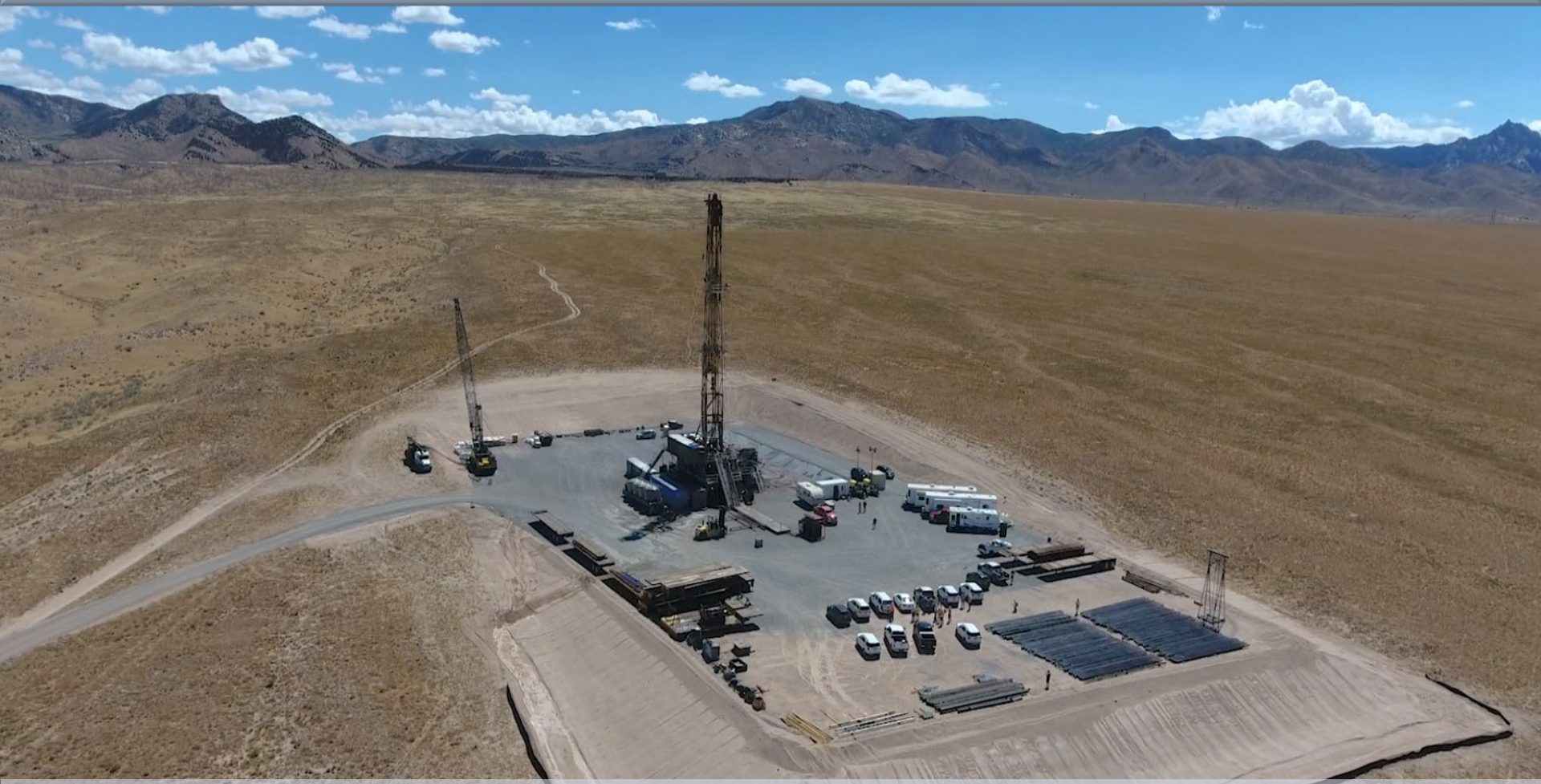
Characteristics of the Utah FORGE Site

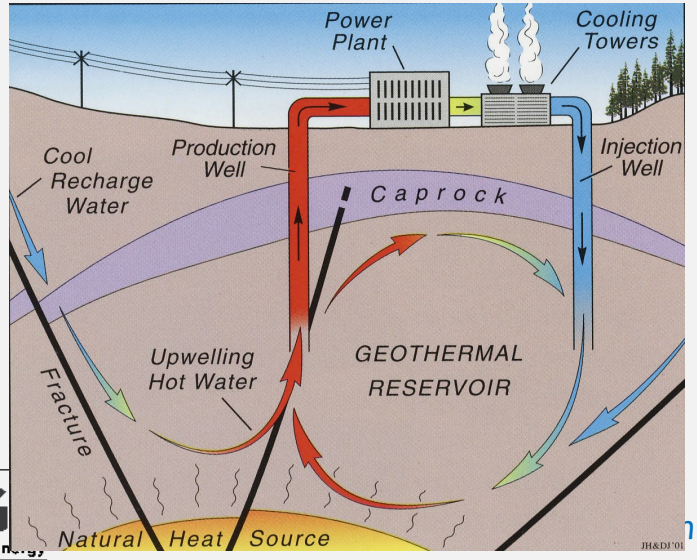


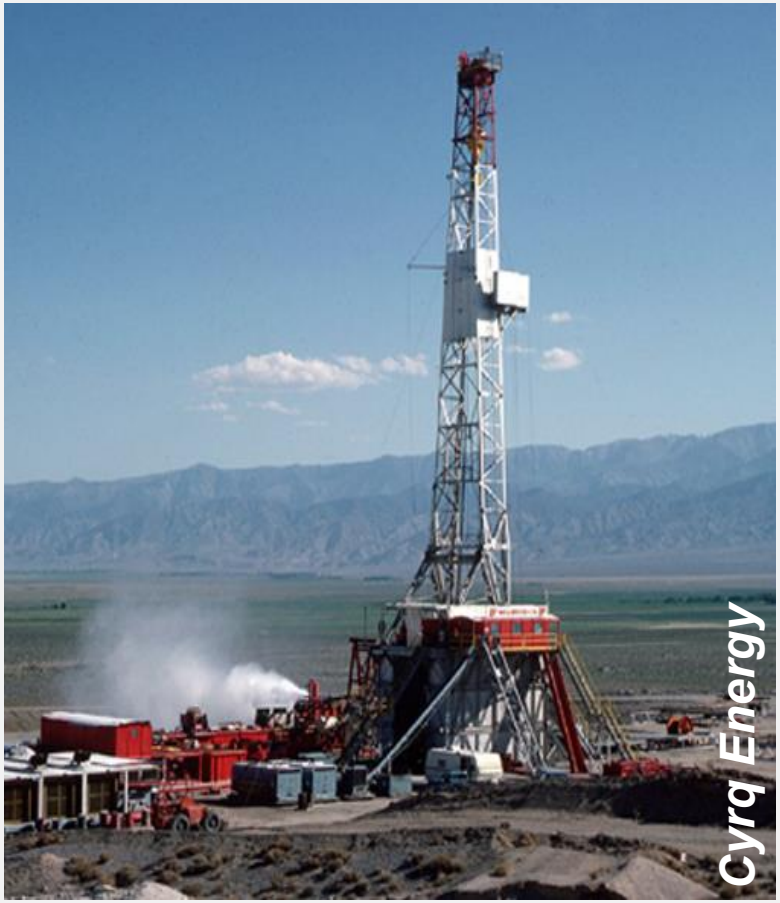
August 7, 2019

Dr. Joseph Moore

Characteristics of Conventional Systems

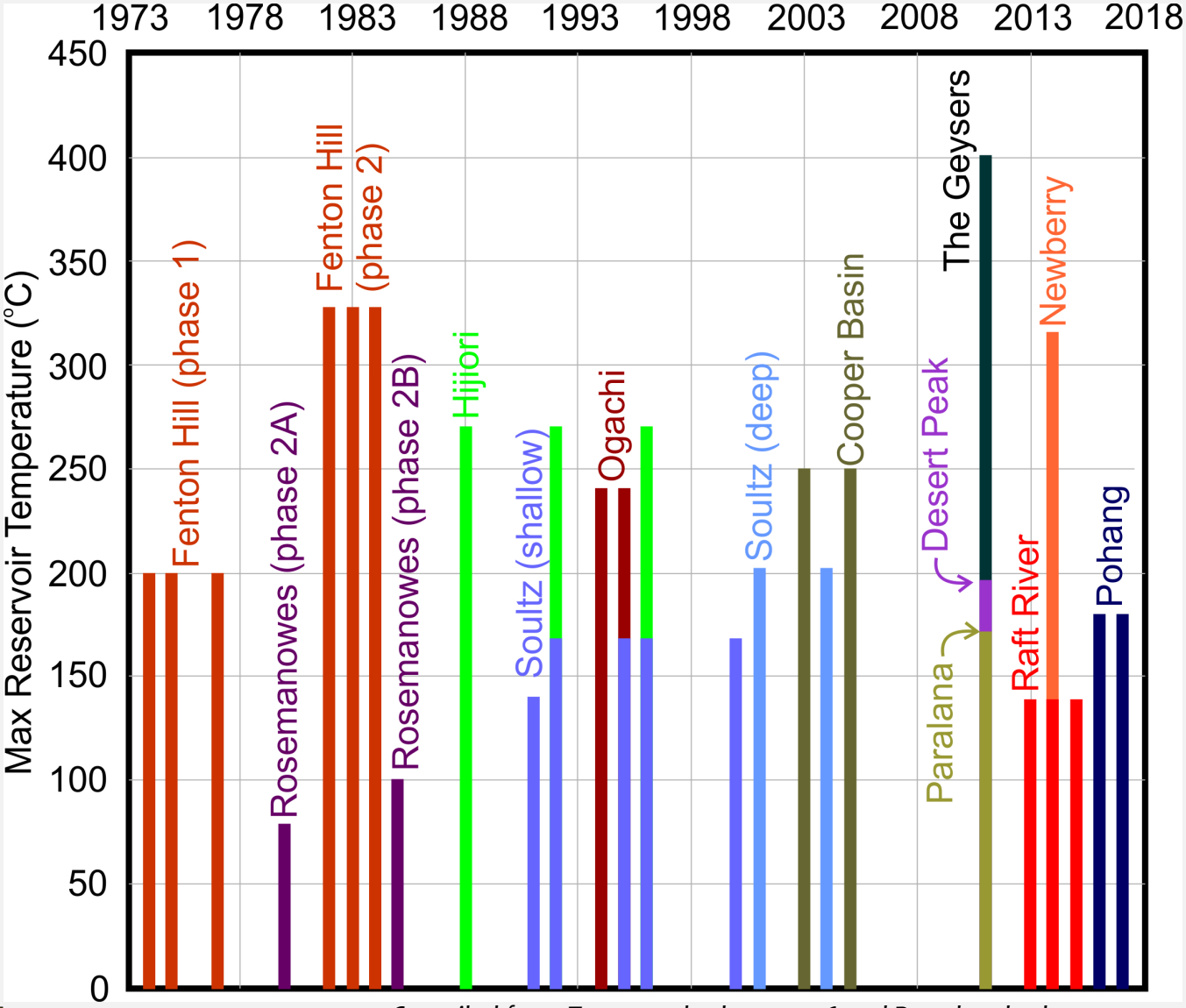
- Large in situ fluid volumes
- Convective heat transfer
- Individual wells produce from a few high permeability fractures
- Flow rates >~ 40 L/sec;
- Energy densities of 10-20 MWe/km^2
- Production from a few to ~800 MWe
- Low levels of microseismicity





Average = 6 MWe;
Biggest = 50 MWe
At 200°C flow rate of 23 L/s = 1MWe
750-1000 US homes

40 Years of EGS Stimulations

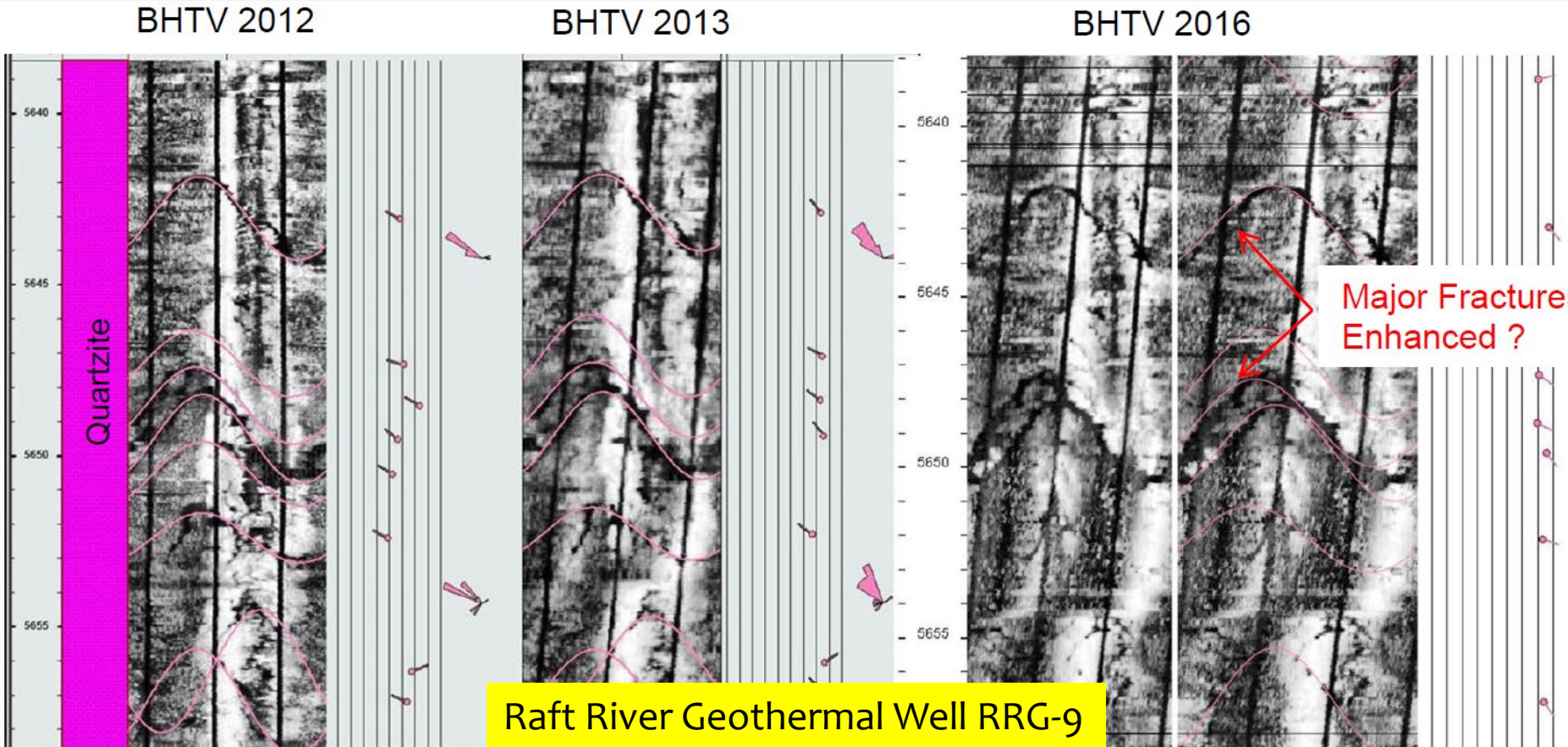


US (5 sites)
England
France
Japan
Australia
South Korea

Compiled from Tester and others, 2006 and Breed and others, 2013

Current Status of Enhanced Geothermal System Development

- No EGS systems greater than a few MWe developed
- Low flow rates (<40 L/s) and low heat recoveries
- Reactivated fracture zones dominate EGS reservoirs
- Mechanism uncertain



What is FORGE?

FORGE (Frontier Observatory for Research in Geothermal Energy) Is An Underground Laboratory for developing, testing and accelerating breakthroughs in EGS development

Phase 1: Desktop study (5 sites)

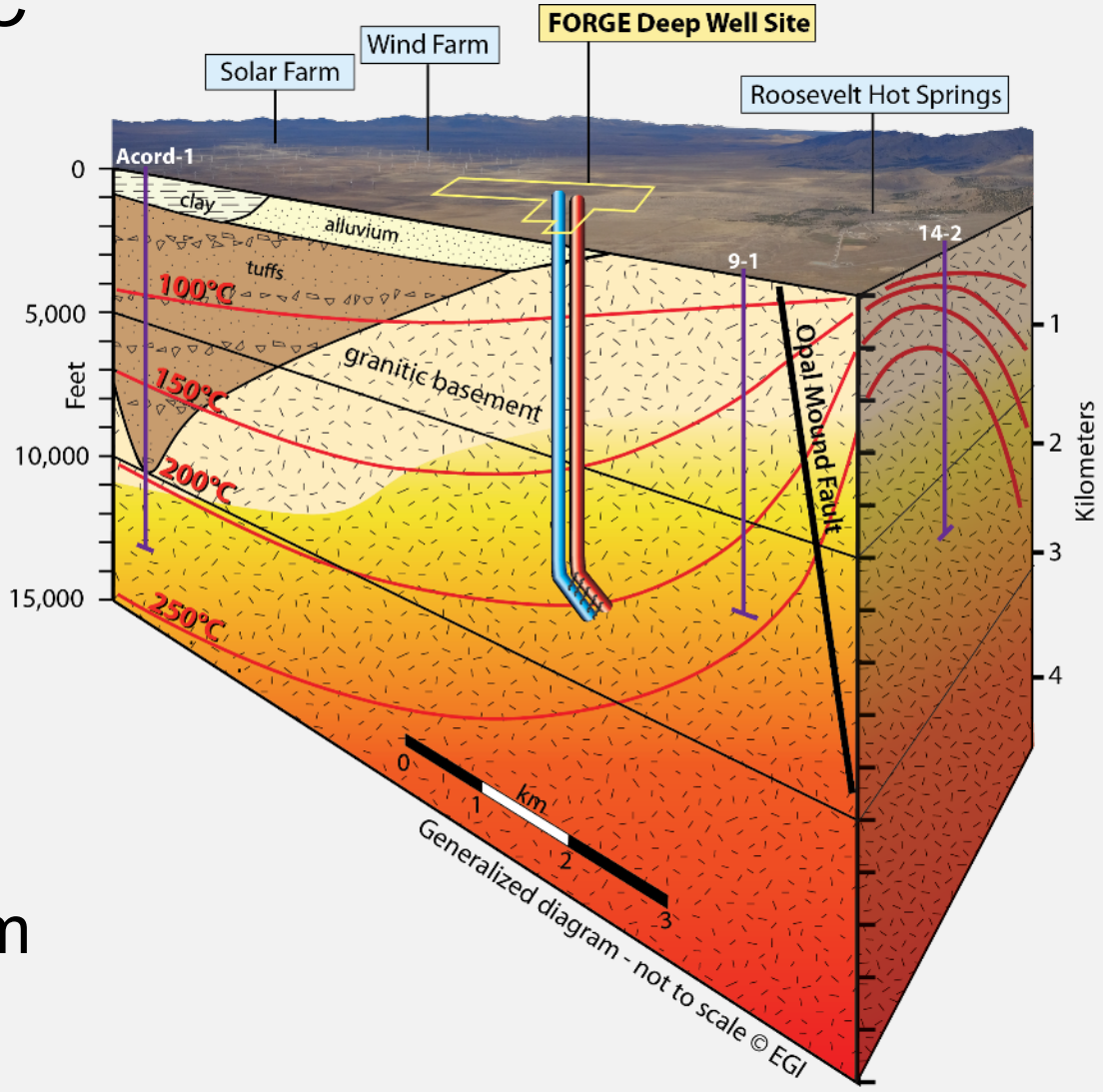
Phase 2: Reservoir confirmation (2 sites with selection of Utah as final site)

Phase 3: Drill and stimulate two deep wells. Develop:

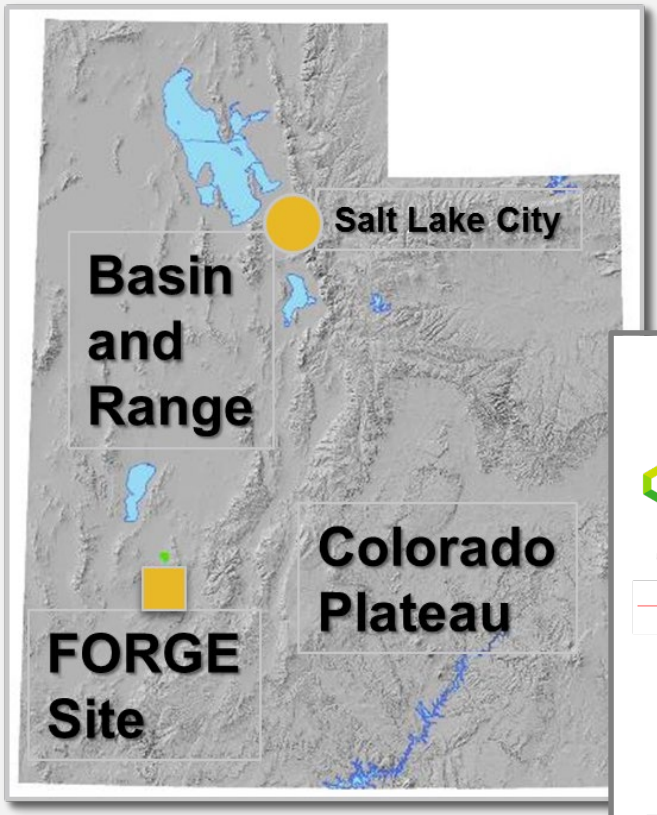
- **High-temperature drilling tools and zonal isolation technologies**
- **Novel stimulation and well completion methodologies**
- **Modify/manage existing stress fields**
- **Manage and forecast induced seismicity**
- **Best management practices**
- **Predictive numerical models**
- **Education and research opportunities**

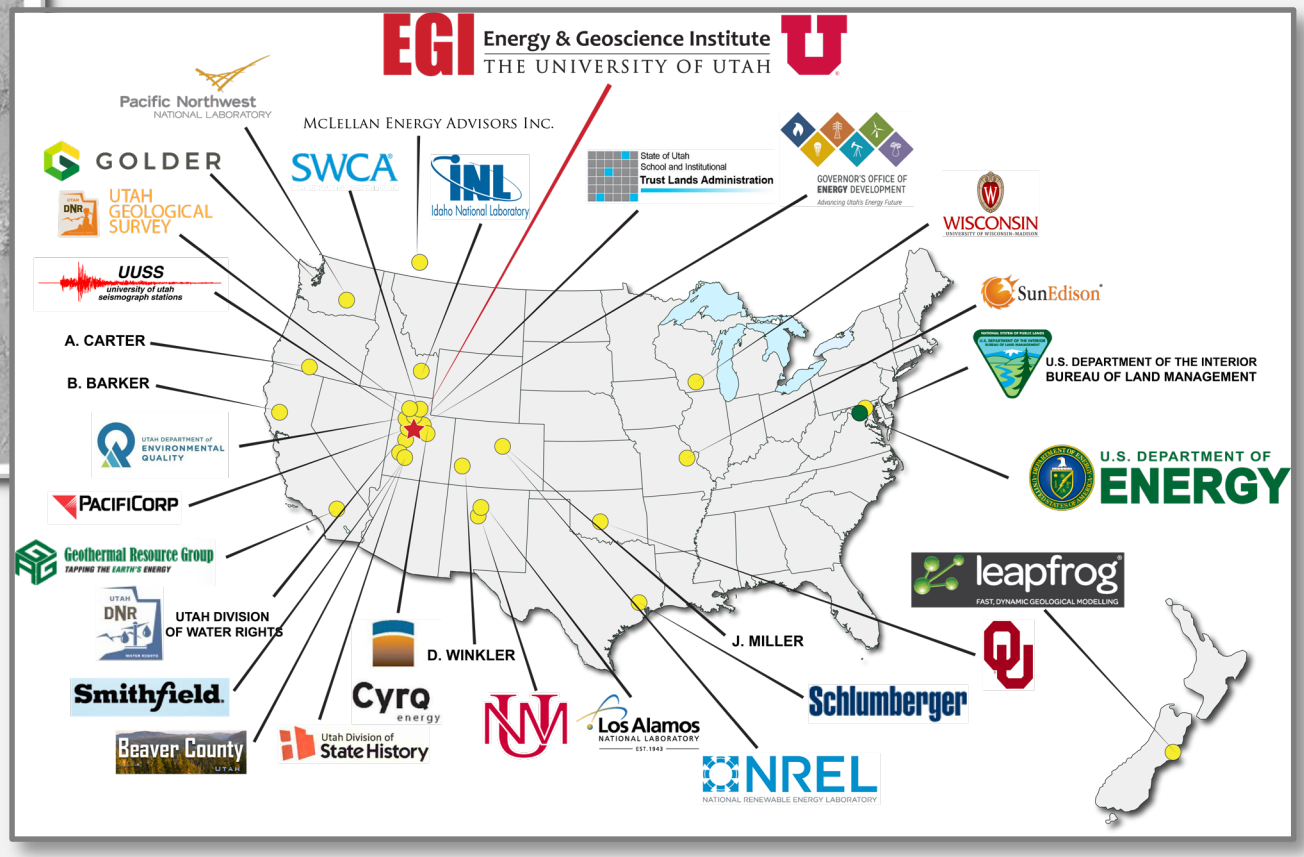
FORGE Criteria

- Temperature >175°C and <225°C
- Depths >1.5 km
- Low permeability rocks (granite)
- Low risk from induced seismicity
- Low environmental risks
- No connection to hydrothermal system



Milford Utah FORGE Site





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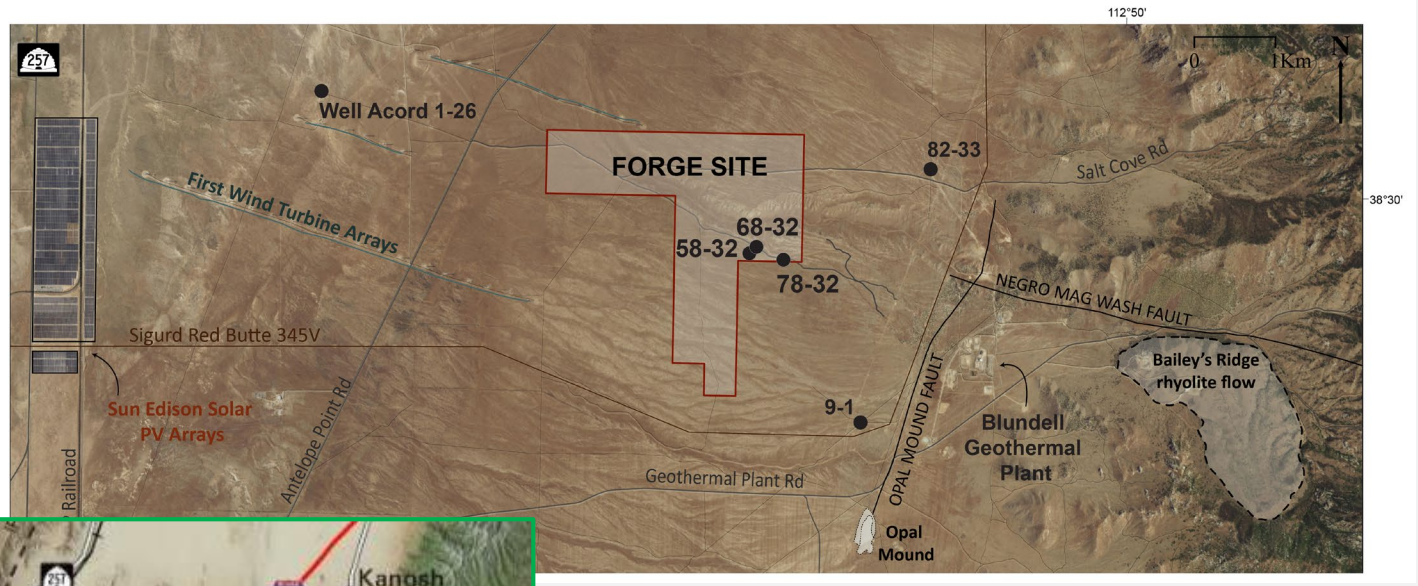
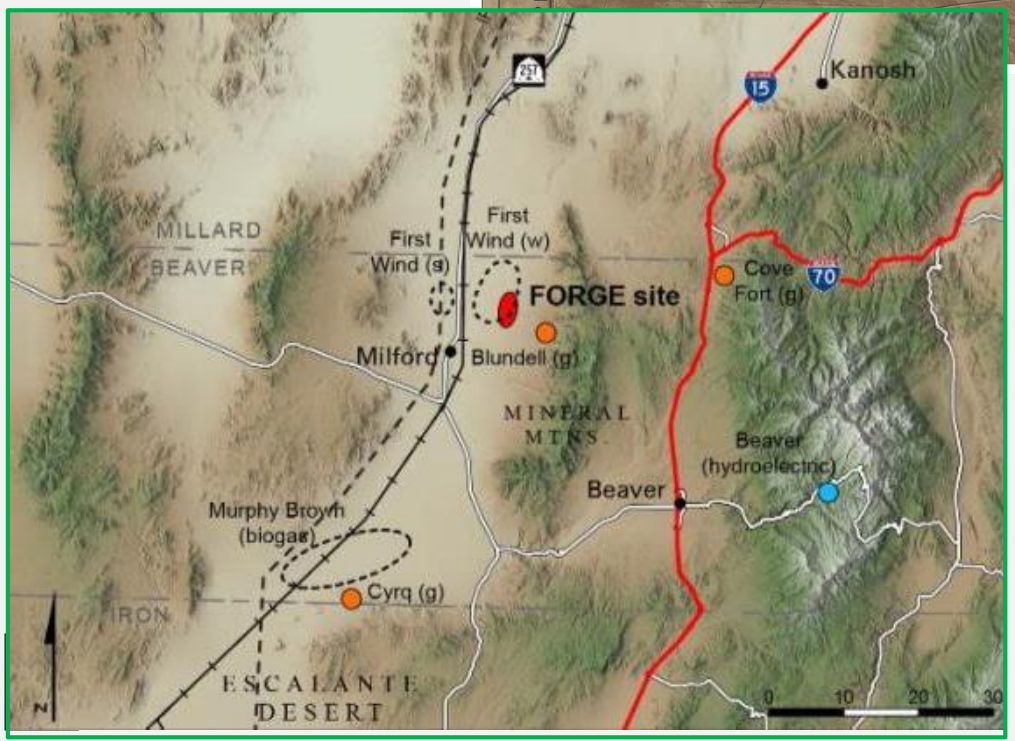
Utah Renewable Energy Corridor

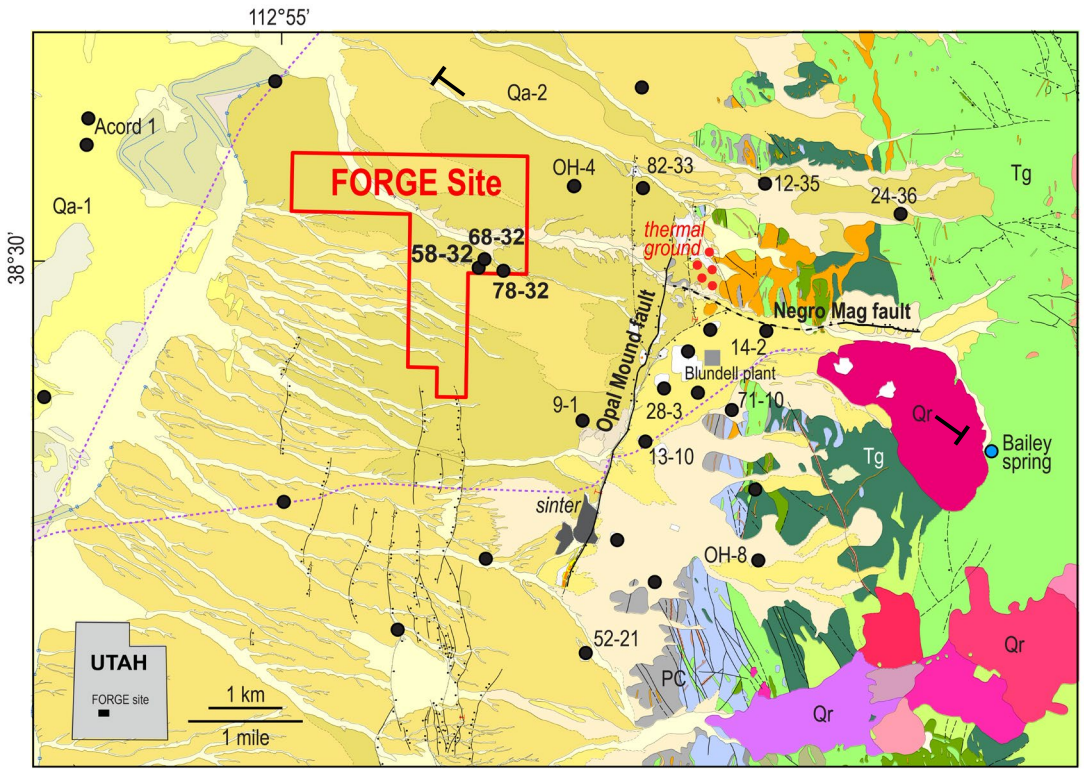




No Endangered Species
No Nearby Human Activity
No potable water

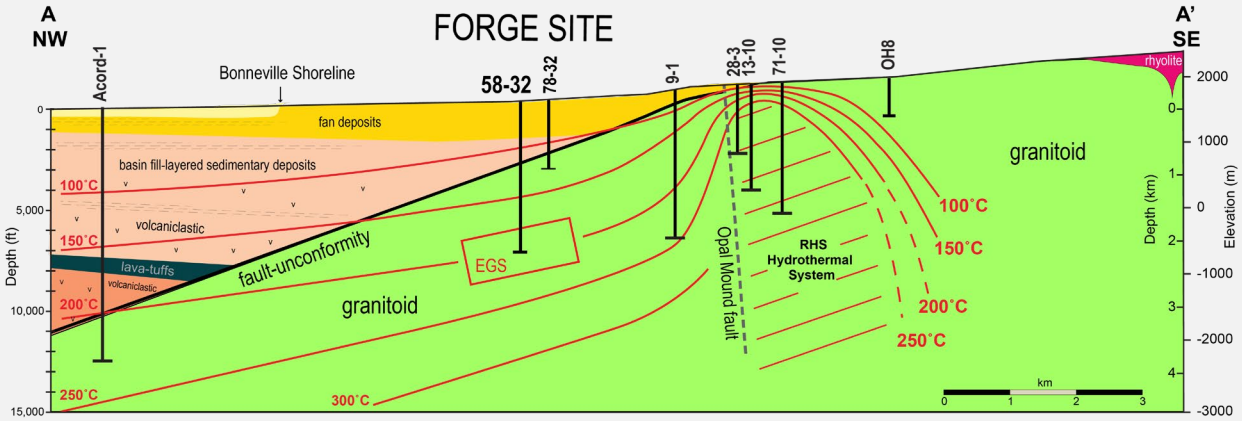
- Geothermal fields (3)
- Windfarm
- Solar field
- Biogas facility

Geological Overview



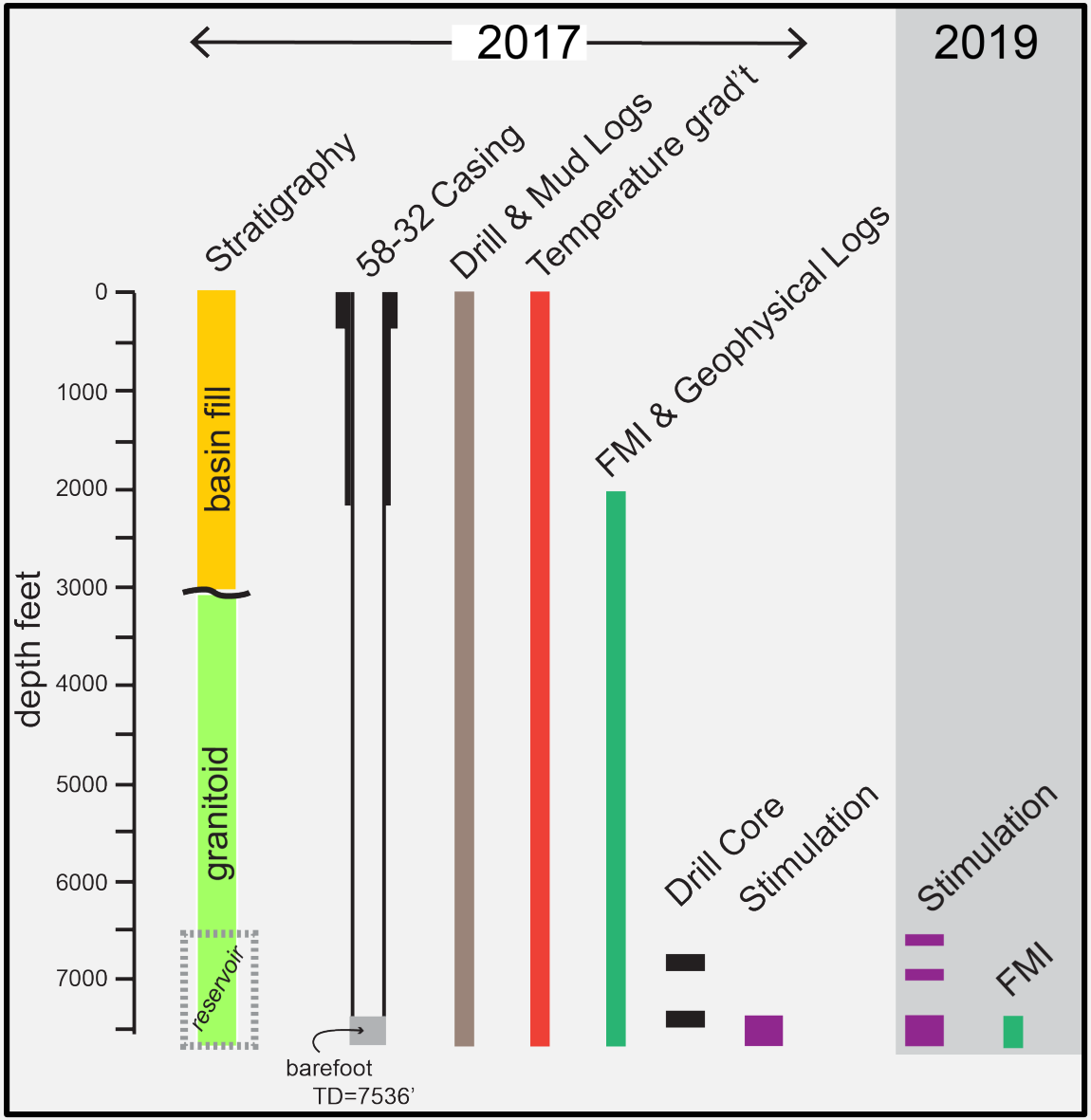
south facing

west facing



Well 58-32

- Completed and tested well to 2297 m (7536 ft)
- Reached a temperature of 199°C (390°F)
- Ran full suite of geophysical and image logs
- Conducted geomechanical tests on core from two intervals (~6 m)
- Performed Micro-hydraulic and Diagnostic Fracture Injection Test (DFIT) in barefoot section of well



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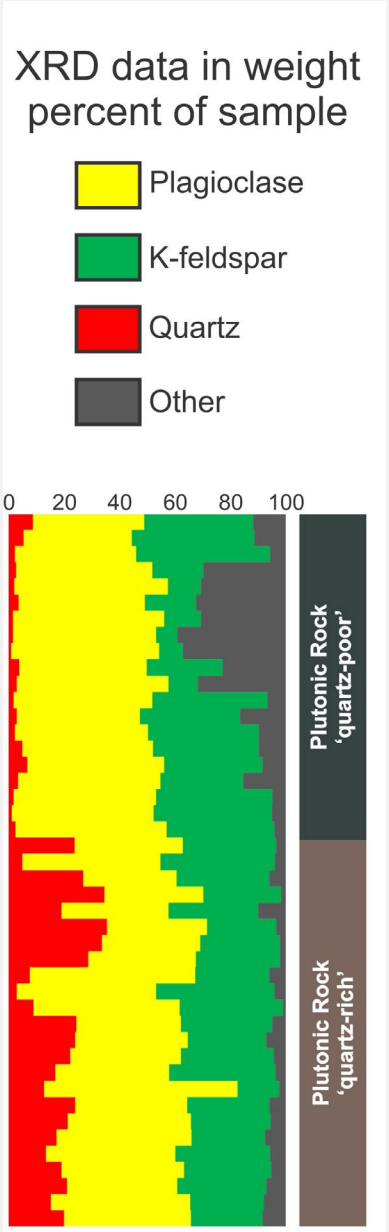
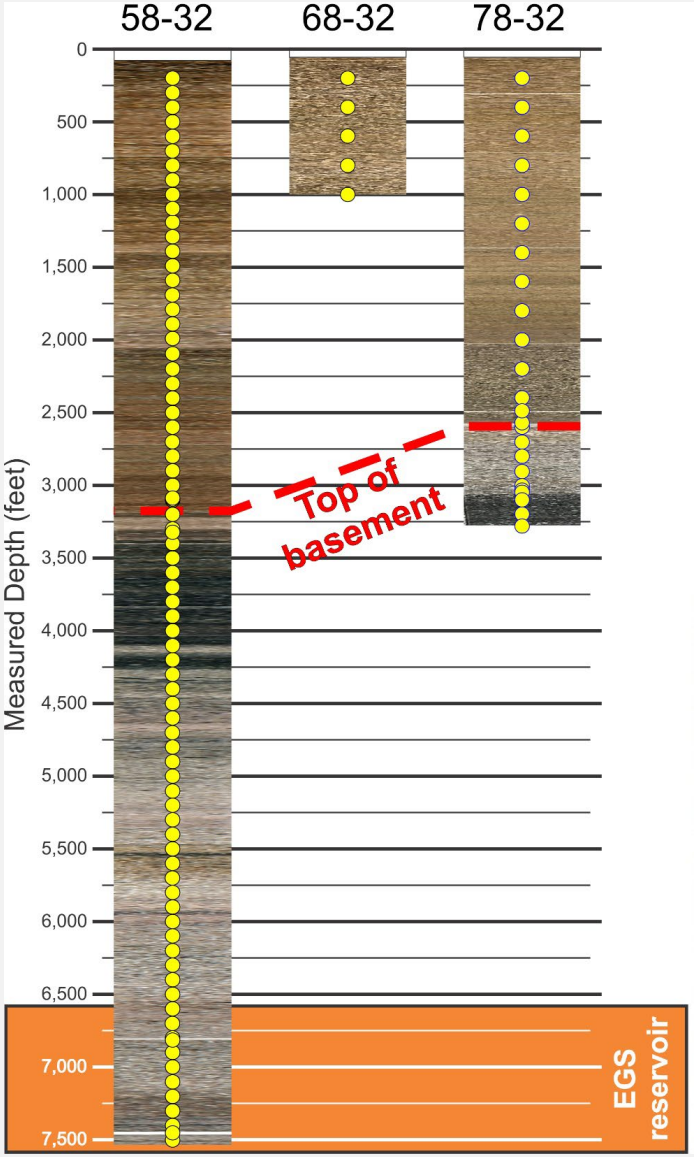
Well Stratigraphy & Lithology





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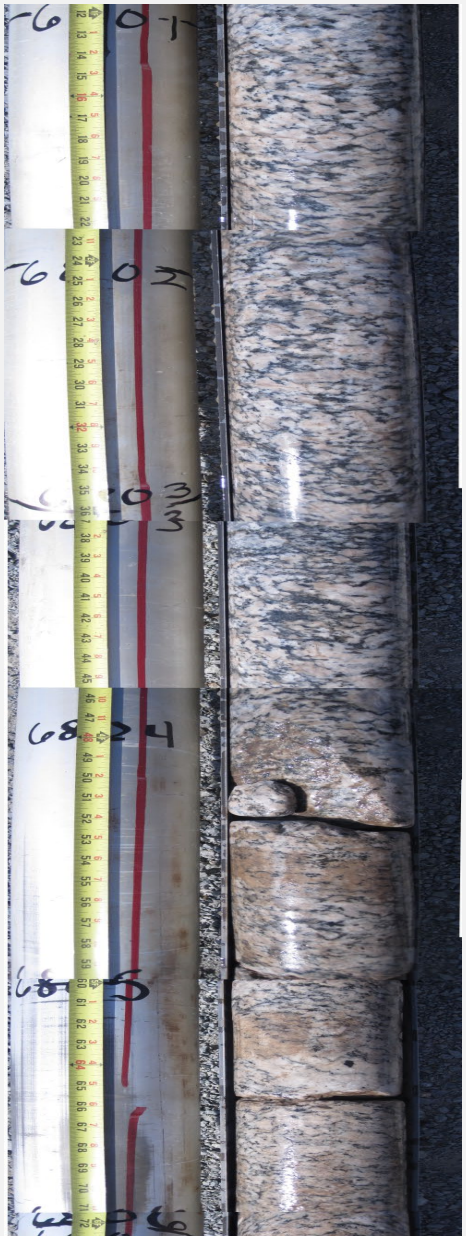
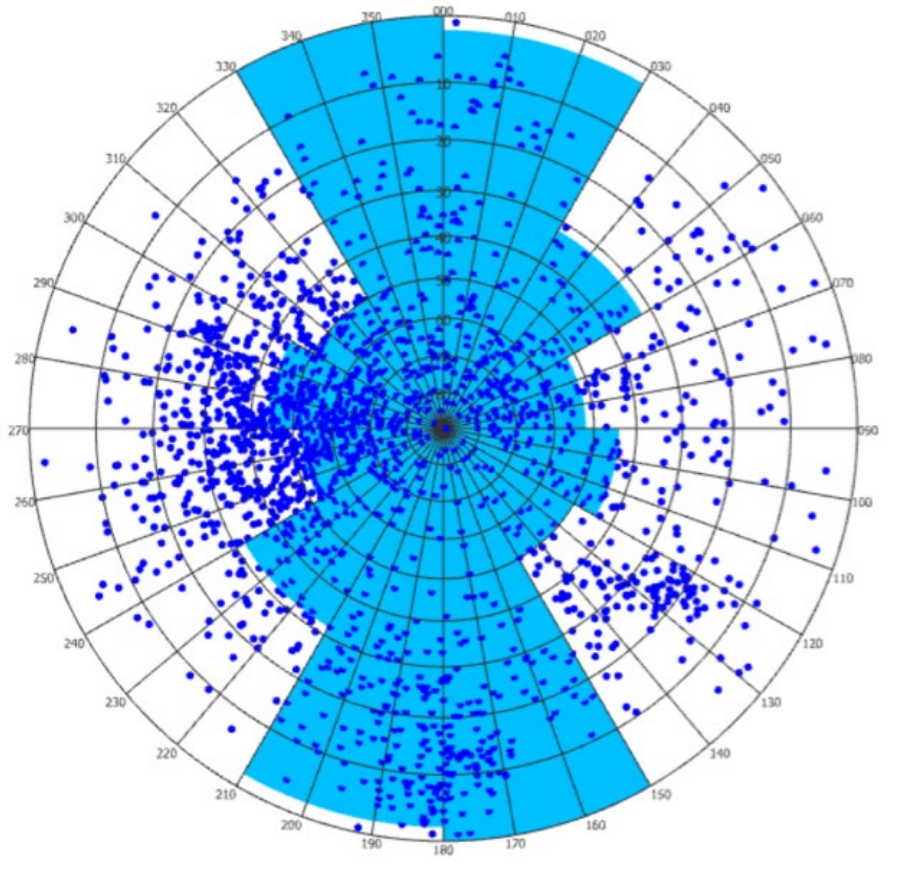
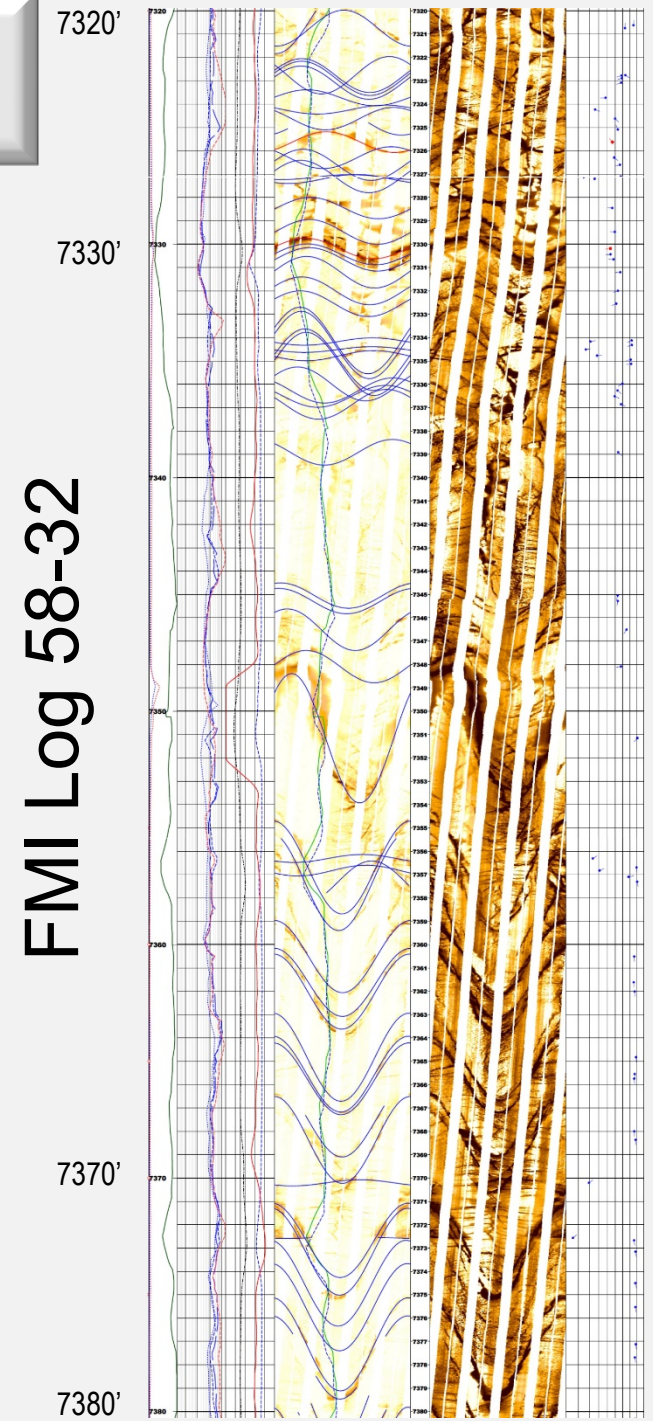


Fractured Reservoir 58-32



Approximately 2000 fractures in FMI log;
Rose diagram & poles projected to upper hemisphere



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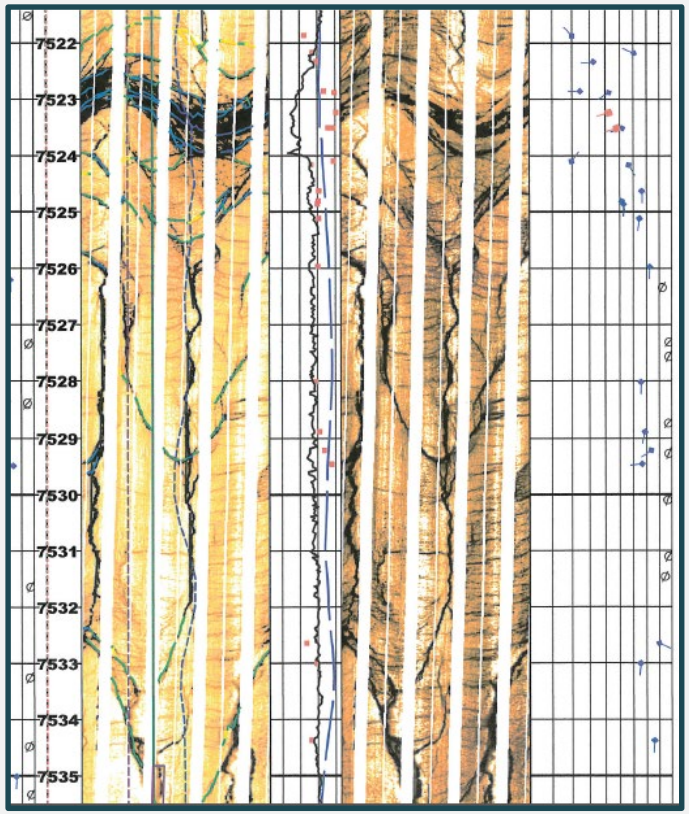
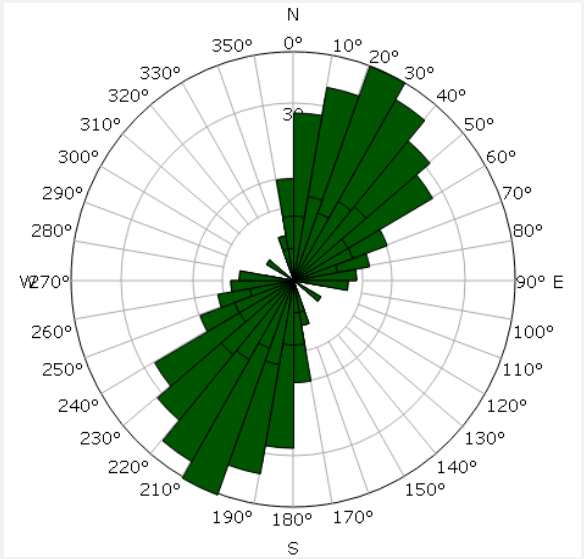
Stress Directions



Tadpole = natural fracture
Circle = induced fracture



Azimuths of induced fractures from FMI log

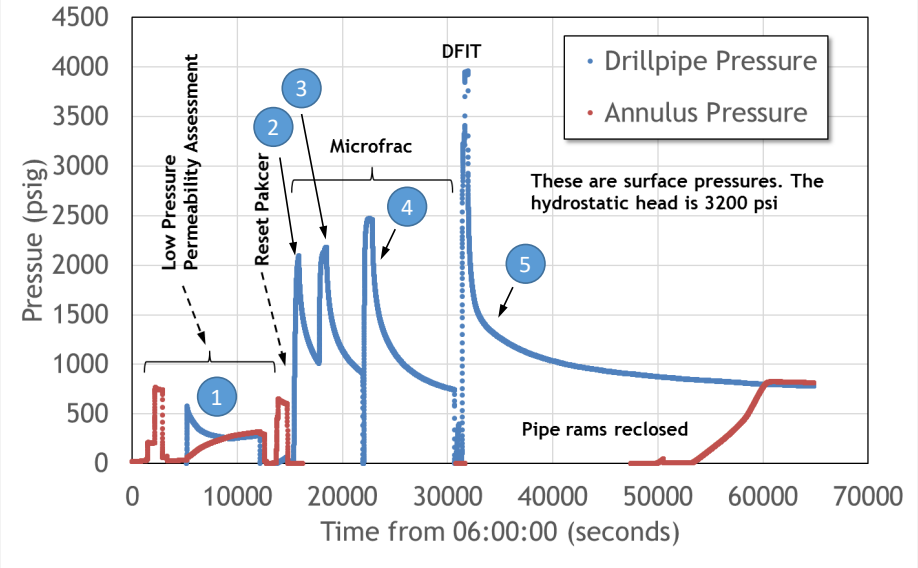
2017 Injection Program

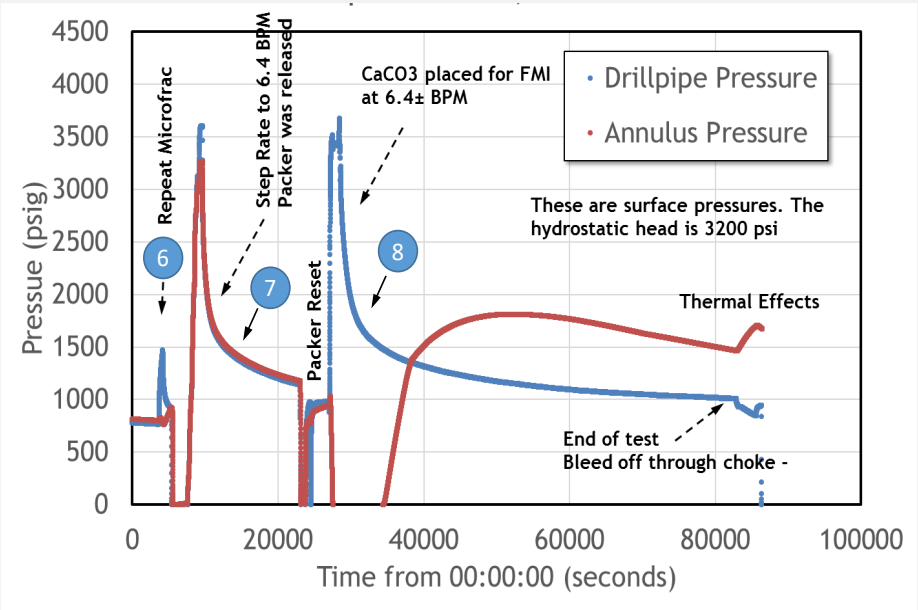
- 8 injection cycles over two days
- Injection rates from 0.3 to ~9 bpm
- Minifrac/DFIT injection times from 8-35 min
- Max surface pressure ~4000 psi
- Permeability of ~30 microdarcies
- Stress gradients

  $S_{H\ min}$ = 0.62 psi/ft

  $S_{H\ max}$ = 0.77 psi/ft

  S_V = 1.13 psi/ft





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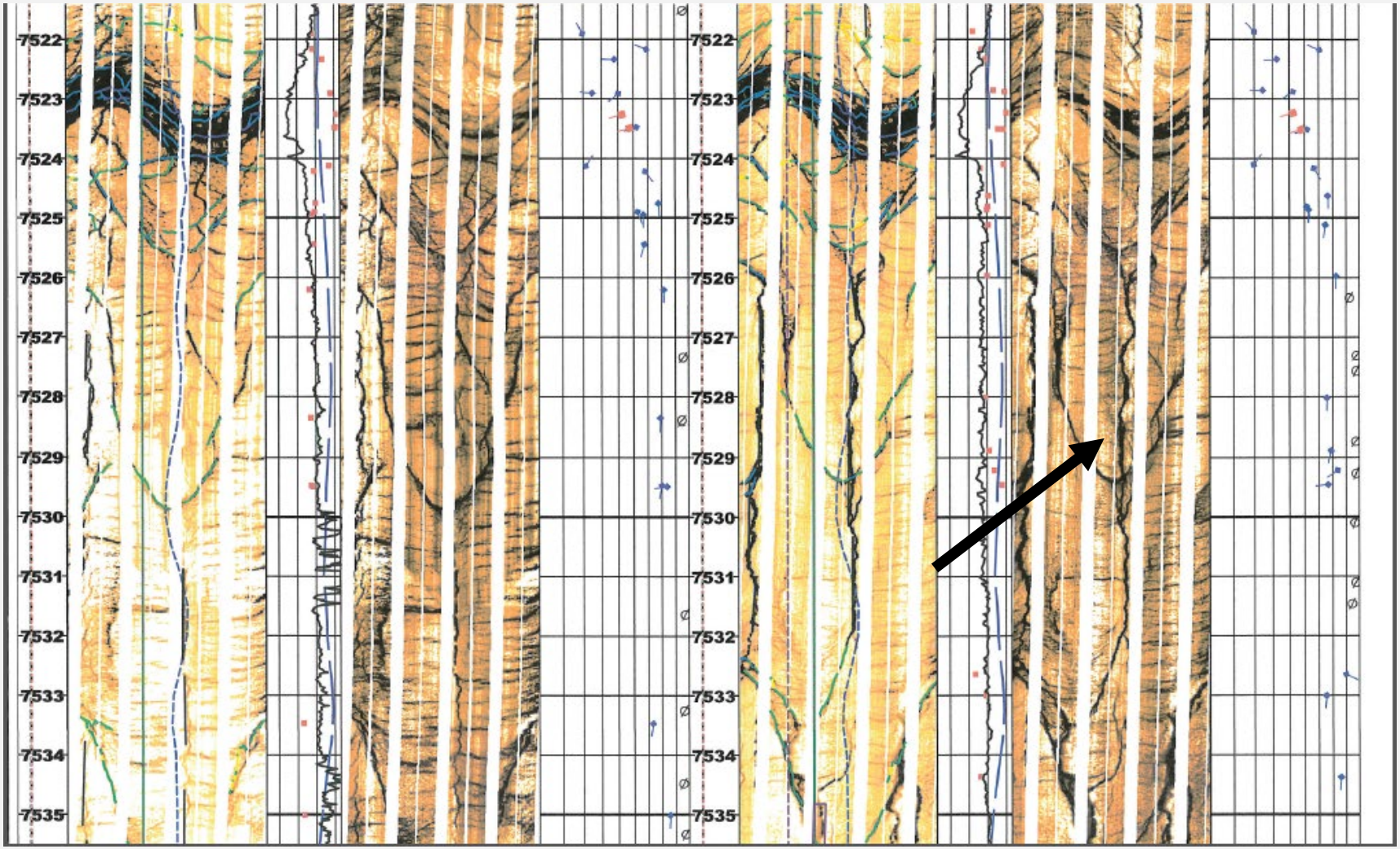
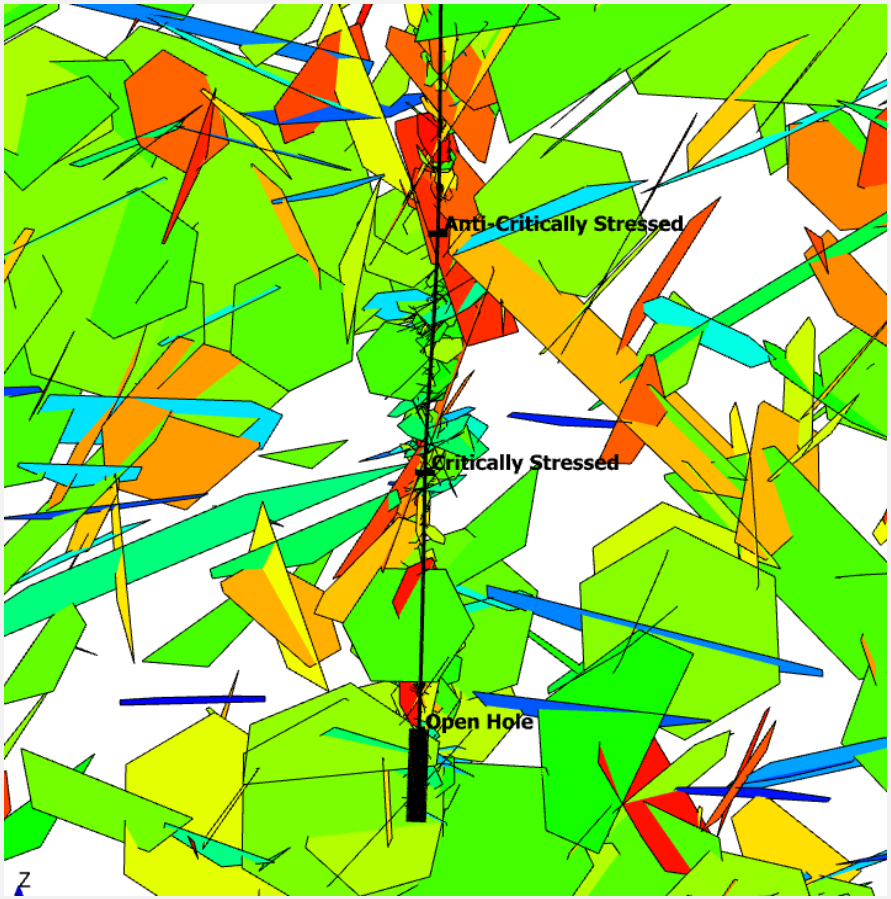
Pre and Post 2017 Stimulation FMI Logs



2019 Activities: Stimulation and Monitoring

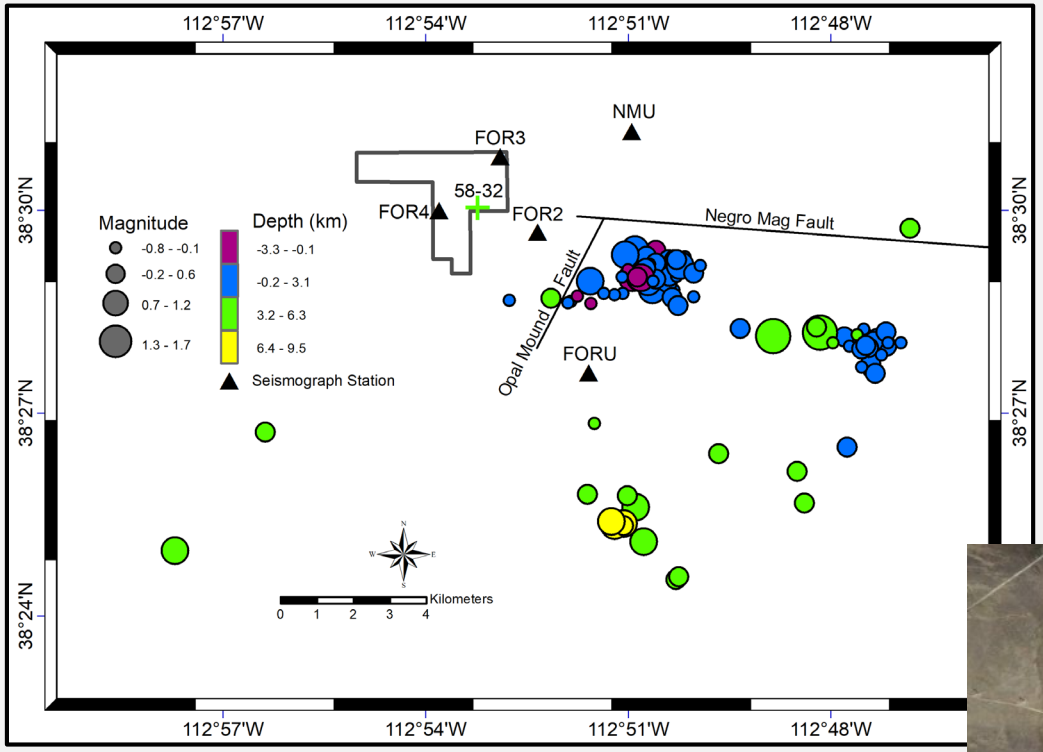
Stimulated three zones in 58-32:

- Open hole section
- Two zones behind casing
- Perform nine injection cycles per zone: step rate and single rate tests at 1,2,3,4,5,8,15 bpm, maximum surface pressure = 7000 psig
- Pump times 1-60 minutes
- Volume pumped range from 1 to 200 bbl
- Overnight shut-in times for large volume injections
- Ran FMI log (no changes observed)



Monitored Microseismicity at the surface and downhole

Seismic Monitoring: Surface Monitoring



- Detect and locate with high precision, injection related seismic events
- Establish microseismic monitoring for times of shut-in or flow tests
- Provide for mechanisms to collect non-traditional seismic data, like DAS, Nodals

Seismometer locations and pre-stimulation microseismic locations (2016-2019)

Nodal Array (150 nodes)

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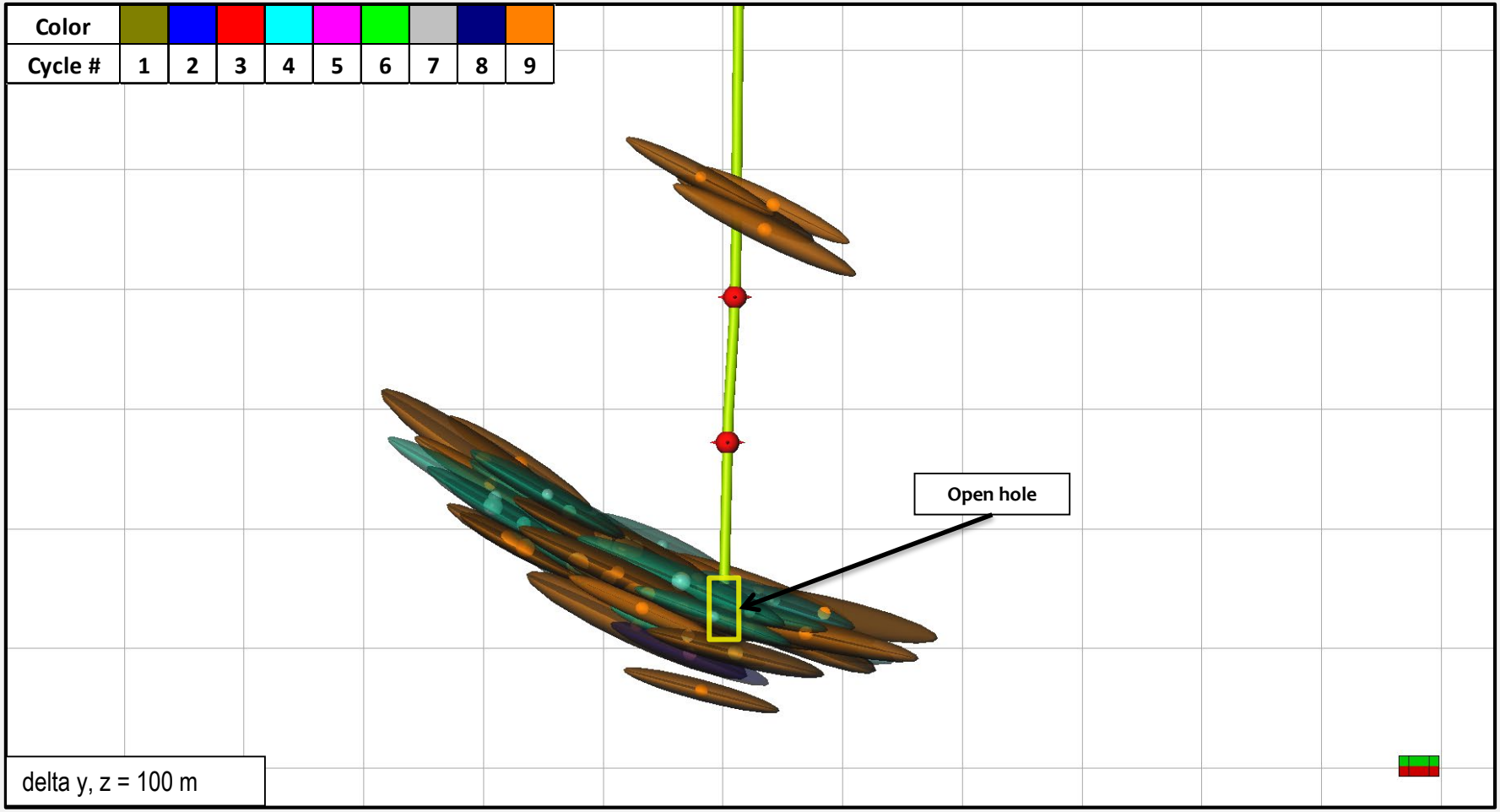
Borehole Instrumentation

- Shallow hole (~ 925'):
  - 3C 15 Hz geophone (4 sensors per component)
  - 3C Silicon Audio accelerometer

- Deep hole (Top of granite 780 m (2560 ft); TD 1000 m (3280 ft):
  - Schlumberger 12-level 3C geophones, 31 m (100 ft) spacing straddling granite contact
  - Distributed Acoustic Sensor (fiber optic cable) cemented into annulus of 5 ½" production casing

Open hole Events Colored by Cycle – Depth View

With Maximum Uncertainty Ellipsoids

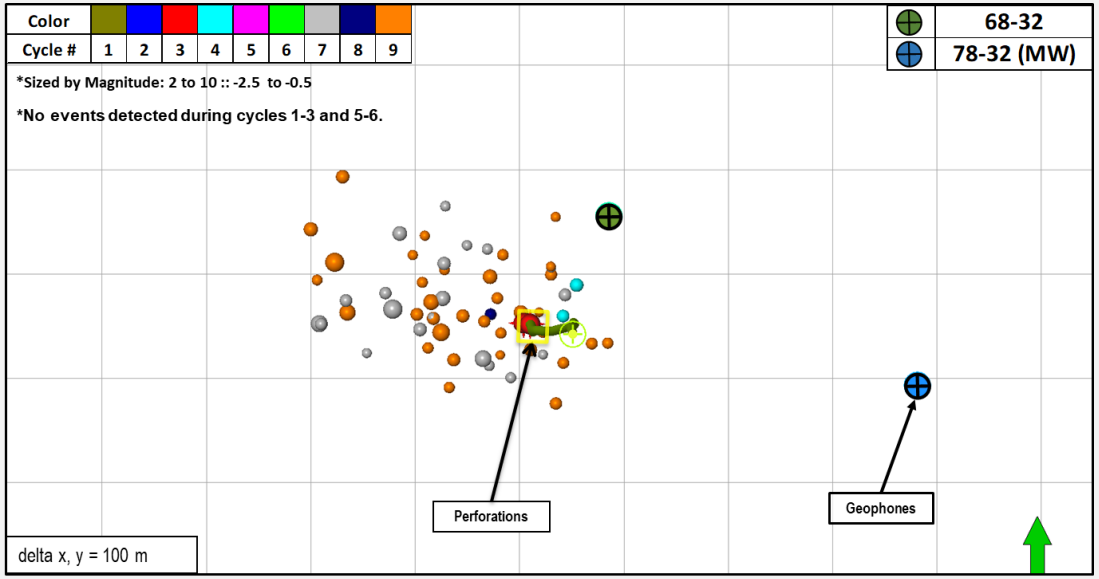


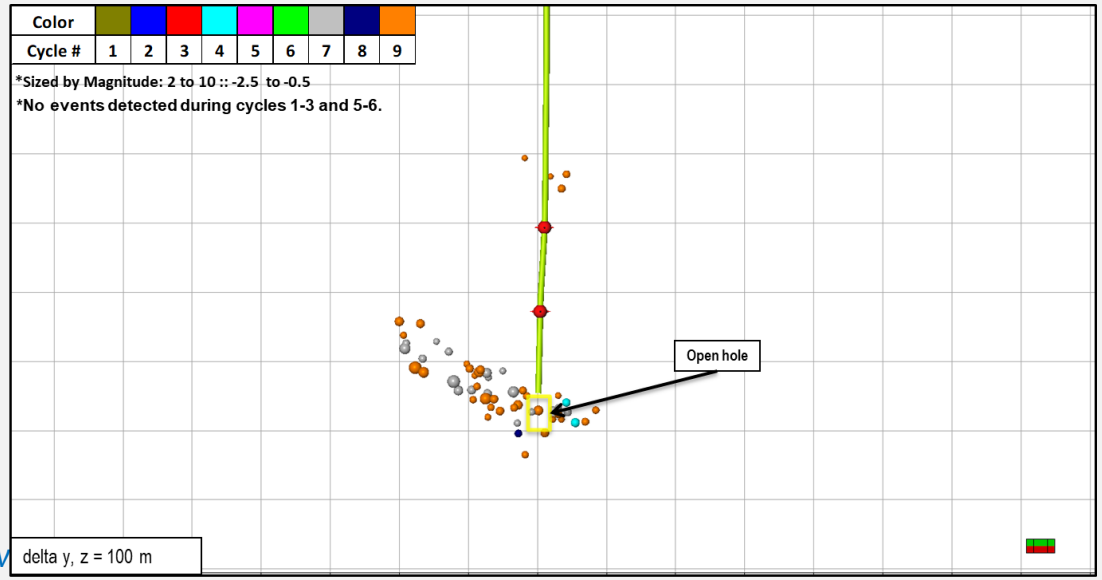
423 events recorded on geophone string; 43 on DAS cable; 19 on shallow borehole*

Stimulation 1: Open Hole

Stimulation 1:

- 2240-2294m (7348-7525 ft) KB
- Repeated 2017 stress, DFIT and permeability measurements (max. injection rate of ~9 bpm)
- Increased rate to 15 bpm with longer shut-ins
- Breakdown occurred at surface pressure 3500 psig
- Ran FMI log after stimulation





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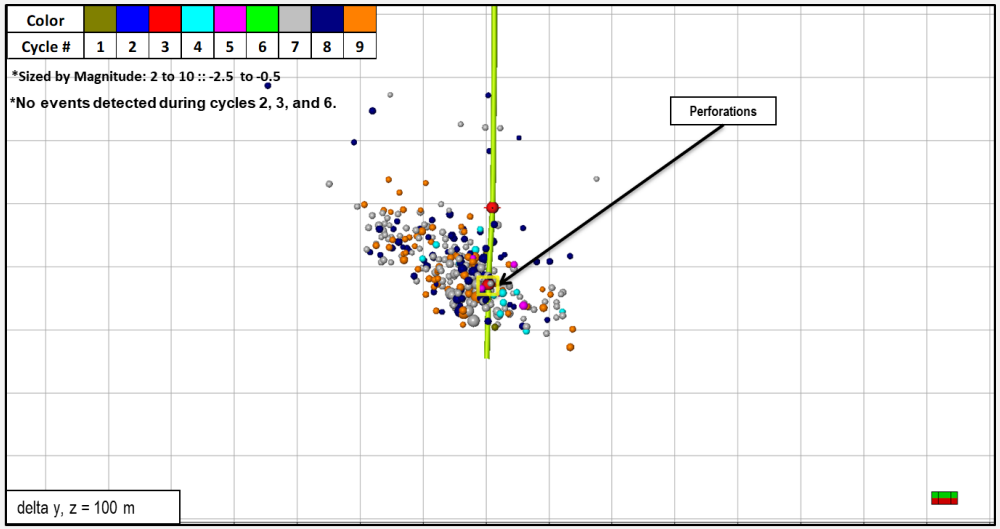
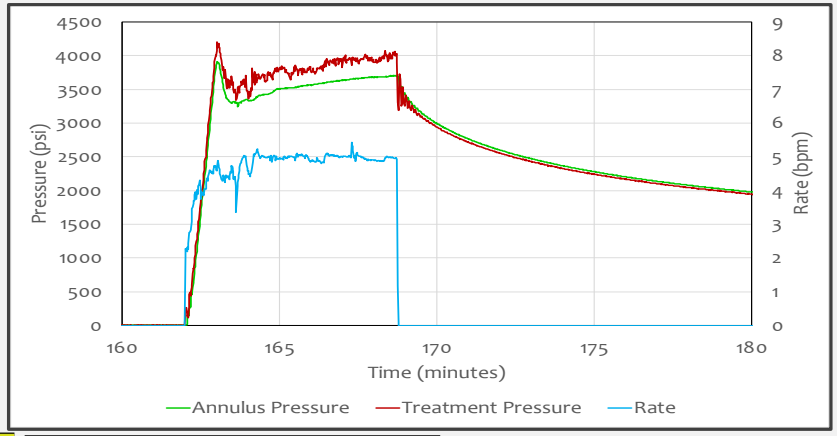
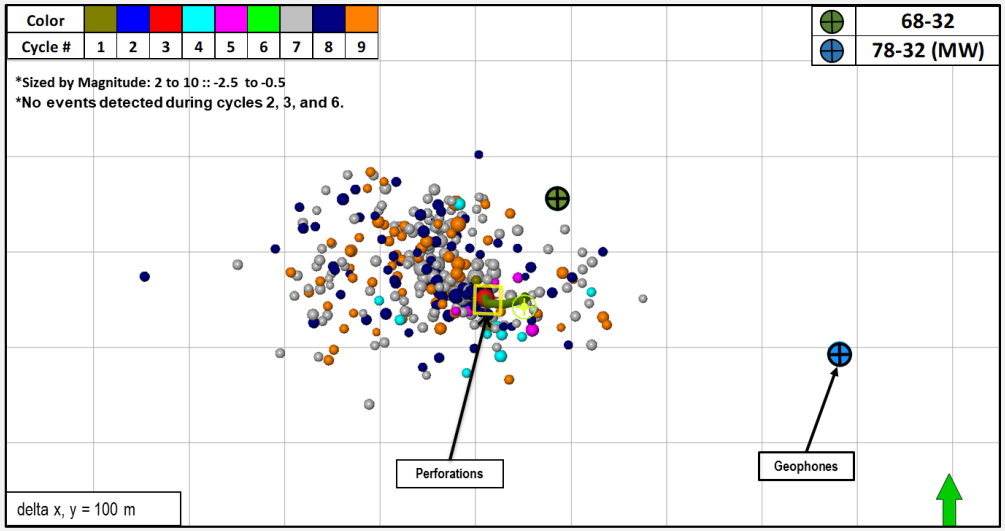
Stimulation 2: Critically Stressed Fractures

Stimulation 2: Cased hole

- Perforated casing from 2123-2126 m (6964-6974 ft) KB
- Stimulated critically stressed fractures (NNE-trending)
- Fracture breakdown initiated during (cycle 4); injection rate of 5 bpm for 6 min; surface pressure 3700 psig



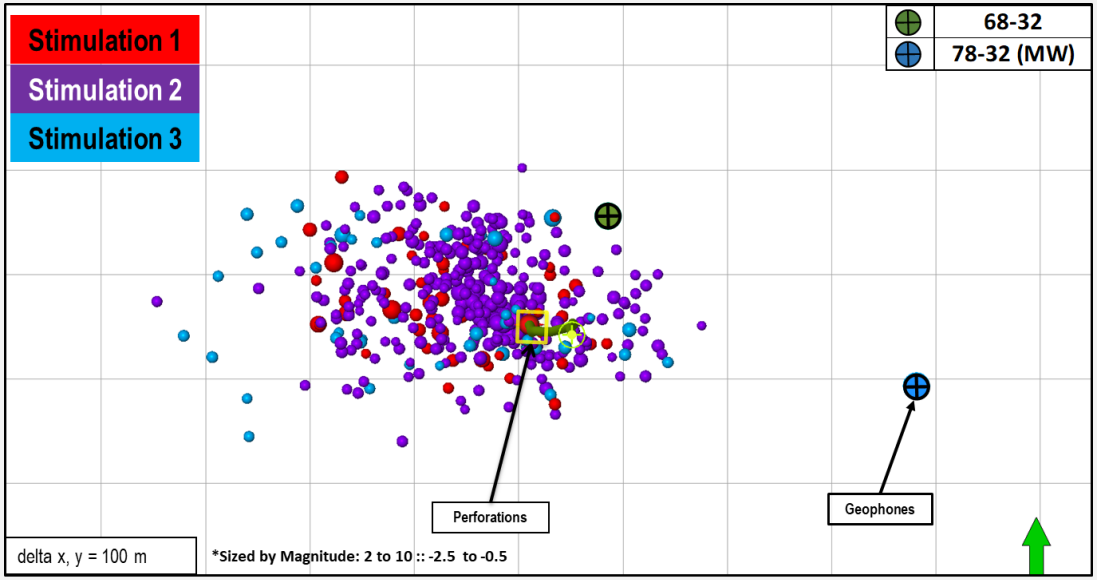


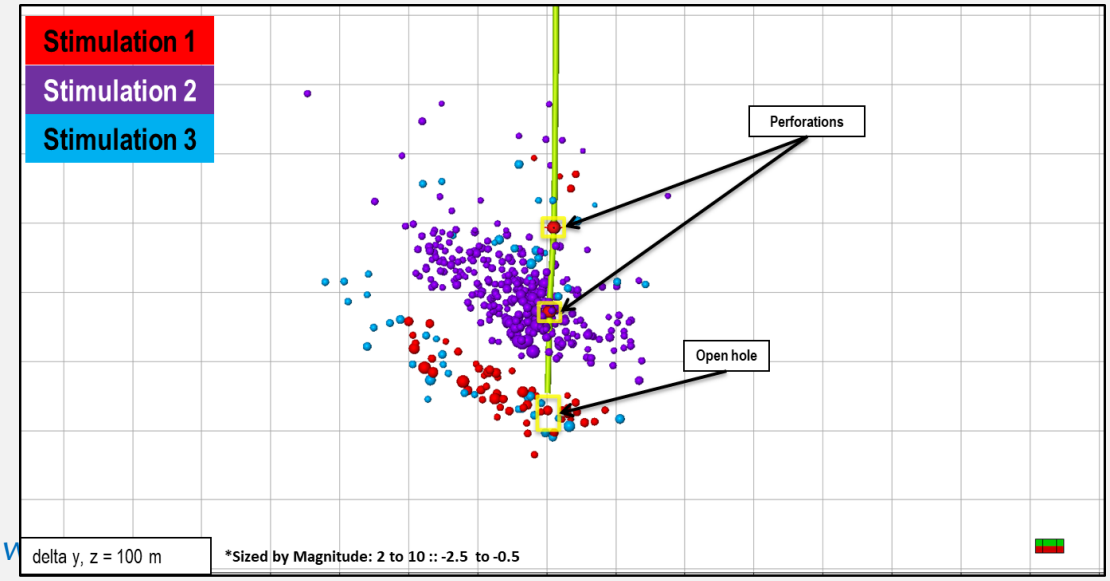


Stimulation 3: Non-Critically Stressed Fractures

Stimulation 3: Cased hole

- Perforated casing from 2001-2004 m (6565-6575 ft) KB
- Stimulate non-critically stressed fractures
- Fracture breakdown uncertain before bridge plug failed at surface pressure of ~6500 psig
- Light blue dots





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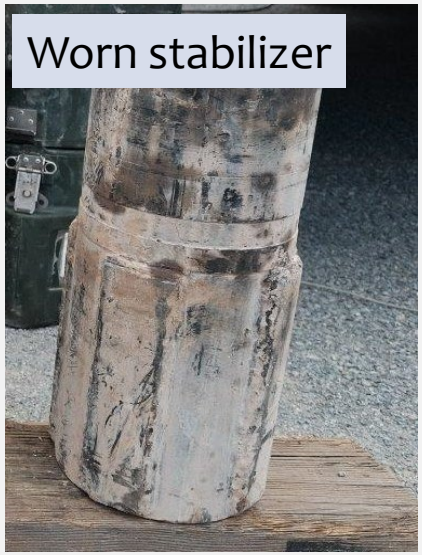
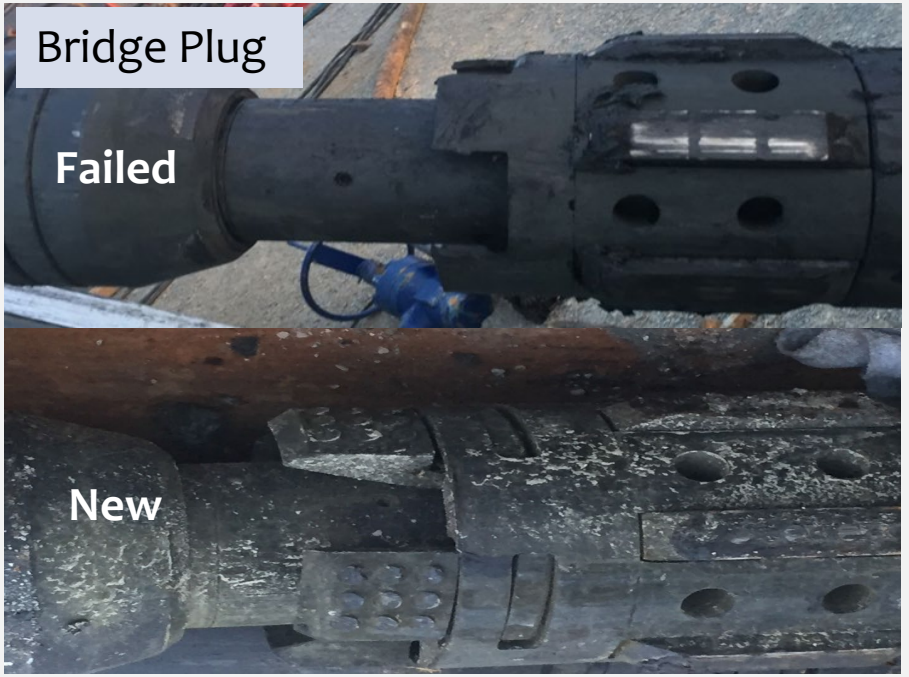
Equipment Failures

Drilling and stimulating hard, abrasive hot rock:

- Bits (short life)
- Mud motors
- Packers
- Bridge Plugs
- Drill strings





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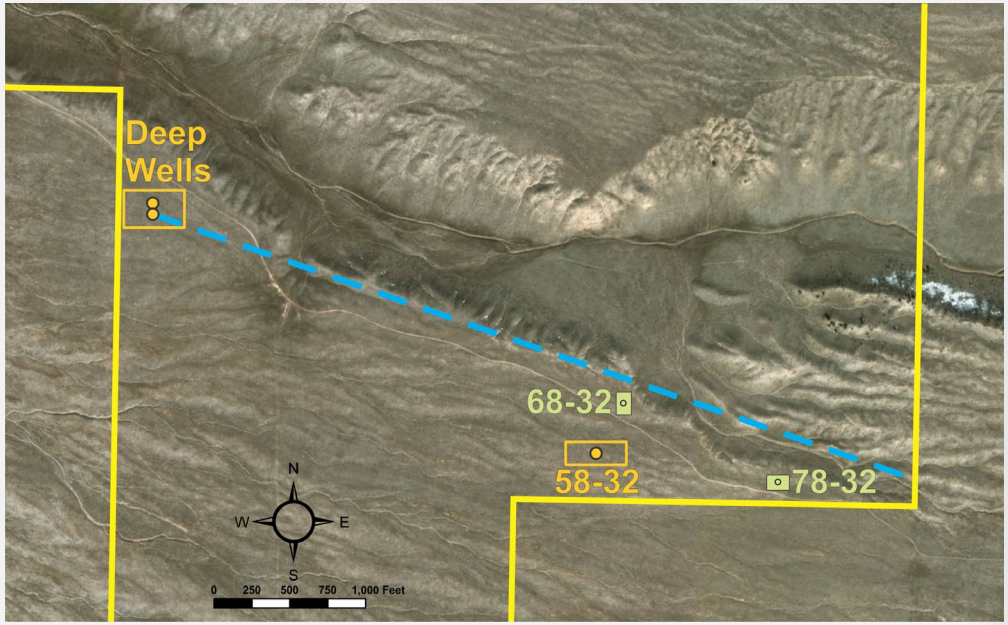
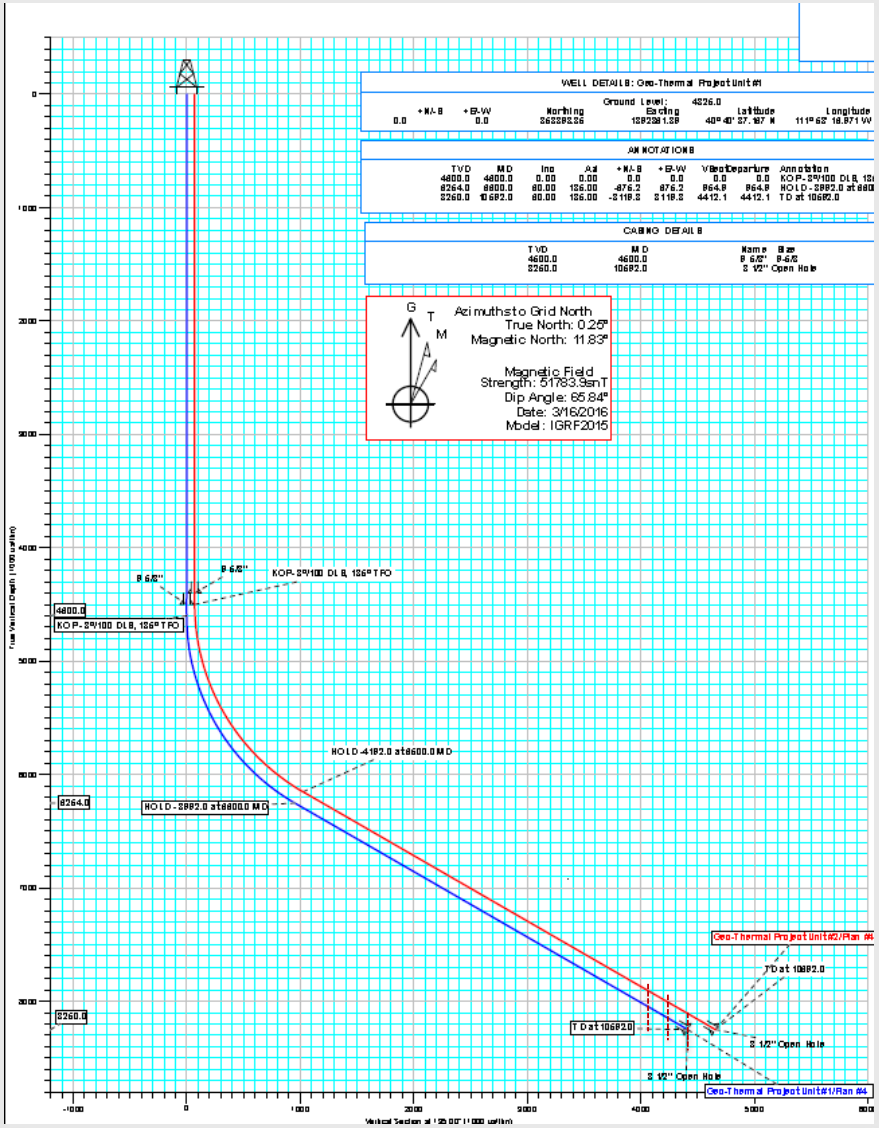
2019-2024 Activities





- Drill and stimulate injection/production pair
- Stimulate 2-3 stages at toe
- Circulate between wells
- Monitor reservoir development and heat sweep

Conclusions

- Granitic rocks at Milford Utah have appropriate temperatures (>175^{o}C), low permeabilities and stress orientations and magnitudes for EGS reservoir development
- Injection tests demonstrate stimulation of critically stressed fractures can be accomplished at relatively low pressures and injection rates
- No endangered flora or fauna
- Groundwater is not potable; is underutilized and not fully allocated; sufficient water rights secured
- Low risk of induced seismicity and seismic hazards

THANK YOU

Funding provided by the US Department of Energy with additional support from Utah School and Institutional Trust Lands Administration, Beaver County, the Governor's Office of Energy Development, and Smithfield Foods.