Utah FORGE
Distributed Fiber Optic Sensing

Introduction and Overview of Results

Acquisition Dates: June 2023 – August 2024

Neubrex Energy Services (US), LLC

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Last update: September 16, 2024

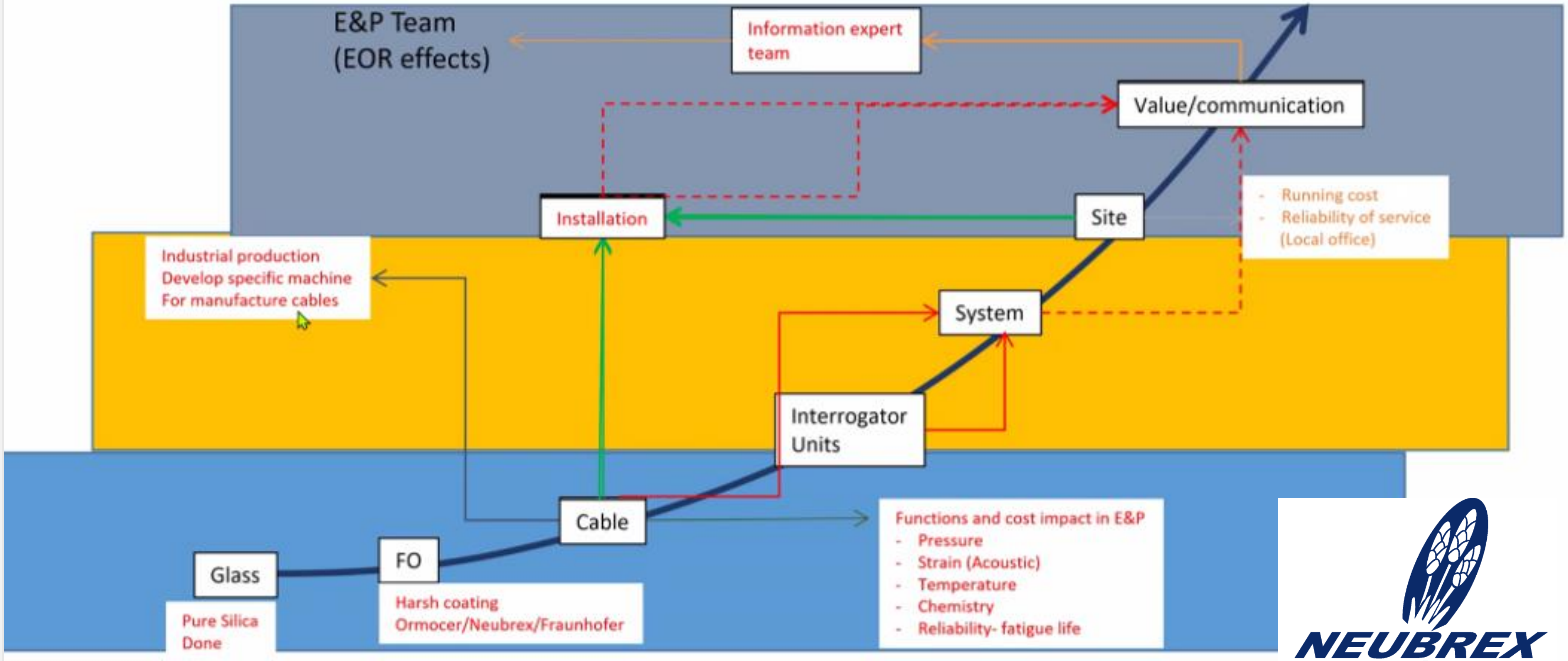
Acknowledgements

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”.

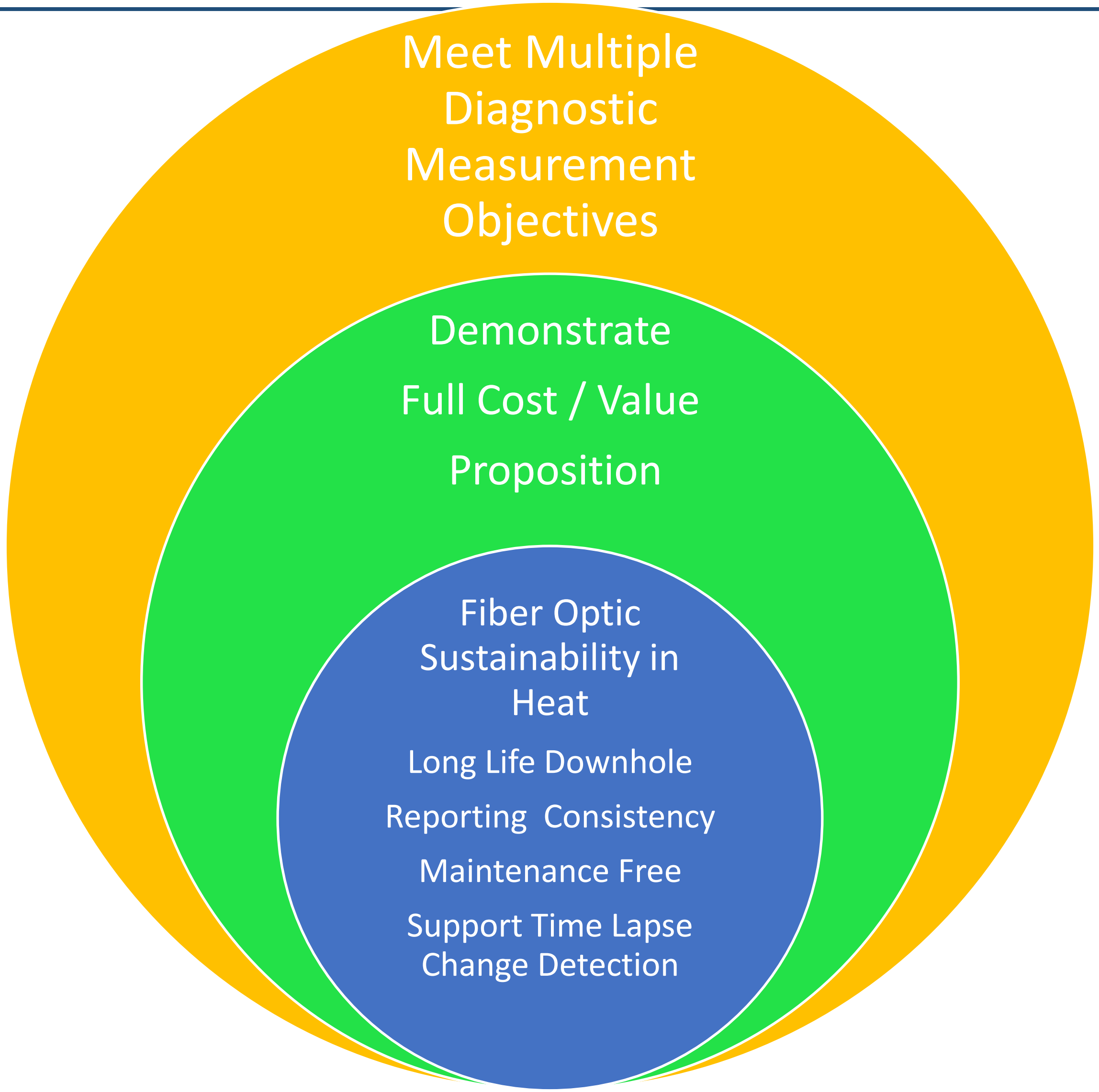
We thank the many stakeholders who are supporting this project, including Smithfield, Utah School and Institutional Trust Lands Administration, and Beaver County as well as the Utah Governor’s Office of Energy Development and Utah’s Congressional Delegation.

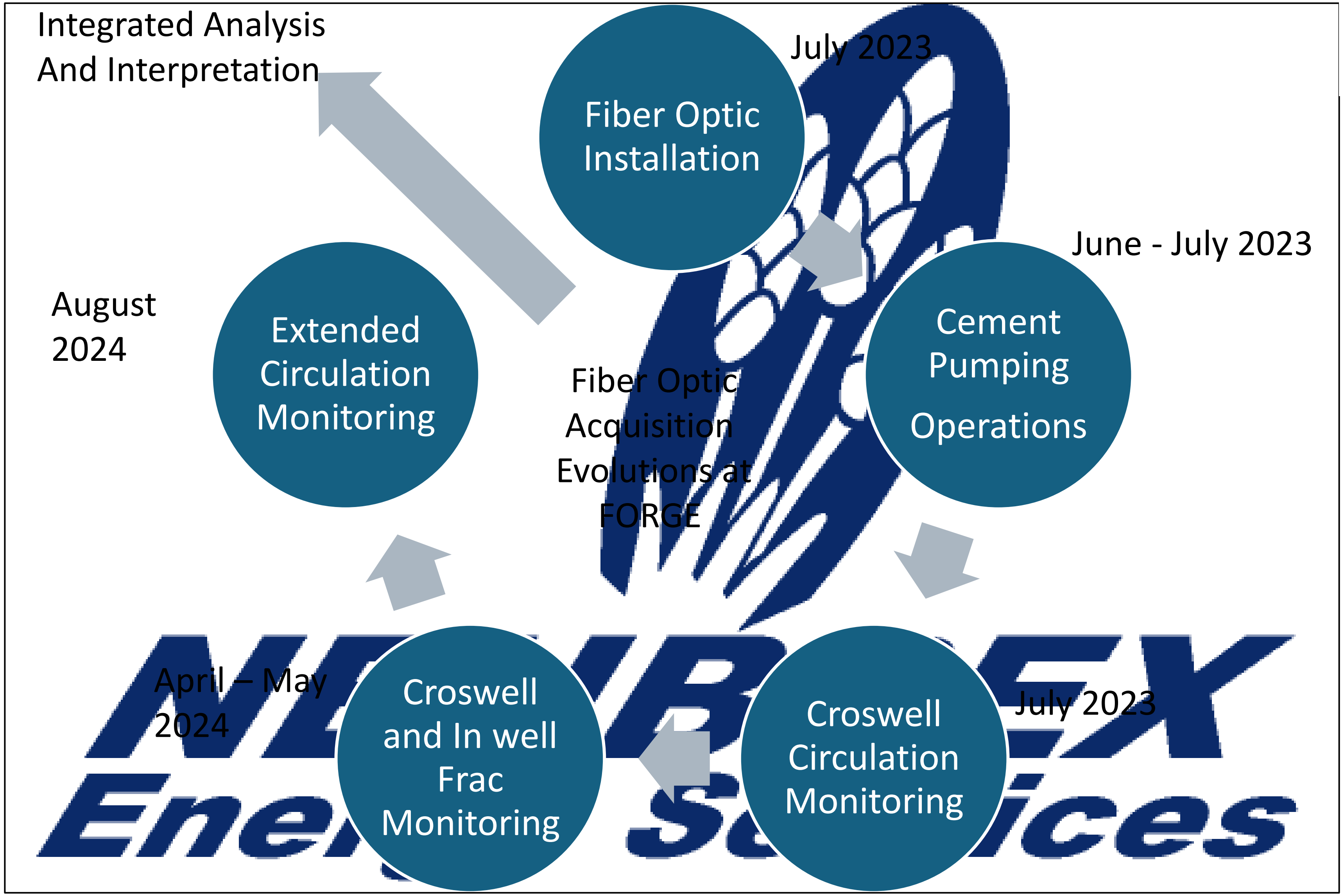
During field operations, Neubrex worked with many operational experts and received critical assistance from many people, including John McLennan, Joseph Moore, Kevin England, Leroy Swearingen, Alan Reynolds, Garth Larson, Monty Keown, Dr. Mukul Sharma, Ben Dyer, Dr. Peter Meier, Dimitrious Karvounis, Wayne Fishback. The frac, drilling, water management crews and HSE managers were instrumental in getting the surface and downhole work accomplished in a safe and effective manner.

Neubrex Fiber Optics Technology Development Since 2001

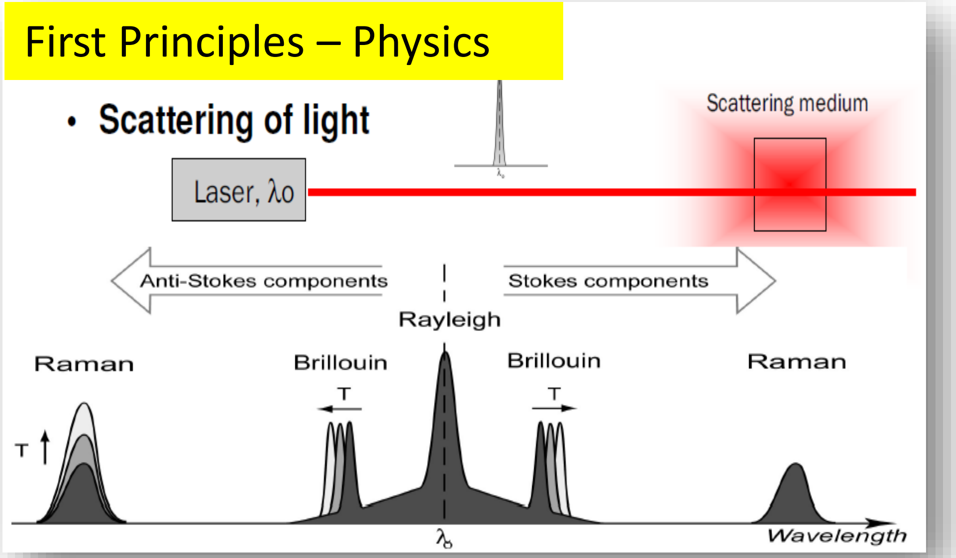


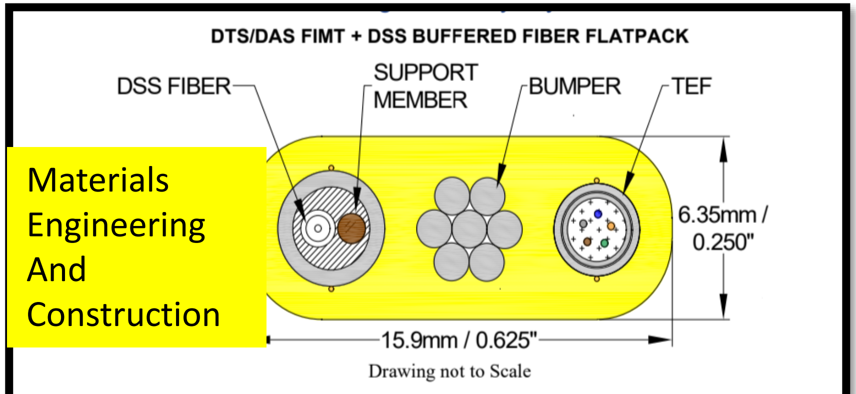
Utah FORGE Fiber Optic Diagnostic Drivers – Value - Objectives




Fiber Optic Acquisition Evolutions at FORGE
Fiber Optic Installation
July 2023
Cement Pumping Operations
June - July 2023
Croswell Circulation Monitoring
July 2023
Croswell and In well Frac Monitoring
April – May 2024
Extended Circulation Monitoring
August 2024
Integrated Analysis And Interpretation

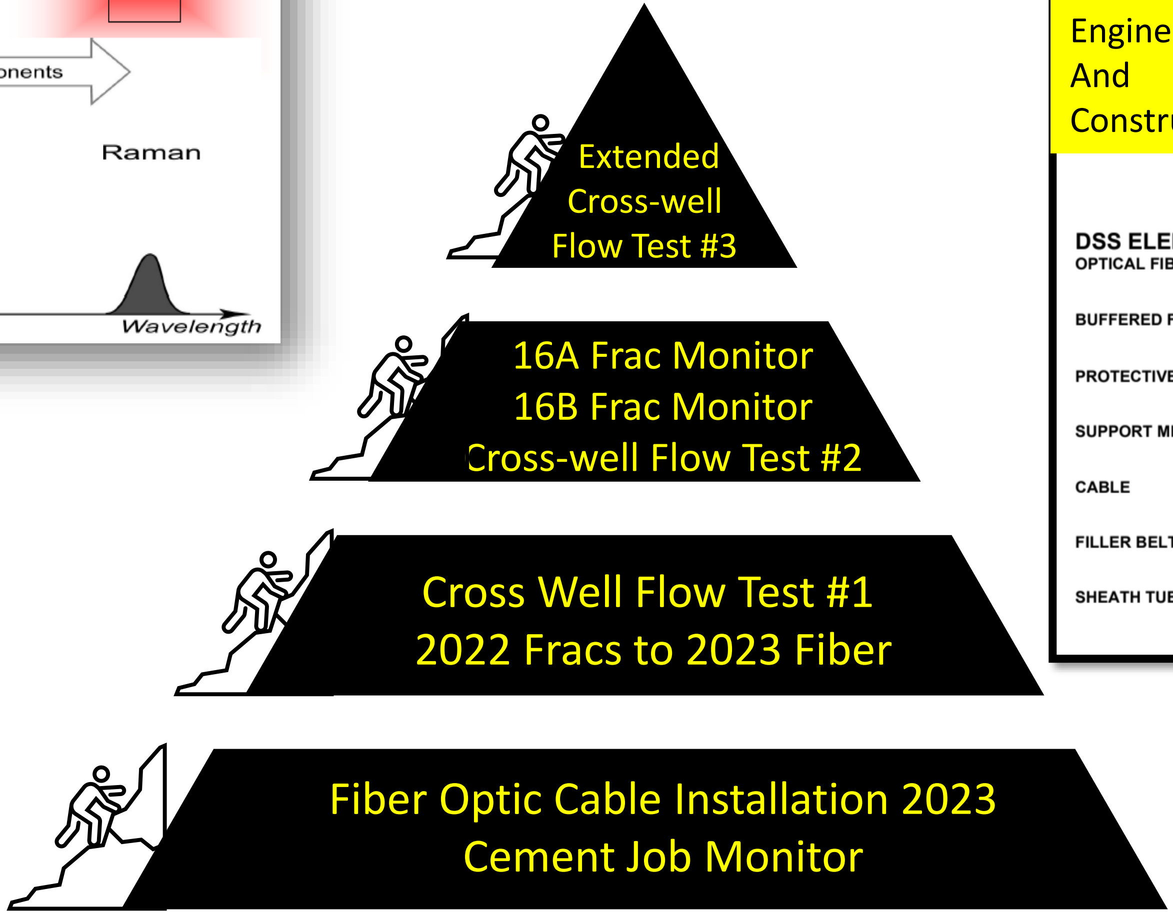
Distributed Fiber Optic Sensing Applications at FORGE





DSS ELEMENT

OPTICAL FIBER (#1)	Fibercore SM1250 CHTDA Single Mode Fiber; Colored white Bare Fiber OD: 245µm ± 15µm
BUFFERED FIBER	White Polyester Elastomer (Hytrel™) O.D.: 900µm +/- 50µm
PROTECTIVE COATING	Clear Polypropylene O.D.: 1.3mm (0.051") Nominal
SUPPORT MEMBER	18AWG Solid Bare Conductor O.D.: 1.04mm (0.041") Nominal
CABLE	DSS Fiber assembly and support member shall be pulled in together in parallel under the filler belt.
FILLER BELT	Round Polypropylene O.D.: 2.79 mm (0.110") Nominal
SHEATH TUBE	825 Alloy Sheath Tube Wall Thickness: 0.56 mm (0.022") Nominal O.D.: 4.0 mm (0.157") Nominal



Summary

The Big Idea

- ✓ Fiber provides scalable diagnostics
- ✓ At economic cost / value proposition
- ✓ Long term reliability system architect
- ✓ Leverage evolving surface tool fiber

Details of what can be measured

$\Delta P / \Delta t$

$\Delta T / \Delta t$

Δepsilon (strain) / Δt

Δseismic attributes / Δt

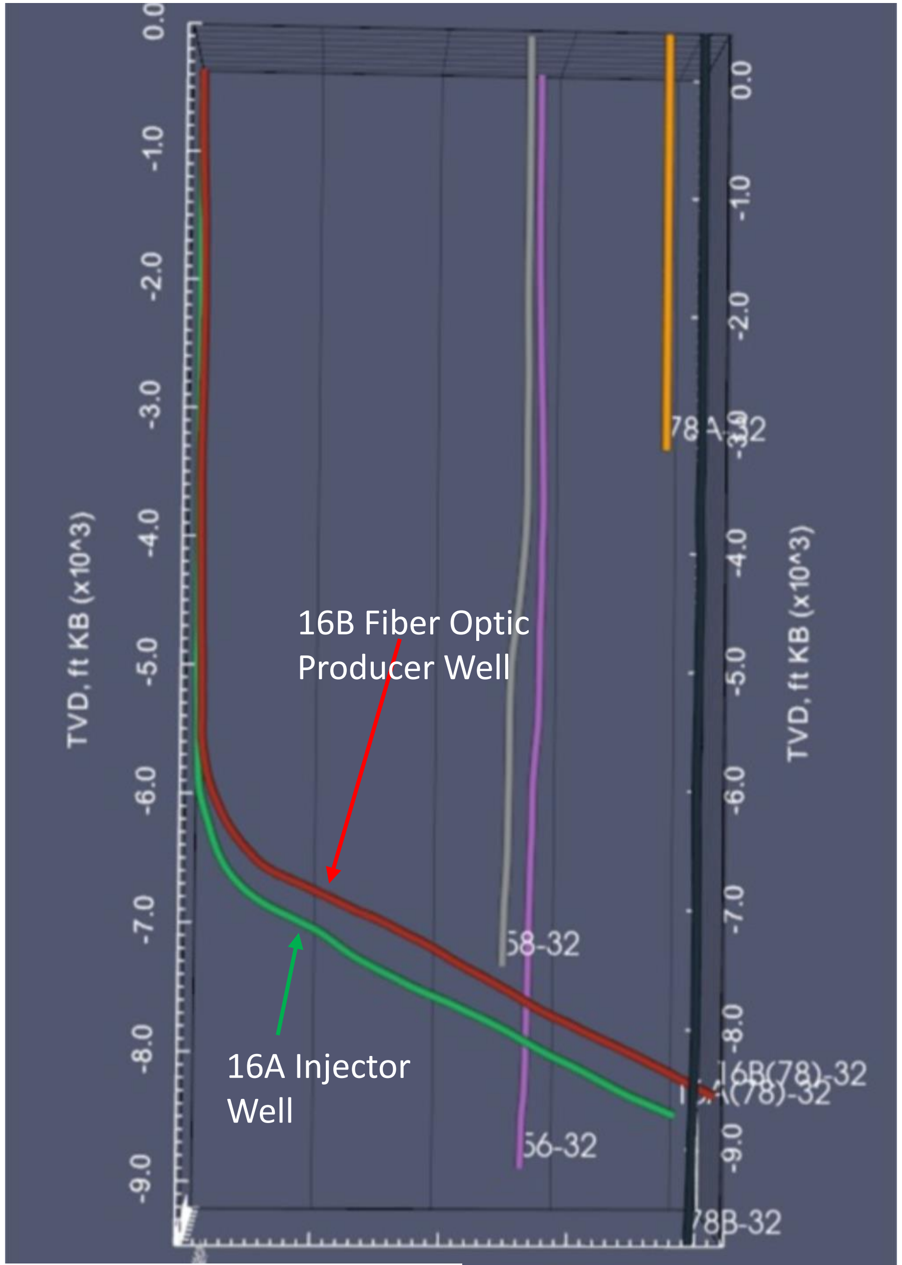
Δinduced seismicity / Δt and Δspace

Key Take Aways

- ➢ Fiber Optics has been a Versatile Tool
- ➢ Relate Diagnostics to Long Cycle Needs
- ➢ Multi-functional design team needed
- ➢ Success requires full cycle planning

Evidence

- ➢ Proven technology for EGS Diagnostics
- ➢ Fiber optics levered from O& G exper
- ➢ FORGE provides critical use case evidence
- ➢ Engineering and Optical Physics mesh



- Utah FORGE Enhanced Geothermal Setting.
- Fiber Optic Cable installed in well 16B(78)-32.

- Fiber installed "behind pipe" and cemented in place.
- Cable contains 2 x Single Mode Fiber & 1 x Multi Mode Fiber.

- Fiber optics "strands" inside the cable are the sensor.
- The fibers response to Strain, Temperature, Vibrations changes.

- Interrogator Units are connected to the fibers at the surface.
- These units "pump" controlled laser pulses or chirps of optical light down the different fibers.

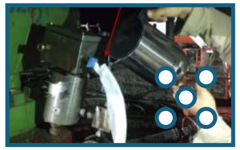
- As the light is transmitted down the fibers, some of it is back scattered up the cable and the optical receiver in the Interrogator Unit senses the backscatter.
- The backscattered energy on the optical receiver plate is digitized, processed and recorded onto mass storage media.

- Based on known optical physics relationships, these measurands are converted to strain, temperature and acoustic vibration strain rate data and further processing and analysis produces information.

16B
Fiber Optic Cable + Fiber Optic Gauge

Well Installation

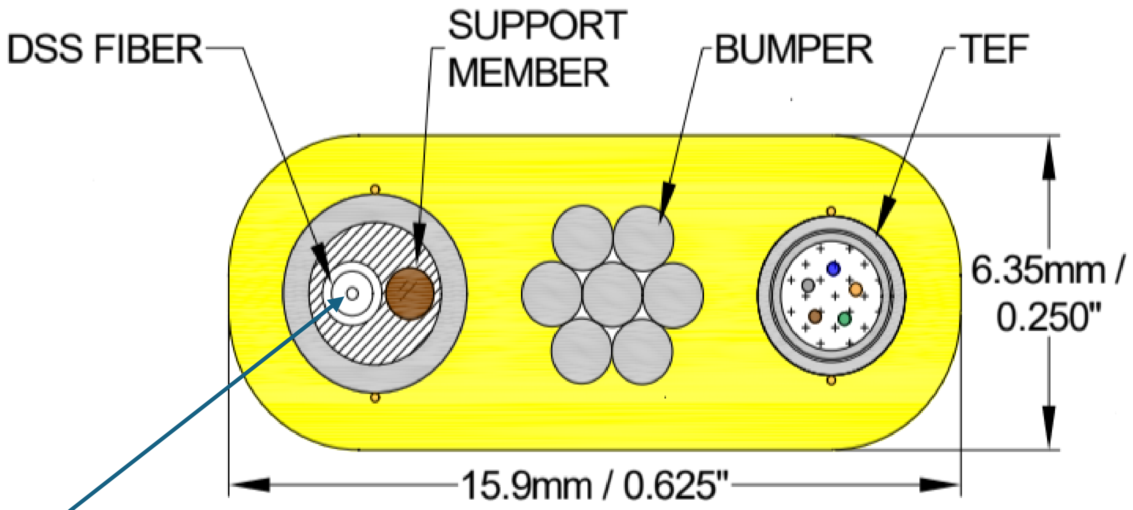
Equipment and Process



Fiber on Pipe | Spooling | Casing Hangers | Clamps & Centralizers | Well Head Exit Hardware

Cross Section of the UT Shell Flat Pack Fiber Optic Cable (courtesy Alan Reynolds)

DTS/DAS FIMT + DSS BUFFERED FIBER FLATPACK



Drawing not to Scale

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UTAH FORGE U.S. Department of Energy

Cable Clamp And Centralizer Elements

Cross Coupling Crossover Clamps

Centralizers

Topsides Connections From Well Fibers To Interrogators

Fusion Splicing

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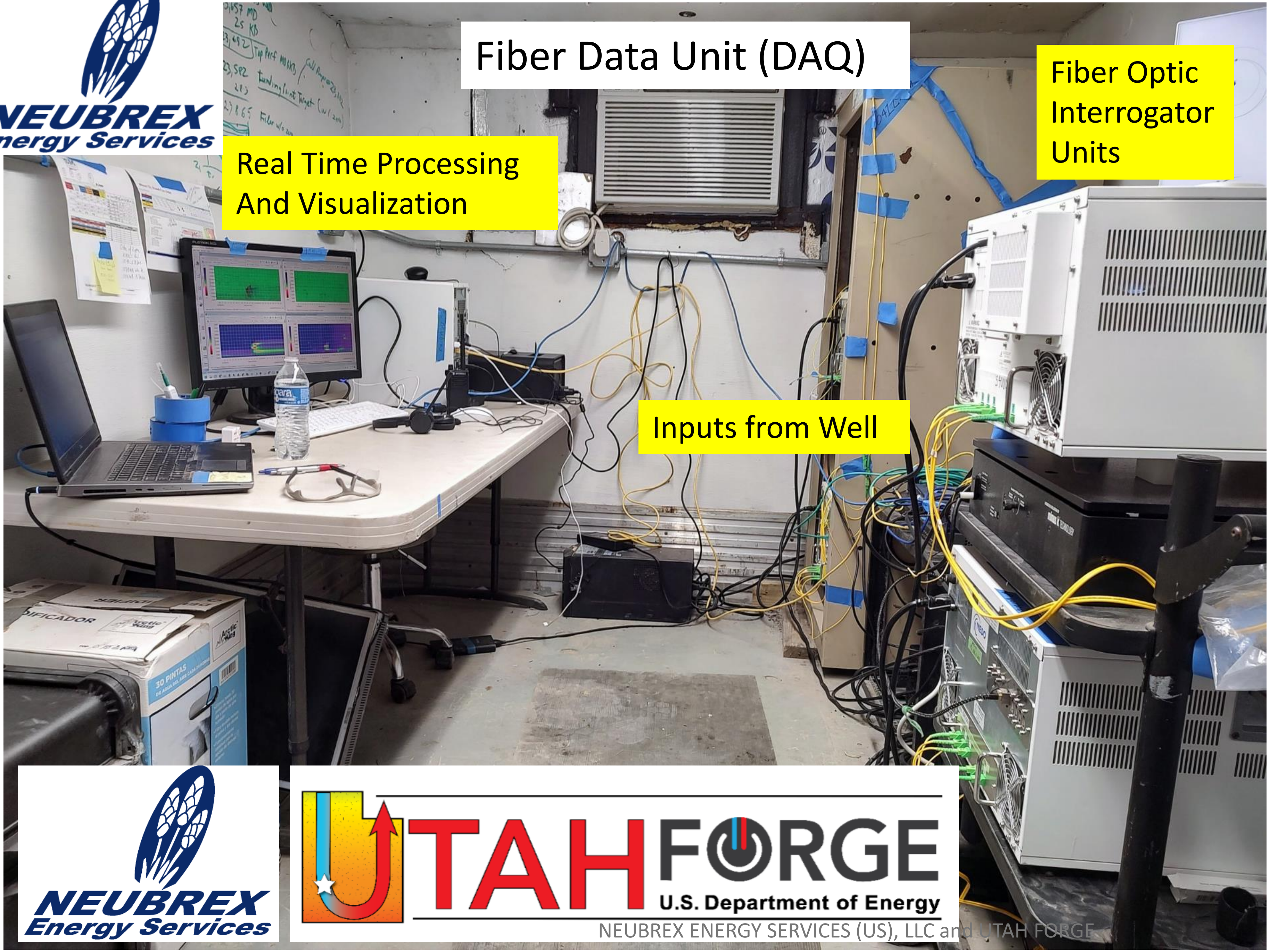

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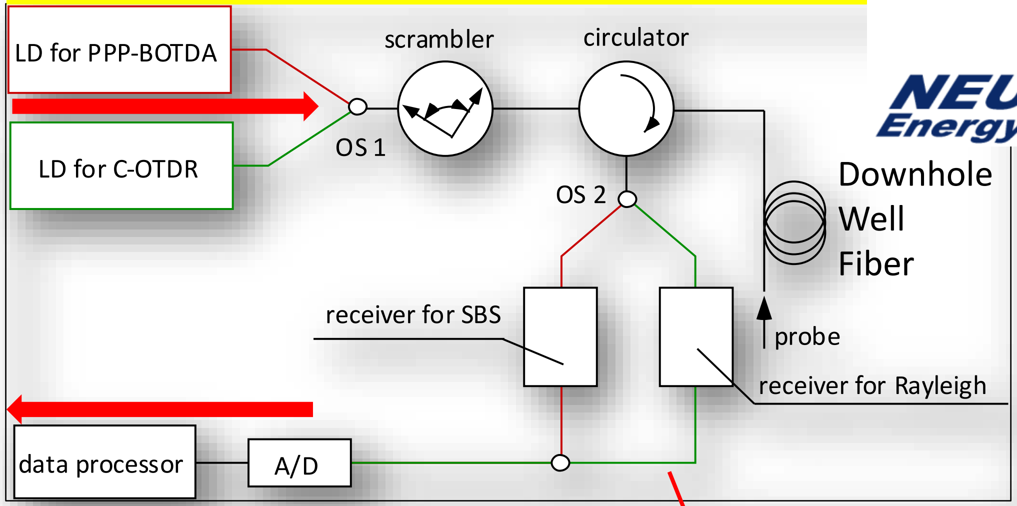
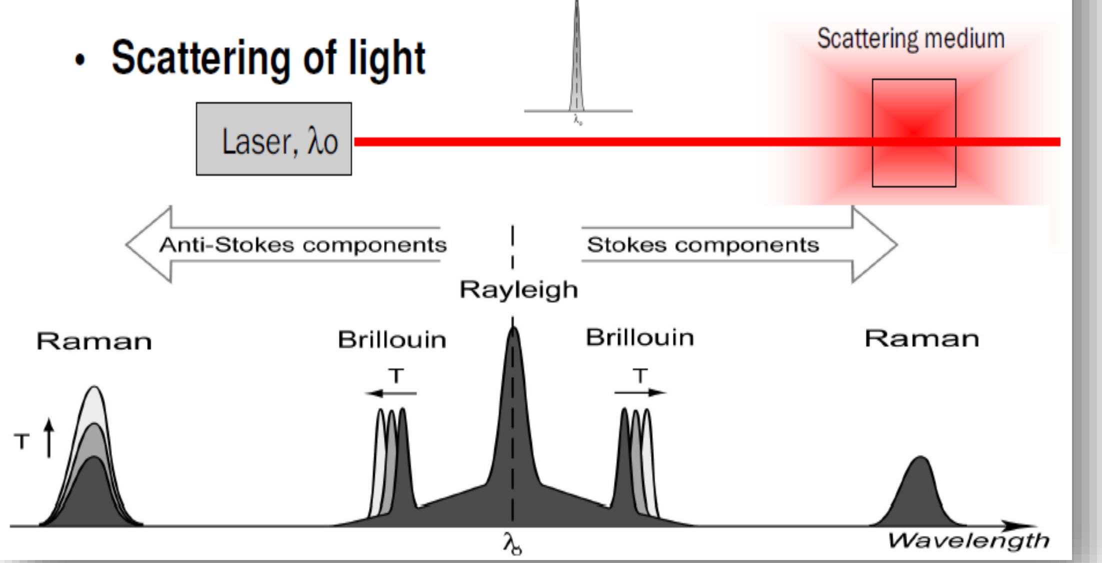
From Theory to Practice

Engineering Interrogator System Schematic

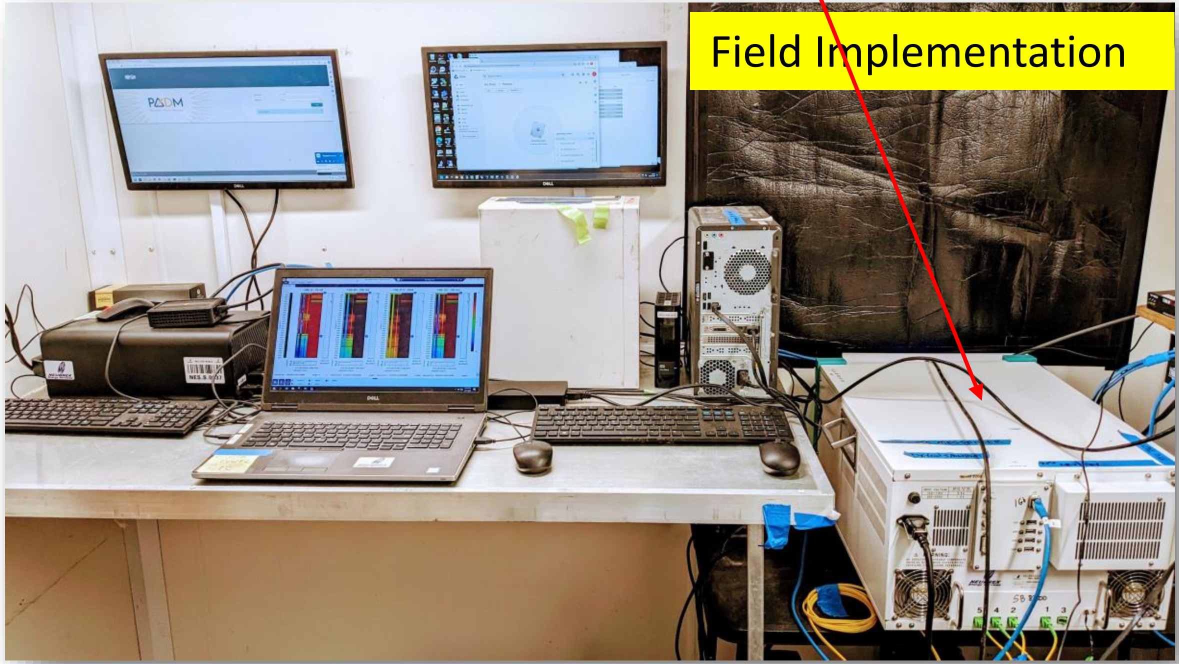


First Principles – Physics



Temperature Strain and DAS

Field Implementation



RFS DSS Measurement Principle

Strain Detection via

Rayleigh **F**requency **S**hift
Distributed **S**train **S**ensing

Original Length Signature

Changed Length Signature

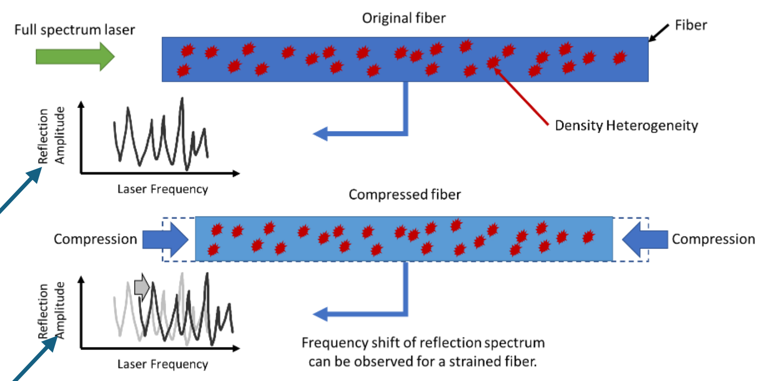


Figure 1: Conceptual illustration of RFS measurement. The frequency shift of Rayleigh reflection spectrum is linearly dependent on fiber temperature and strain changes.

optimization using multi-well simulation for the lower Spraberry shale in Midland basin. In *SPE Liquids-Rich Basins Conference-North America*. Society of Petroleum Engineers. https://doi.org/10.2118/187485-ms.

In general, has sensitivity in Strain Change of < 0.5 microstrain unit, and

Temperature change sensitivity on the order of 0.1 °C

1 µ epsilon = 1 x 10**-6 strain units

Strain unit is dimensionless
Strain Change can be conceived of

Δ length length/ original length mm

∴ 1 µ epsilon of strain change = 1x10** -6 mm change/ 1 mm length

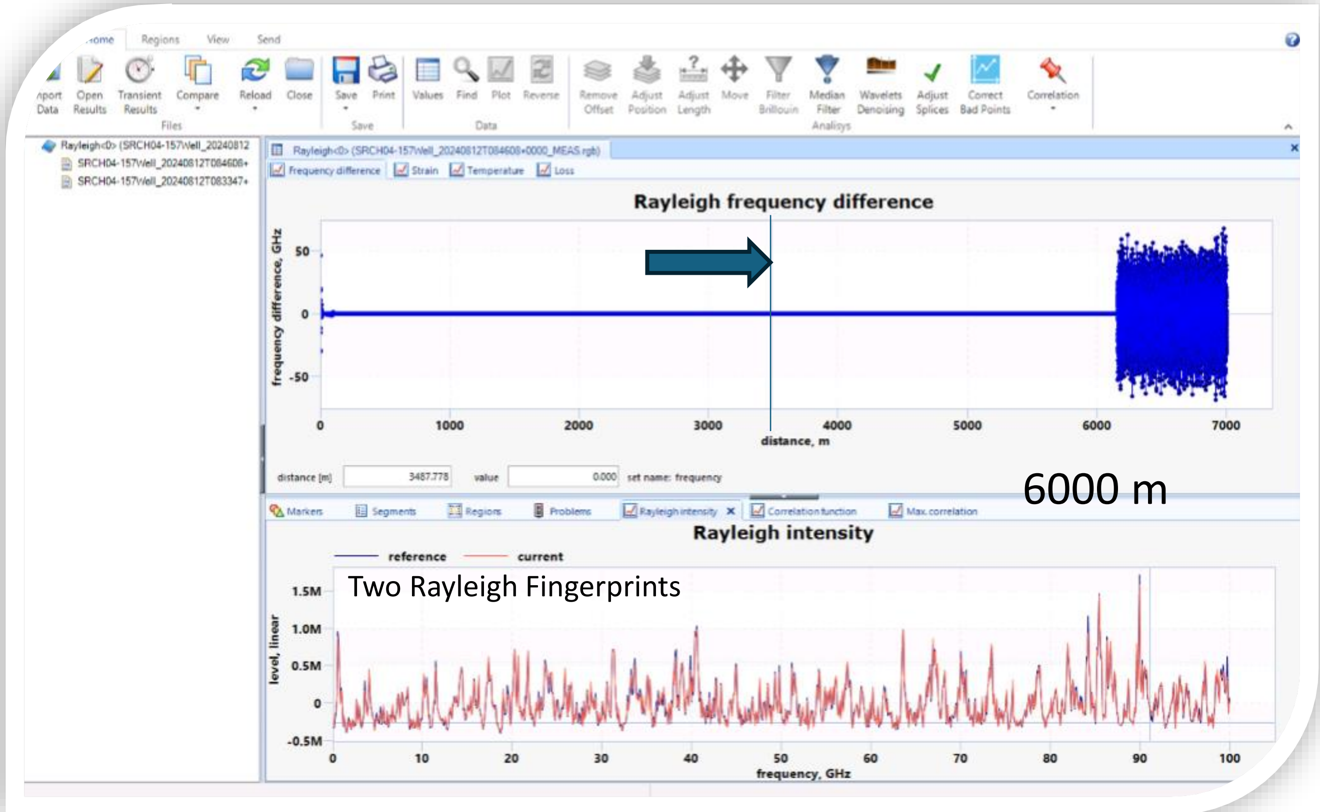
Small changes are detectable !

Rayleigh Backscatter frequency shift (RFS) is obtained by signature cross correlation analysis between a reference trace and a second trace. The strain change is measured via the Rayleigh Frequency Shift ($\Delta V(R)$).

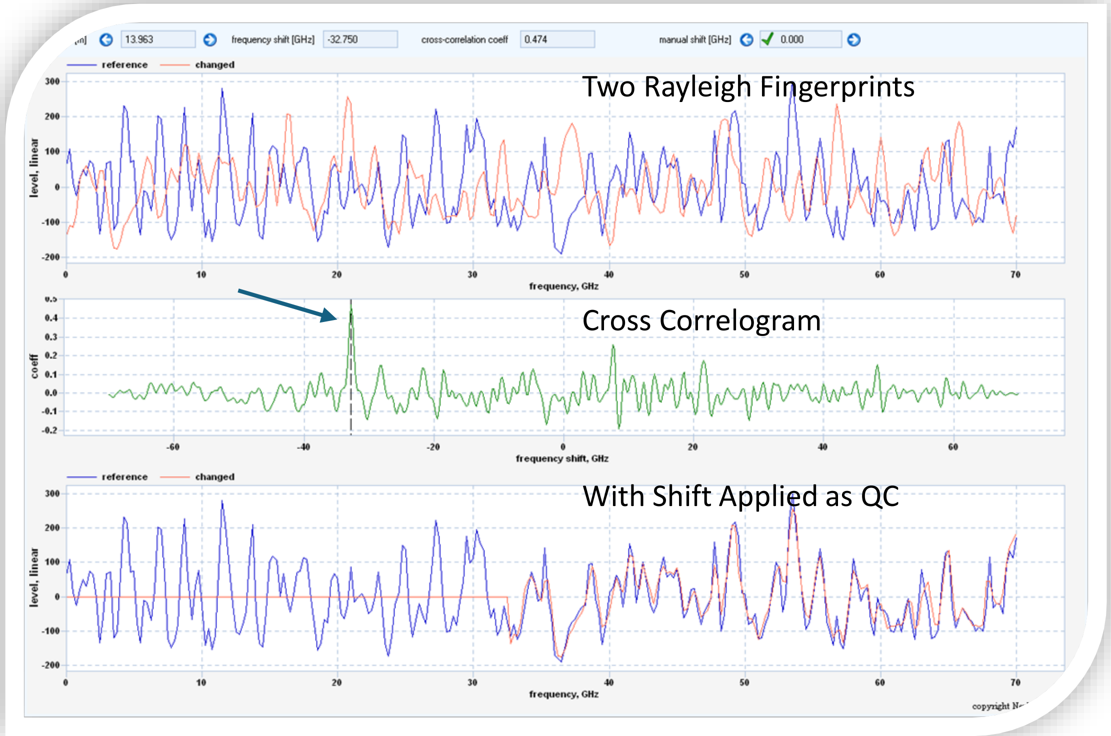
Frequency "fingerprints" of TW-ODTR at two times (reference and current) at the same location are illustrated.

$$\Delta\nu_R = C_{21}\Delta\varepsilon + C_{22}\Delta T$$

where C_{21} and C_{22} stand for Rayleigh strain-frequency and temperature-frequency coefficients,



Two Rayleigh Backscatter frequency fingerprints measured at different times every 20 cm on fiber. The frequency fingerprints match almost exactly. Means there has been no detectable strain Change between the two time periods at this depth.



Two Rayleigh Backscatter frequency fingerprints measured at different times at One Location. The fingerprints DO NOT MATCH. The value of XCORR LAG provides the Frequency Shift Value ($\Delta V(R)$) from which strain is derived.

DAS Measurement Principle

Dual Optical Pulse Phase Shift
Fiber Optic sensing using
Time Domain
Reflectometry (T- OTDR)

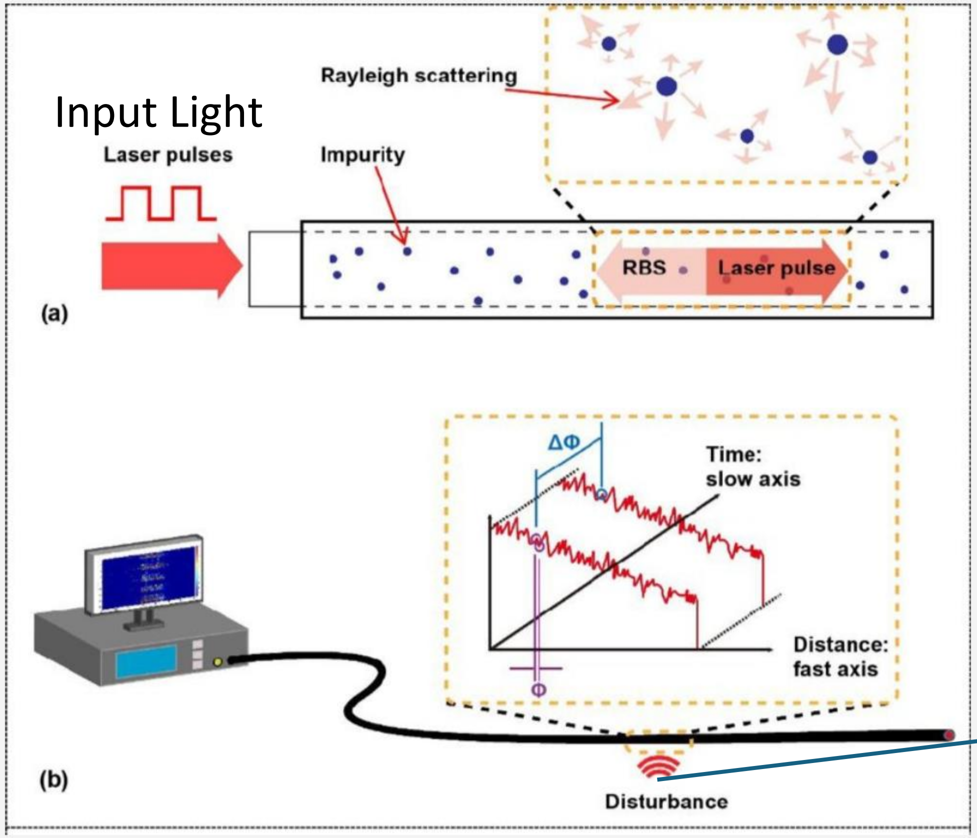
DAS is sensitive to fast vibrations.

It can measure acoustic signals.

Low Frequency portion of the
Acoustic range is Strain Rate
Equivalent.

DAS Measures quickly in time.
Sample every 1/5000 sec.

Spatial resolution is 1 meter
Compared to
20cm resolution of RFS DSS



Distributed Acoustic Sensing (DAS)
For Geomechanics Characterization: A
Concise Review

Tao Xie, Shi, Zhang, Chen
2021; IOP Conference

Figure 1

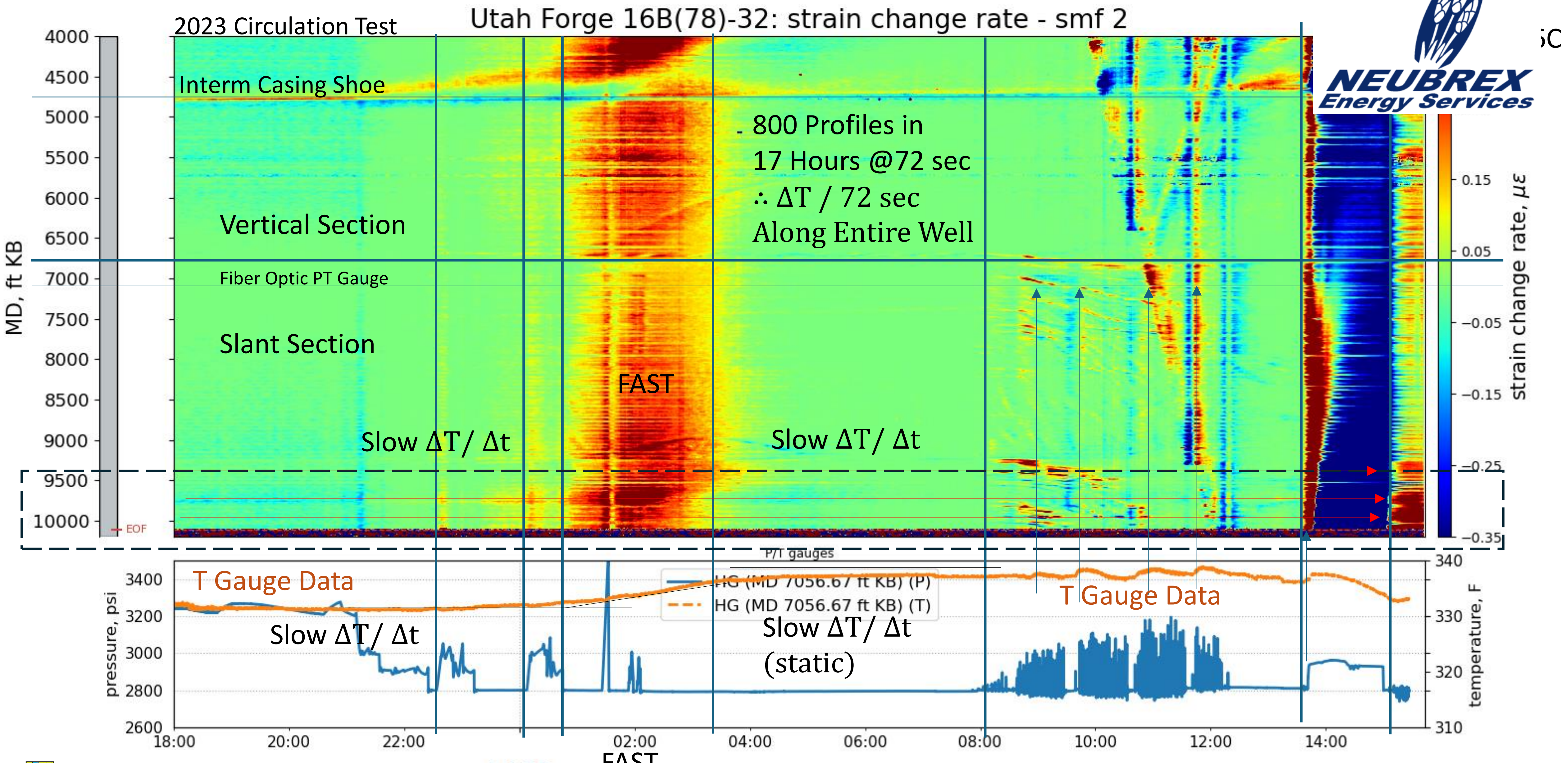
Figure 1. Measurement principle of DAS based on
phase-sensitive optical time-domain reflectometry

Like a set of microphones
At 1 meter interval,
The acoustic vibrations
Are detected and
Measured using DAS.

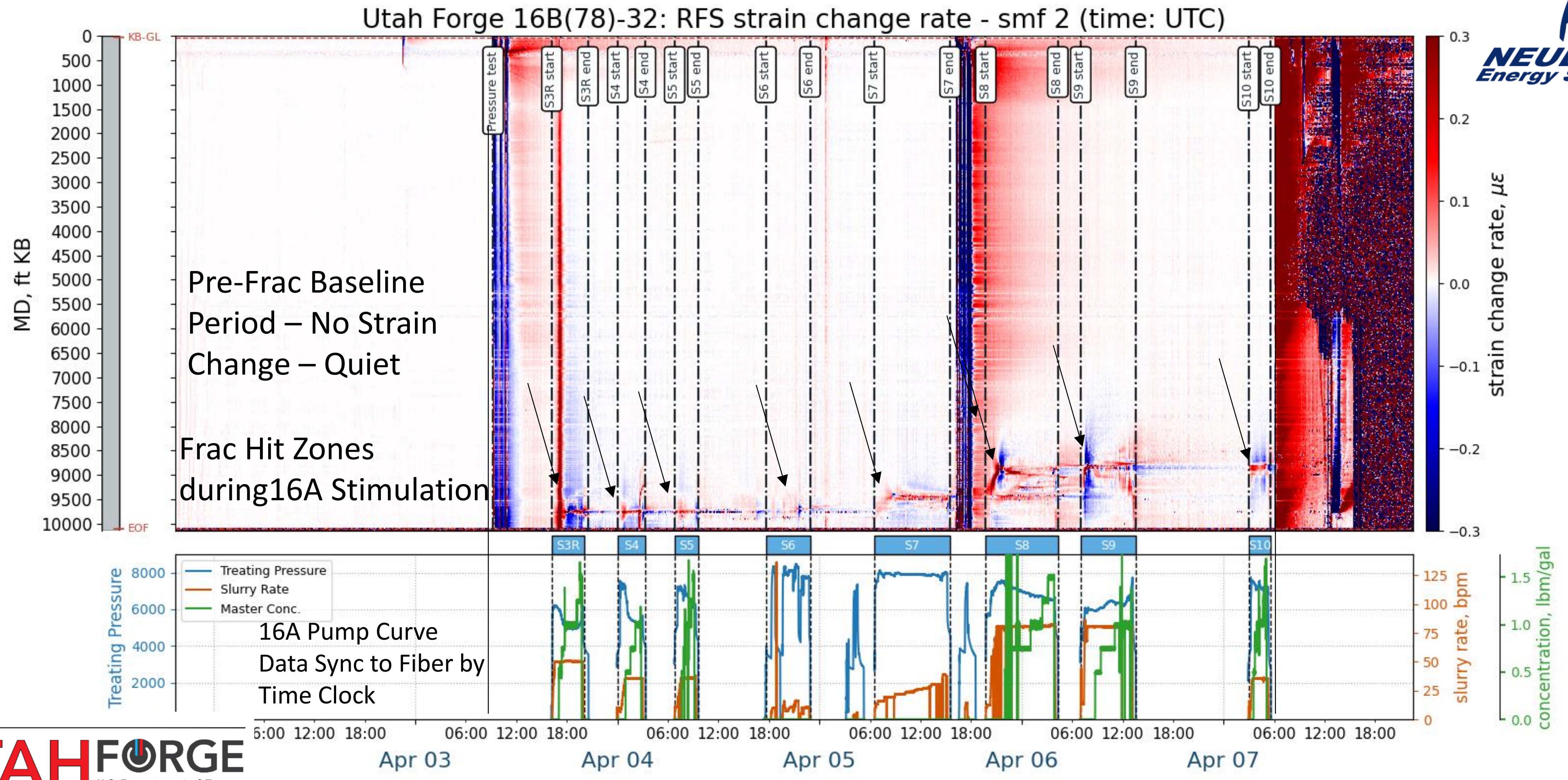
A phase shift between
The first laser pulse and
The second laser pulse
Is related to the vibration
Of very small density
Impurities in the glass.
The phase shift is related
To Strain rate changes at
Very high speed (5kspS)


who cares?

RFS DSS STRAIN RATE under Fluid Circulation Conditions



RFS DSS STRAIN RATE From Fracture Driven Interactions (FDI) during 16A Frac at 16B Monitor Well



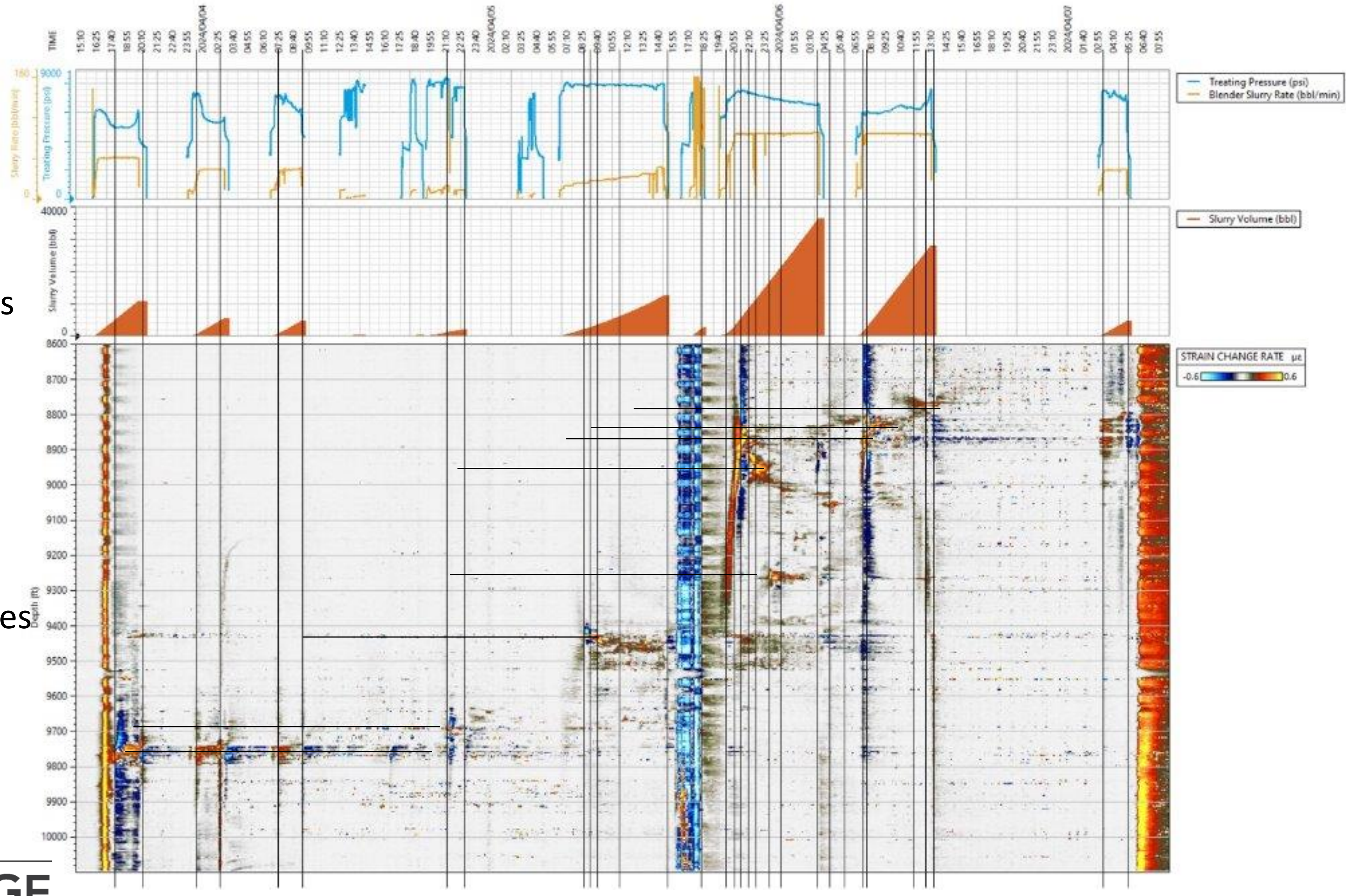
Integrating HF Pump Curve Data with Croswell Strain Data

Stage by Stage
Treating Pressure
And Rate

Cumulative Volumes

RFS DSS Strain Rate
Frac Data in offset
Observation Well.

The depths and times
Of cross well frac
Hits are derived
From this data.



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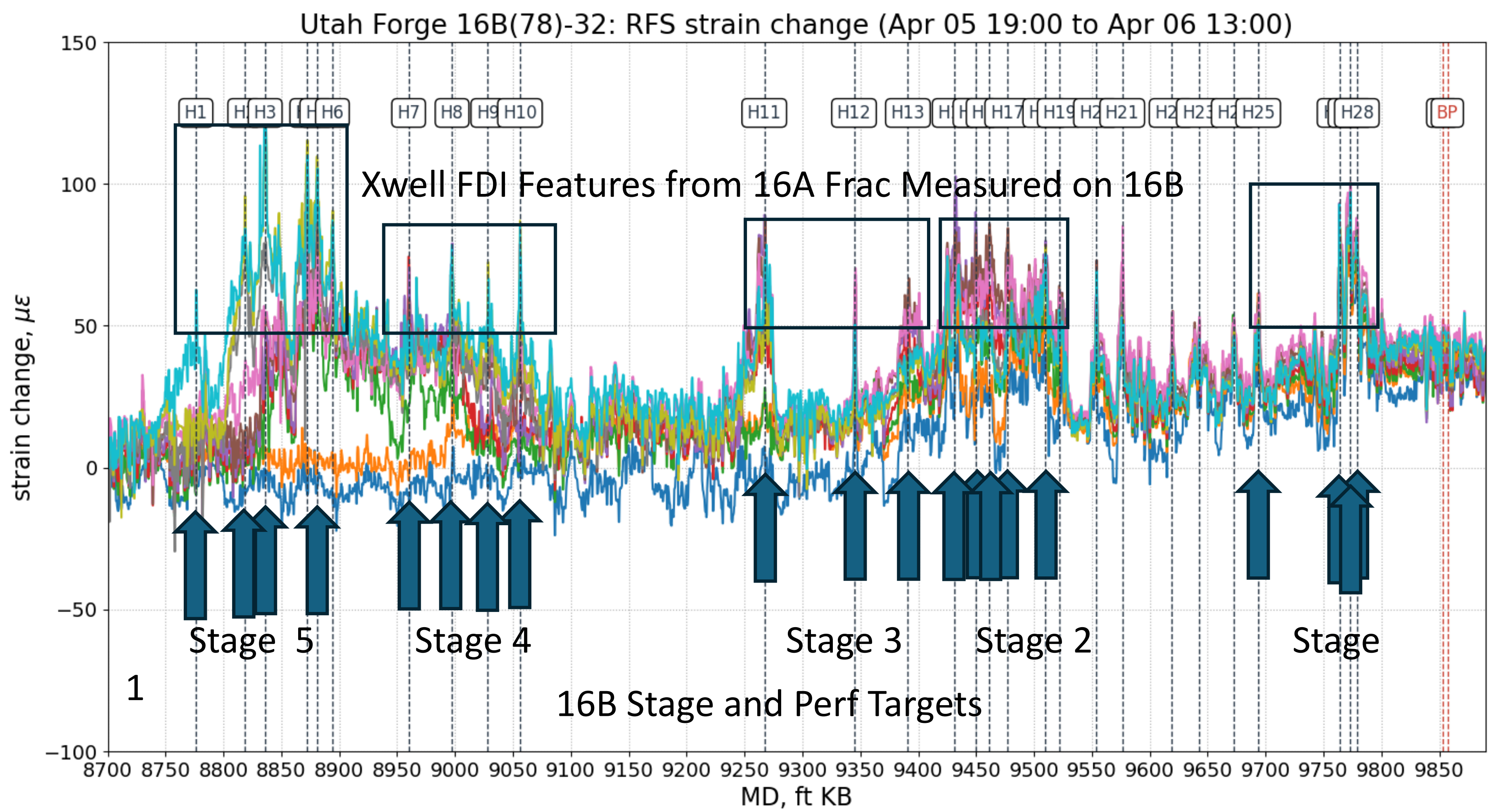
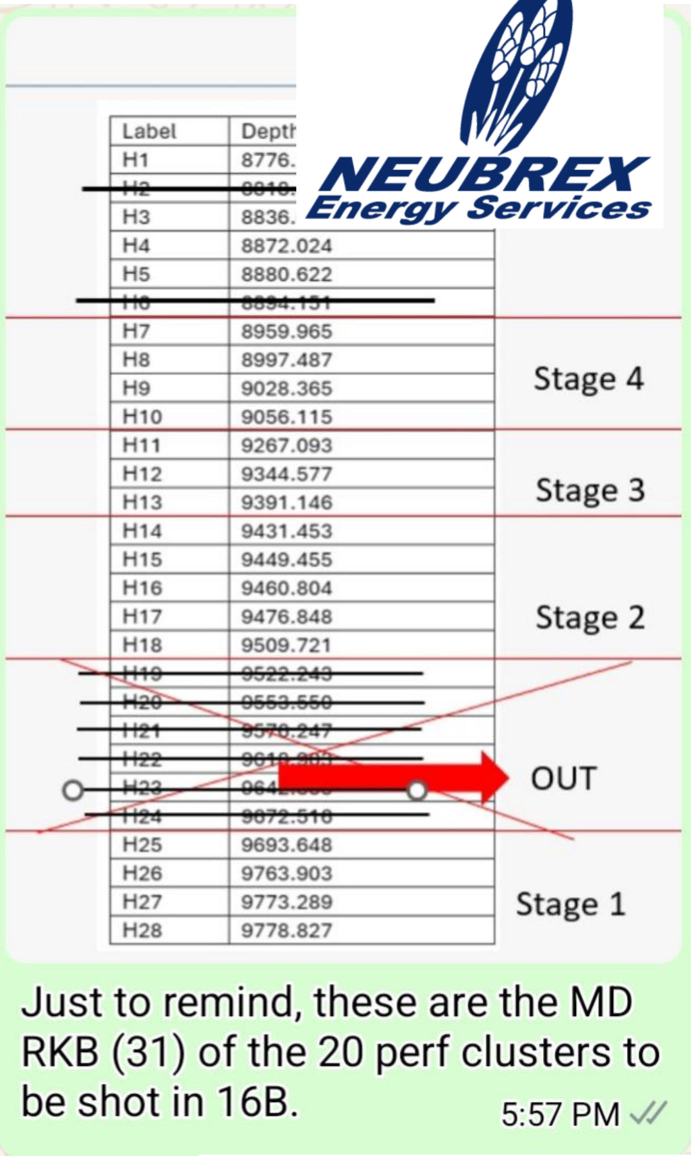




Label	Depth
H1	8776.
~~H2~~	~~8818.~~
H3	8836.
H4	8872.024
H5	8880.622
~~H6~~	~~8894.151~~
H7	8959.965
H8	8997.487
H9	9028.365
H10	9056.115
H11	9267.093
H12	9344.577
H13	9391.146
H14	9431.453
H15	9449.455
H16	9460.804
H17	9476.848
H18	9509.721
~~H19~~	~~9522.243~~
~~H20~~	~~9553.550~~
~~H21~~	~~9570.247~~
~~H22~~	~~9618.[illegible]~~
~~H23~~	~~964[illegible]~~
~~H24~~	~~9672.516~~
H25	9693.648
H26	9763.903
H27	9773.289
H28	9778.827

Stage 4
Stage 3
Stage 2
OUT
Stage 1

Just to remind, these are the MD RKB (31) of the 20 perf clusters to be shot in 16B.
5:57 PM

RFS DSS STRAIN RATE Depth Profiles Extracted at Different Times during Frac Period.
This data was used to “Pick” discrete Fracture Driven Interactions produced During the 16A frac and these were cataloged relative to their MD in 16B.

This Catalog was analyzed on job site to “high grade” 16B FDI targets for 16B Plug and Perf Action

16B Frac Pumping Parameters and Actual Stage / Cluster Depths

Well 16B(78)-32: Actual Pumped

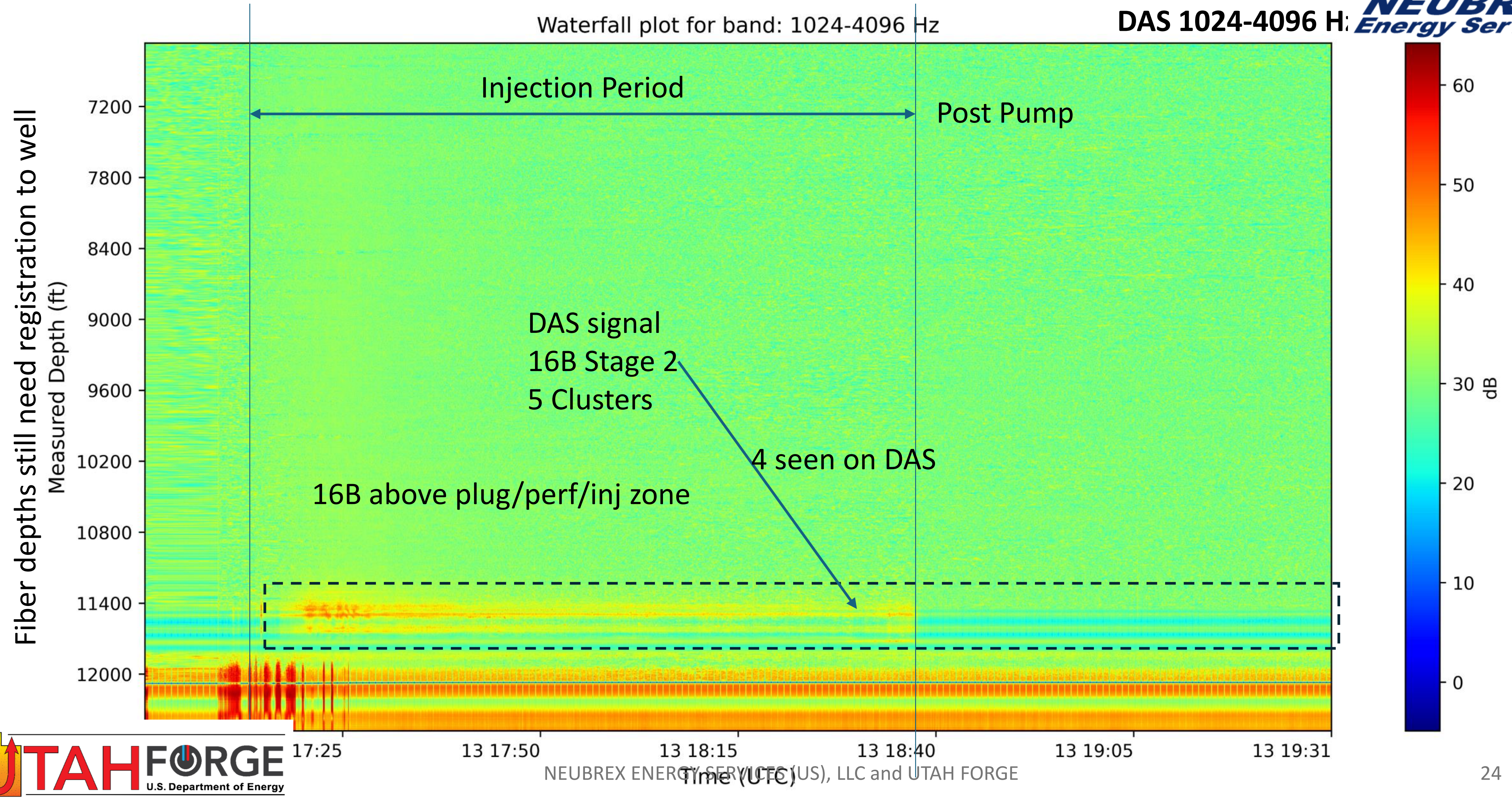
Stage Name	Number of Clusters	Fluid Type	Fluid Volume (bbl)	Pump Rate (bpm)	100-mesh Prop Volume (lb_m)	40/70-mesh Prop Volume (lb_m)
Stage 1	4	Slickwater	3,624	60 (Avg = 55)	45,600	66,840
Stage 2	5	Slickwater	4,734	60 (Avg = 56)	46,770	102,000
Stage 3	3	Slickwater	4,321	60 (Avg = 51)	43,322	70,163
Stage 4	4	Slickwater	3,800	60 (Avg = 56)	43,217	65,317
Stage 5	4	Slickwater	N/A	N/A	N/A	N/A

Measured Depth (Referenced to KB = 31.5 ft)

	Gun 1	Gun 2	Gun 3	Gun 4	Gun 5	Frac Plug Top
Frac Plug #1						9,777
Stage 1 (16B)	9,769 - 9,773	9,756 - 9,760	9,745 - 9,749	9,690 - 9,694		
Frac Plug #2						9,600
Stage 2 (16B)	9,508 - 9,512	9,475 - 9,479	9,459 - 9,463	9,447 - 9,451	9,429 - 9,433	
Frac Plug #3						9,415
Stage 3 (16B)	9,389 - 9,393	9,343 - 9,347	9,265 - 9,269			
Frac Plug #4						9,165
Stage 4 (16B)	9,054 - 9,058	9,026 - 9,030	8,995 - 8,999	8,958 - 8,962		
Frac Plug #5						~~8,915~~
Stage 5 (16B)	8,879 - 8,883	8,870 - 8,874	8,834 - 8,838	8,774 - 8,778		

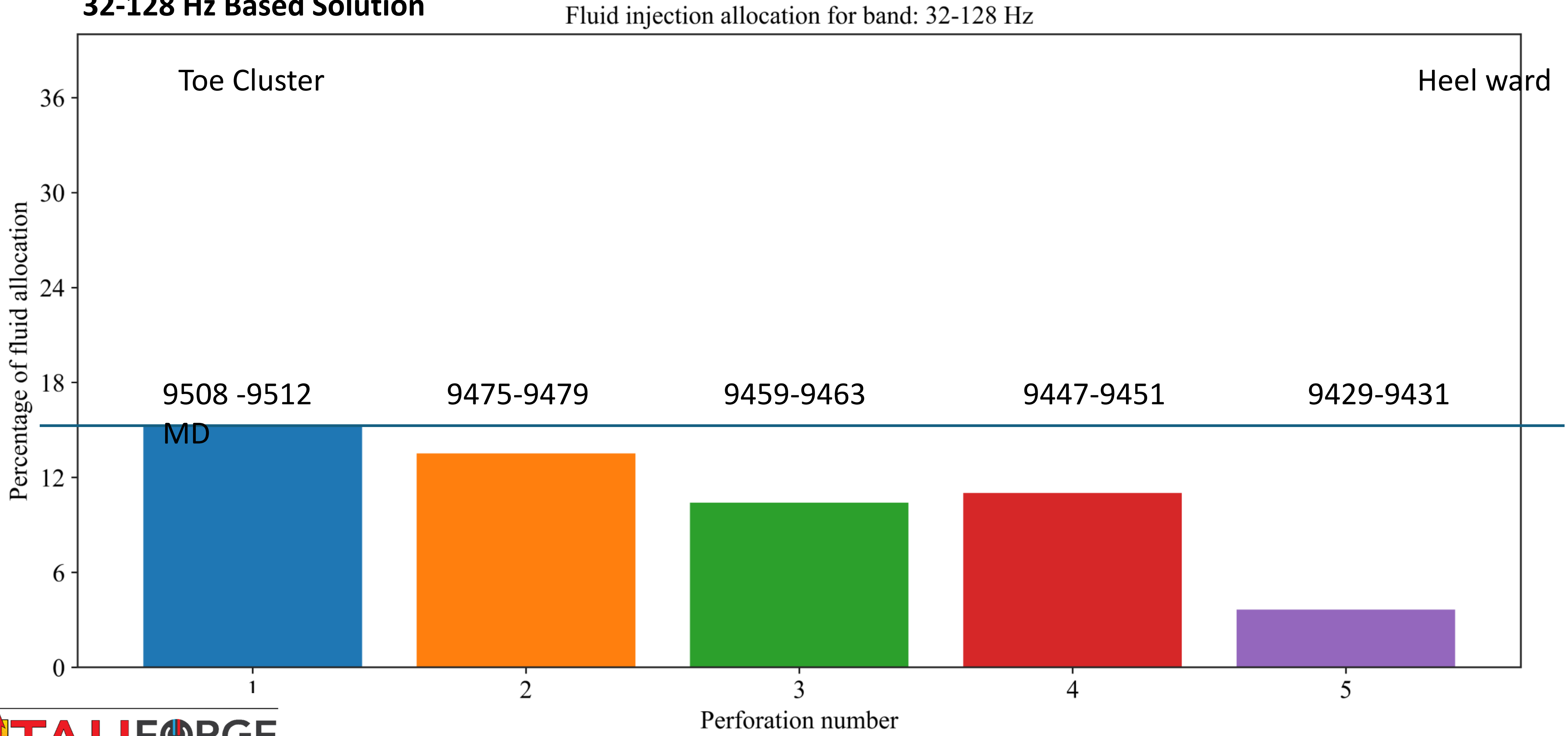
Stage 2: In-Well Frac Period Injection Noise using DAS Acoustics

DAS 1024-4096 H:



Stage 2: Fluid Injection Allocation Results Derived from DAS

32-128 Hz Based Solution



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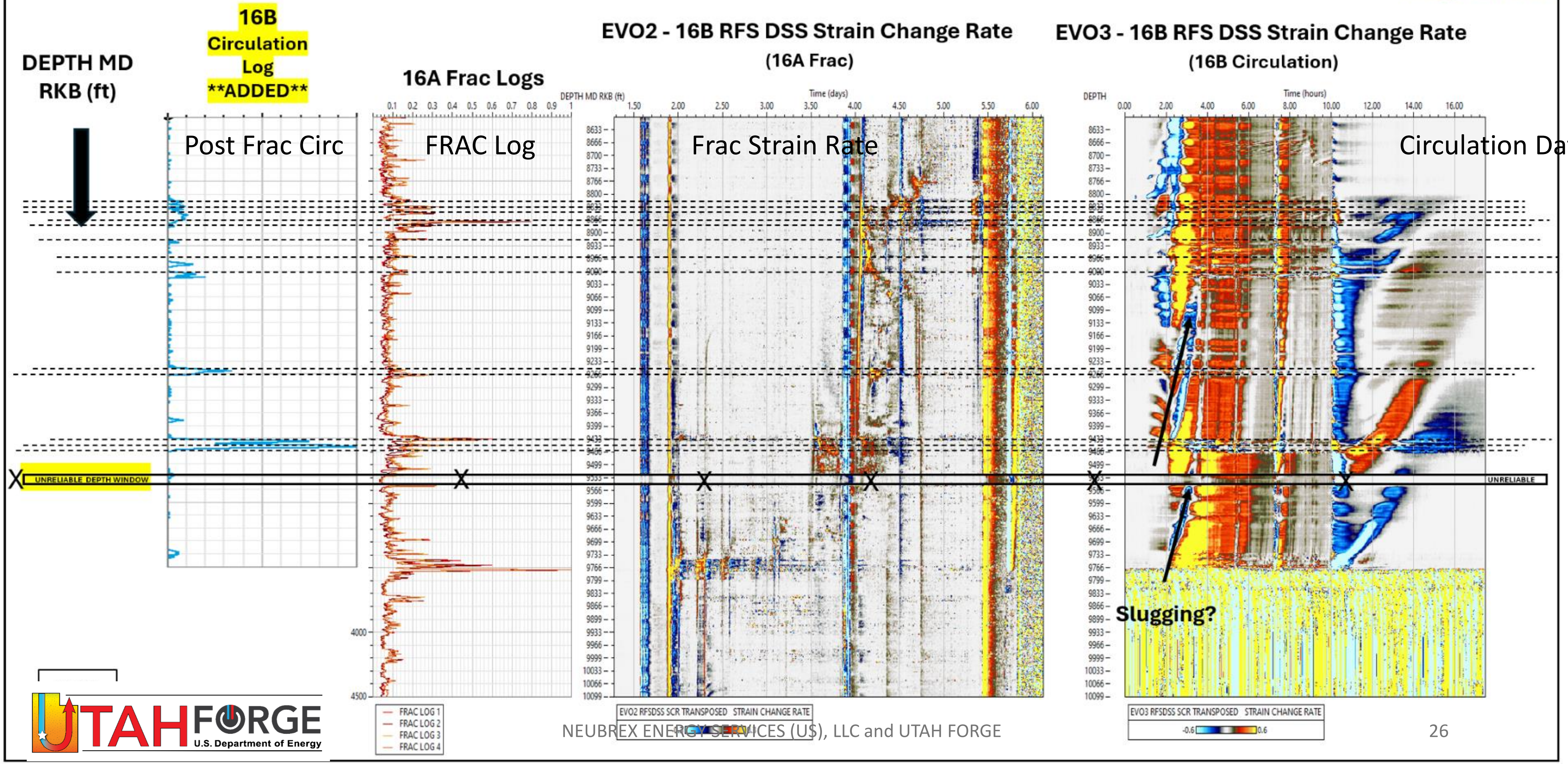
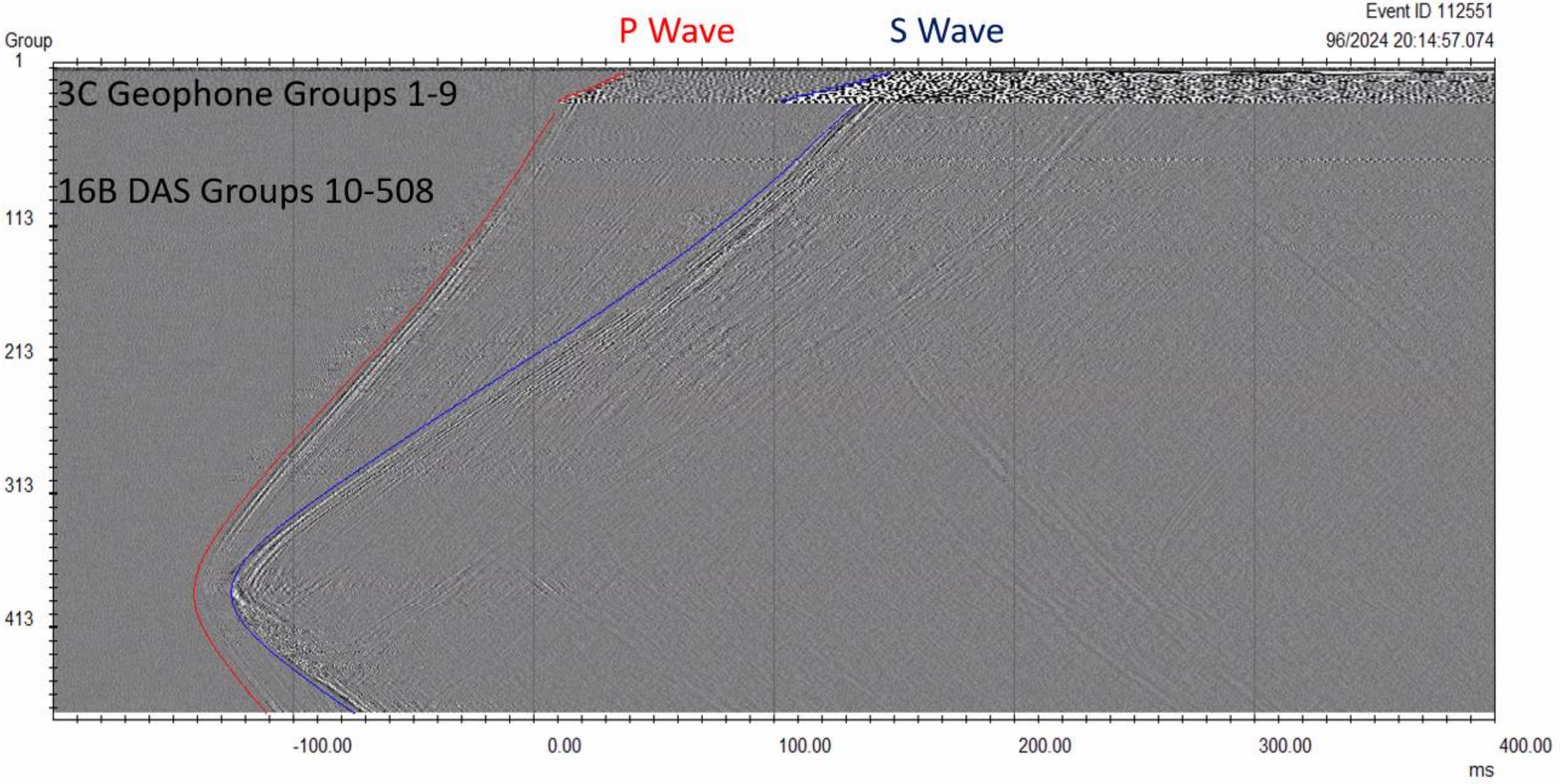
EVO2 - 16A FRAC & EVO3 – 16B CIRCULATION

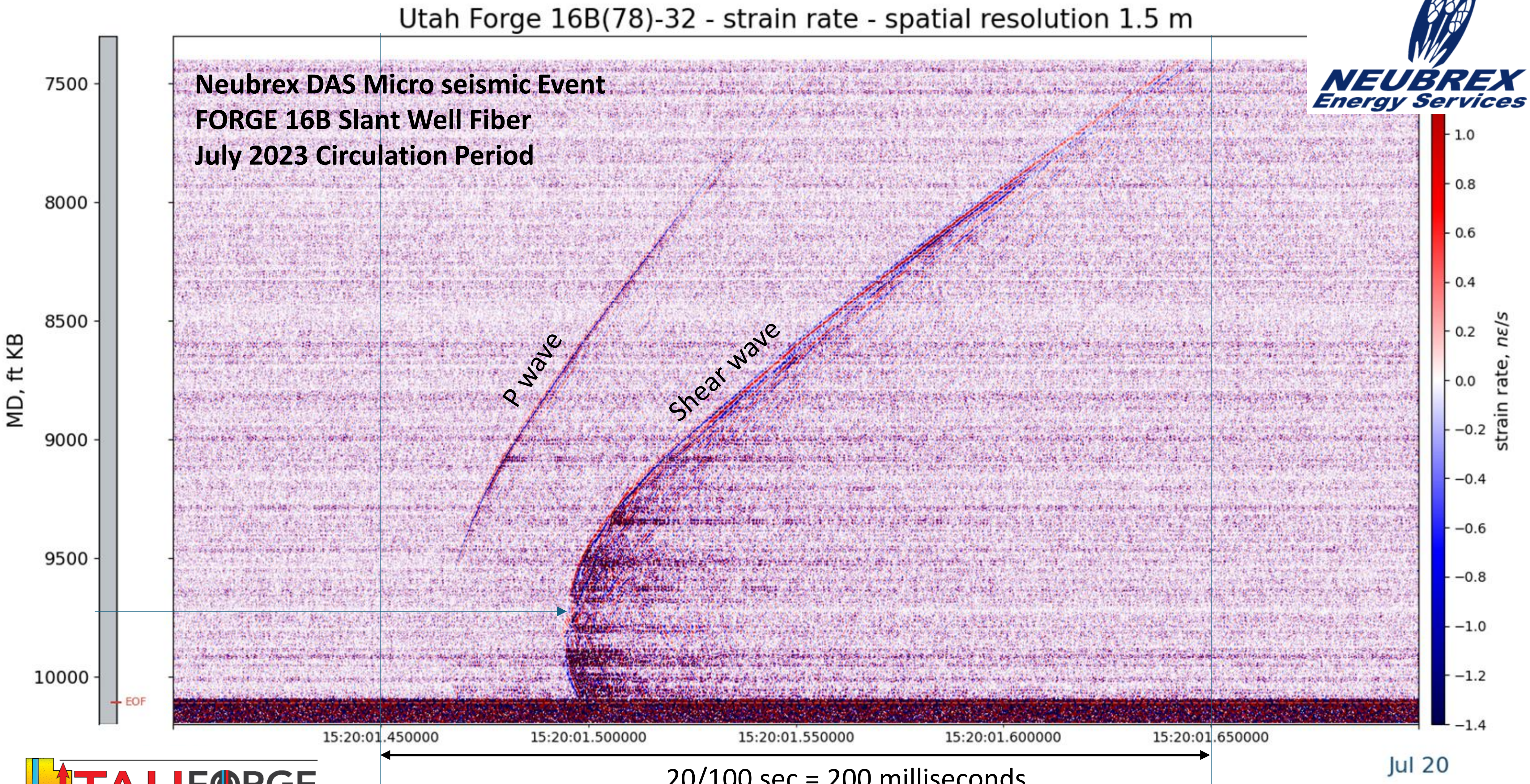
April, 2024



DAS Data at 3m Trace Intervals, 1.5Mw

Acoustic Signals from Induced Micro seismic Events.




Utah Forge 16B(78)-32 - strain rate - spatial resolution 1.5 m
Neubrex DAS Micro seismic Event
FORGE 16B Slant Well Fiber
July 2023 Circulation Period
P wave
Shear wave
MD, ft KB
7500
8000
8500
9000
9500
10000
EOF
15:20:01.450000
15:20:01.500000
15:20:01.550000
15:20:01.600000
15:20:01.650000
Jul 20
strain rate, nε/s
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
20/100 sec = 200 milliseconds

End of Technical Report & Contact Information

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