FORGE (Frontier Observatory for Research in Geothermal Energy)

John McLennan
Kevin England

September 19, 2023

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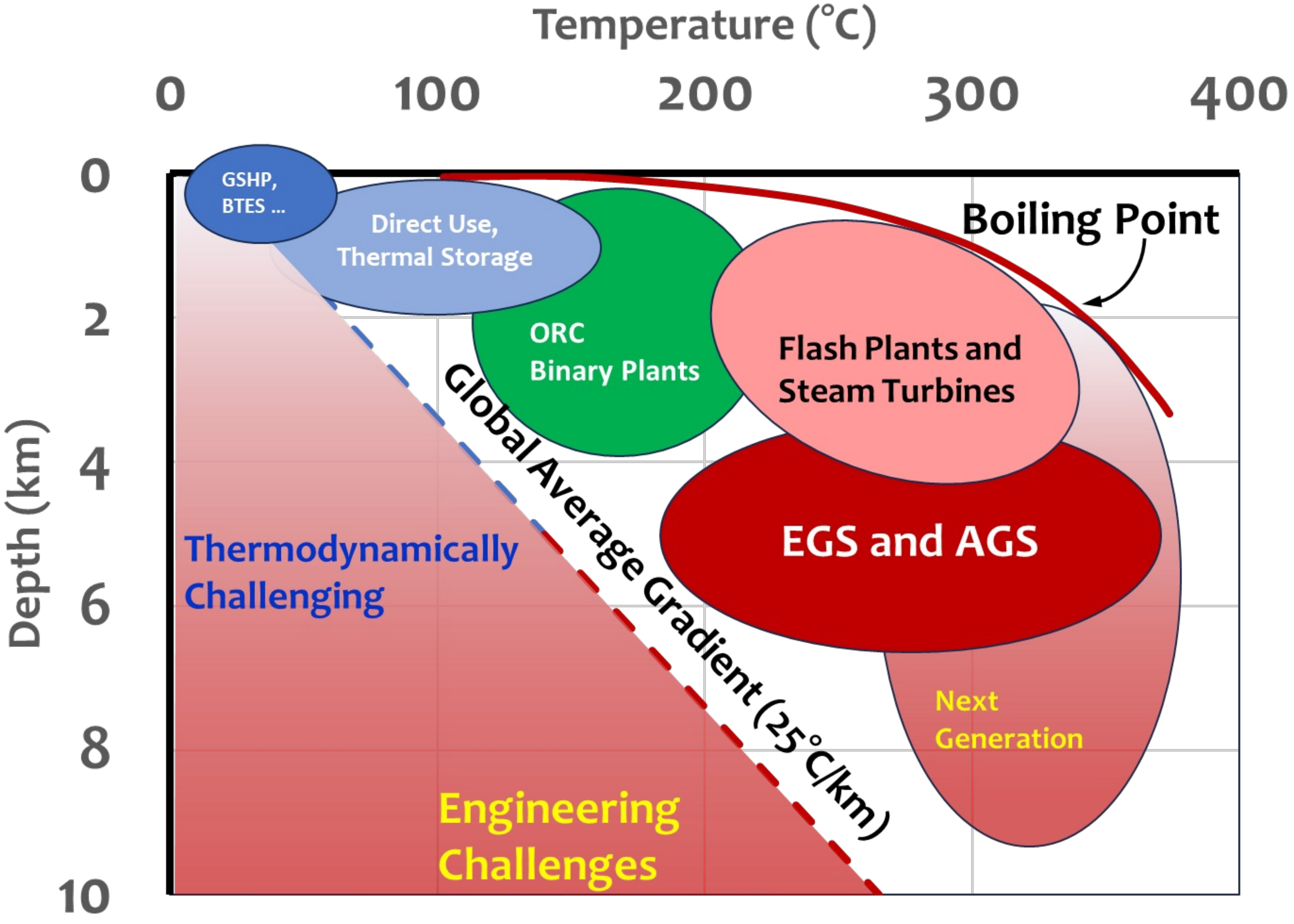
Since 1972

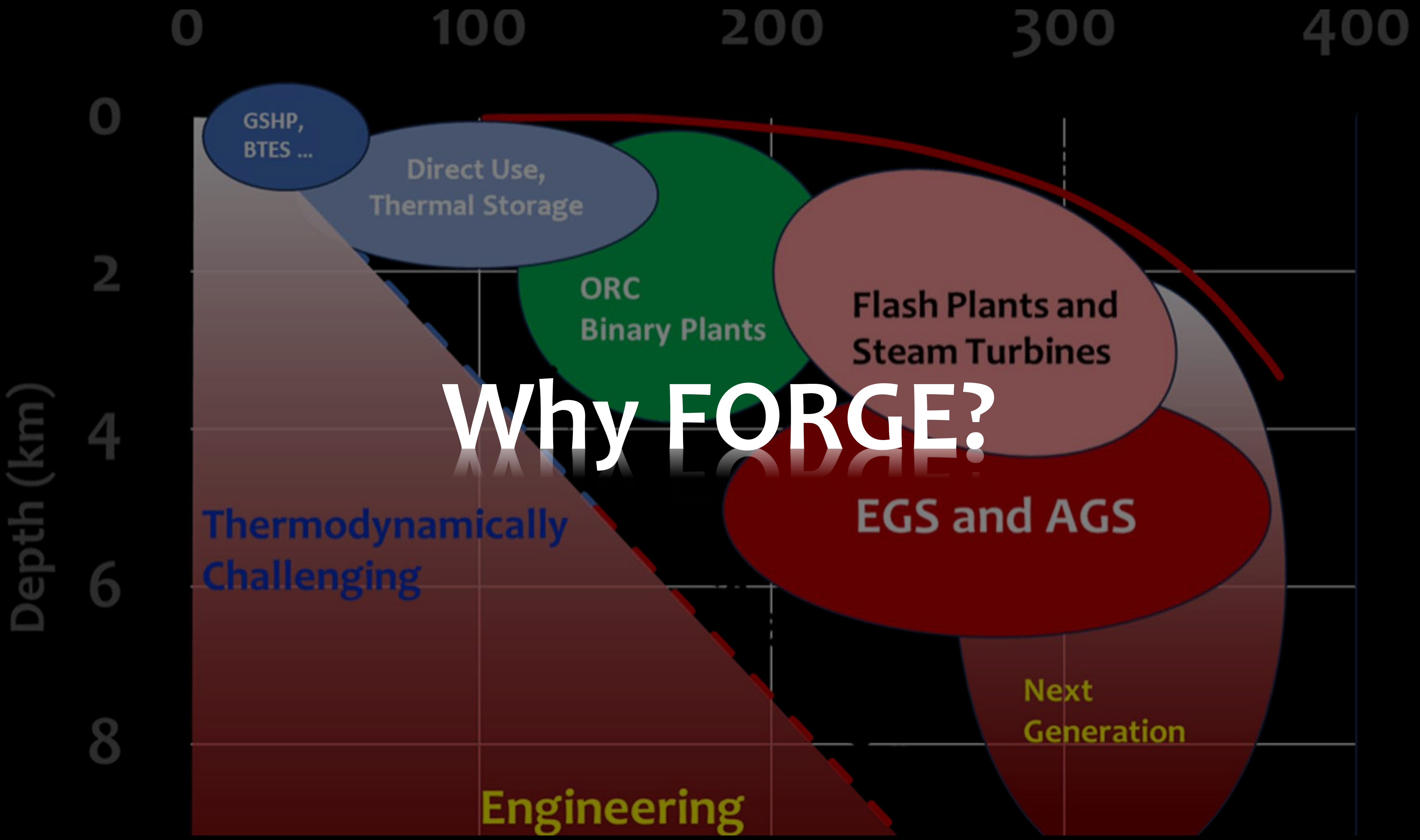
UTAH FORGE
U.S. Department of Energy

Geothermal Systems



Modified after Moore and Simmons, 2013

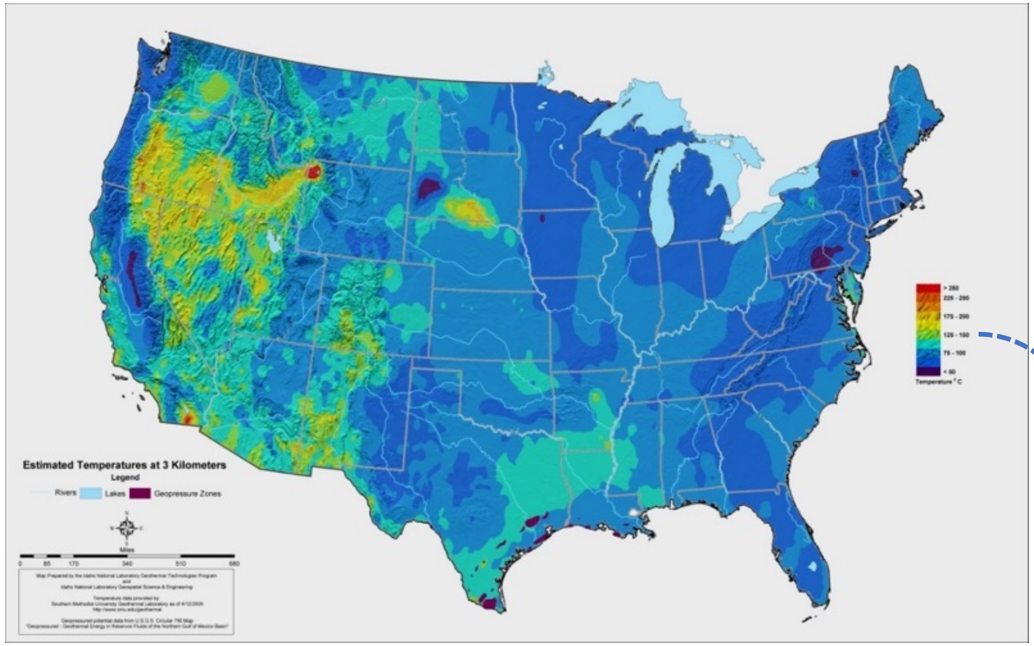
Why FORGE?


0
100
200
300
400
0
2
4
6
8
Depth (km)
GSHP, BTES ...
Direct Use, Thermal Storage
ORC Binary Plants
Flash Plants and Steam Turbines
EGS and AGS
Next Generation
Thermodynamically Challenging
Engineering

Opportunity Exists → → → Technology Gaps?

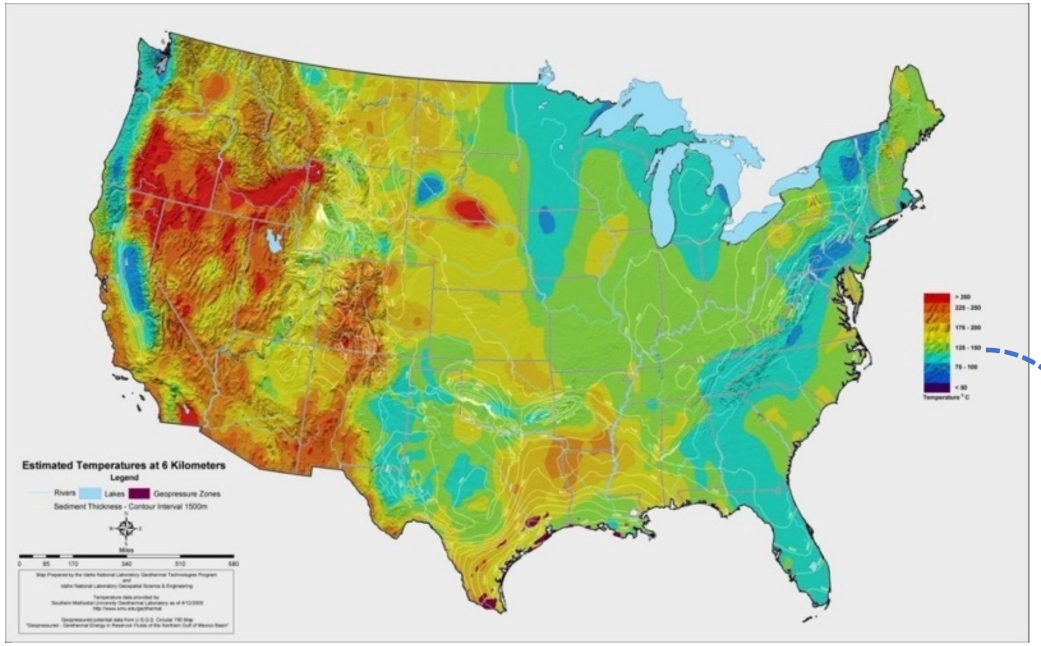
Resource Base:

USGS Estimated Potential in Western States is 518,000 MWe



150°C

Temperatures at 3 km

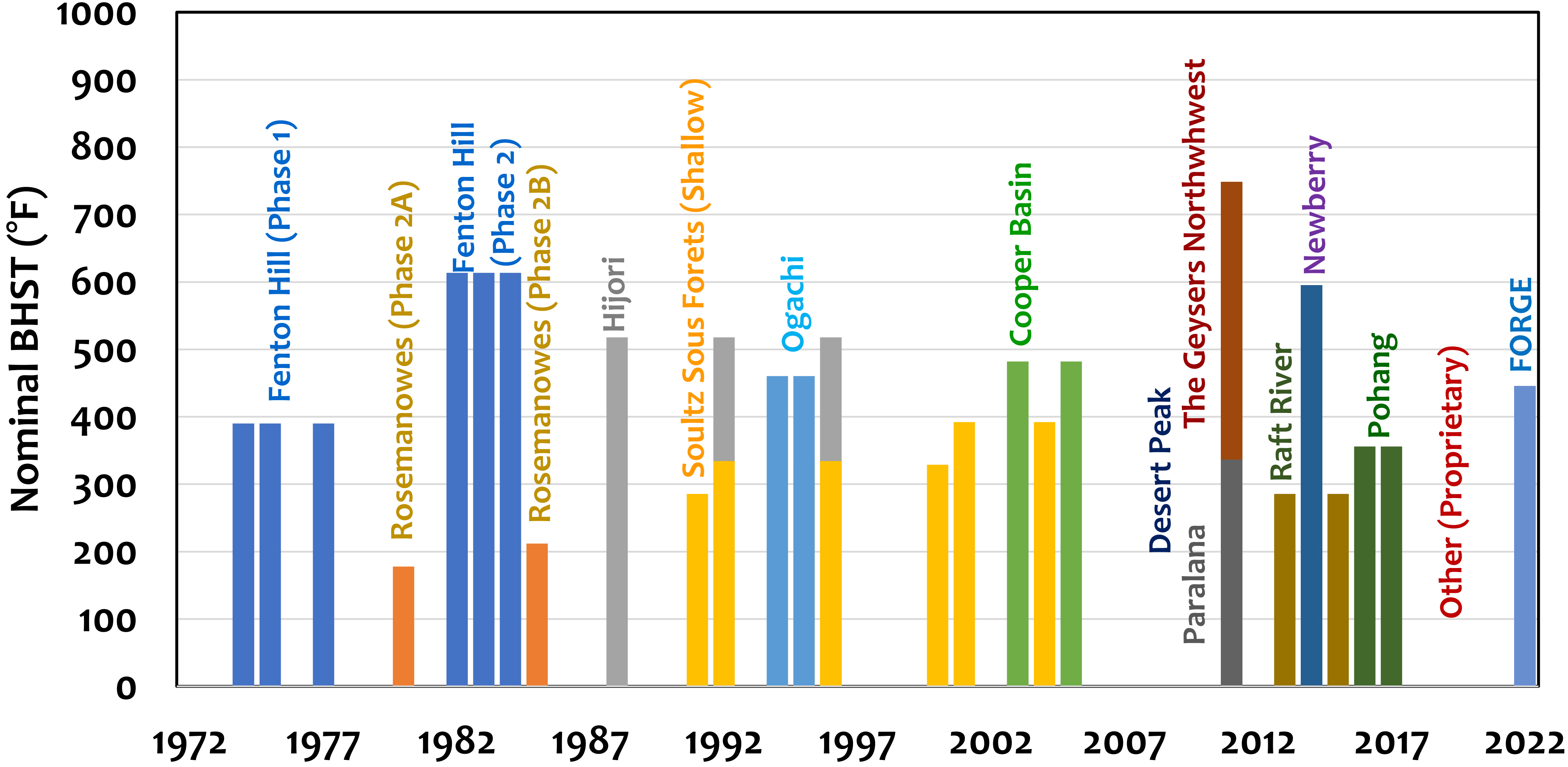


150°C

Temperatures at 6 km

Data from SMU and Tester and others, 2006

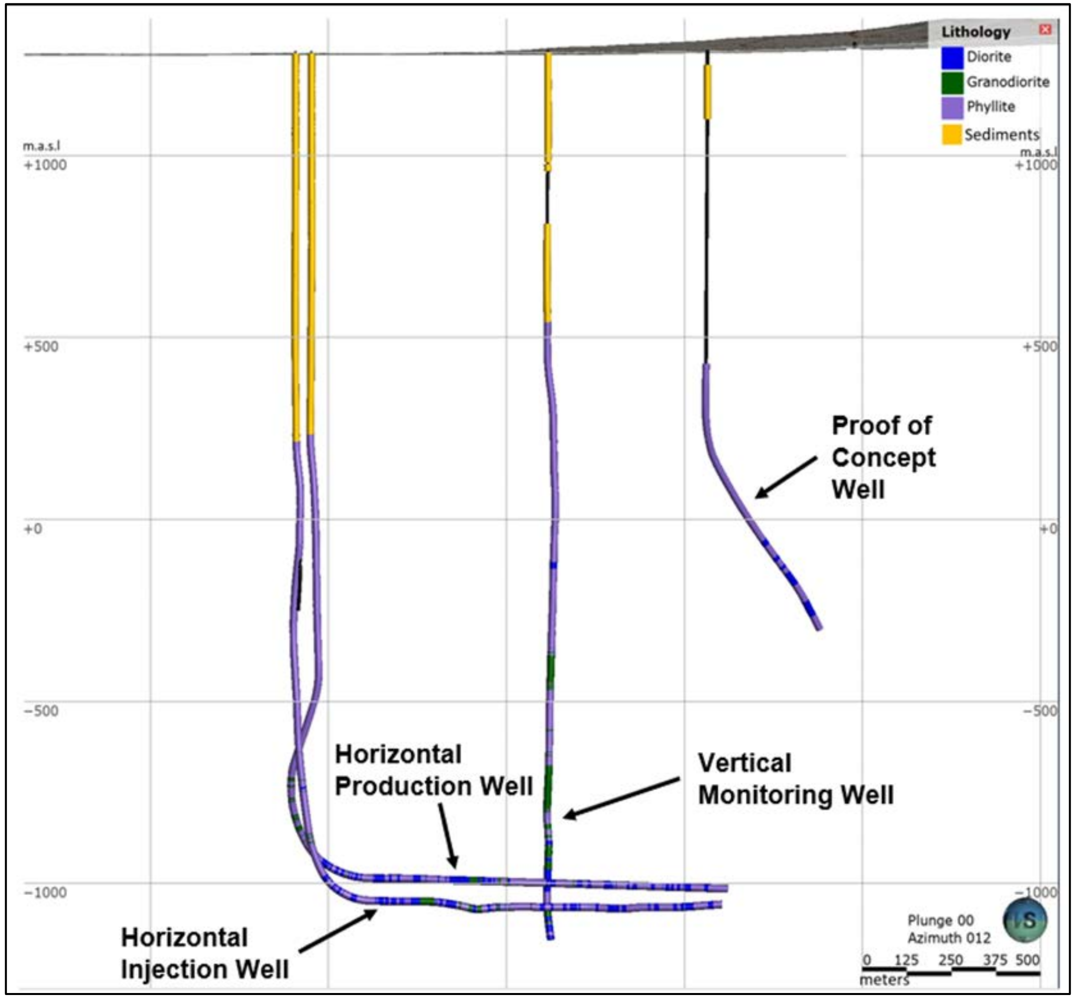
Nearly 50 Years of EGS Stimulations



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

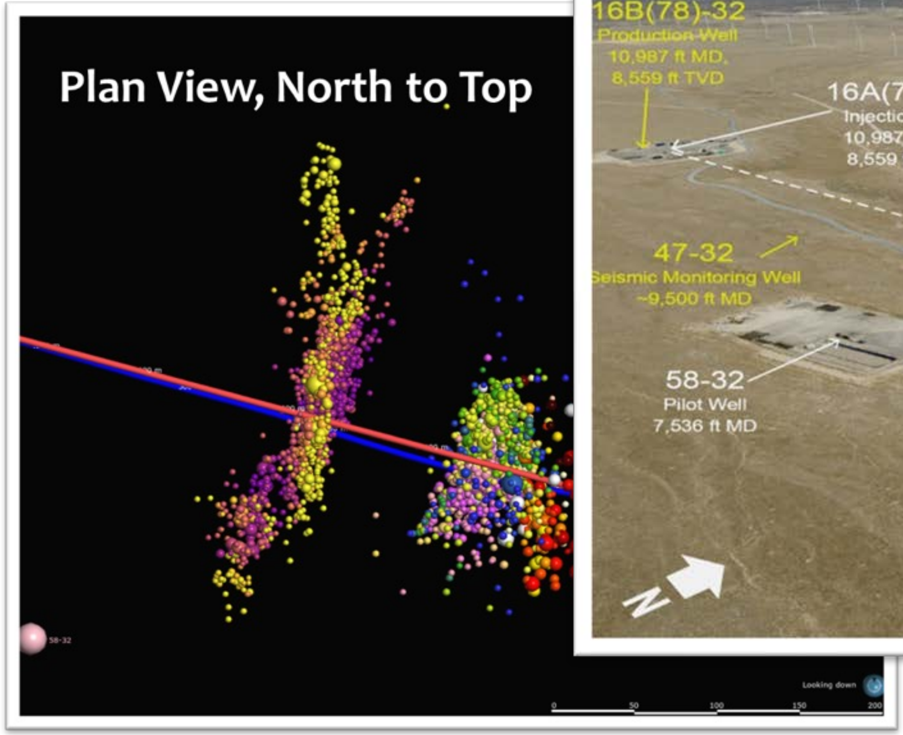
Fervo Energy Drills and Completes First Successful Horizontal EGS

1. Monitoring Well 73-22 – to 8009' TVD to host microseismic array, permanent fiber, and PT gauge
2. Injection Well 34A-22 – to 7700' TVD with a 3250' lateral'
3. Horizontal Production Well 34-22 – drilled through SRV
4. Maximum Temperature - 191 °C
5. Metasedimentary and granite
6. 9 7/8" lateral with 7" casing



Utah FORGE - DOE's Frontier Observatory for Research in Geothermal Energy

Field laboratory for developing, testing, and prototyping technologies that could be adopted for commercializing Enhanced Geothermal Systems (EGS)



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DOE FORGE: Revitalizing Classical EGS (HDR)

Conceptual Reservoir Development

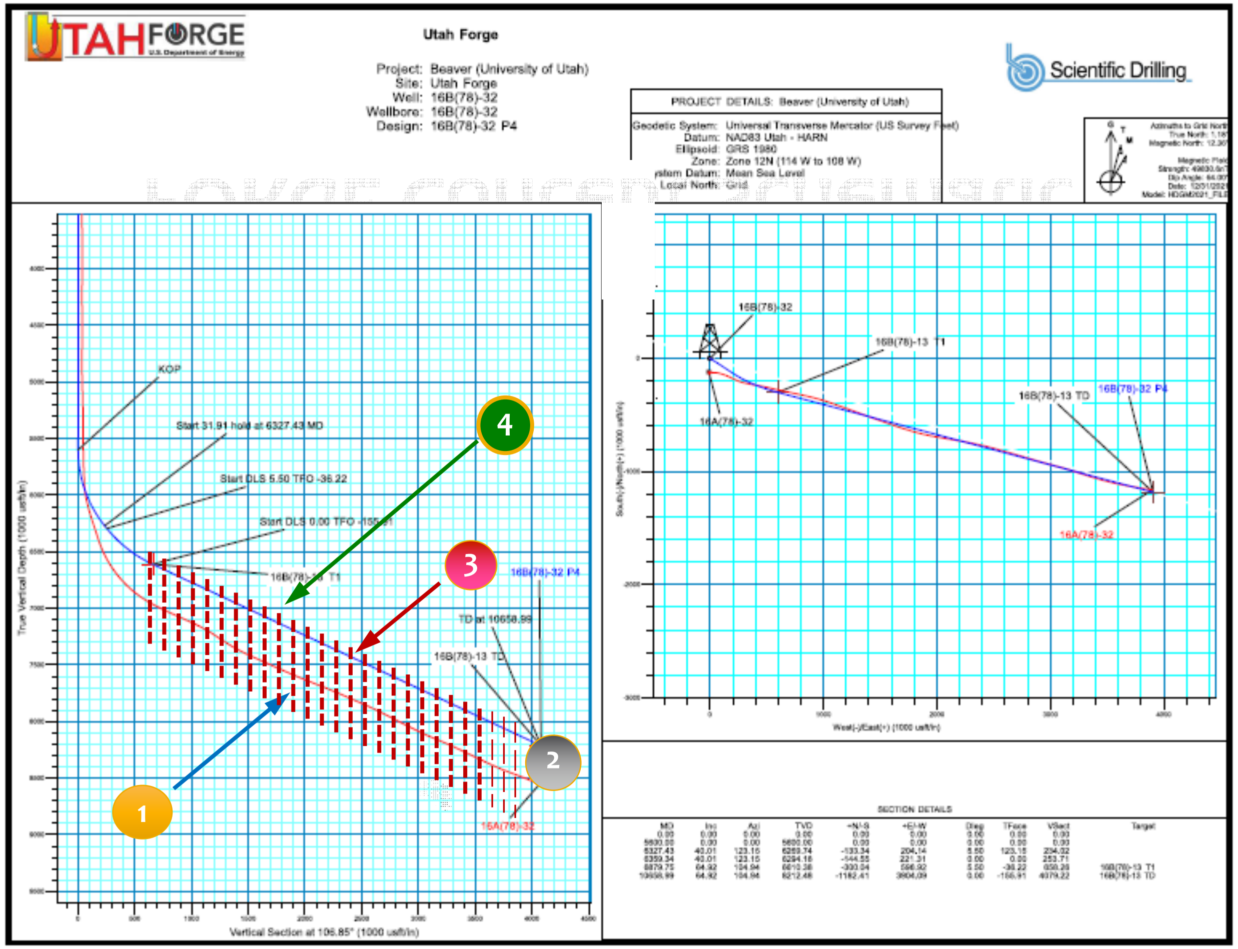
1. Drill Injection Well: 16A(78)-32
2. Hydraulically Fracture (Multiple Stages)
3. Drill Production Well to Intersect Fractures: 16B(78)-32
4. Populate Well with Frac Stages

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

Surface Area for Heat Exchange

FORGE Concept Schematic



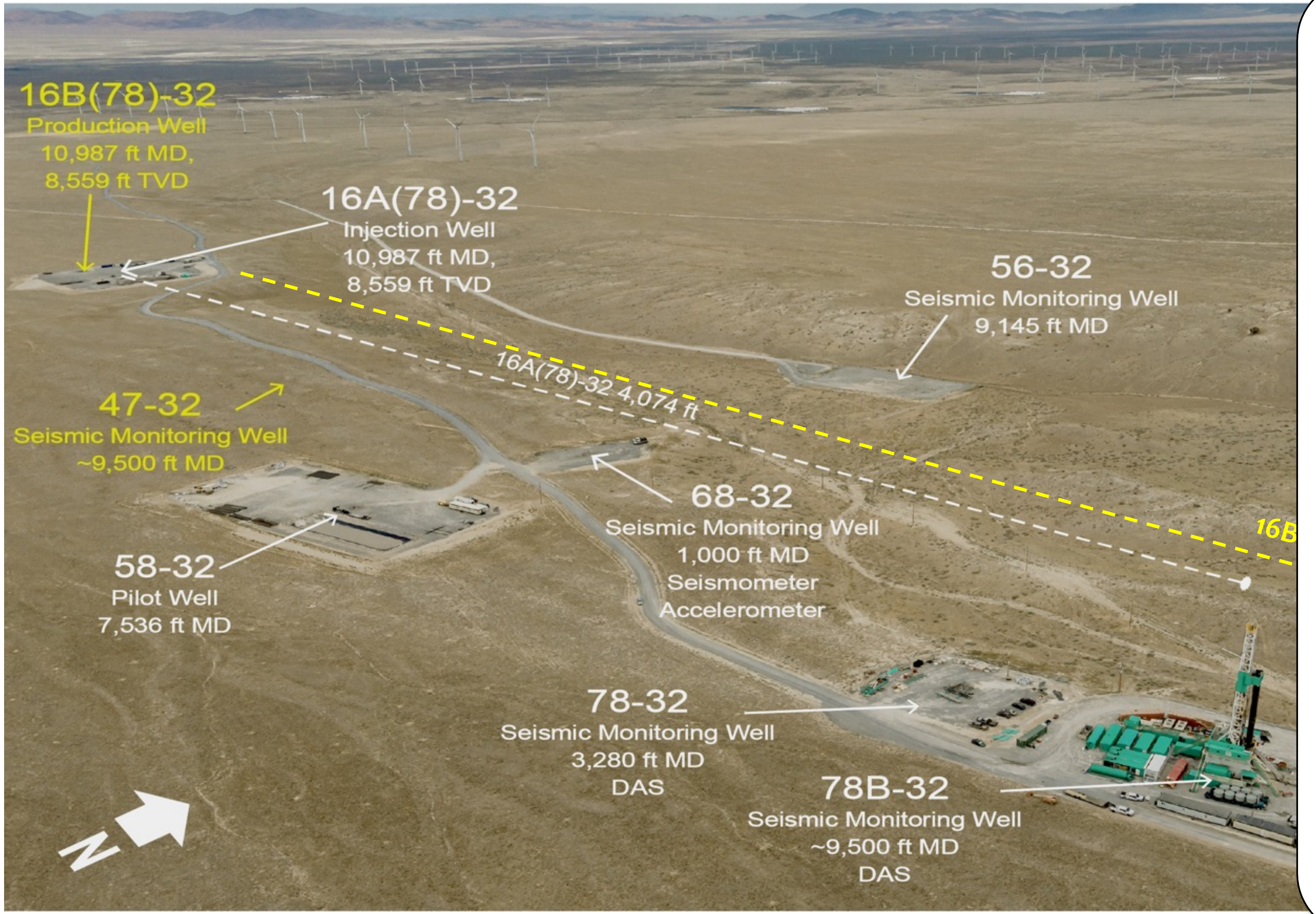
Elevation (Side) View

Plan (Map) View

Where Are We?


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
56-32
Seismic Monitoring Well
9,145 ft MD
16A(78)-32 4,074 ft
47-32
Seismic Monitoring Well
~9,500 ft MD
68-32
Seismic Monitoring Well
1,000 ft MD
Seismometer
Accelerometer
16B(78)-32 10,947 ft MD
58-32
Pilot Well
7,536 ft MD
78-32
Seismic Monitoring Well
3,280 ft MD
DAS
78B-32
Seismic Monitoring Well
~9,500 ft MD
DAS
N

Challenges: Temperature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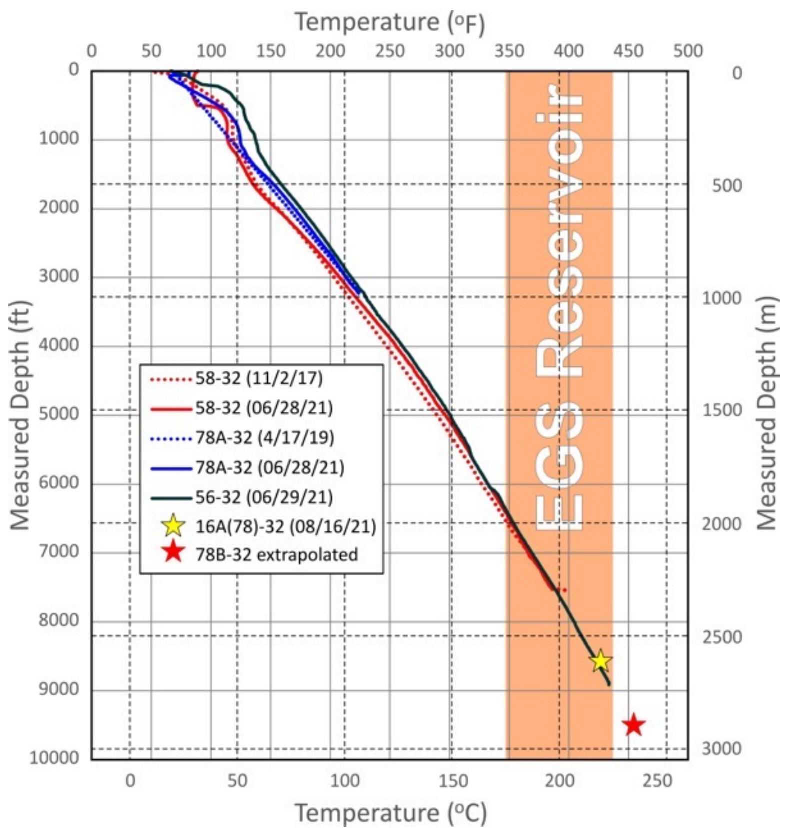
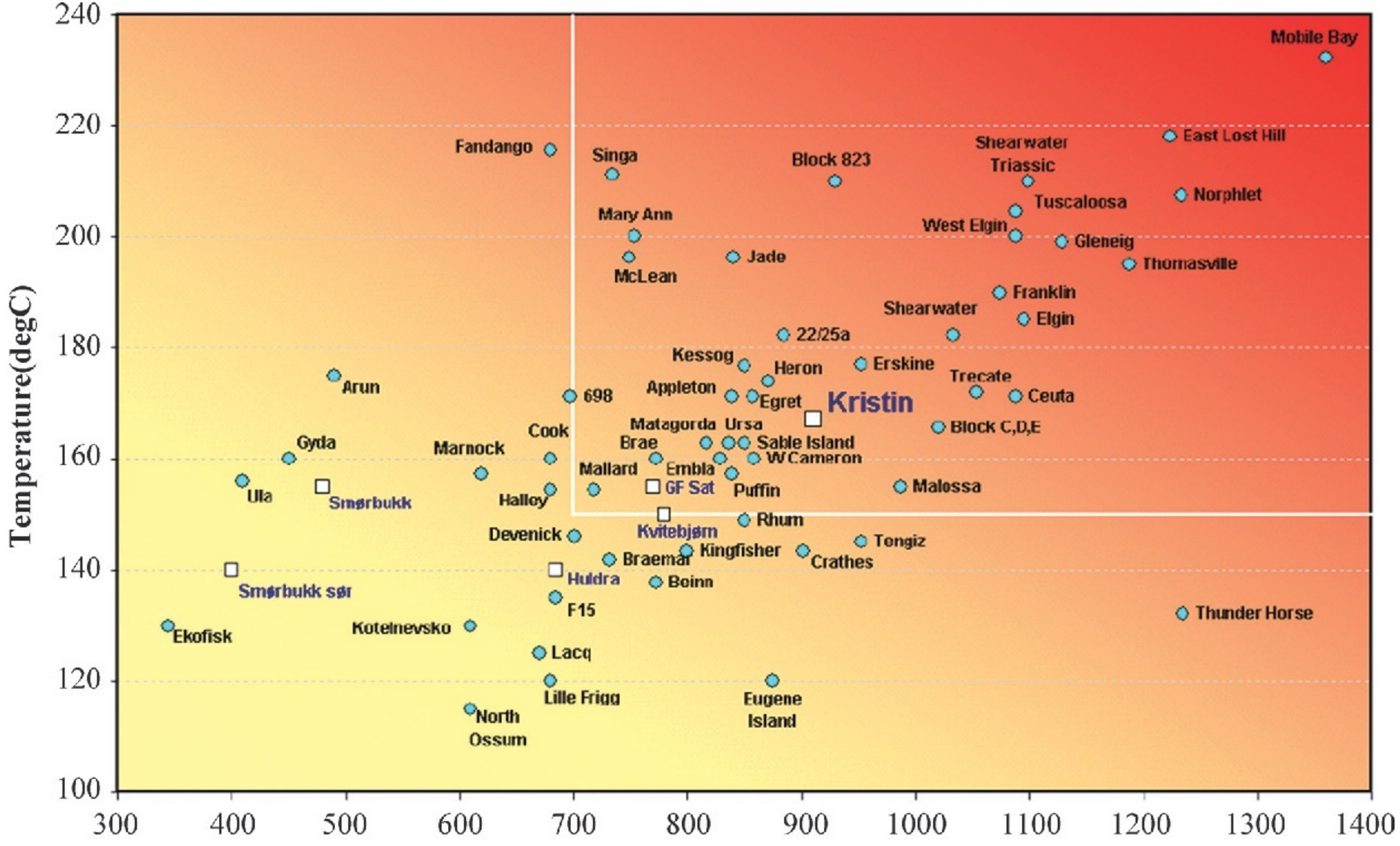

Temperature (°F)
Temperature (°C)
Measured Depth (ft)
Measured Depth (m)
EGS Reservoir
58-32 (11/2/17)
58-32 (06/28/21)
78A-32 (4/17/19)
78A-32 (06/28/21)
56-32 (06/29/21)
16A(78)-32 (08/16/21)
78B-32 extrapolated

FORGE



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

Isolation Tools … Problematic Previously

Zone 2 Packer Failure

"When packer pulled above the slips, the broken ring [Zone 3] fell into our hands"

Zone 3 Packer. Rings and slips caused significant drag

Status - Temperature

Where We Are?

Drilling:
- Evidence of Ruggedized Bit Design
- Favorable Demonstration of Eavor's Insulated Drillpipe

Logging:
- Successful ThruBit Logging

Stimulation:
- Successful use of slickwater and CMHPG, bridge plugs
- Fibers installed, planning next stimulations

Operations:
- Implementation of R&D projects

What is Problematic?

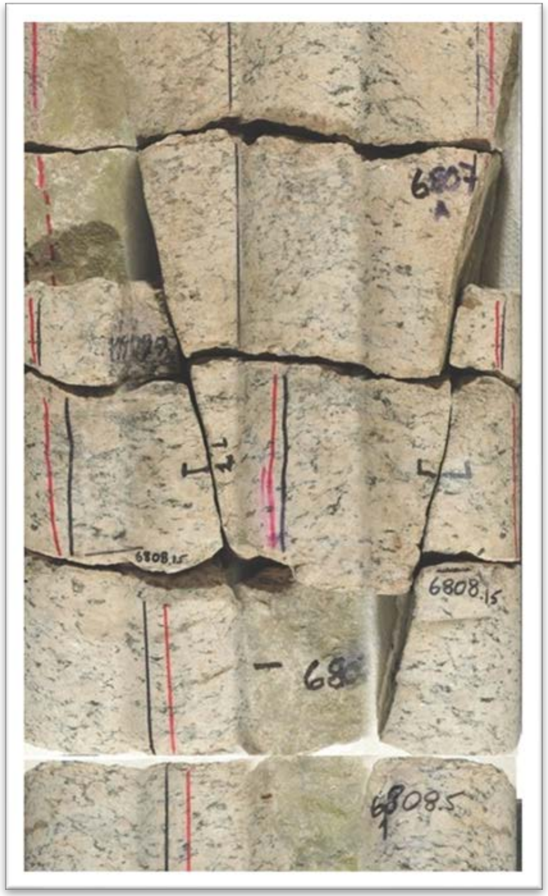
Drilling:
- Eliminate requirements for aggressive cooling
- Close calls with batteries

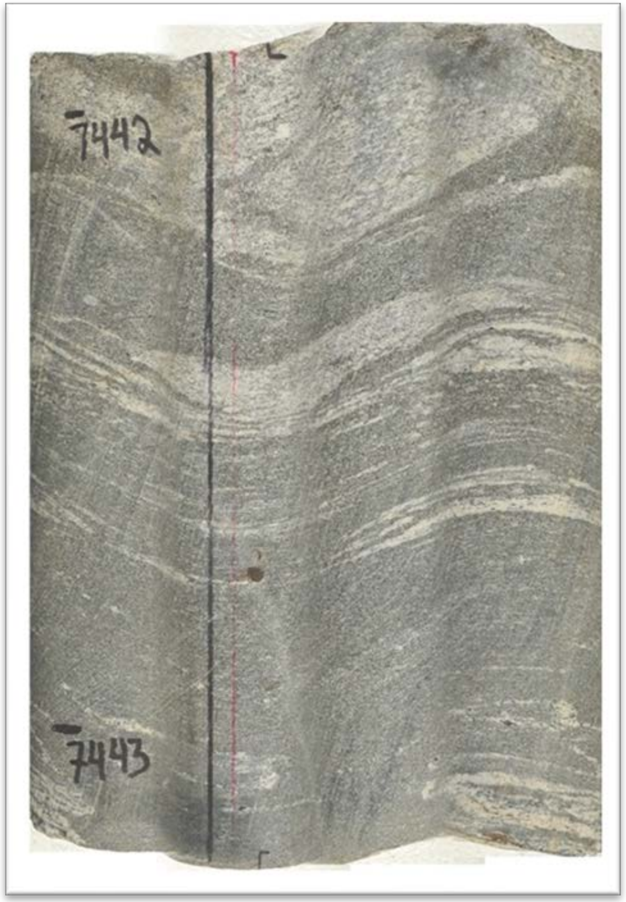
Logging:
- Reduce requirements on cooling and other mitigation technologies

Stimulation:
- Carrying proppant
- Monitoring microseismically
- Choosing isolation and perforating techniques

Operations:
- Yet to be determined

Challenges?
(and Mysteries)
Lithology and Natural Fractures





High Strength/Moduli, Abrasive Granitoid to Gneiss

Rock Mass Properties, Fracture Properties, Bit as a Laboratory

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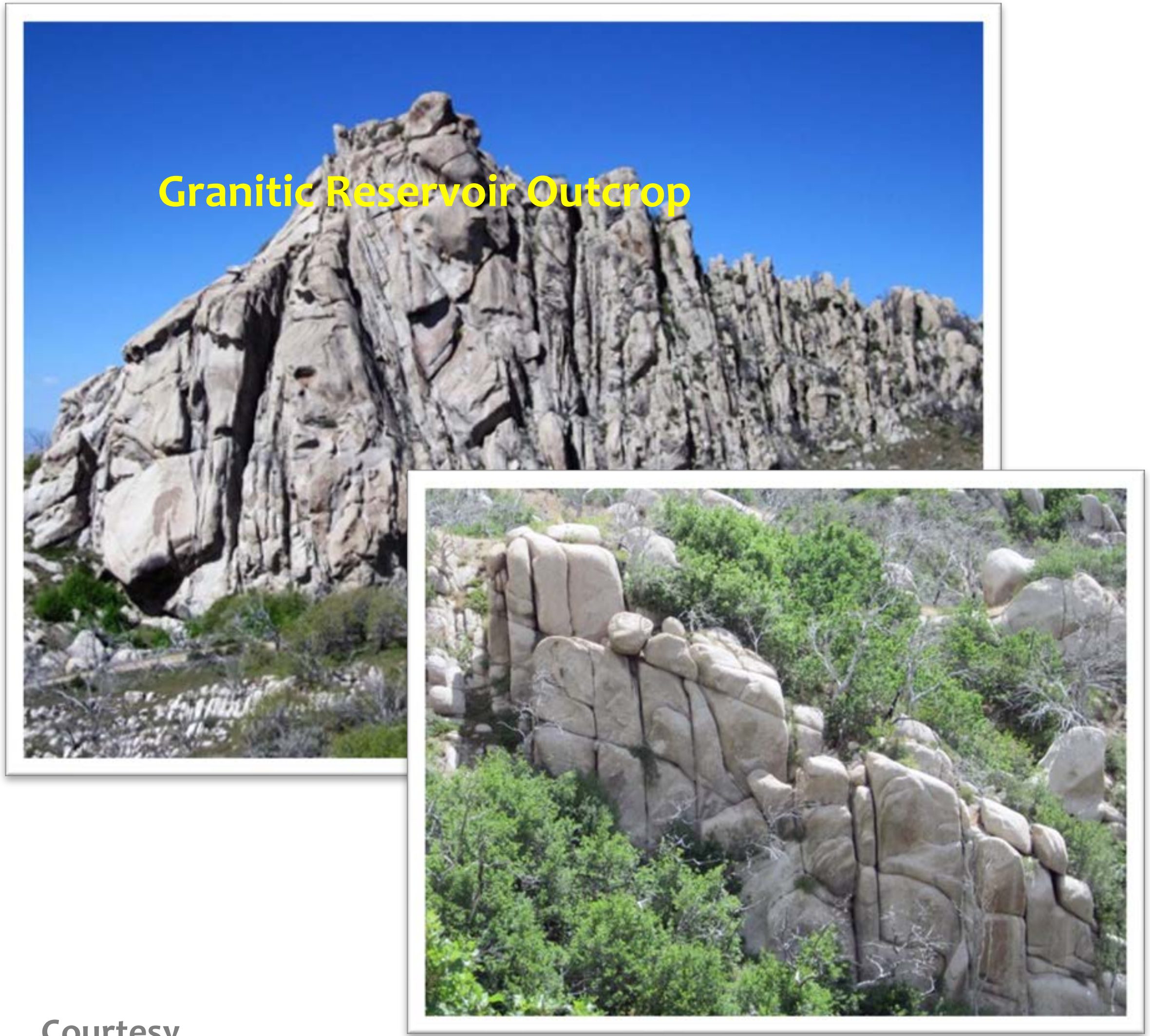
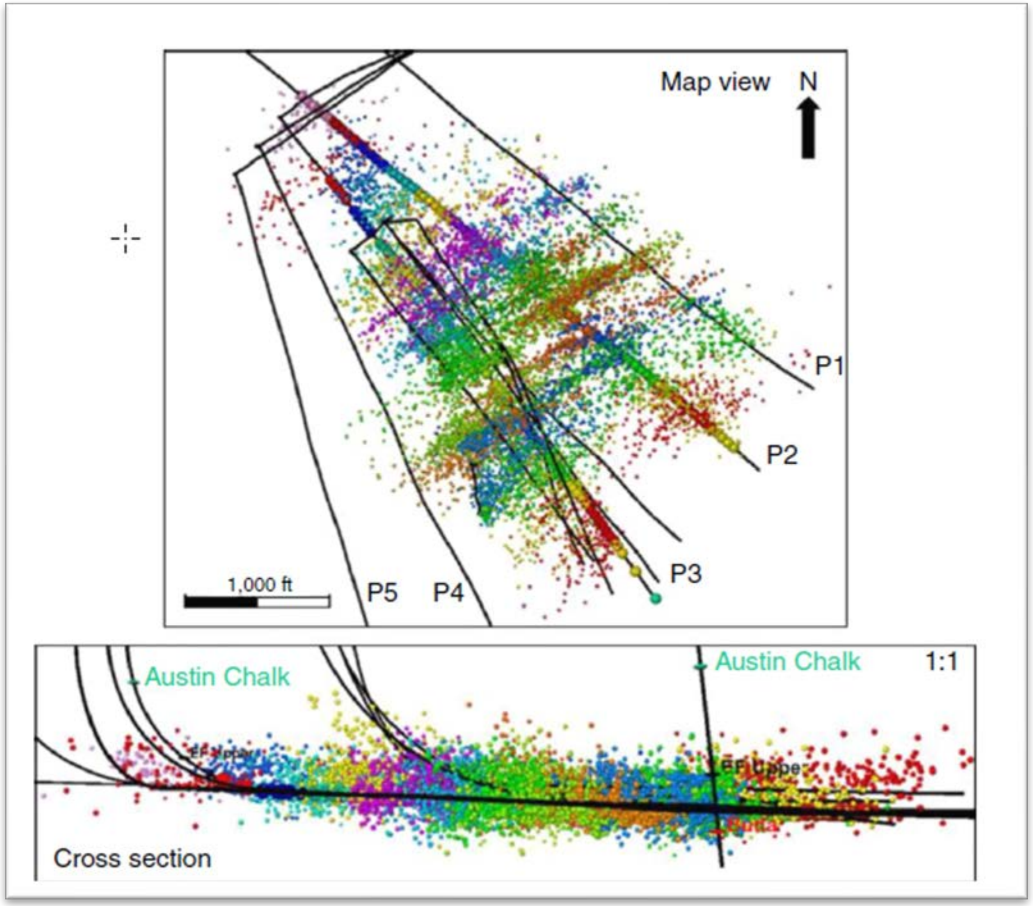
Natural Fracture Influence?

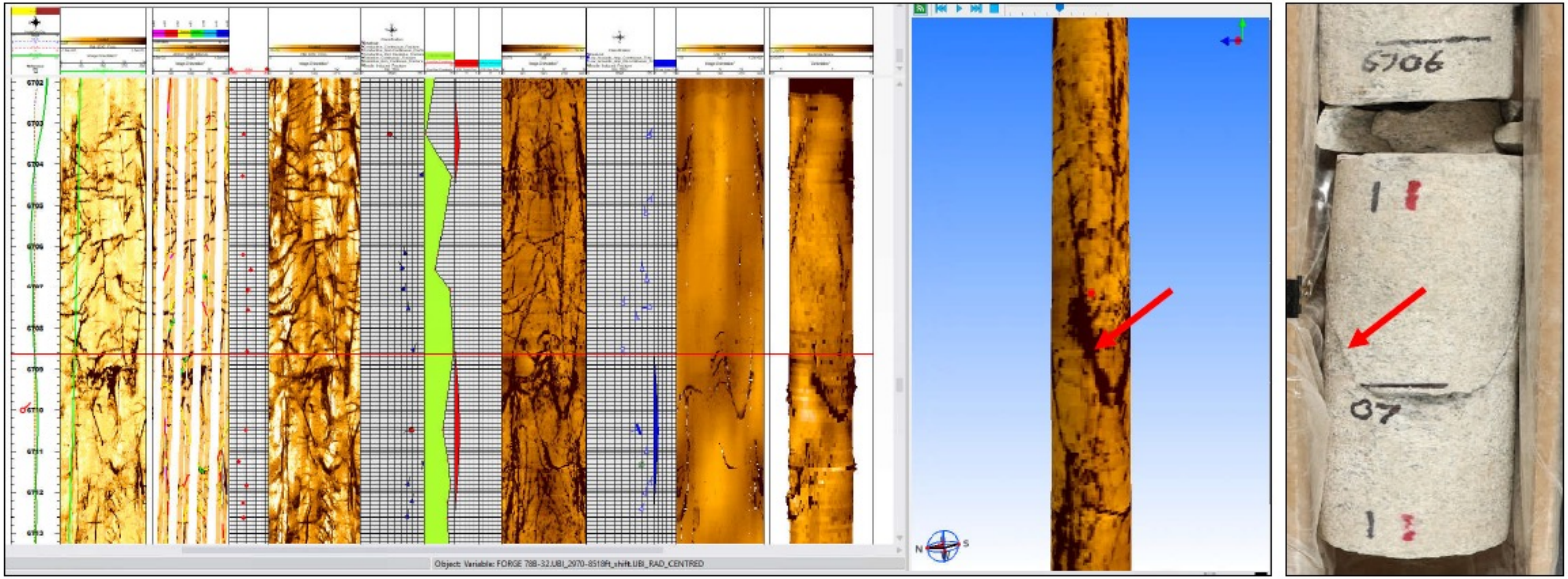




Courtesy
Bartley 2019

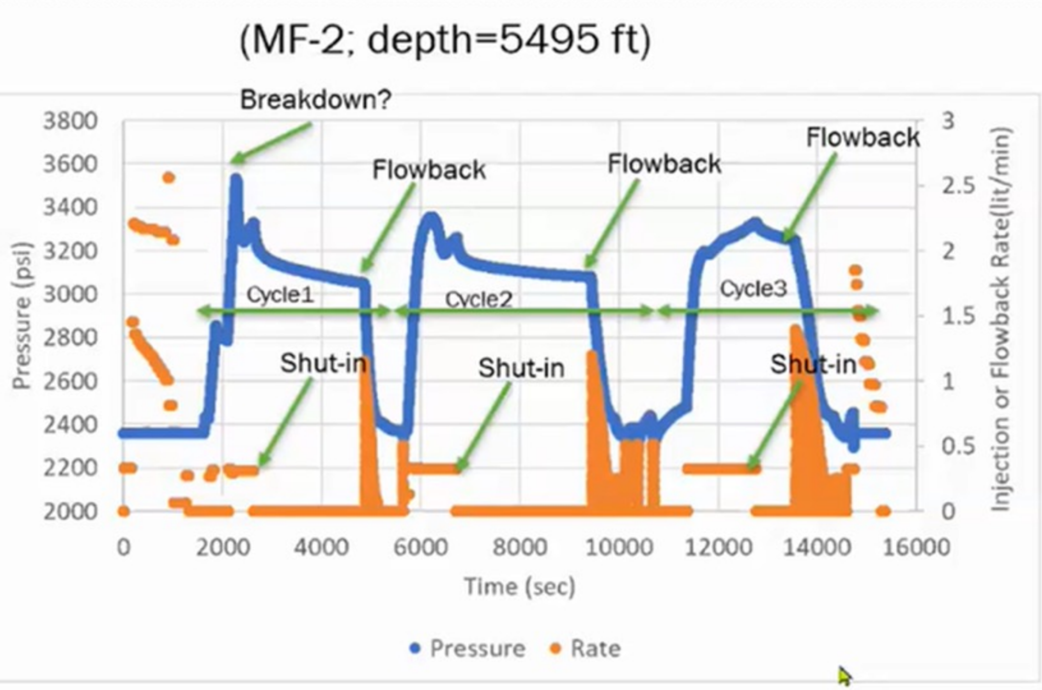
Raterman et al. 2018. Sampling a Stimulated Rock Volume : An Eagle Ford Example, SPE 191375, SPE Reservoir Evaluation & Engineering

Reservoir Characterization Remains Challenging

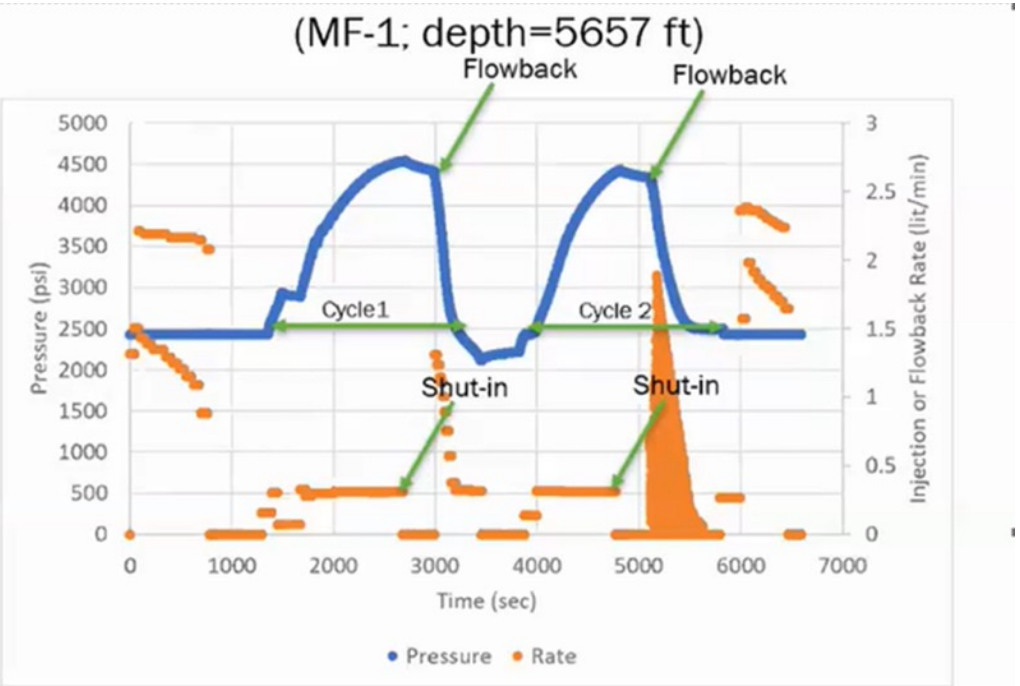


FORGE 78B-32

Courtesy: Andy Wray, SLB, September 2023



Bottom Hole Pressure and Injection/Flow Back Rate of the Station 2 Test
Breakdown Observed? and Low ISIP Gradient



Bottom Hole Pressure and Injection/Flow Back Rate of the Station 1 Test
No obvious Breakdown and Higher ISIP Gradient

Station	Station/Cycle	Depth MD (ft)	Depth TVD (ft)	Breakdown/Reopening Pressure Gradient (psi/ft)	ISIP Gradient (psi/ft)
1	1	5,657	5,655.2	N/A	0.80
1	2	5,657	5,655.2	N/A	0.78
2	1	5,495	5,494	0.64	0.60
2	2	5,495	5,494	0.61	0.59

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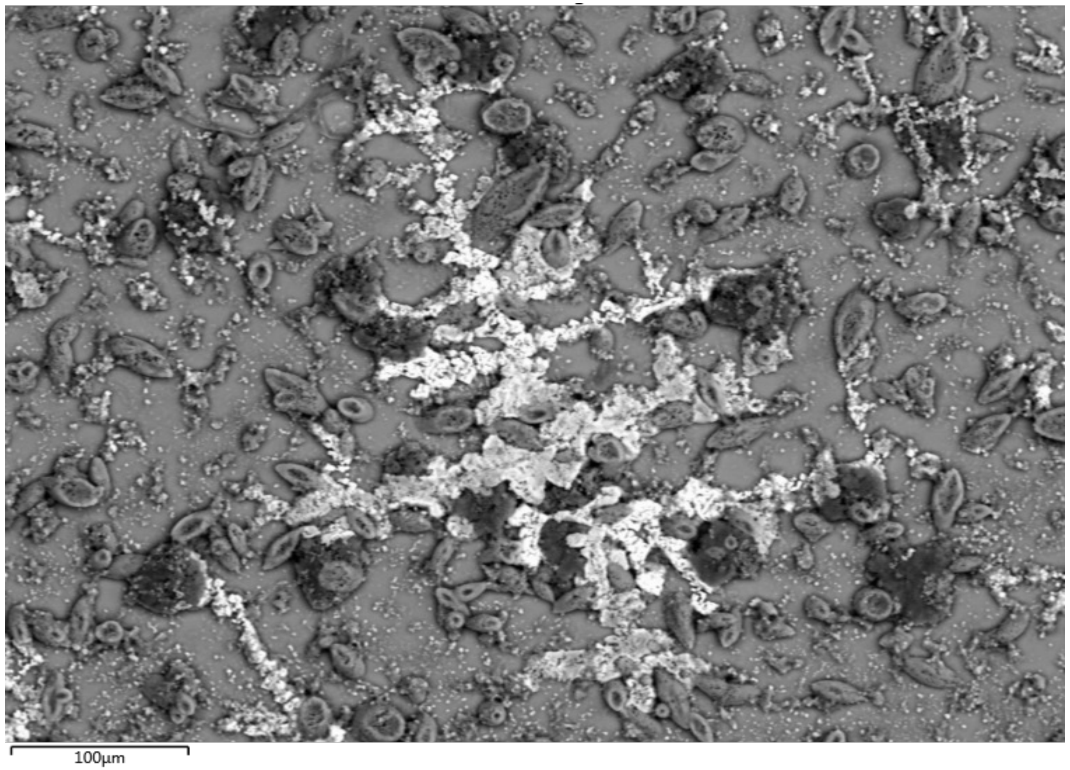
Courtesy Mark Kelley, Battelle

Fracture Infill and Flowback Chemistry

SEM-EDS of Drilling Fluids



"Confirmed the presence of halite, sylvite and calcite."

Clay Jones, Personal Communication, June 22, 2023

Flowback After Fracs

"The observed increases in dissolved solids in the flowback waters, from baseline samples that have salinities on the order of hundreds of ppm, to thousands of ppm at the end of flowback … equates to thousands of kg of dissolved solids having been removed via solution."

Jones et al., 2023

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Status – Role of Natural Fractures

Where We Are?

Drilling:

- To date (!!) no significant losses, except potentially during cementing

Logging:

- Effectively mapped with FMI and UBI
- Deep Sonic can be helpful
- Flowback for stress
- Battelle stress measurements

Stimulation:

- Fluid type could play a role

Operations:

- Too early to tell

Where We Need to Go?

Drilling:

- We don't know what we don't know.
- Why significant vibrations …

Logging:

- Are we over-representing fractures that may have just been caused by thermal effects while drilling

Stimulation:

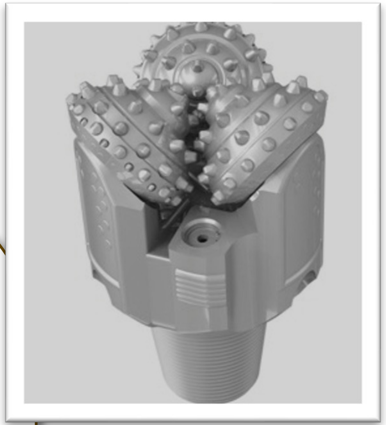
- To be determined ….

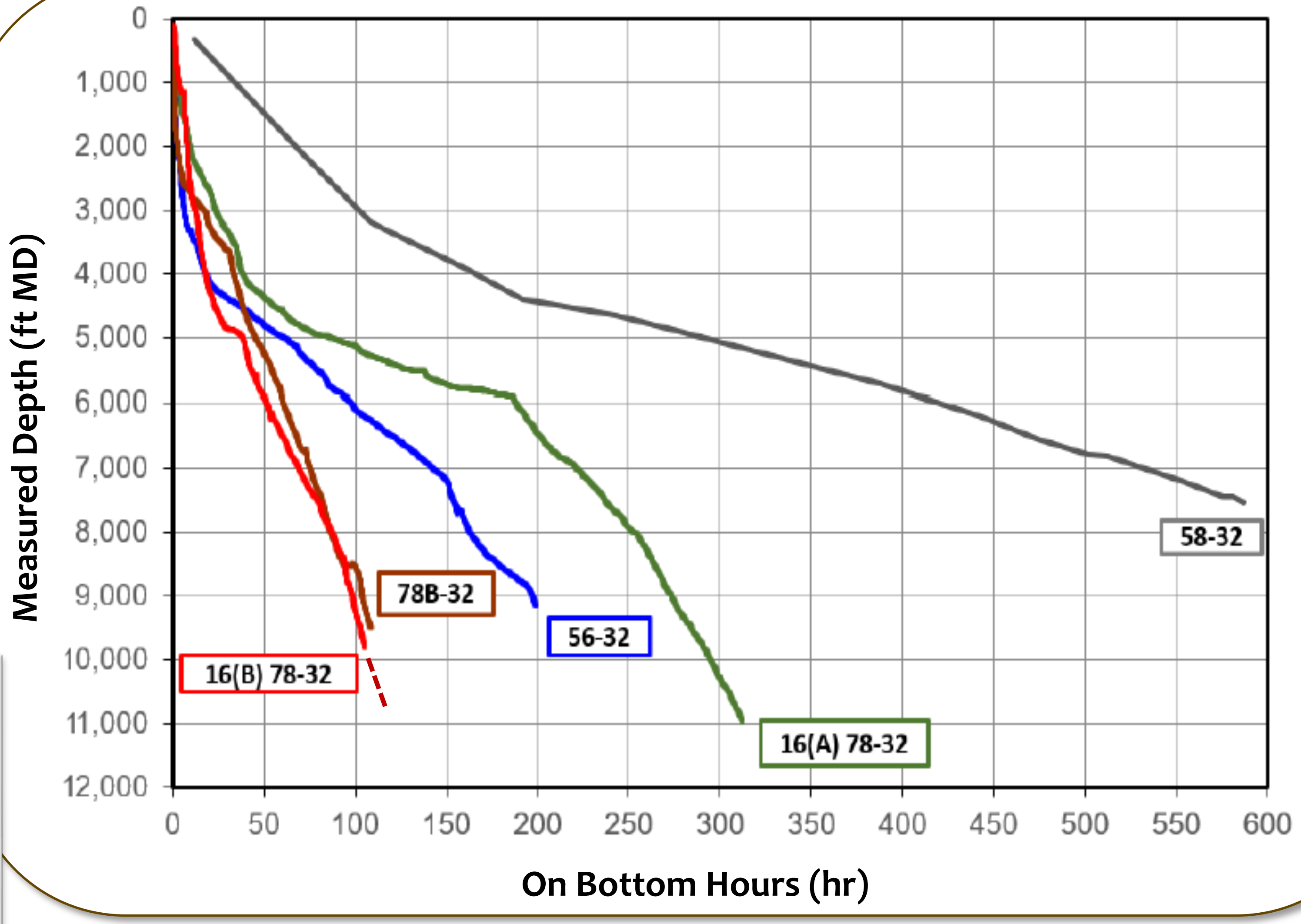
Operations:

- Too early to tell

Drilling Technology

Significant Performance Improvements

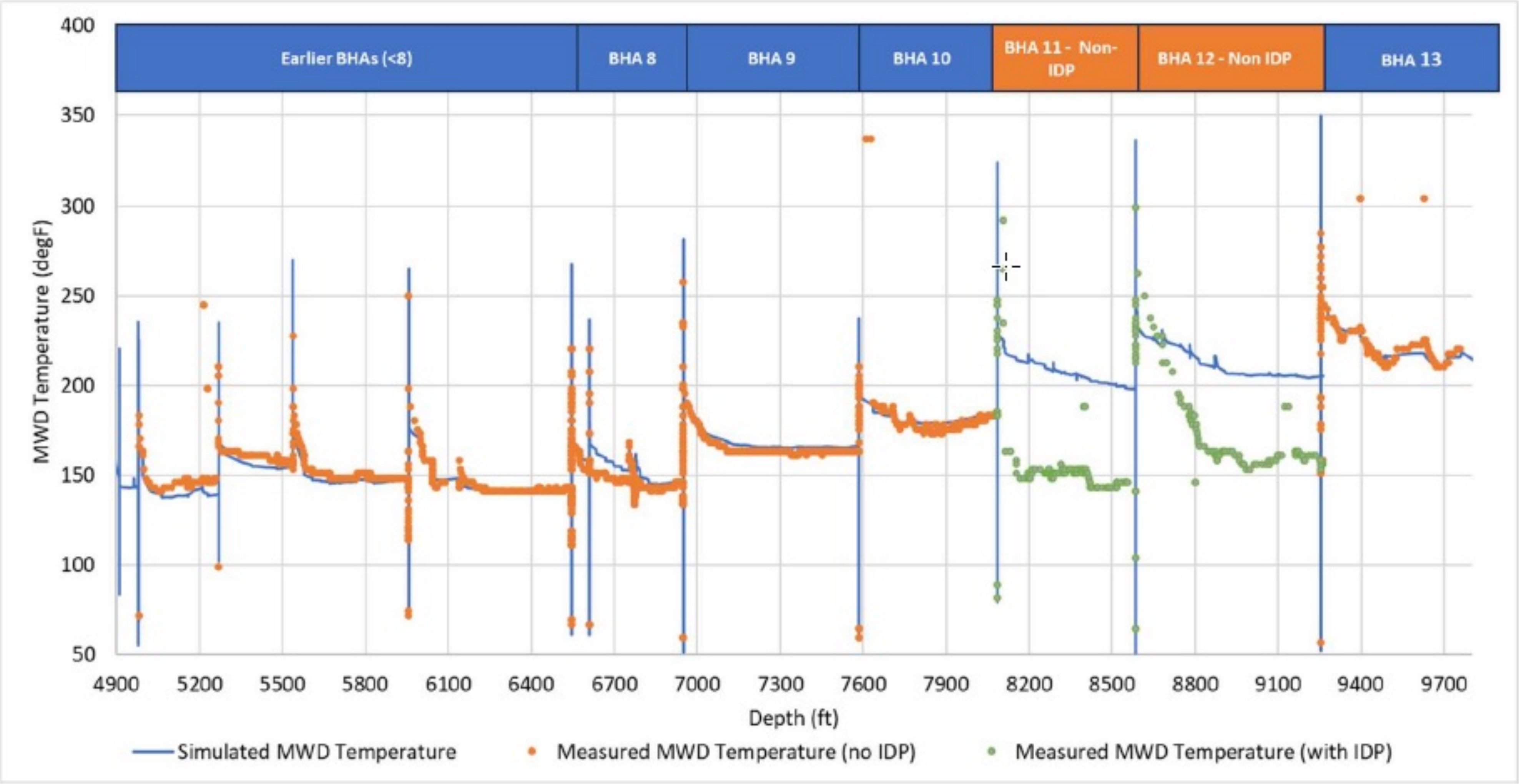




Dupriest and Noynaert (2022) , Modified after Olson (2023)

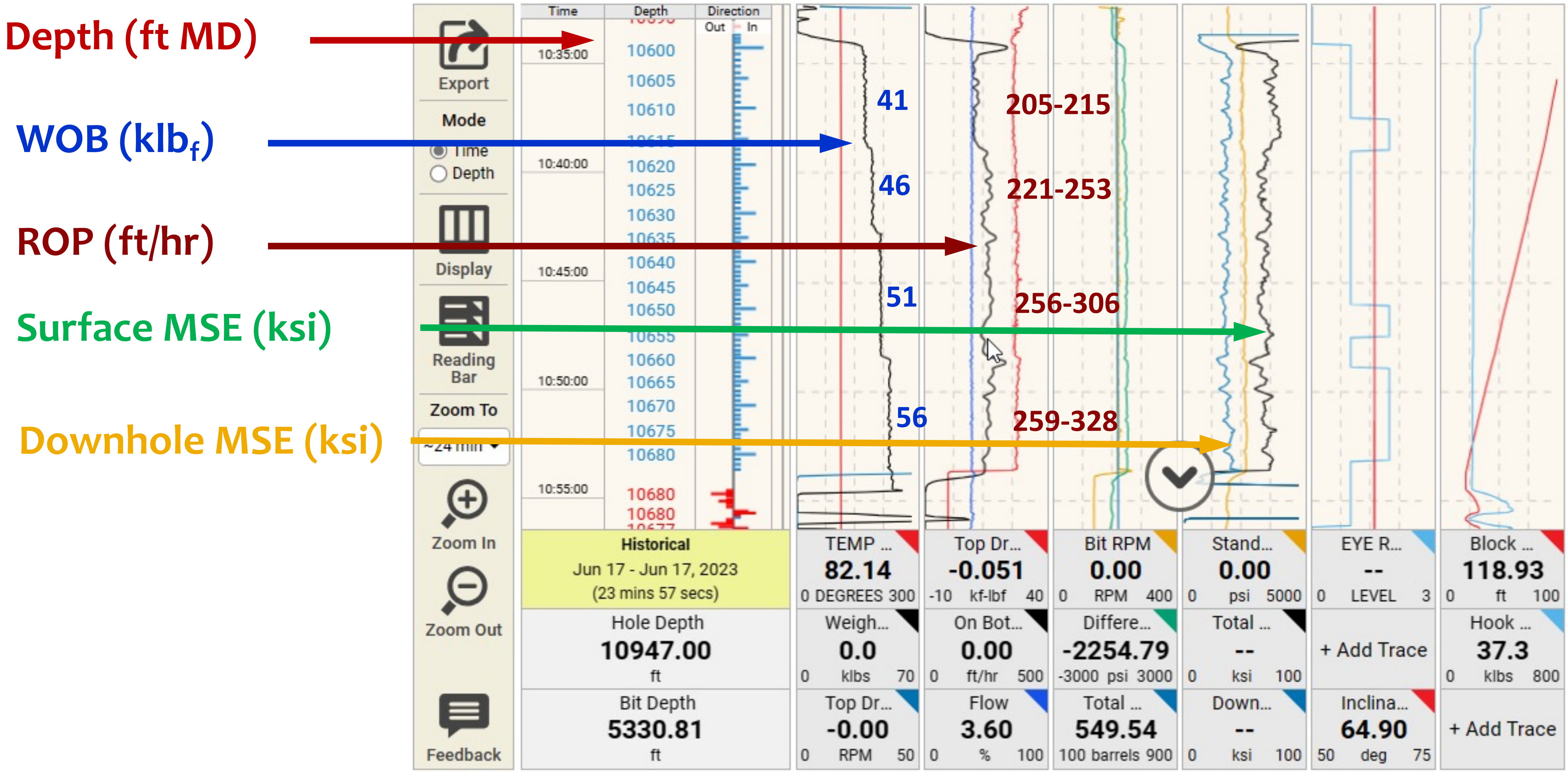
Insulated Drill Pipe – Eavor Technologies

Insulated Drill Pipe – Eavor Technologies



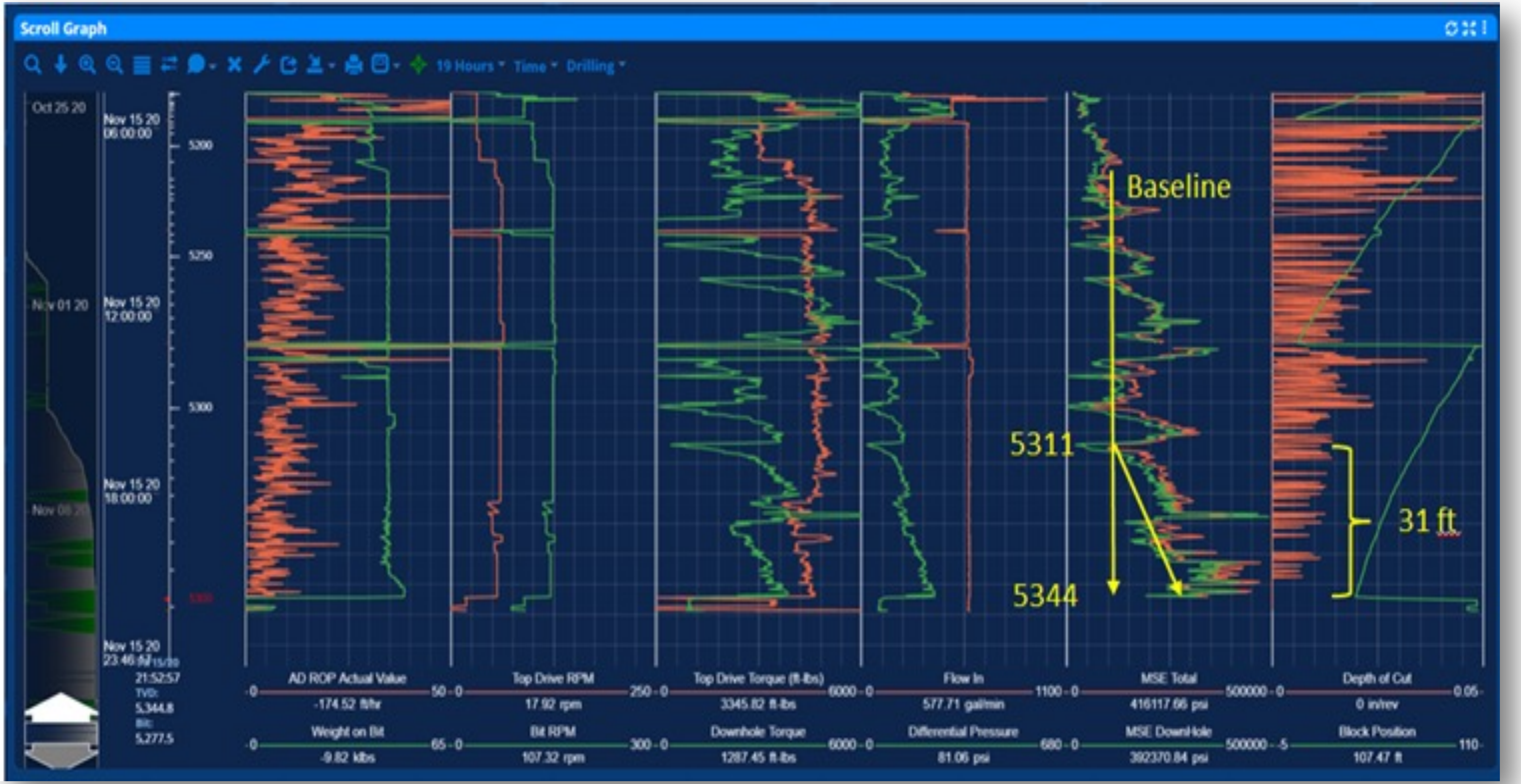
Eavor™ Courtesy Mark Hodder Eavor Technologies

WOB and ROP



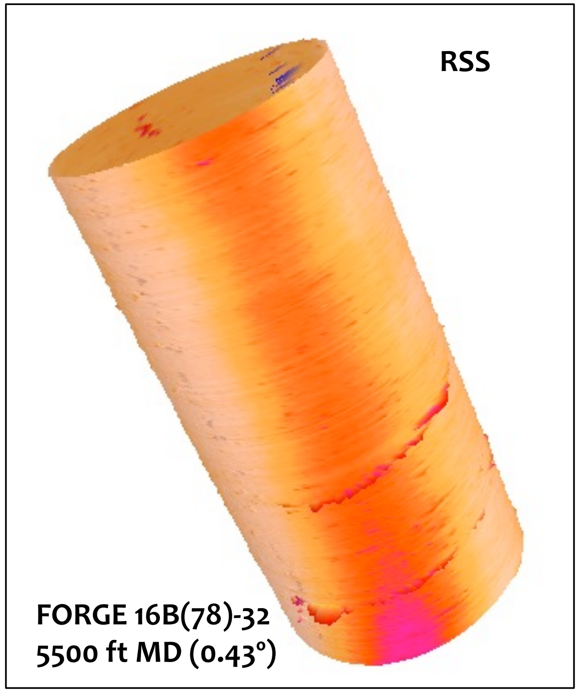
Depth (ft MD)
WOB (klbf)
ROP (ft/hr)
Surface MSE (ksi)
Downhole MSE (ksi)
41
46
51
56
205-215
221-253
256-306
259-328
Export
Mode
Time
Depth
Display
Reading Bar
Zoom To
Zoom In
Zoom Out
Feedback
Time
Depth
Direction
Out
In
10:35:00
10:40:00
10:45:00
10:50:00
10:55:00
10600
10605
10610
10620
10625
10630
10640
10645
10650
10660
10665
10670
10675
10680
10680
10680
Historical
Jun 17 - Jun 17, 2023
(23 mins 57 secs)
Hole Depth
10947.00
ft
Bit Depth
5330.81
ft
TEMP ...
82.14
0 DEGREES 300
Top Dr...
-0.051
-10 kf-lbf 40
Bit RPM
0.00
0 RPM 400
Stand...
0.00
0 psi 5000
EYE R...
--
0 LEVEL 3
Block ...
118.93
0 ft 100
Weigh...
0.0
0 klbs 70
On Bot...
0.00
0 ft/hr 500
Differe...
-2254.79
-3000 psi 3000
Total ...
--
0 ksi 100
+ Add Trace
Hook ...
37.3
0 klbs 800
Top Dr...
-0.00
0 RPM 50
Flow
3.60
0 % 100
Total ...
549.54
100 barrels 900
Down...
--
0 ksi 100
Inclina...
64.90
50 deg 75
+ Add Trace

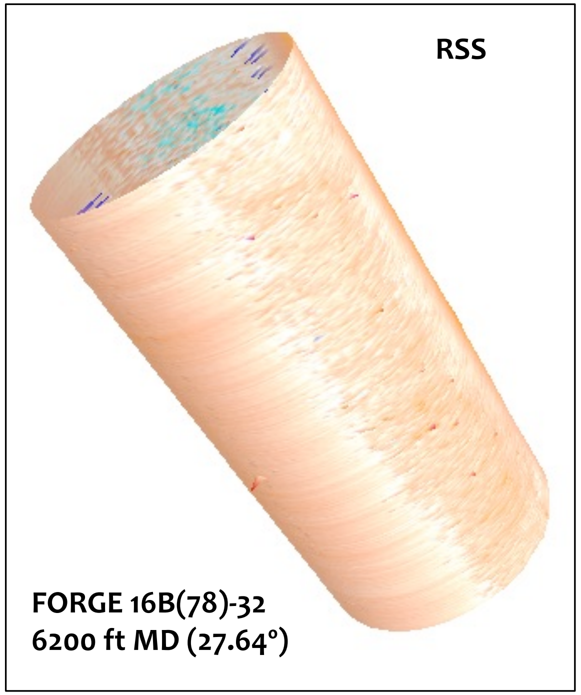
Mechanics of Drilling: Physics-Based Drilling



Images Courtesy Fred Dupriest TAMU

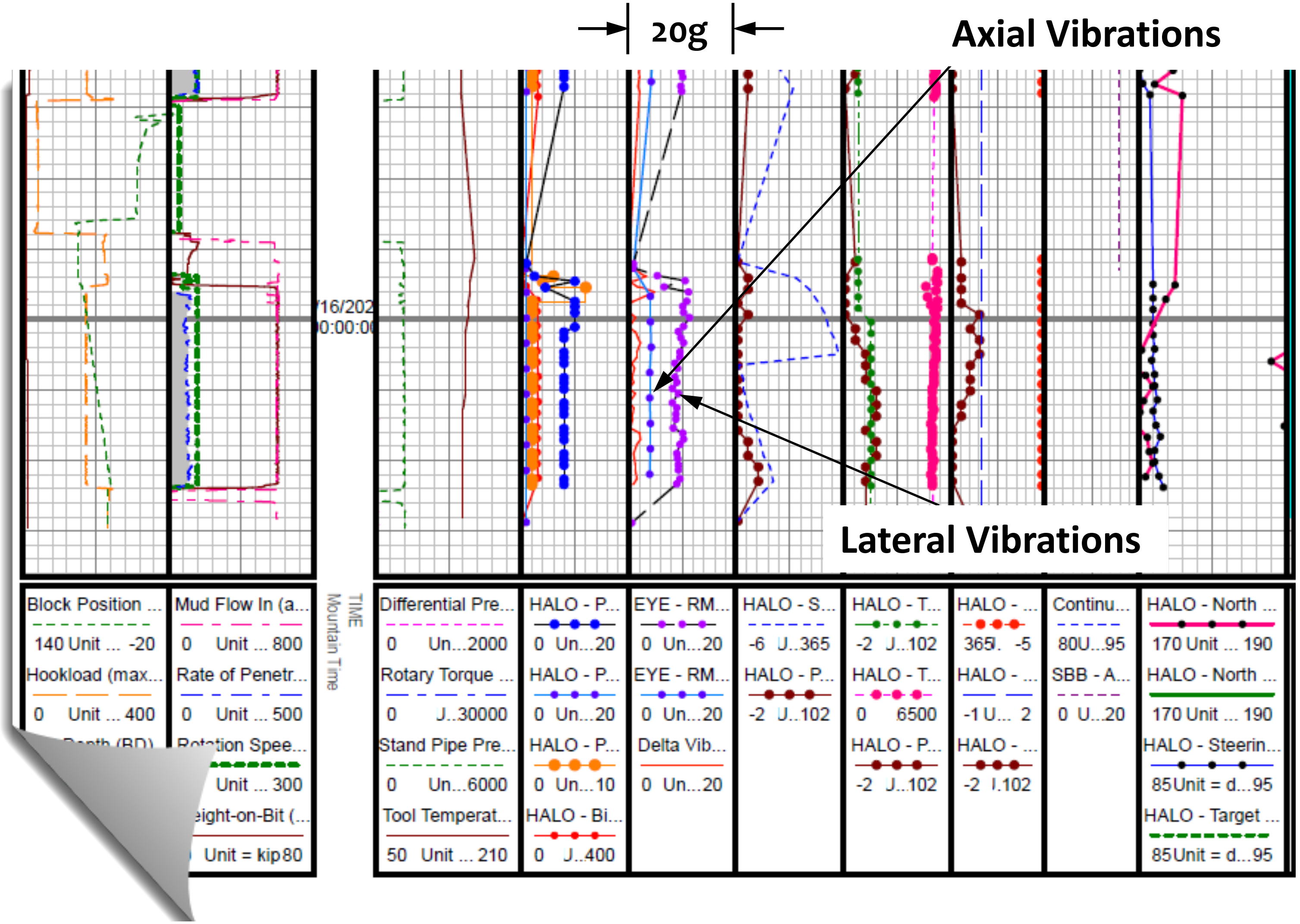
Rotary Steerable System (RSS) 16B(78)-32





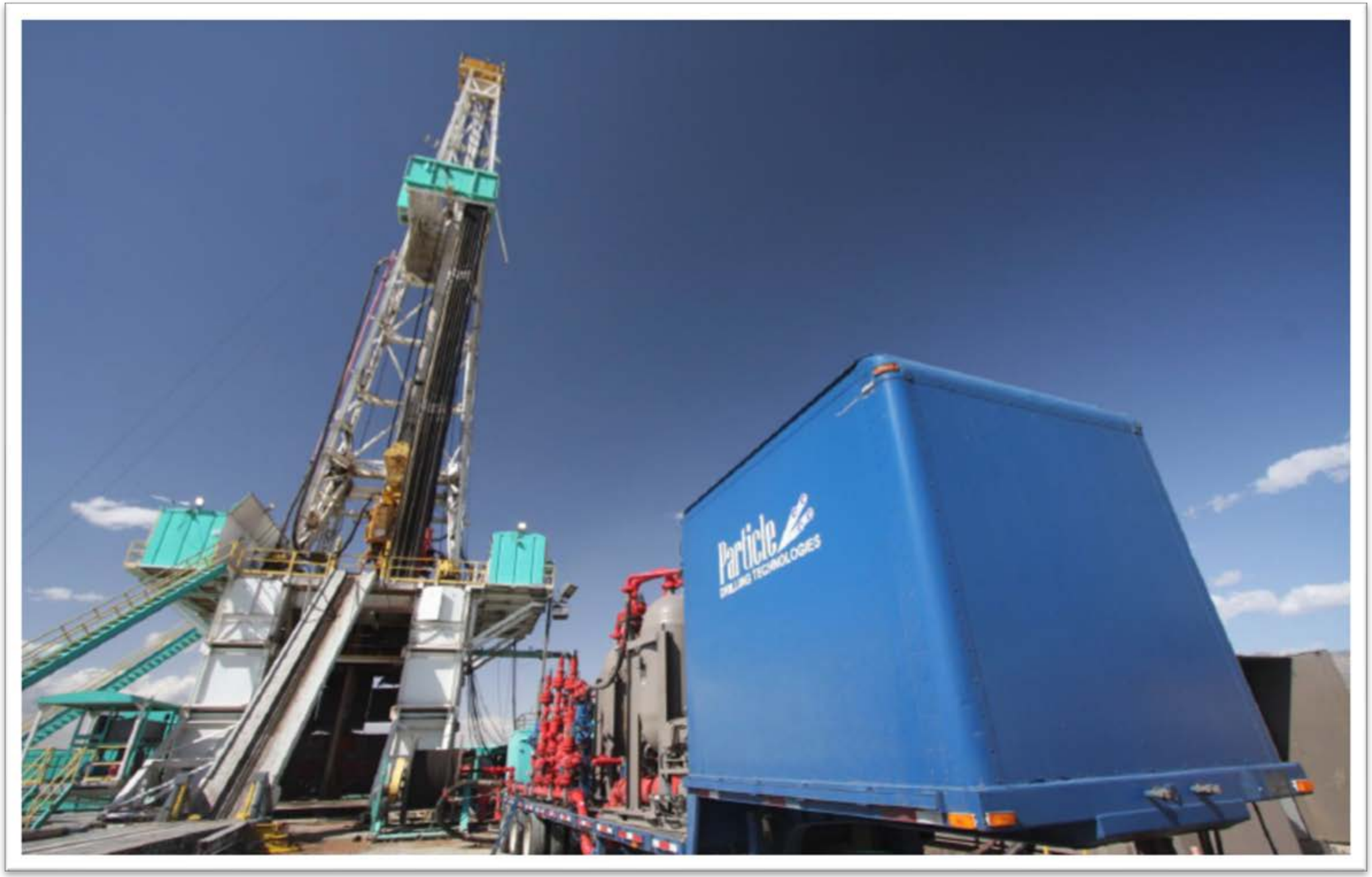
Vibrations as a Significant Dysfunction

Courtesy SGS



Courtesy Scientific Drilling

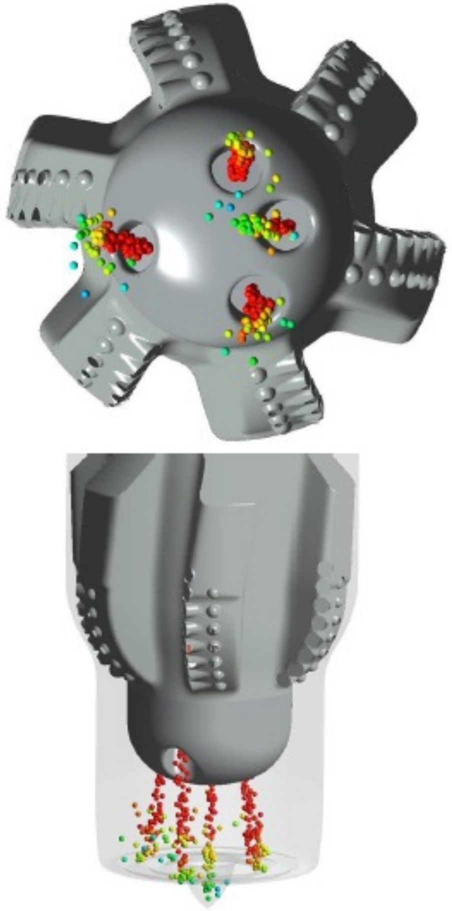
Particle Drilling



ReedHycalog | NOV Wellbore Technologies

Particle
DRILLING TECHNOLOGIES

Particle Drilling



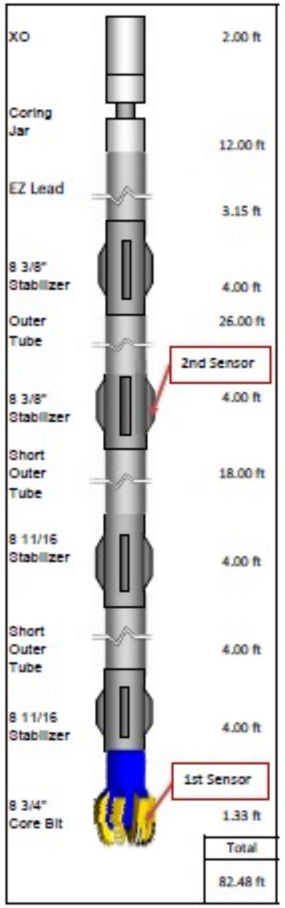
ReedHycalog | NOV Wellbore Technologies

Particle DRILLING TECHNOLOGIES

Coring

CANAMERA CORING

CORING BHA #



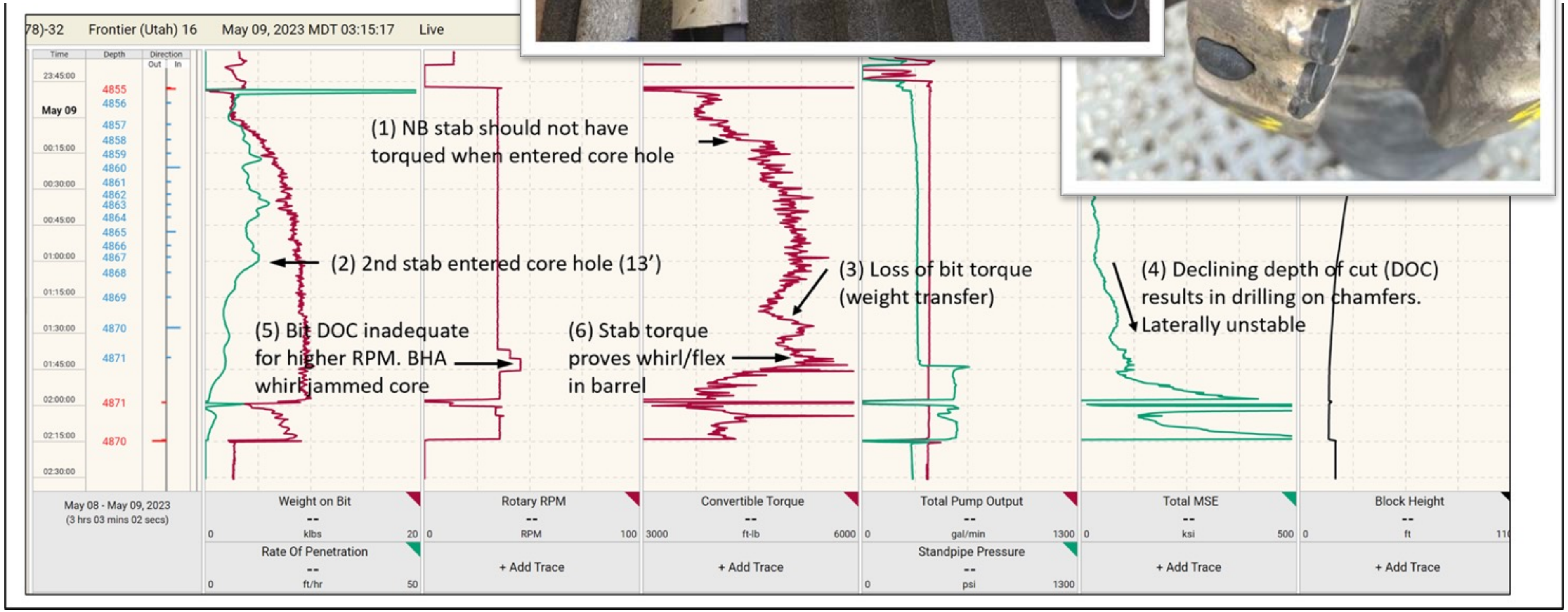


Chart Courtesy Fred Dupriest

Status – Drilling and Coring

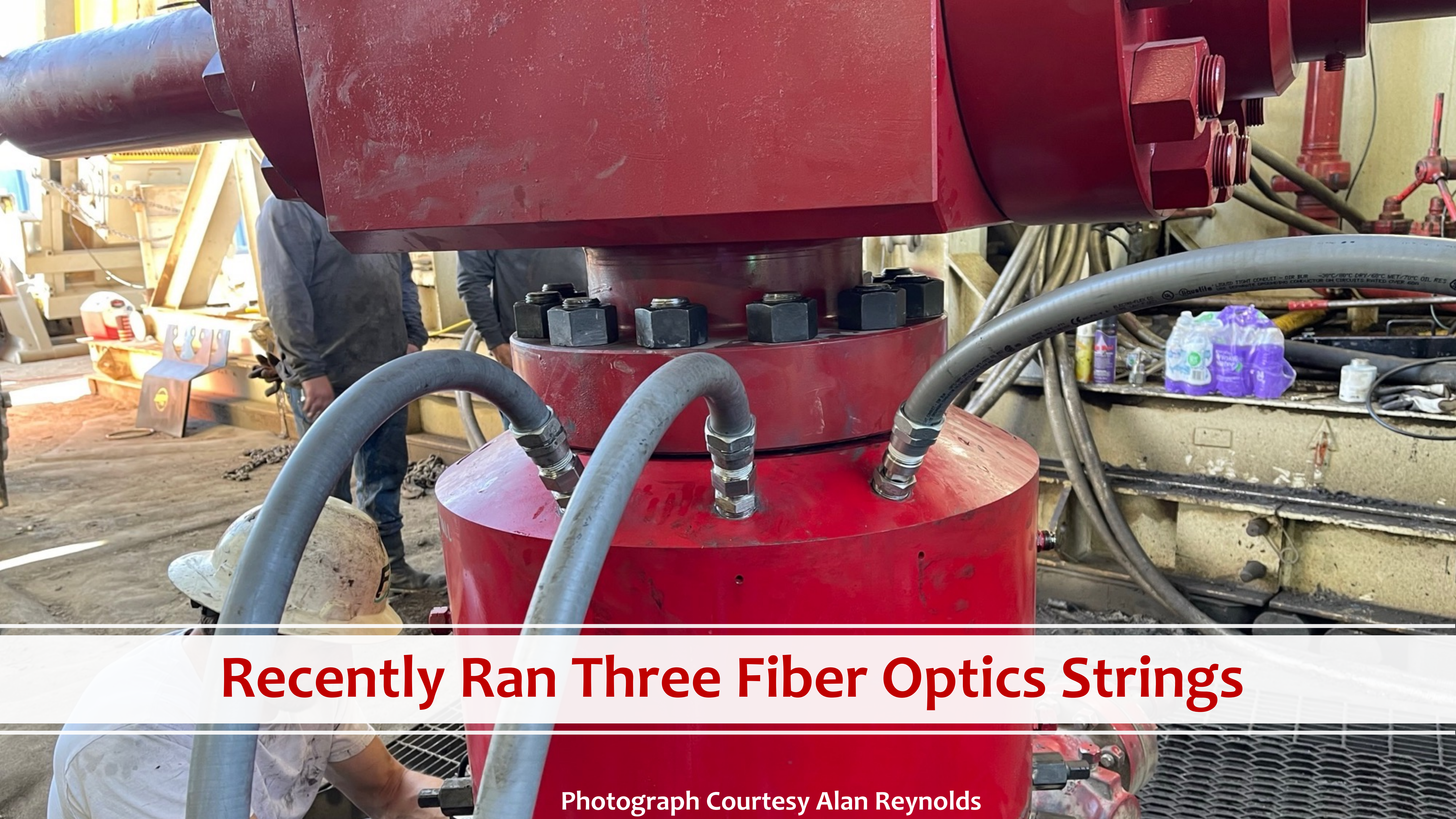
Where We Are?

- Implementation of TAMU training
- Workflow for eliminating dysfunction and limiters
- Unprecedented increases in ROP
- Evaluation of viable new technologies
- Assessment of Rotary Steerable Technologies
- Unparalleled data set measuring *in situ* properties (at bit and in BHA)
- Approximately 150 ft of new core
- Torque Control at Top Drive

Where We Need to Go?

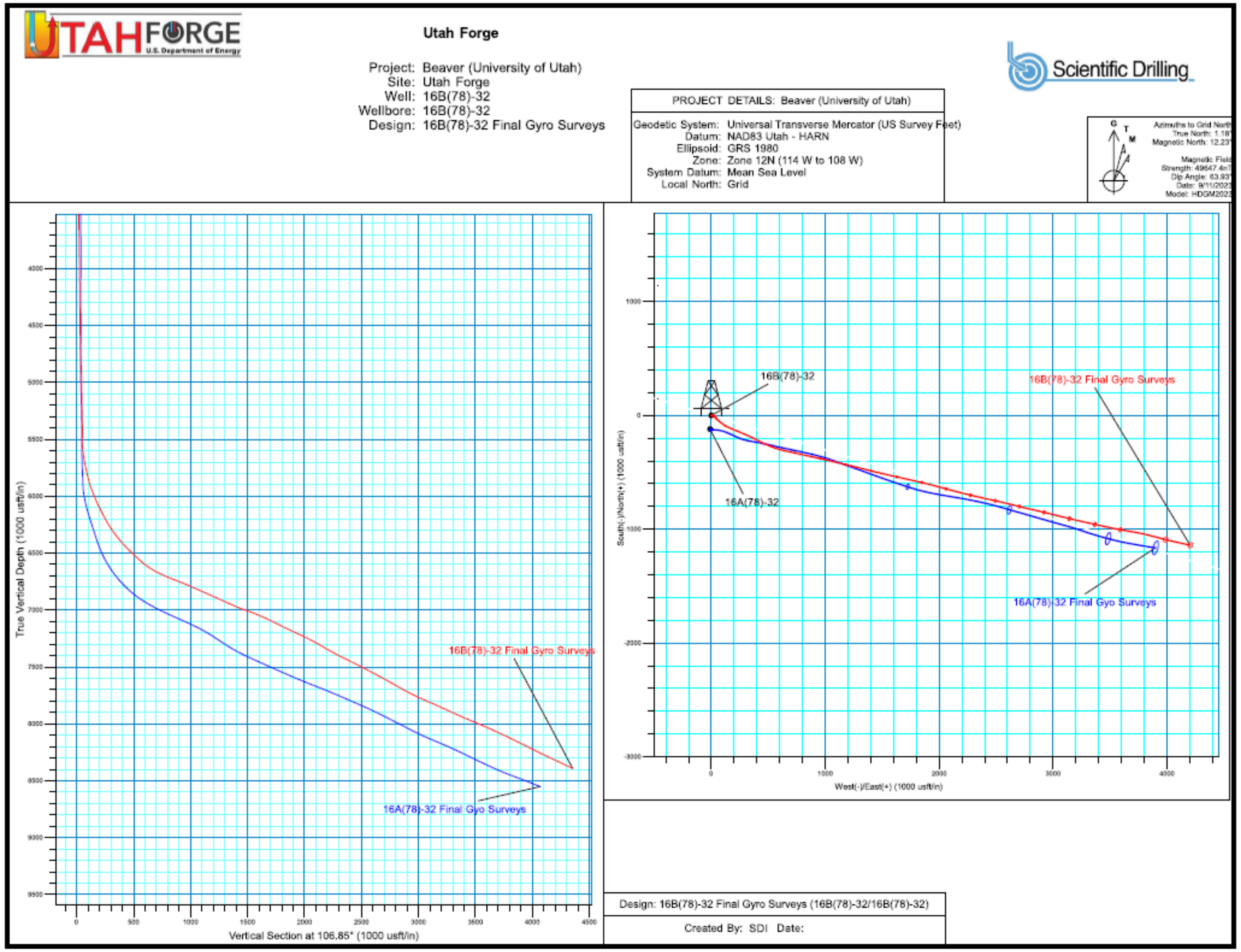
- How can learnings be applied elsewhere and modified for geologically different conditions?
- Evaluation of the data collected, particularly during the drilling of 16B(78)-32.
- Vibrations and BHA design
- Coring ROP
- Temperature tolerance of tools

Recently Ran Three Fiber Optics Strings



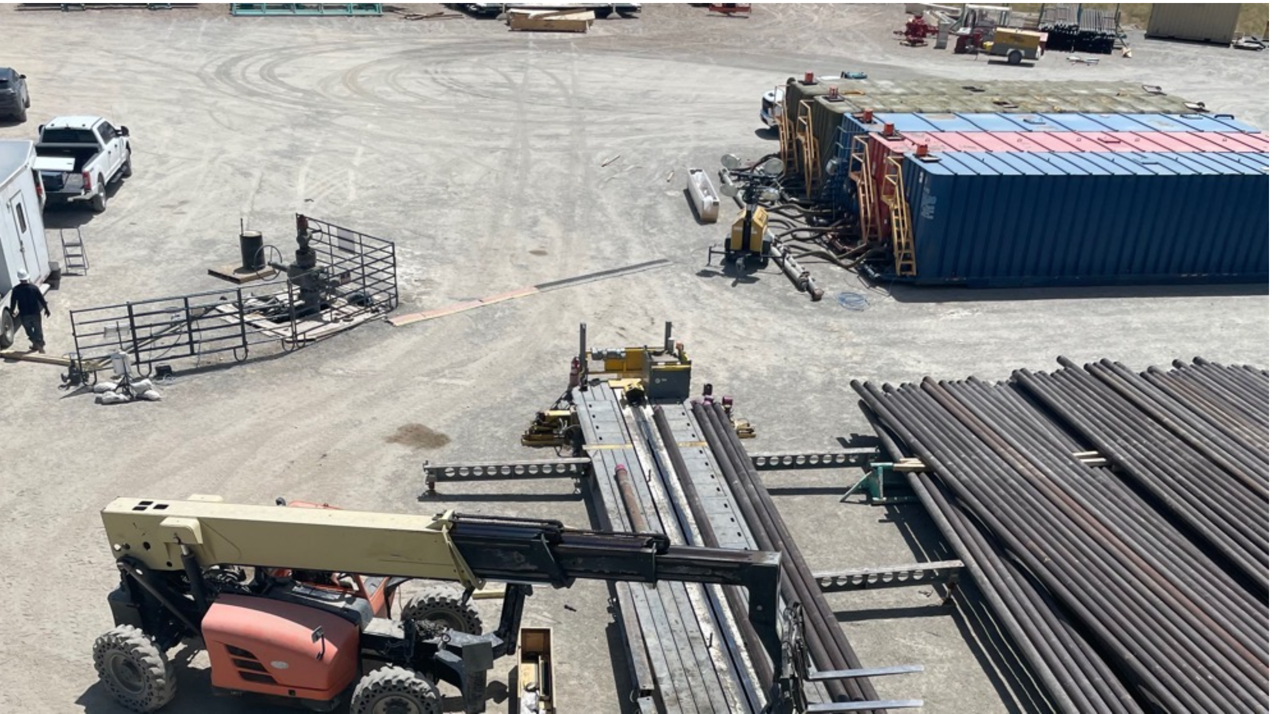
Photograph Courtesy Alan Reynolds

Three Fiber Optics Cables



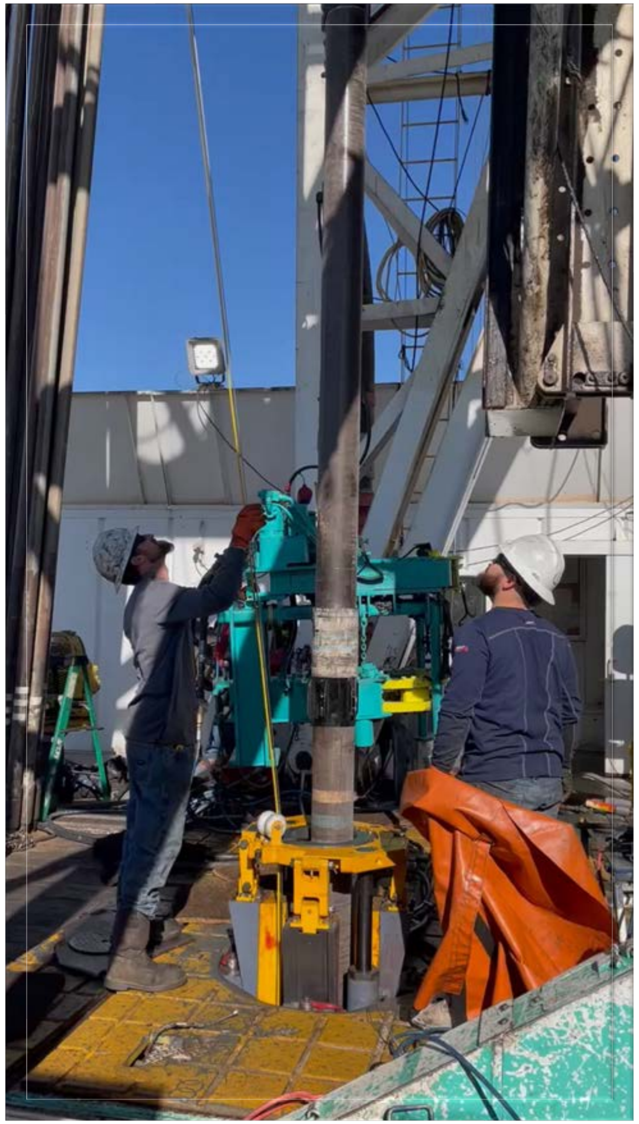


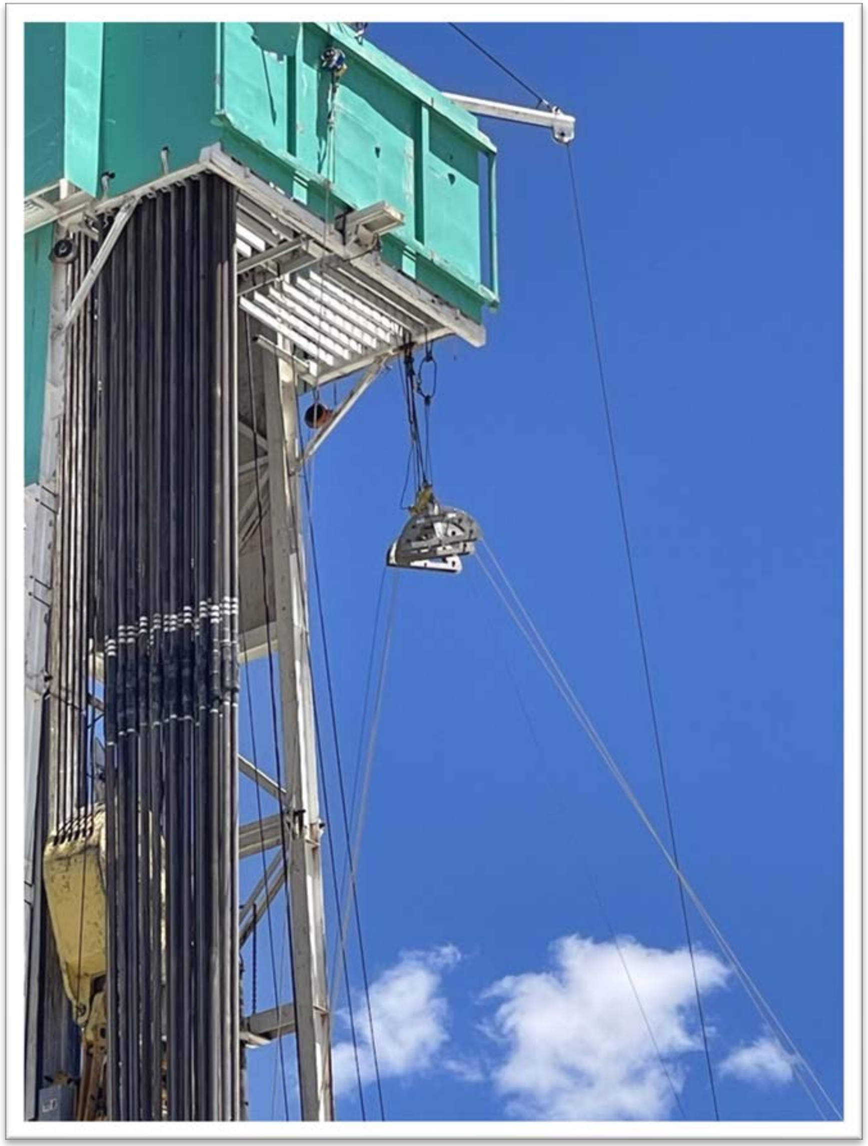


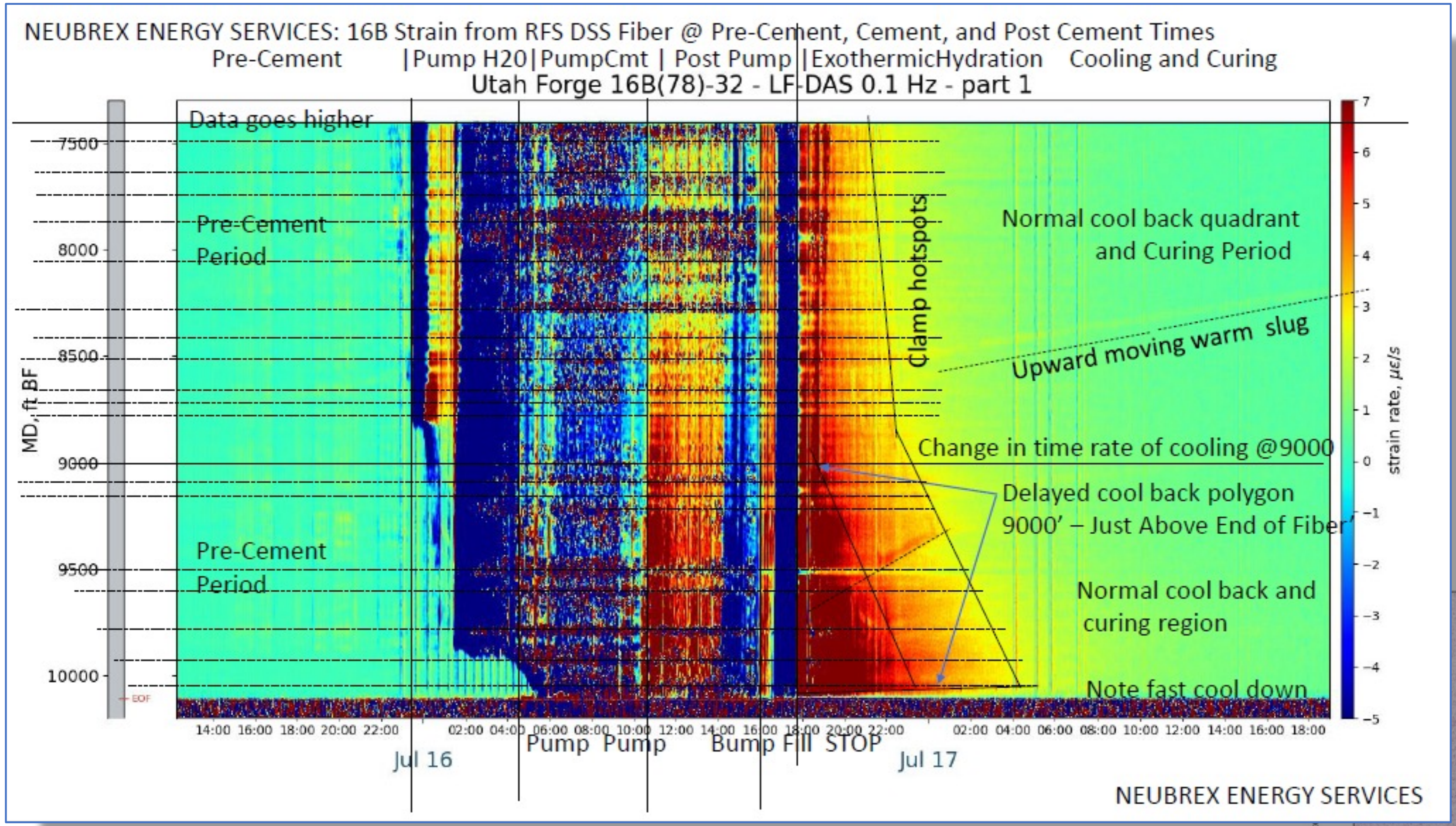


Fiber Optics Installation

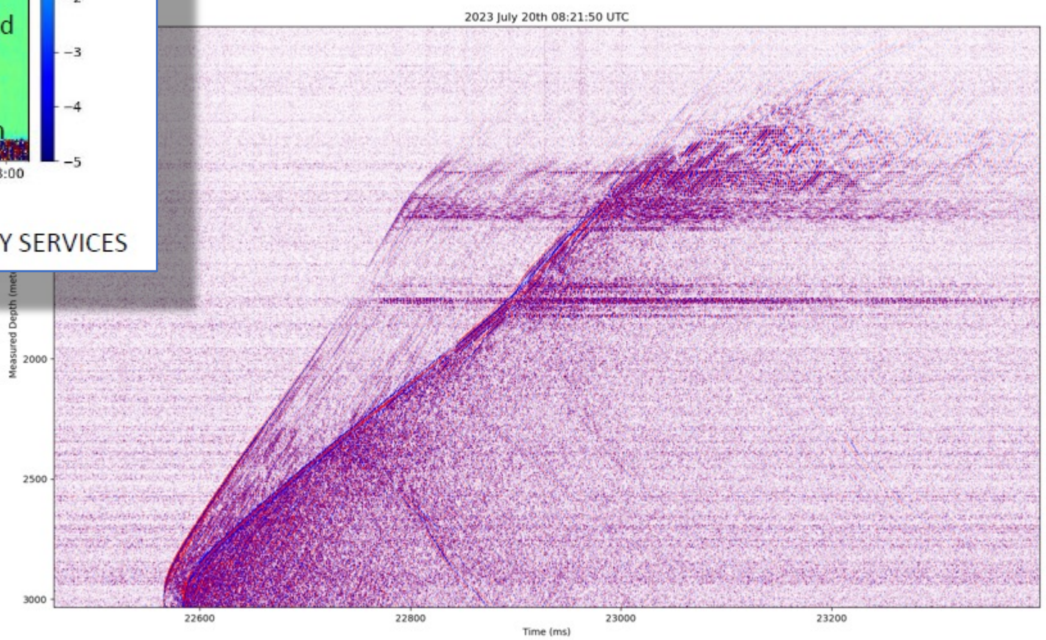
Significant Installation Protocols







Courtesy Dana Jurick Neubrex Energy Services



Courtesy Joseph Wolpert, Silixa

Status – Running Fiber Optics

Where We Are?

- Research Contracts:
  - Rice University and Silixa
  - UT Austin with Shell
- FORGE participates with Neubrex and GeoEnergie Suisse
- 78-32 has about 3500 ft of Silixa fiber
- Failed installations in 56-32 and 78B-32
- No fiber in 16A(78)-32
- Careful planning and supervision by Alan Reynolds (consultant) for 16B(78)-32 - SUCCESS

Where We Need to Go?

- Process the acquired data – from cementing and from circulation testing
- Provide guidance during next frac campaign
- TBD ….

Cementing Technology

Status – Cementing Technology

Where We Are?

- Multiple Occurrences of Issues Ranging from Flash Set to Fallback to Mixing Issues on Every Well
- Well 16B(78)-32
  - Surface - Cemented Well
  - Intermediate - Went "Perfectly" but Fell Back and Required Top Out
  - Production – Poor Mixing, Fall Back, Top Job Not Possible for Now

Where We Need to Go?

- Blending and testing to avoid flash set and fallback.
- Why can't we avoid fallback? Still uncertainty about the stress field?
- Blends for temperature
- Need for R&D

Connecting Wells … 2022 Fracs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8,559 ft TVD
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DAS
78B-32
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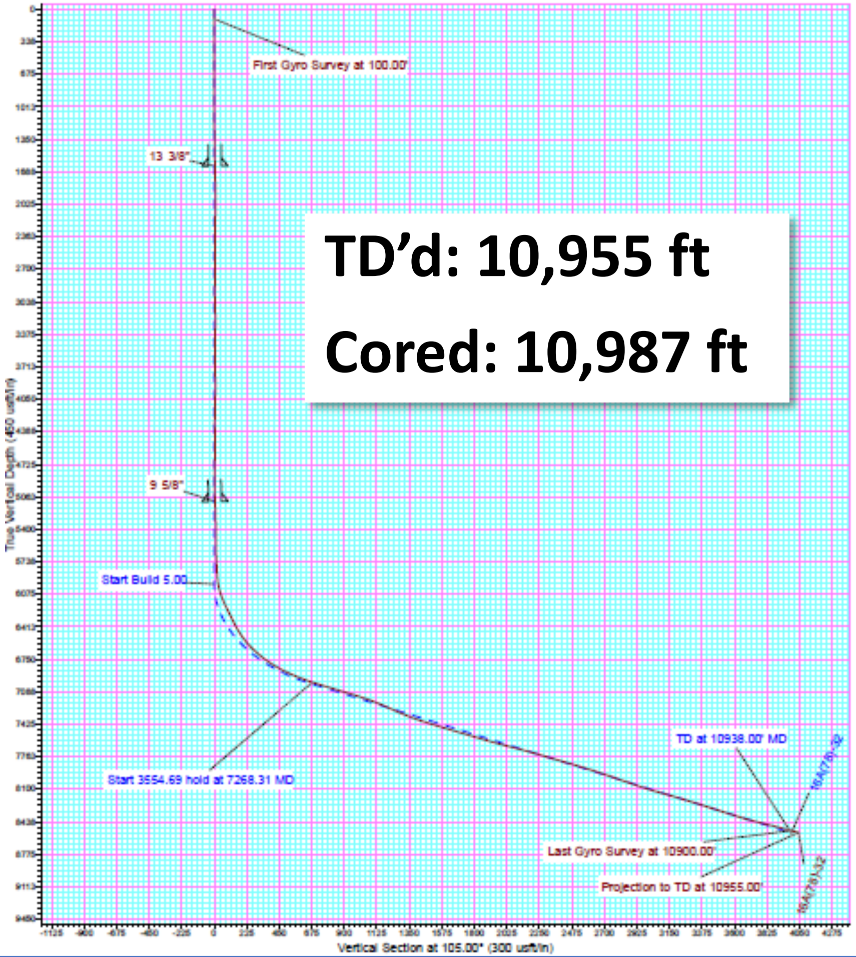
~9,500 ft MD
DAS
Monitoring Well
N

Treatments: Well 16A(78)-32

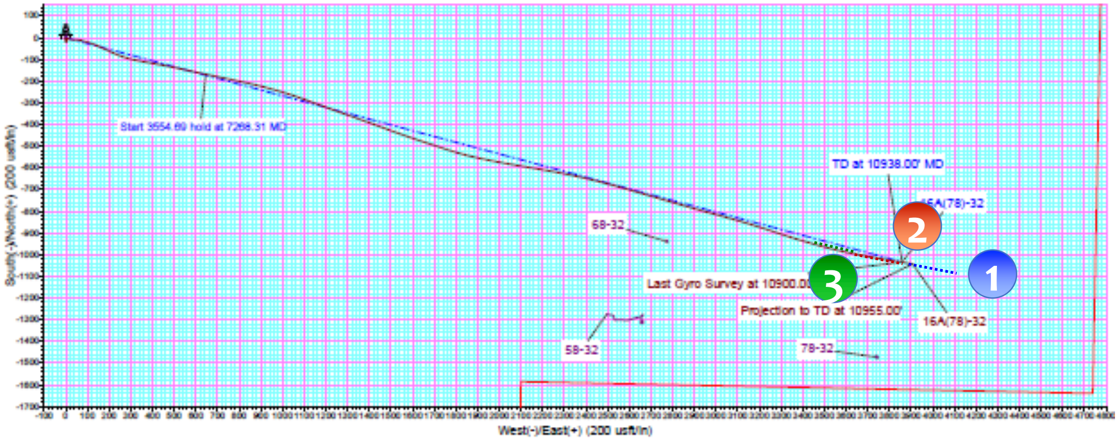
UTAH FORGE
U.S. Department of Energy

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



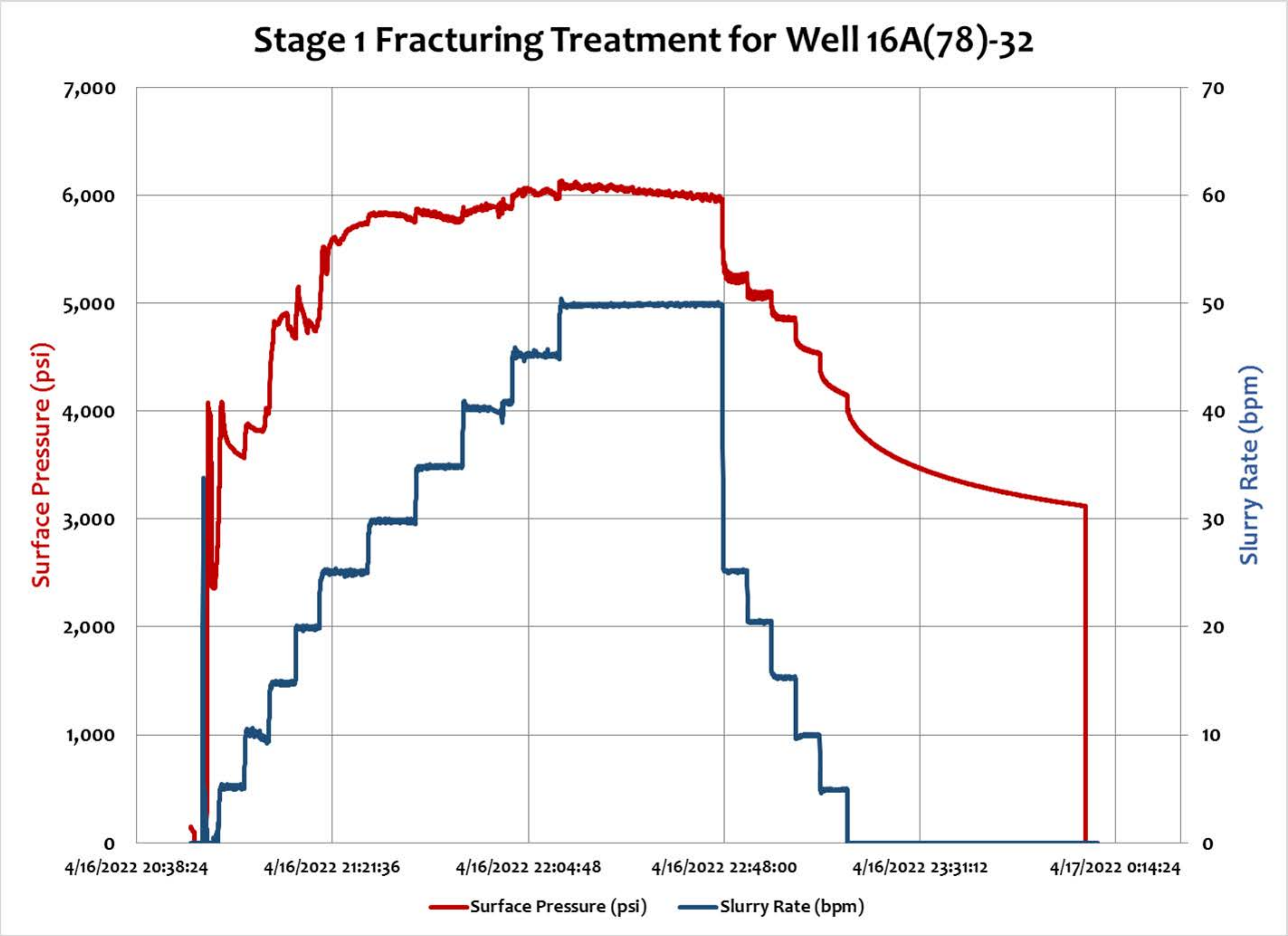
Stage 1: Openhole portion of the well below ~10,787 ft – **Slickwater, Tagged**

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

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

Pumped Stage 1

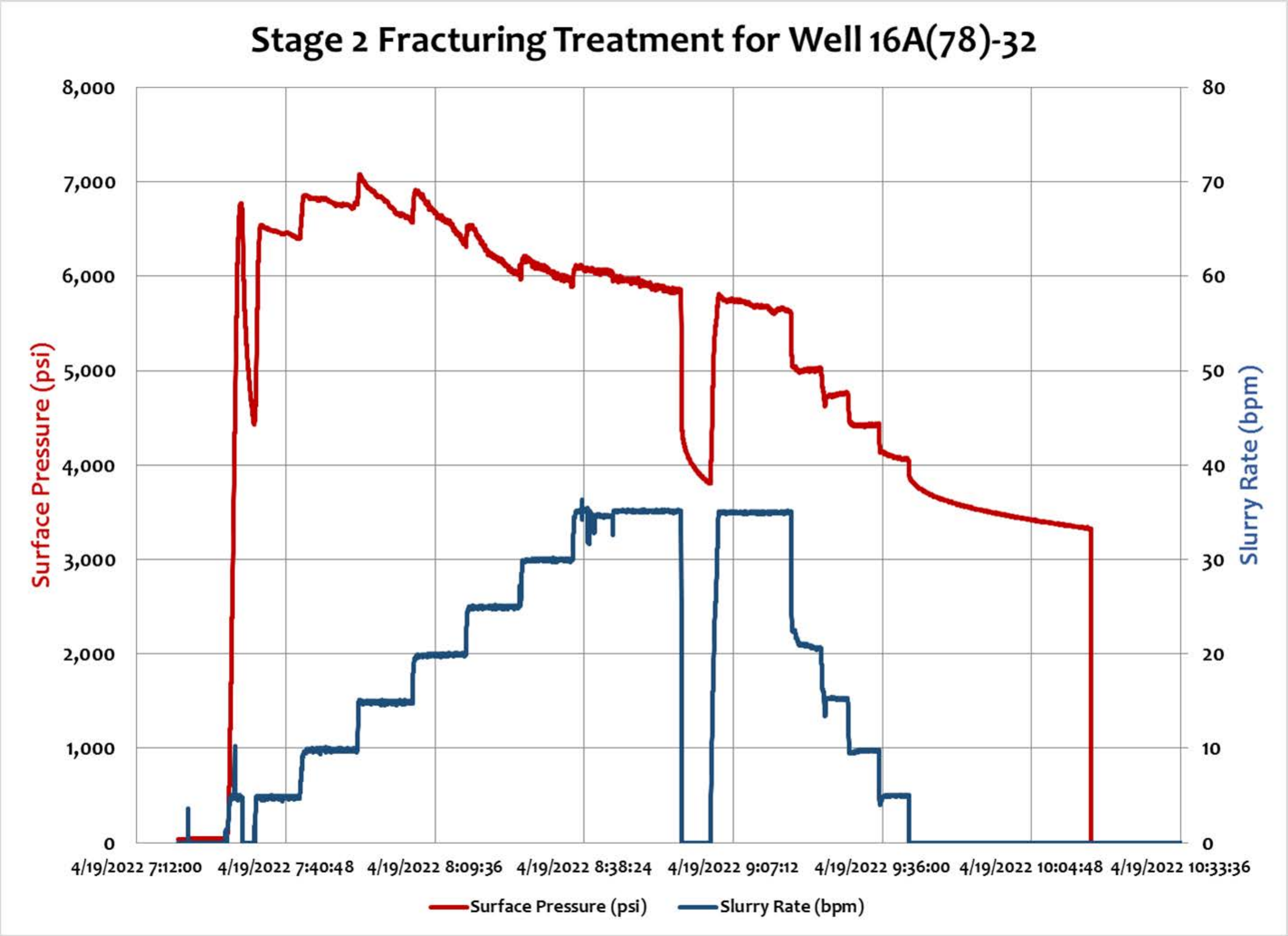
- Pumped down casing into open-hole interval below 7” casing shoe
- Reached planned injection rate of 50 bpm of slickwater
- 4,261 bbl pumped
- At EOJ, well shut in and pressure decline monitored for 4 hours
- Well flowed back for 16 hours



Stage 1 Fracturing Treatment for Well 16A(78)-32
Surface Pressure (psi)
Slurry Rate (bpm)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
70
60
50
40
30
20
10
0
4/16/2022 20:38:24
4/16/2022 21:21:36
4/16/2022 22:04:48
4/16/2022 22:48:00
4/16/2022 23:31:12
4/17/2022 0:14:24
Surface Pressure (psi)
Slurry Rate (bpm)

Stage 2 Pumped

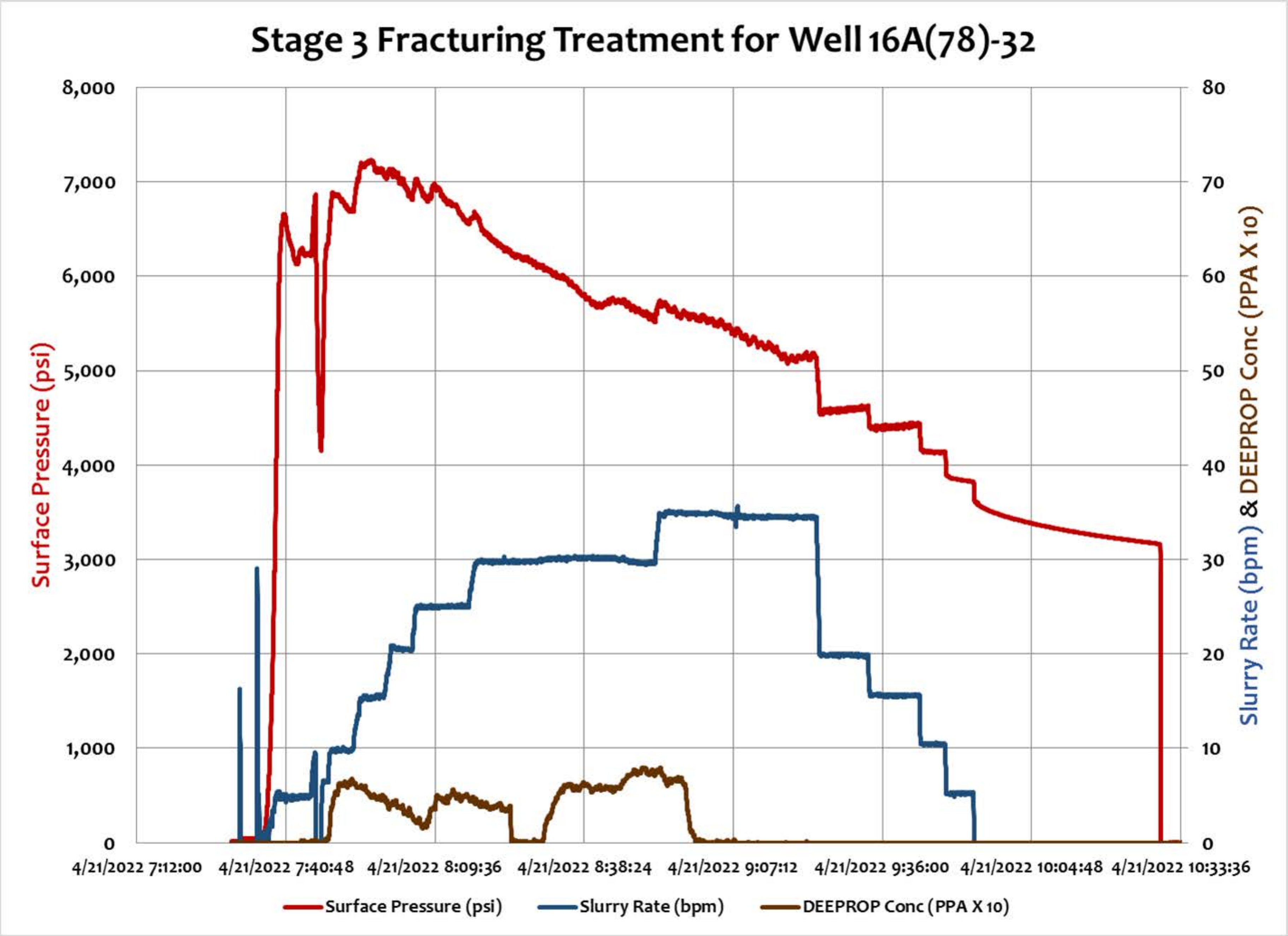
- Pumped 2,777 bbl of slickwater down casing into single perforated interval reaching 35 bpm
- Intentional hard shutdown in the initial 5 bpm stage and part way through 35-bpm stage
- At EOJ, well shut in and pressure decline monitored for 4 hours
- Well flowed back for 12 hours



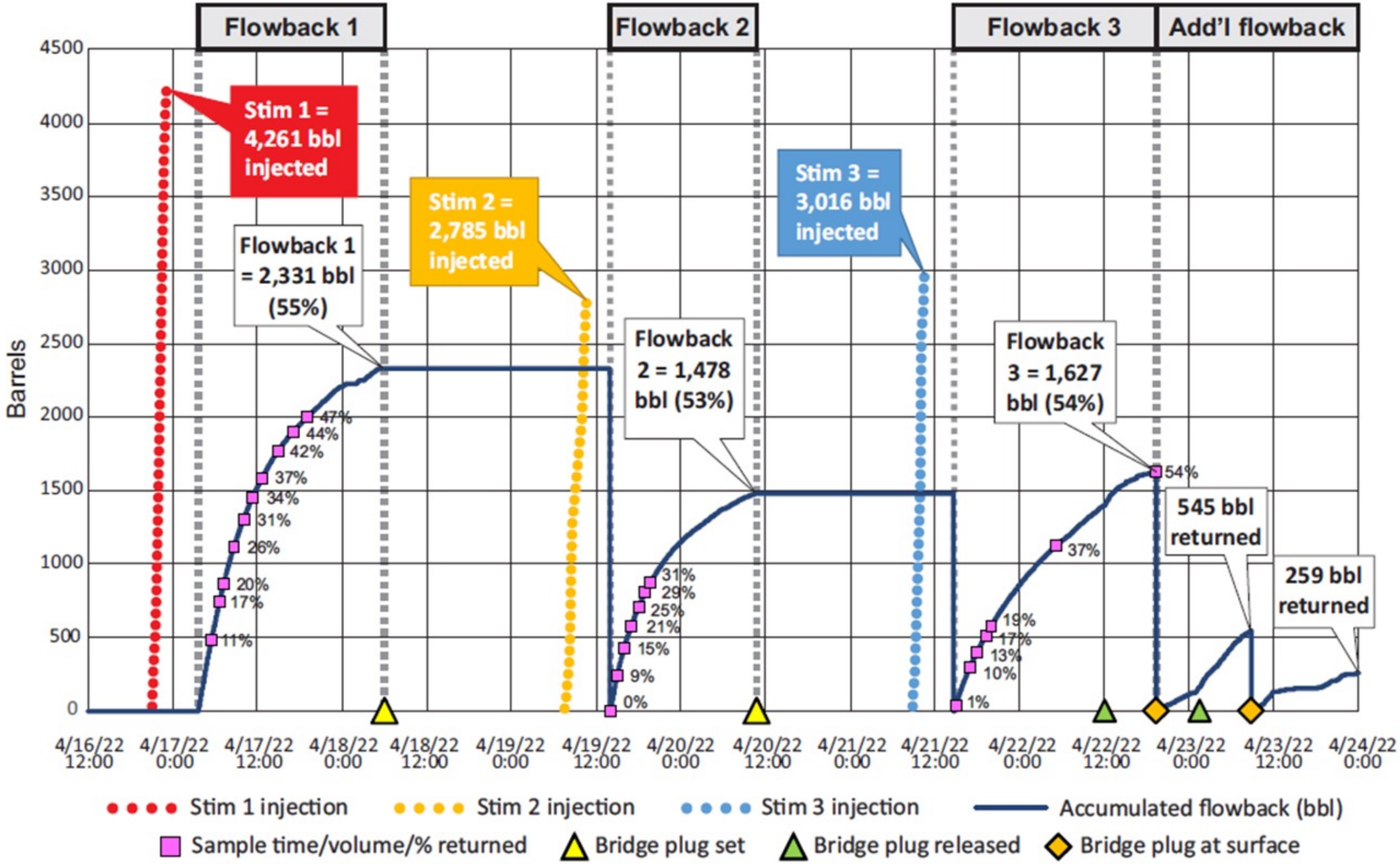
Stage 2 Fracturing Treatment for Well 16A(78)-32
Surface Pressure (psi)
Slurry Rate (bpm)
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
80
70
60
50
40
30
20
10
0
4/19/2022 7:12:00
4/19/2022 7:40:48
4/19/2022 8:09:36
4/19/2022 8:38:24
4/19/2022 9:07:12
4/19/2022 9:36:00
4/19/2022 10:04:48
4/19/2022 10:33:36
Surface Pressure (psi)
Slurry Rate (bpm)

Stage 3 Frac

- Pumped down casing through perforated interval 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)

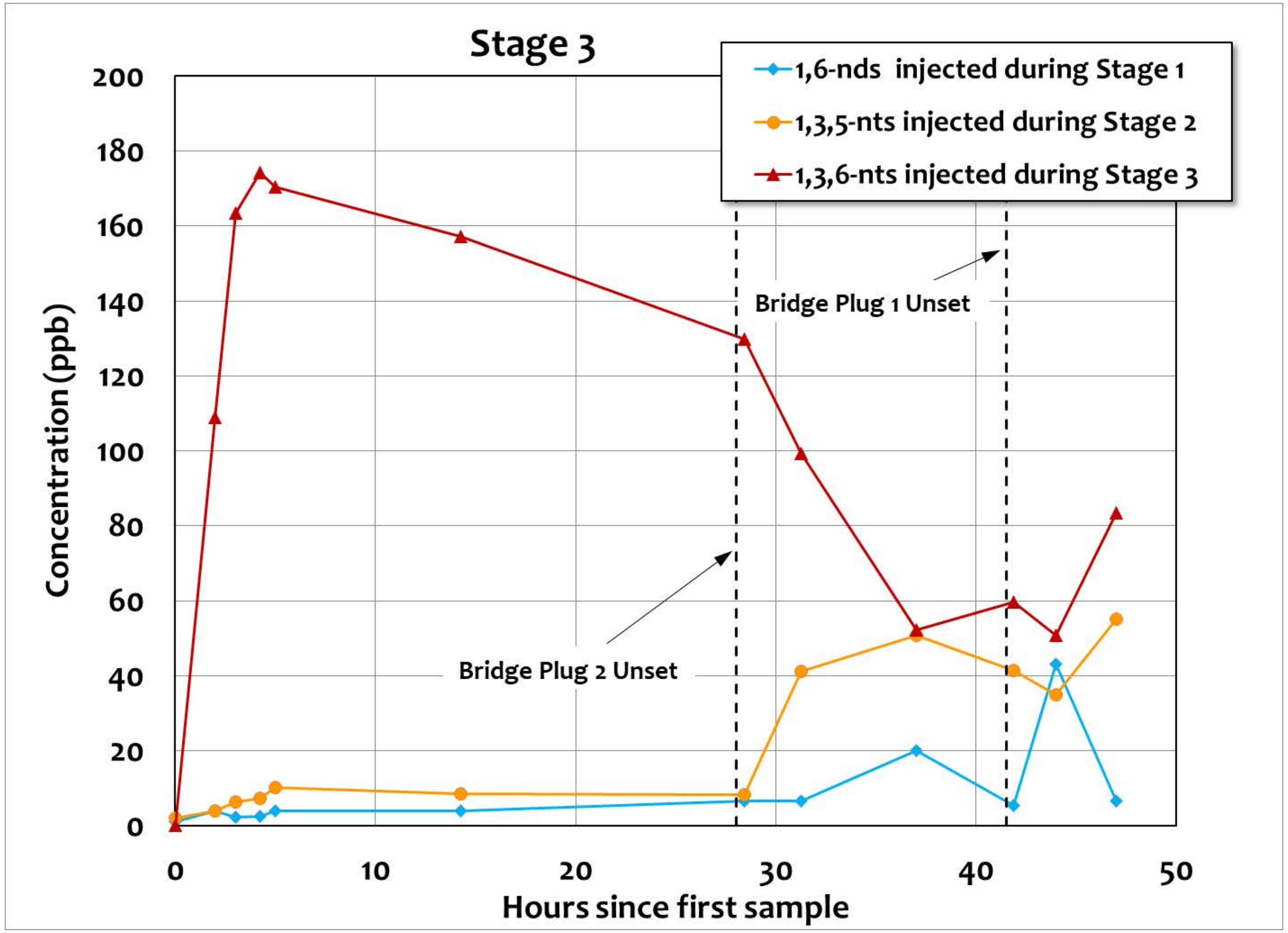

Stage 3 Fracturing Treatment for Well 16A(78)-32
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Surface Pressure (psi)
80
70
60
50
40
30
20
10
0
Slurry Rate (bpm) & DEEPROP Conc (PPA X 10)
4/21/2022 7:12:00
4/21/2022 7:40:48
4/21/2022 8:09:36
4/21/2022 8:38:24
4/21/2022 9:07:12
4/21/2022 9:36:00
4/21/2022 10:04:48
4/21/2022 10:33:36
Surface Pressure (psi)
Slurry Rate (bpm)
DEEPROP Conc (PPA X 10)

Flowback Summary



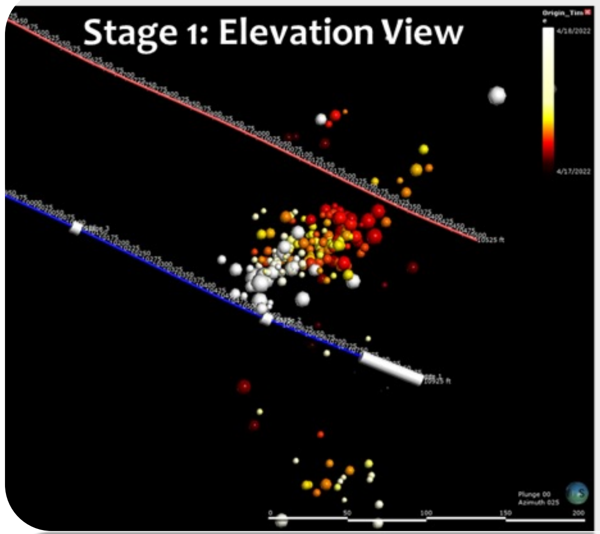
After Clay Jones

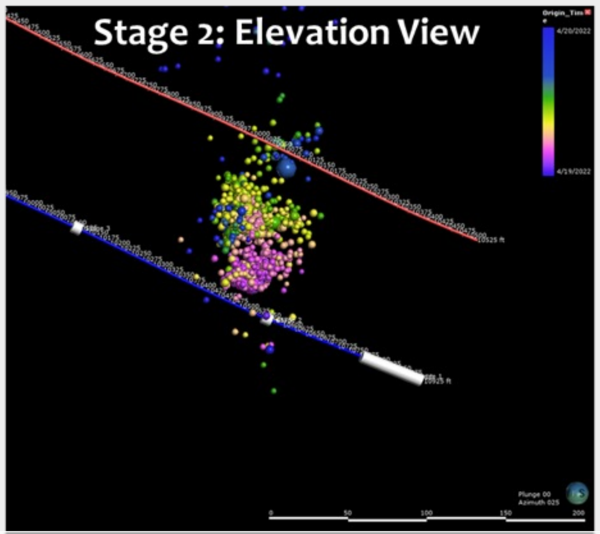
After Stage 3

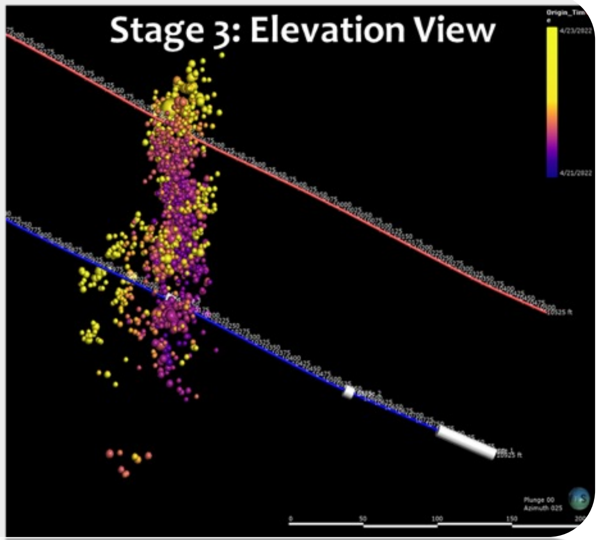


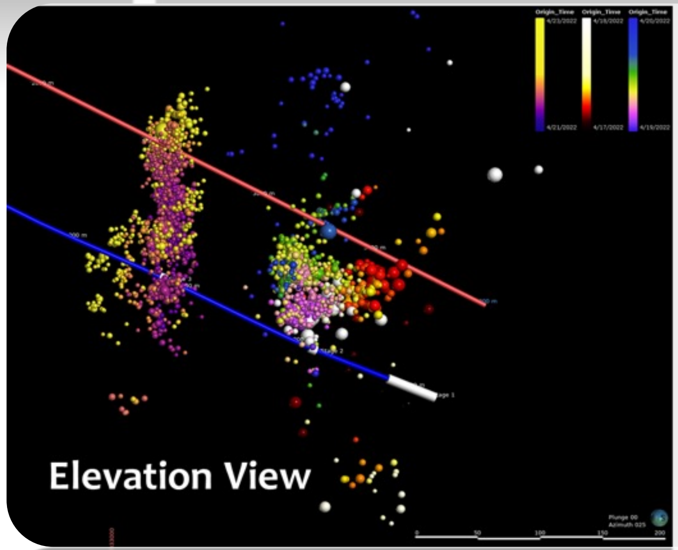
Courtesy Peter Rose

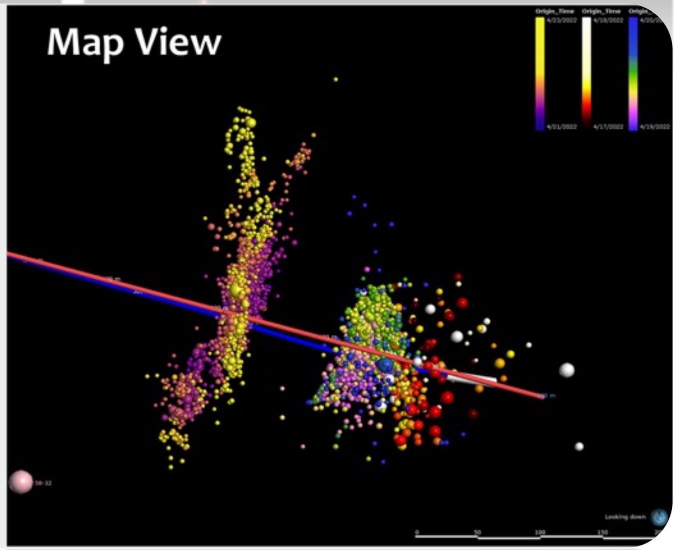
Treatment Extent Bracketed by Microseismicity











Courtesy GeoEnergie Suisse

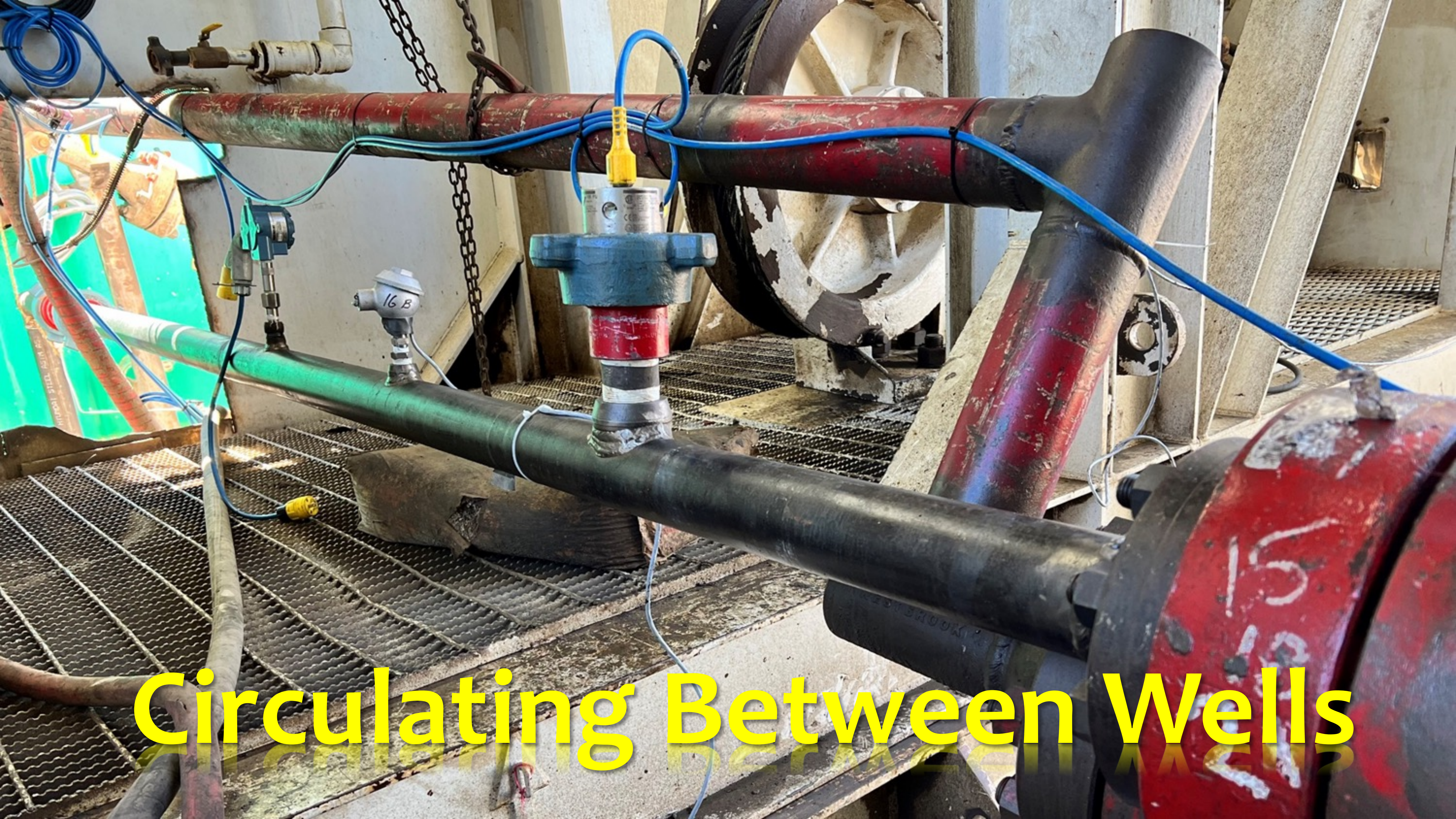
Status – Stimulation Technology

Where We Are?

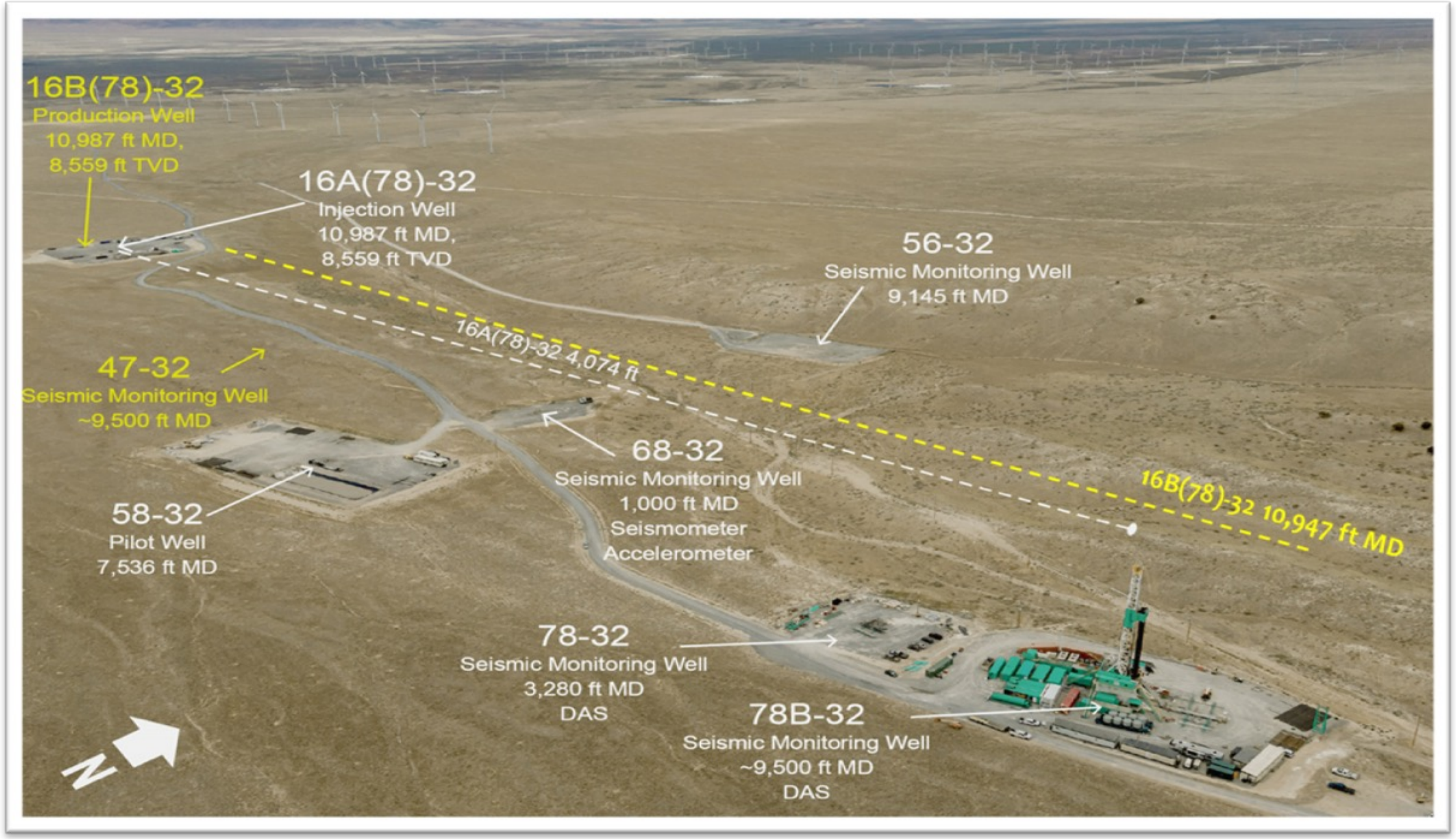
- Rig required to enable firing perforating guns and to set bridge plugs
- No proppant
- Microseismic cloud suggests adequate height growth for connection with 16B(78)-32
- Some apparent morphologic differences depending on fluid selected
- Near-well tortuosity?

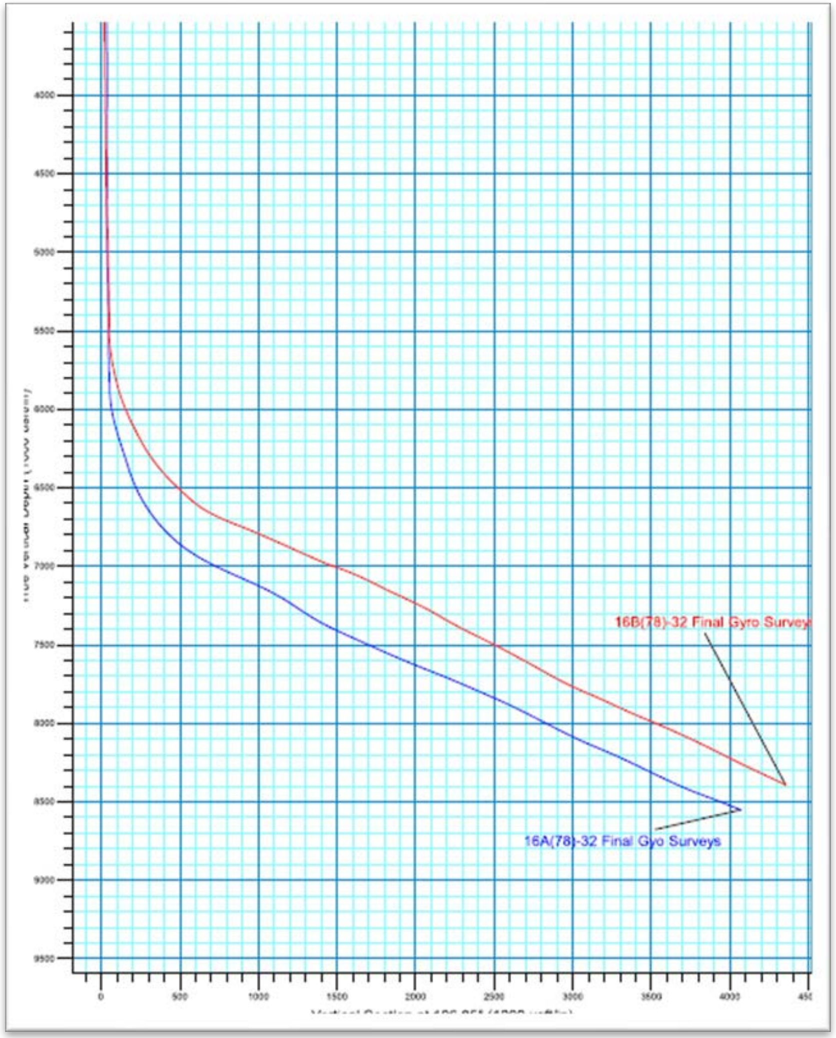
Where We Need to Go?

- Planning the next round of fracs uphole from these three
- DOE (Design of Experiments) proposed by Fervo and UT Austin as part of their R&D commitments
- Variables include stage volumes, fluid selected, number of clusters, proppant program, isolation devices, going rigless, injection into Well 16B(78)-32
- Looking to treat early in 2024


Circulating Between Wells
16 B
15

Interactions with Well 16B(78)-32





Connectivity – Conductivity – Conformance - Circulation

Status – Circulation – Connectivity, Conductivity

Where We Are?

Spoiler Alert

- There is connection

Where We Need to Go?

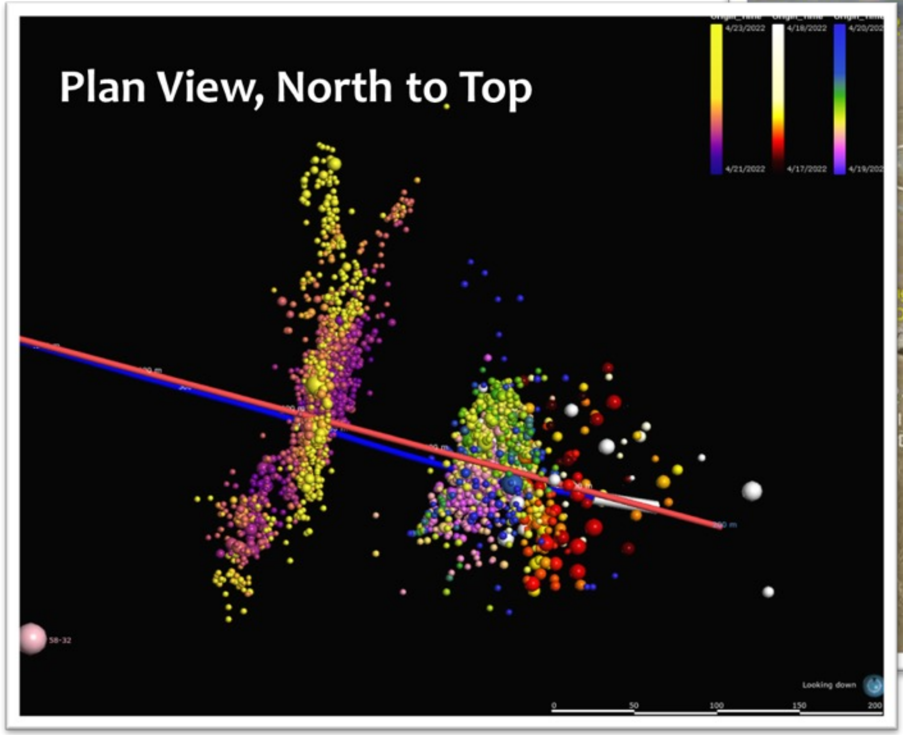
Spoiler Alert

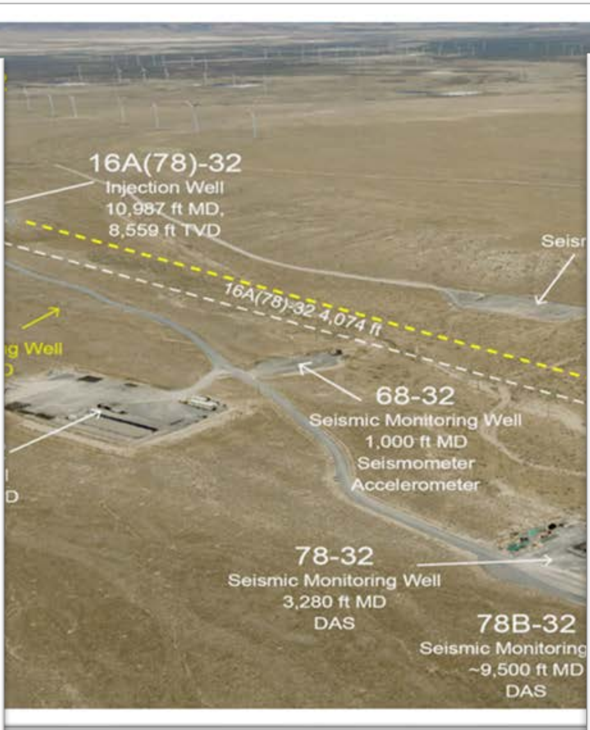
- Connection Not Commercial Quality
- Refrac as part of 2024 campaign
- New stages
- Log fibers and treat production well
- Planning longer term circulation for after next round of hydraulic fracturing


Where Are We Going?
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
56-32
Seismic Monitoring Well
9,145 ft MD
16A(78)-32 4,074 ft
47-32
Seismic Monitoring Well
~9,500 ft MD
68-32
Seismic Monitoring Well
1,000 ft MD
Seismometer
Accelerometer
58-32
Pilot Well
7,536 ft MD
16B(78)-32 10,947 ft MD
78-32
Seismic Monitoring Well
3,280 ft MD
DAS
78B-32
Seismic Monitoring Well
~9,500 ft MD
DAS
N

Utah FORGE - DOE's Frontier Observatory for Research in Geothermal Energy

Field laboratory for developing, testing, and prototyping technologies that could be adopted for commercializing Enhanced Geothermal Systems (EGS)

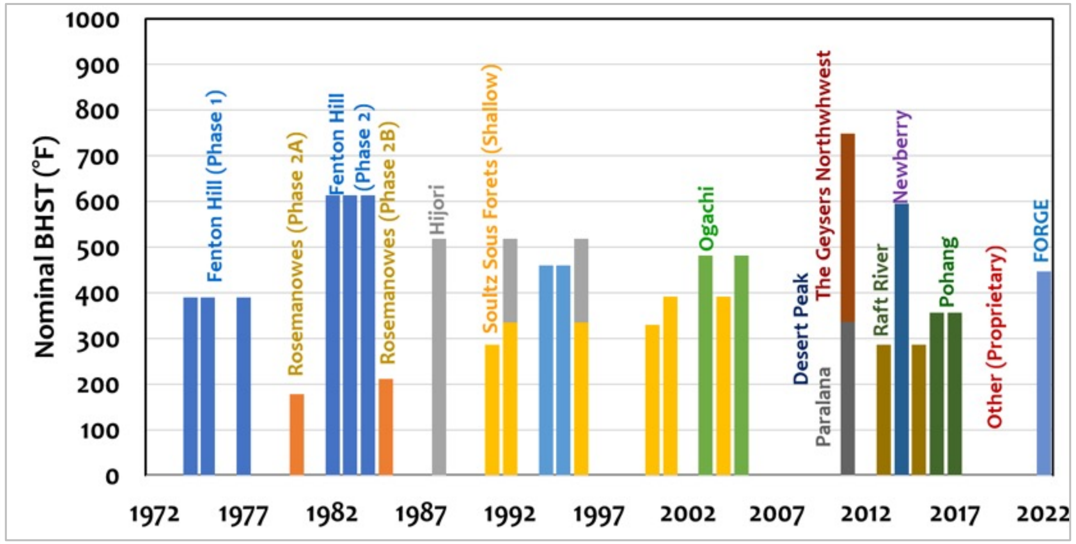


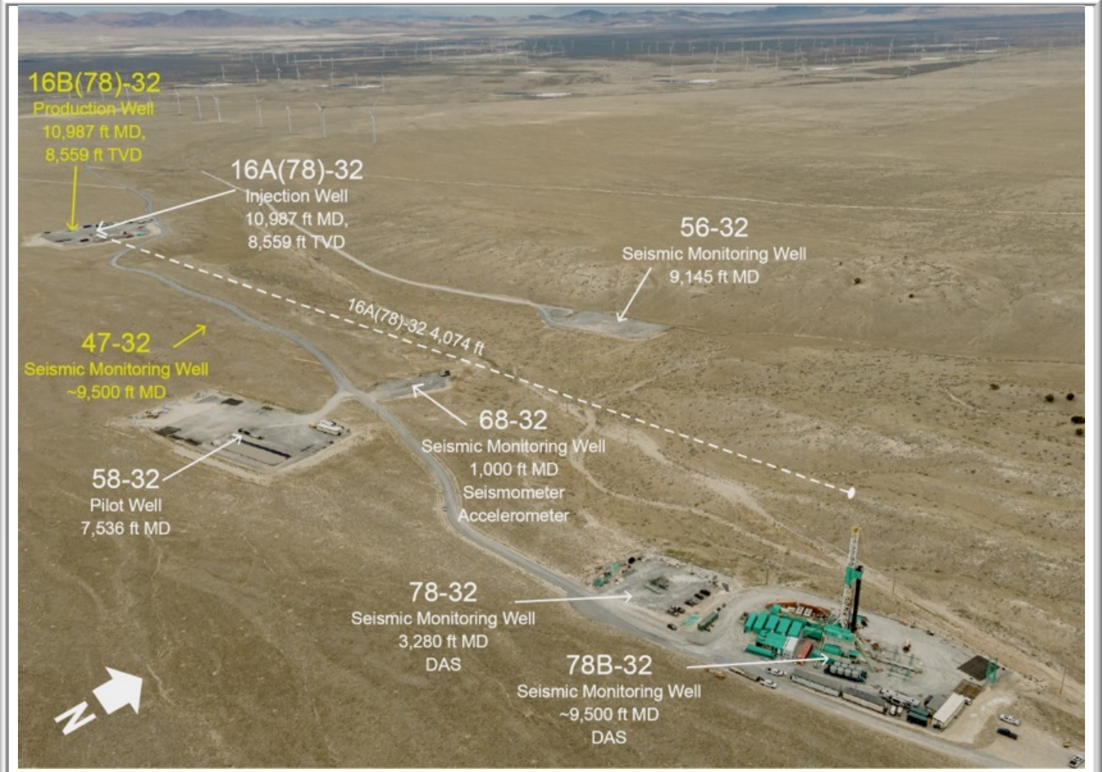


UTAH FORGE
U.S. Department of Energy

EGI Energy & Geoscience Institute
... the science to find energy
Since 1972

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





UTAH FORGE
U.S. Department of Energy

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