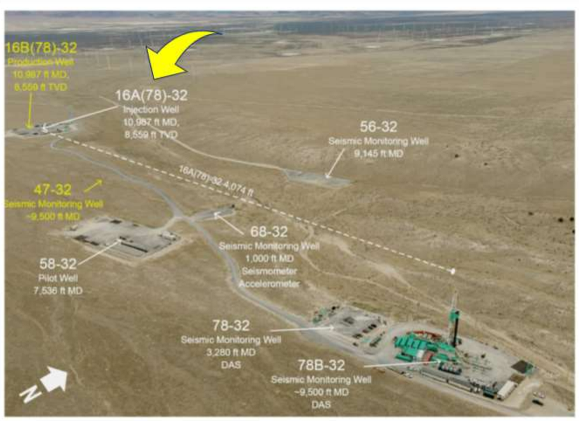
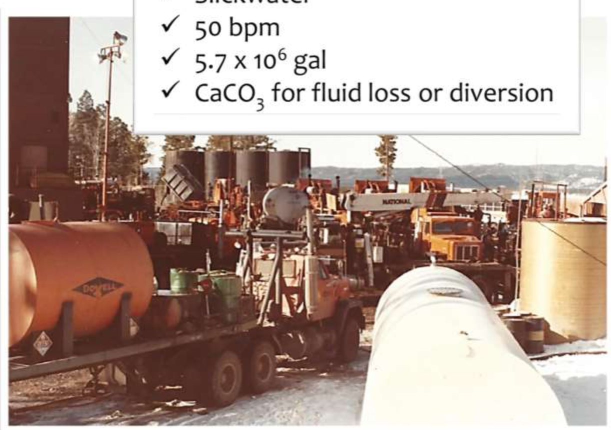
Stimulation of Well 16A(78)-32?



Fenton Hill, December 1983
- ✓ Slickwater
- ✓ 50 bpm
- ✓ 5.7 x 10^6 gal
- ✓ $CaCO_3$ for fluid loss or diversion



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AT THE UNIVERSITY OF UTAH

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Stimulation: What Can Be Tried?

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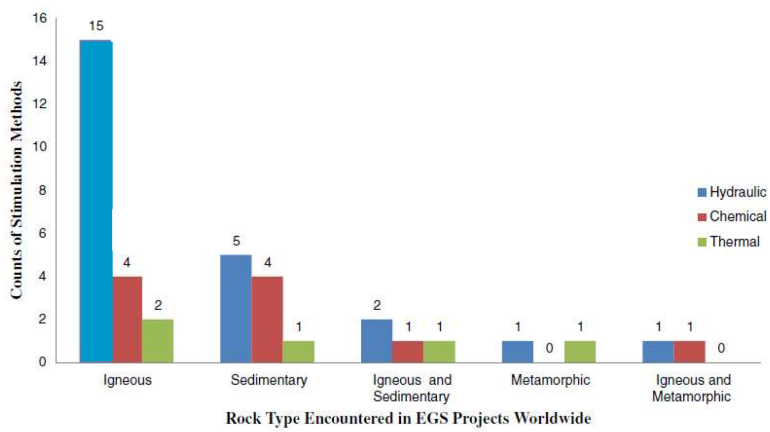
- Mostly vertical or slightly deviated
- Mostly open hole
- Many favored hydraulic shearing ahead of hydraulic fracturing



Breede et al. Geothermal Energy 2013
www.geothermal-energy-journal.com/content/1/1/4

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Role of Natural Fractures?

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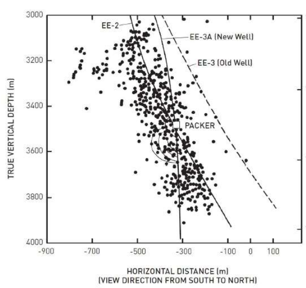
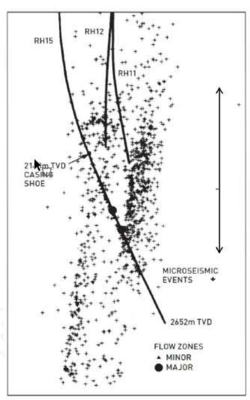
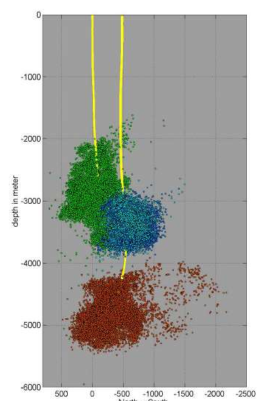
Fenton Hill



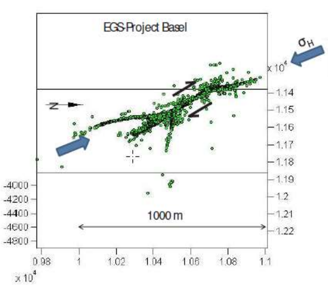
Rosemanowes



Soultz sous Forêts



Basel



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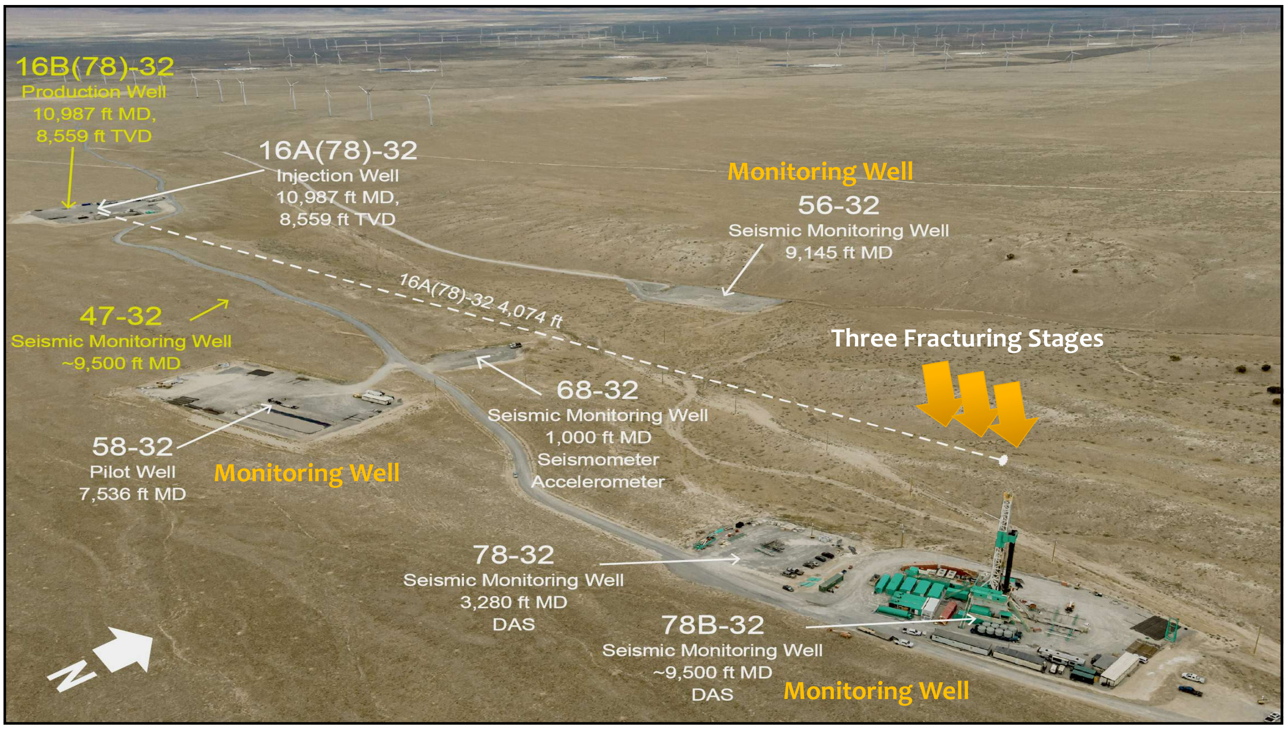
16B(78)-32
Production Well
10,987 ft MD,
8,559 ft TVD
16A(78)-32
Injection Well
10,987 ft MD,
8,559 ft TVD
Monitoring Well
56-32
Seismic Monitoring Well
9,145 ft MD
16A(78)-32 4,074 ft
47-32
Seismic Monitoring Well
~9,500 ft MD
Three Fracturing Stages
68-32
Seismic Monitoring Well
1,000 ft MD
Seismometer
Accelerometer
58-32
Pilot Well
7,536 ft MD
Monitoring Well
78-32
Seismic Monitoring Well
3,280 ft MD
DAS
78B-32
Seismic Monitoring Well
~9,500 ft MD
DAS
Monitoring Well
N

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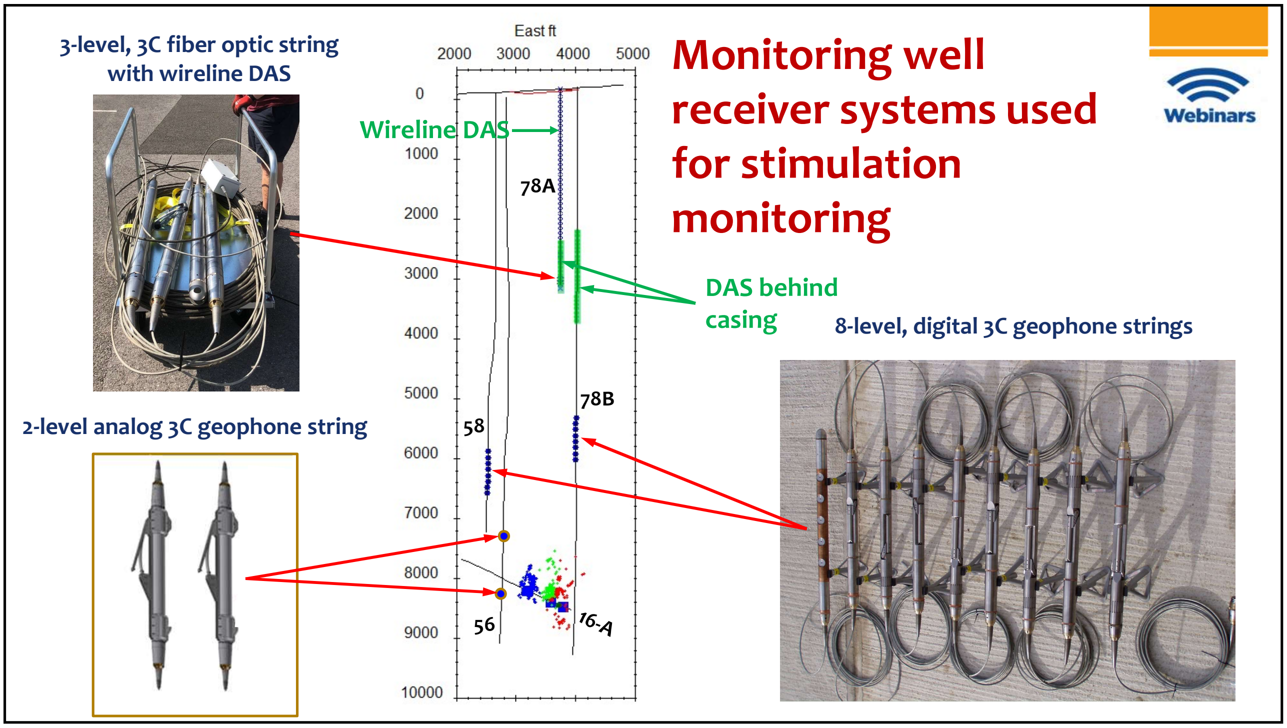
Monitoring well receiver systems used for stimulation monitoring



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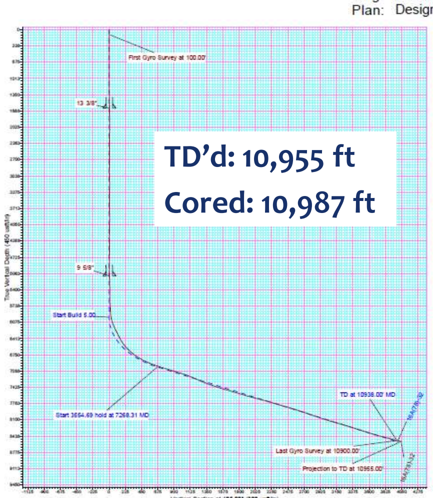
Treatments: Well 16A(78)-32

Project: Forge
Site: Beaver County, UT
Well: 16A(78)-32
GL: GE + RKB (5414' + 30') @ 5444.00usft (Frontier 16)
SHL Northing: 13987645.20
SHL Easting: 1097896.92
Rig: Frontier 16
Plan: Design: 16A(78)-32 plan 1



TD'd: 10,955 ft

Cored: 10,987 ft

Stage 1: Openhole portion of the well below ~10,787 ft – **Slickwater, Tagged**

Stage 2: Cased and perforated – above 7-inch shoe – **Slickwater, Tagged**

Stage 3: Move slightly uphole from Stage 2 – **Crosslinked, Tagged**

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MIRU Frontier Rig 28

- Frontier Rig 28 Brought into Service
- Operational Flexibility for Circulation, Setting Tools …

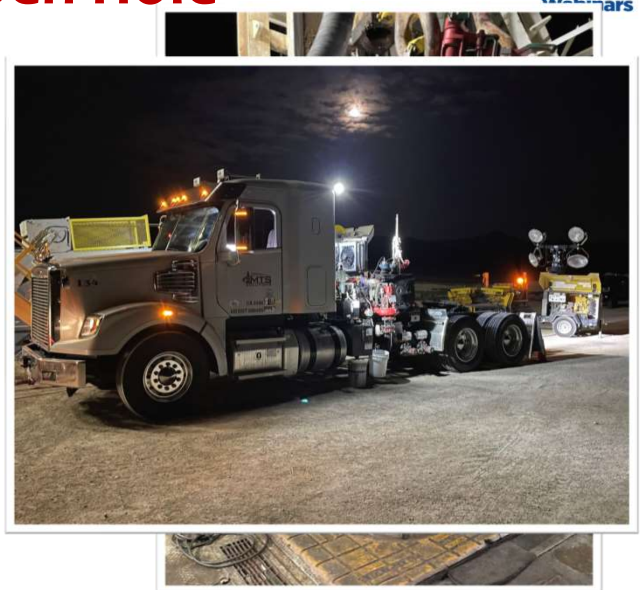
55

Mechanical CCL above Check Shot

- Extreme Wireline ran a perforating gun on drill pipe into openhole (below 10,787 ft MD)
- Orient Geophones
- Ran mechanical casing collar locator and confirmed casing tally for depth of guns

Check Shot Fired Open Hole

- 3-1/8" diameter, 2 ft long gun with 6 shots per foot at 60° phasing
- MTS Solutions pumped down drill pipe to seat a dropped ball and fire the guns
- Successful firing served as a check shot for orienting geophones in the offset wells



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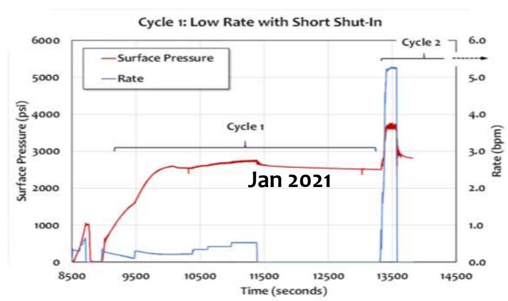
Shear Stimulation Test

- MTS Pumped Shear Stimulation Test
- One hour at an average rate of 0.36 bpm followed by shutdown and monitoring pressure decline for an hour
- 52 bbl of water pumped



Pumped Stage 1

- Liberty Oilfield Services pumped down casing
- Reached planned injection rate of 50 bpm of slickwater
- 4,261 bbl pumped
- Well shut in for four hours and flowed back.

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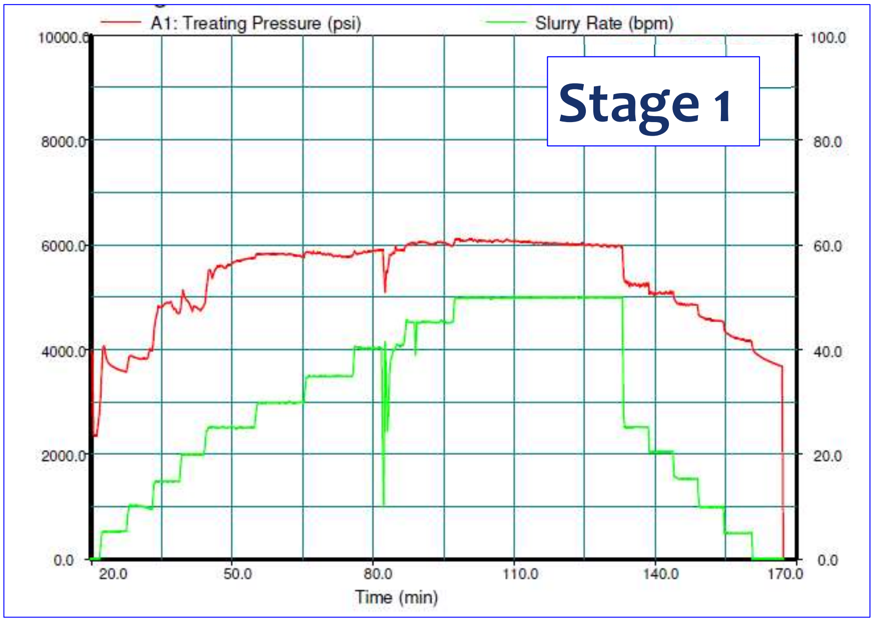
A1: Treating Pressure (psi)
Slurry Rate (bpm)
Stage 1
10000.0
8000.0
6000.0
4000.0
2000.0
0.0
100.0
80.0
60.0
40.0
20.0
0.0
20.0
50.0
80.0
110.0
140.0
170.0
Time (min)

60

Flowing Back Stage 1

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Set Bridge Plug for Stage 2

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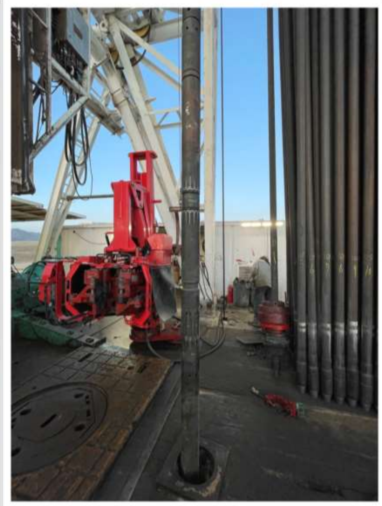
- 16 hours of flowback
- Interwell ran bridge plug to 10,670 ft MD
- Pumped to set bridge plug
- Tested to 7,000 psi using frac pumping equipment, down casing



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Stage 2 Perforated

- Perforating gun run into hole on drill pipe.
- 20-ft long gun (6 shots per ft, 60° phasing, 21-gram Hero charges)
- 10,560 to 10,580 ft MD.
- All 120 shots fired
- Looking for potential weak points (natural fractures) to facilitate initiation

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Stage 2 Pumped

- Pumped 2,777 bbl of slickwater down casing reaching 35 bpm
- Intentional hard shutdown in the initial 5 bpm stage and part way through 35-bpm stage
- At EOJ, well shut in and pressure decline monitored for 4 hours
- Well flowed back for 12 hours

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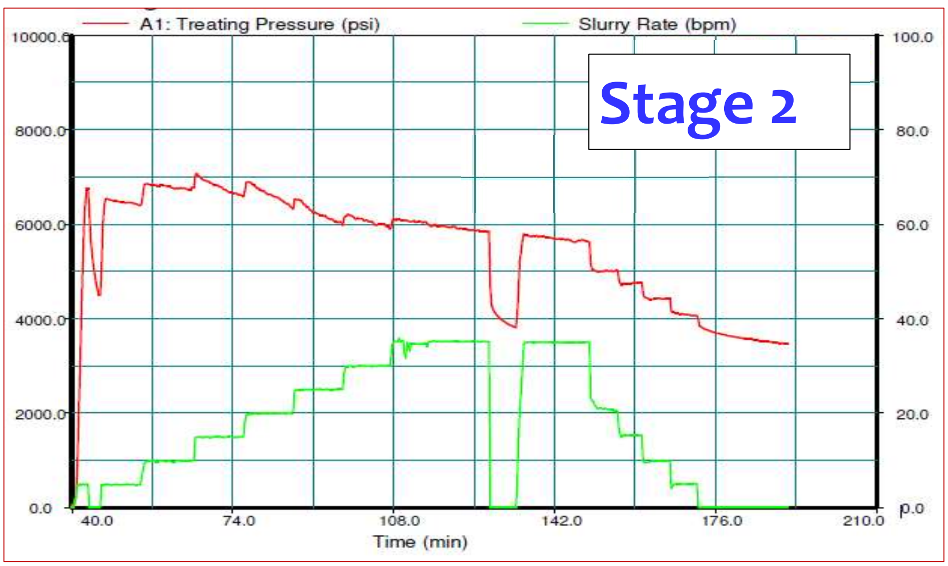
A1: Treating Pressure (psi)
Slurry Rate (bpm)
Stage 2
10000.0
8000.0
6000.0
4000.0
2000.0
0.0
100.0
80.0
60.0
40.0
20.0
0.0
40.0
74.0
108.0
142.0
176.0
210.0
Time (min)

65

Stage 3 Run Bridge Plug

- After flowback, ran second bridge plug to 10,466 ft MD
- Pumped to set bridge plug.
- Bridge plug pressure tested to 6,800 psi pumping down casing
- Run gun and perforate

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Stage 3 Frac

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- Pumped in steps to 35 bpm and back down in rate
- Slickwater pad followed by crosslinked CMHPG fluid with microproppant at planned concentrations of 0.5 to 0.75 ppa
- Total pumped fluid volume - 3,016 bbl
- Well shut in and flowed back (for more than 15 hr)

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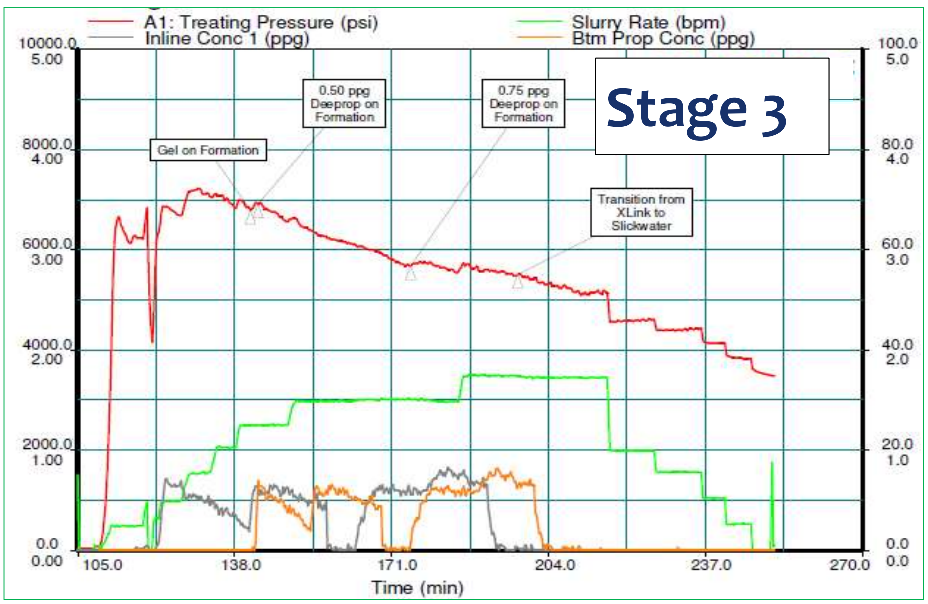

A1: Treating Pressure (psi)
Inline Conc 1 (ppg)
Slurry Rate (bpm)
Btm Prop Conc (ppg)
Stage 3
0.50 ppg Deeprop on Formation
0.75 ppg Deeprop on Formation
Gel on Formation
Transition from XLink to Slickwater
10000.0 5.00
8000.0 4.00
6000.0 3.00
4000.0 2.00
2000.0 1.00
0.0 0.00
100.0 5.0
80.0 4.0
60.0 3.0
40.0 2.0
20.0 1.0
0.0 0.0
105.0
138.0
171.0
204.0
237.0
270.0
Time (min)

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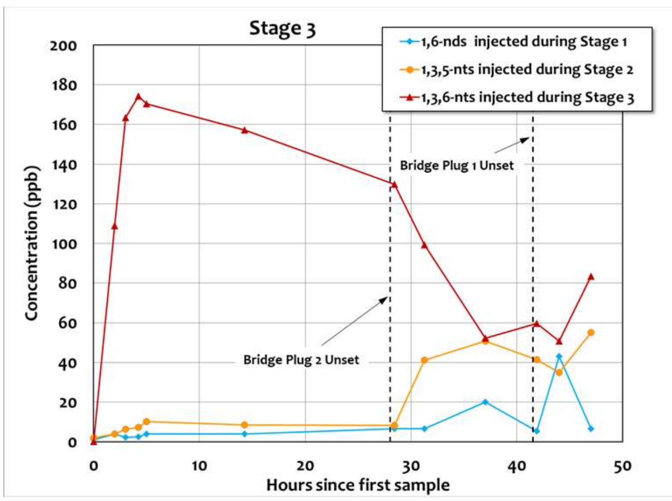
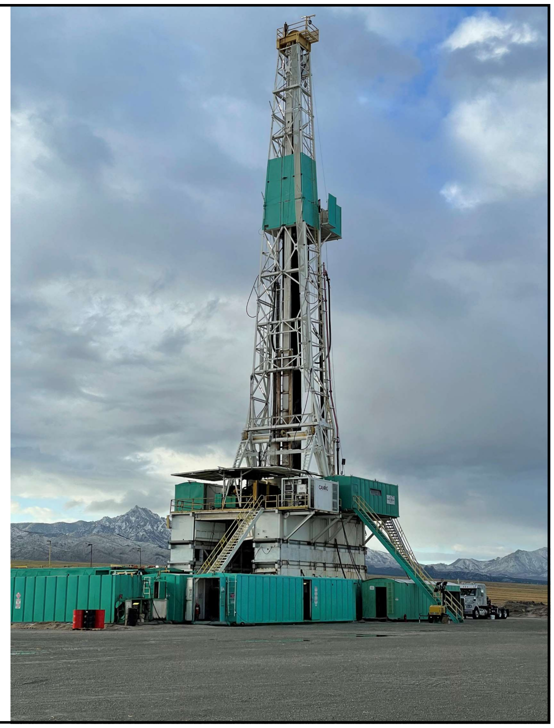
After Stage 3





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Stage 1 Microseismic Monitoring: Stage 1

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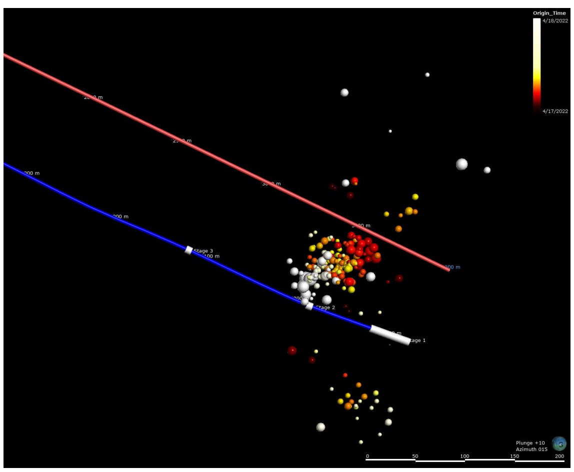
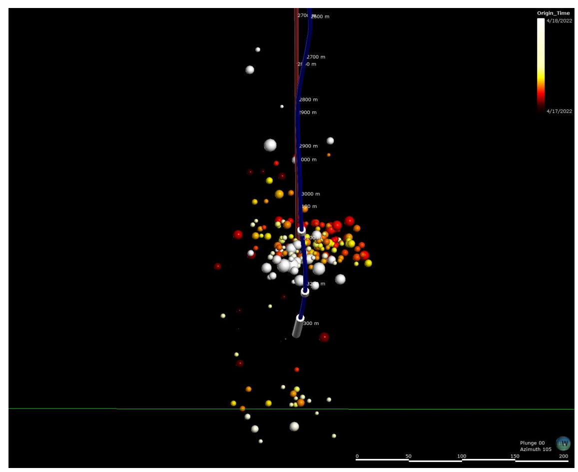
Vertical Section Looking North



Looking Up



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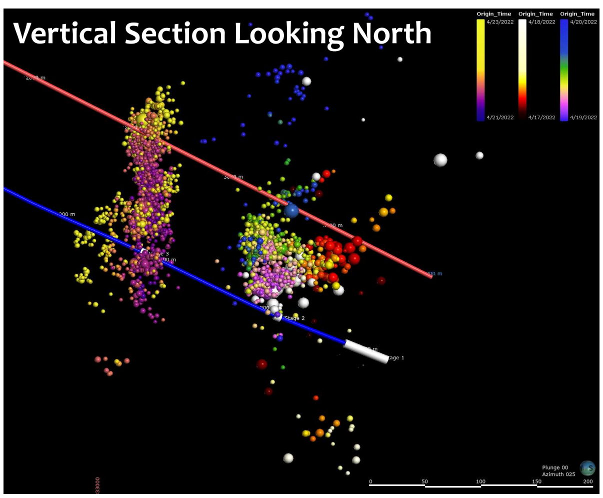
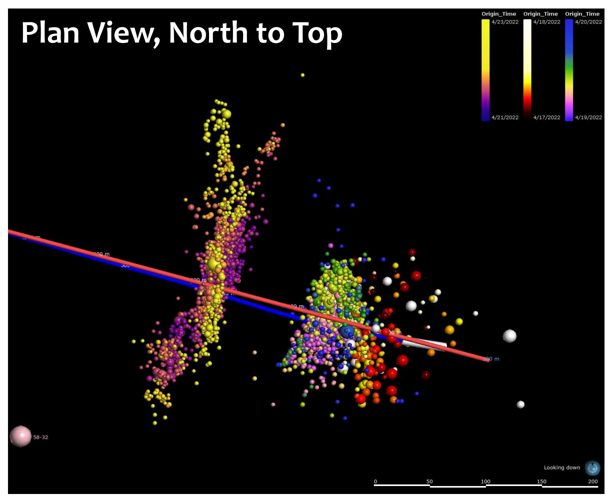
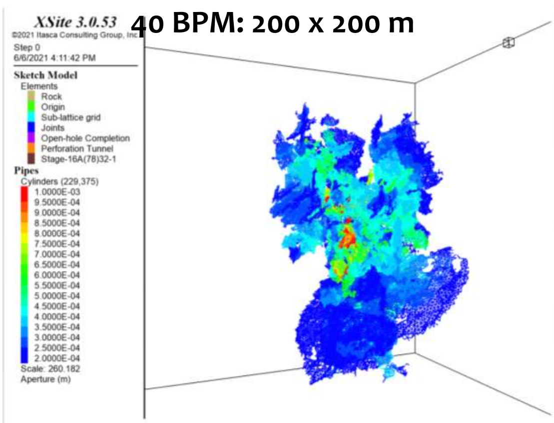
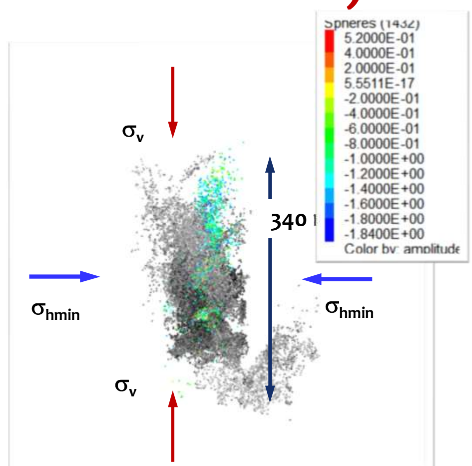
Microseismic Monitoring: All Stages





Stimulated Area (Aperture > 0.2 mm)





Simulation results for permeable and frictional DFN, viscosity 100 cP
Simulation max magnitude 0.64
Field stimulation max magnitude 0.5

Courtesy FORGE Modeling and Simulation Team, Itasca Consulting Group

Microseismic Monitoring: Stage 2

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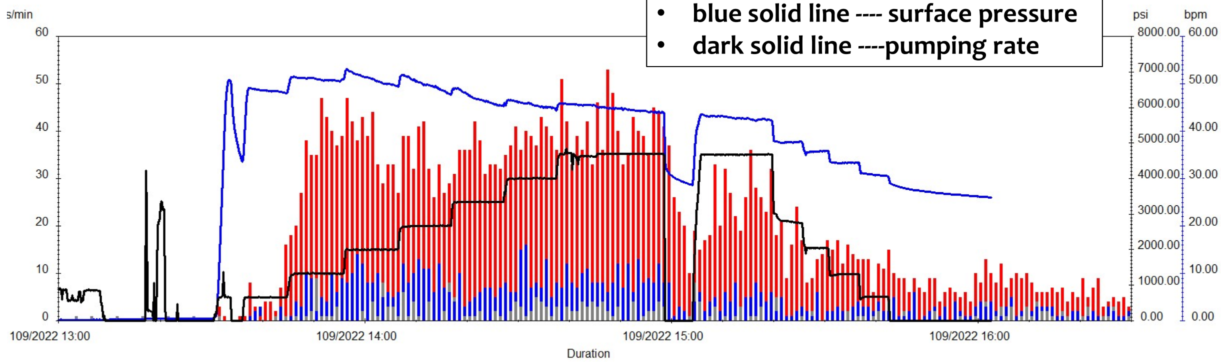
- red bars ---- trigger rates
- blue bars ---- located event rates
- grey bars ----- noise trigger rate
- blue solid line ---- surface pressure
- dark solid line ----pumping rate



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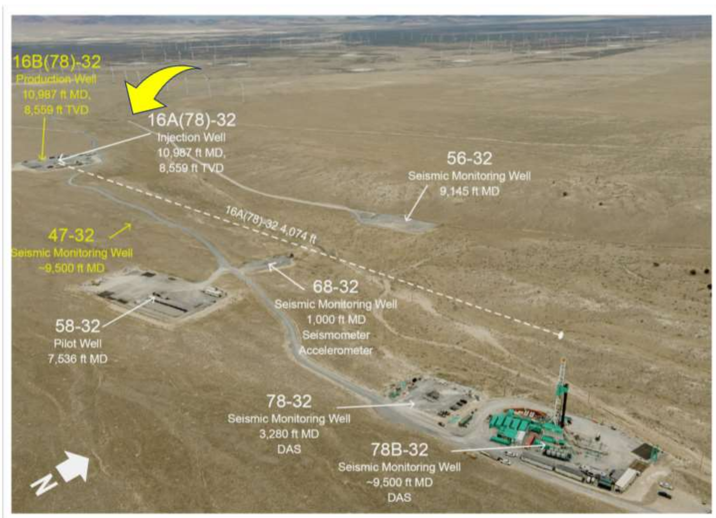
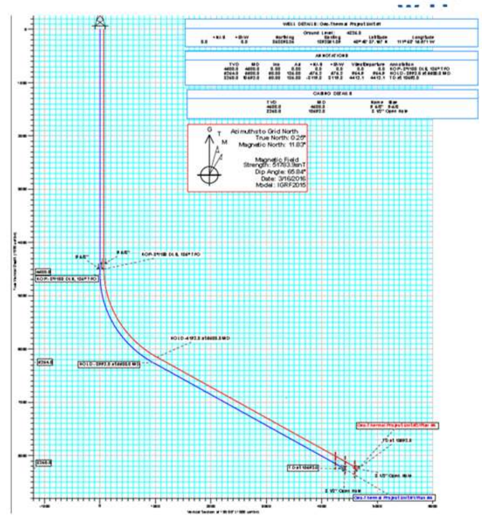
Interactions with Well 16B(78)-32





Connectivity – Conductivity – Conformance - Circulation

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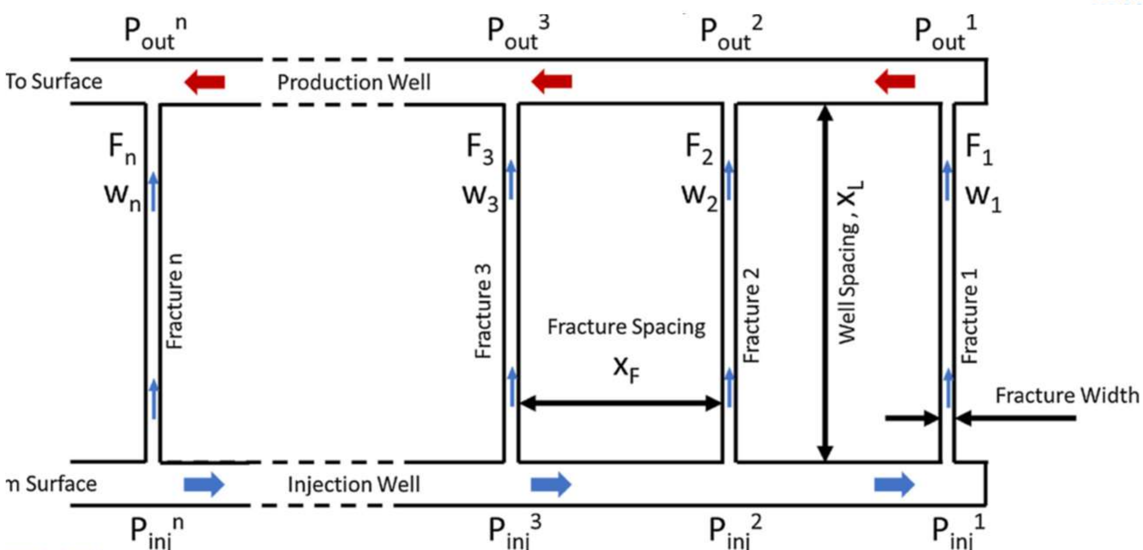
Engineering Questions



After Asai et al., 2018

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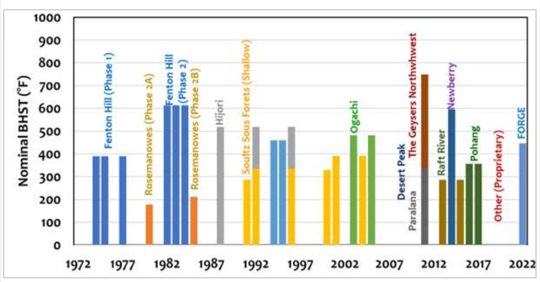
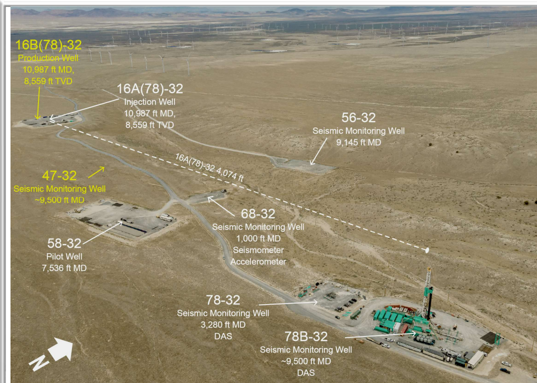
From Fenton Hill – to – FORGE (Frontier Observatory for Research in Geothermal Energy)





UTAH FORGE U.S. Department of Energy

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We thank the many stakeholders who are supporting this project, including Smithfield, Utah School and Institutional Trust Lands Administration, and Beaver County as well as the Utah Governor's Office of Energy Development and Utah's Congressional Delegation.

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