Overview of Hydraulic Fracturing Test Sites (HFTS) and Summary of Selected Results

HFTS-I in Midland and HFTS-II in Delaware

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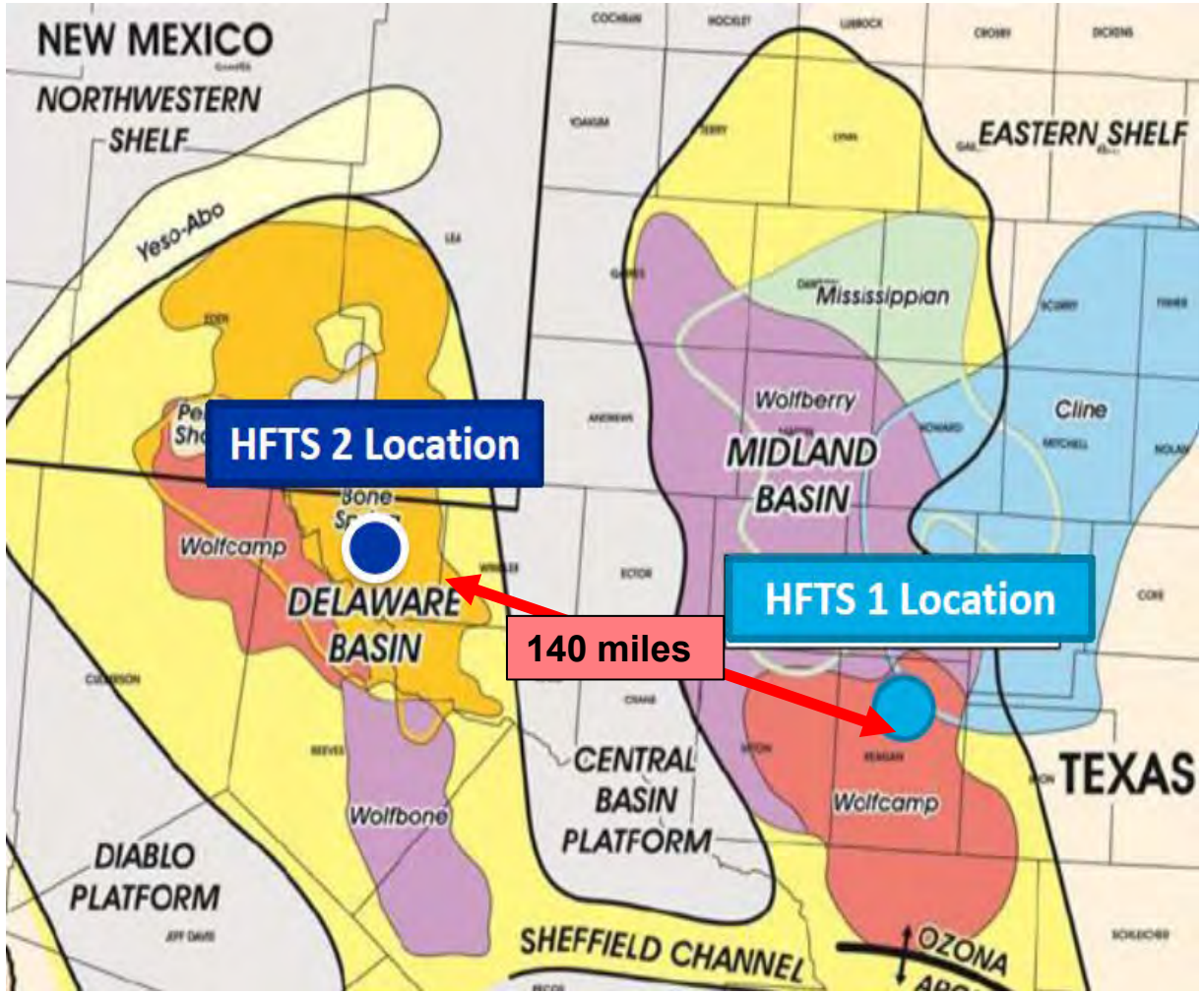
ARMA Workshop: Efficient Energy: Observations, Monitoring & Diagnostics
June 27, 2019 - New York City

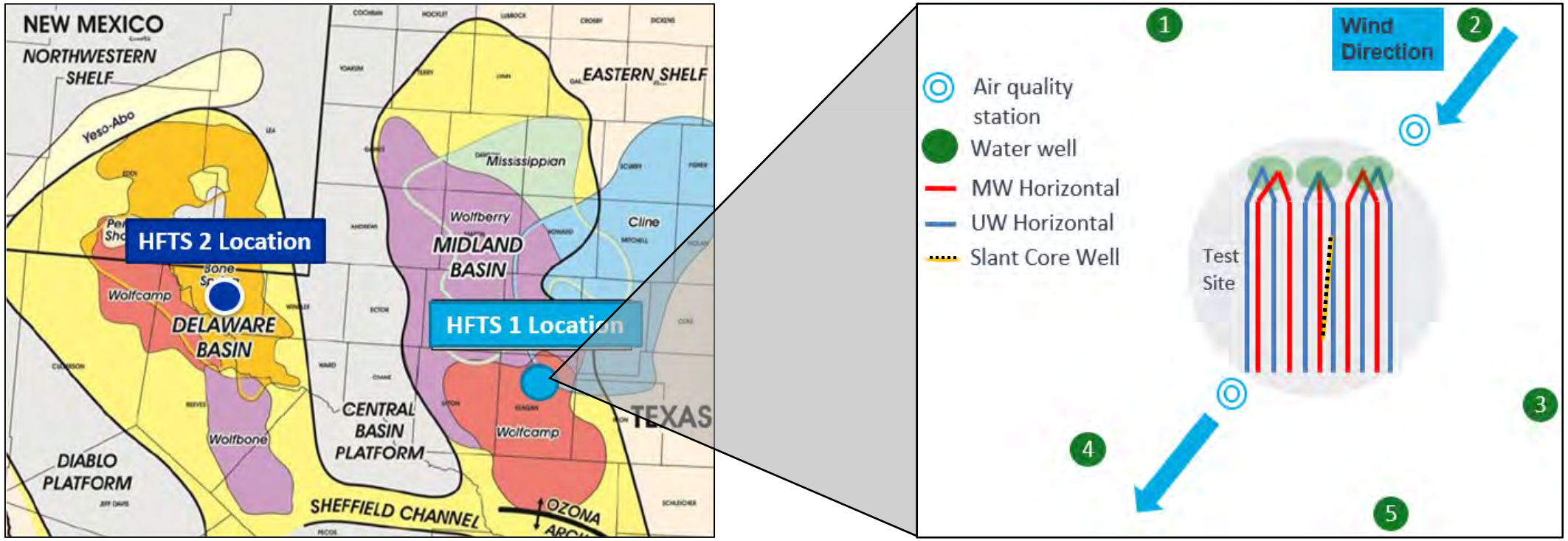
Summary of HFTS 1 and 2



- Field-based research programs utilizing producing and dedicated science wells to advance understanding of the hydraulic fracturing in shales
- Capture fundamental insights of the fracturing process, HF/NF attributes, proppant distribution
- Ground truth SRV core; indisputable evidence
- Advanced diagnostics; reservoir pressure monitoring, proppant quantification, FO measurements, etc.
- Public-private partnership
- Potential to reduce the number of wells required to develop west Texas resources by thousands

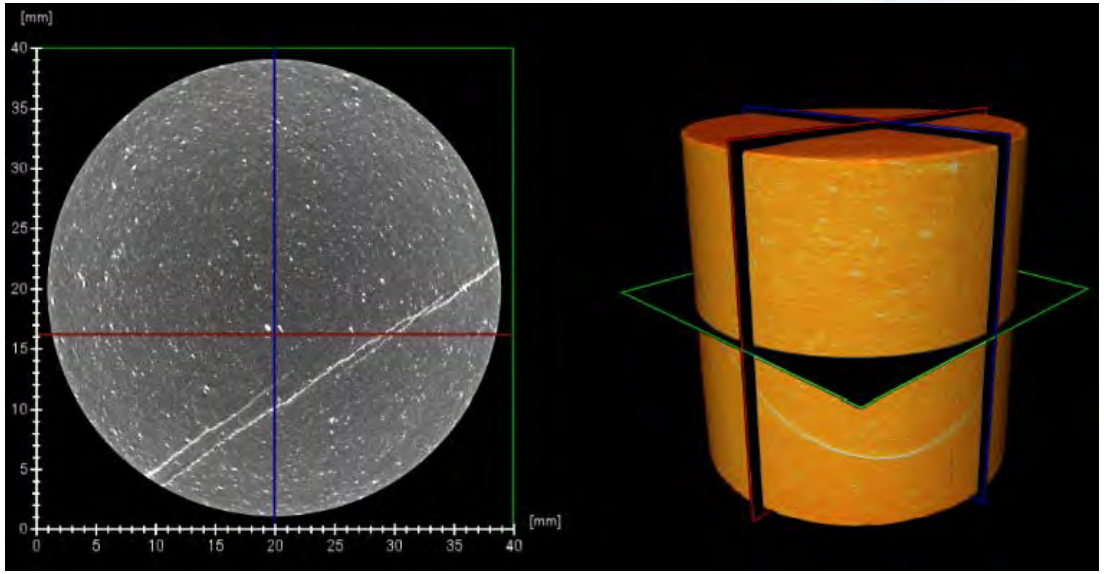
HFTS 1 Location

Permian - Midland Basin, Reagan County, 6 UW & 5 MW 10,000’ Wells



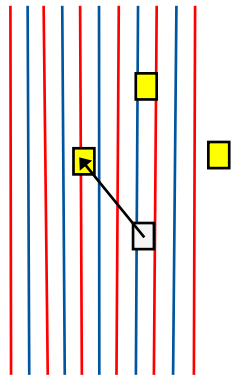
Field Data Acquisition and Diagnostics

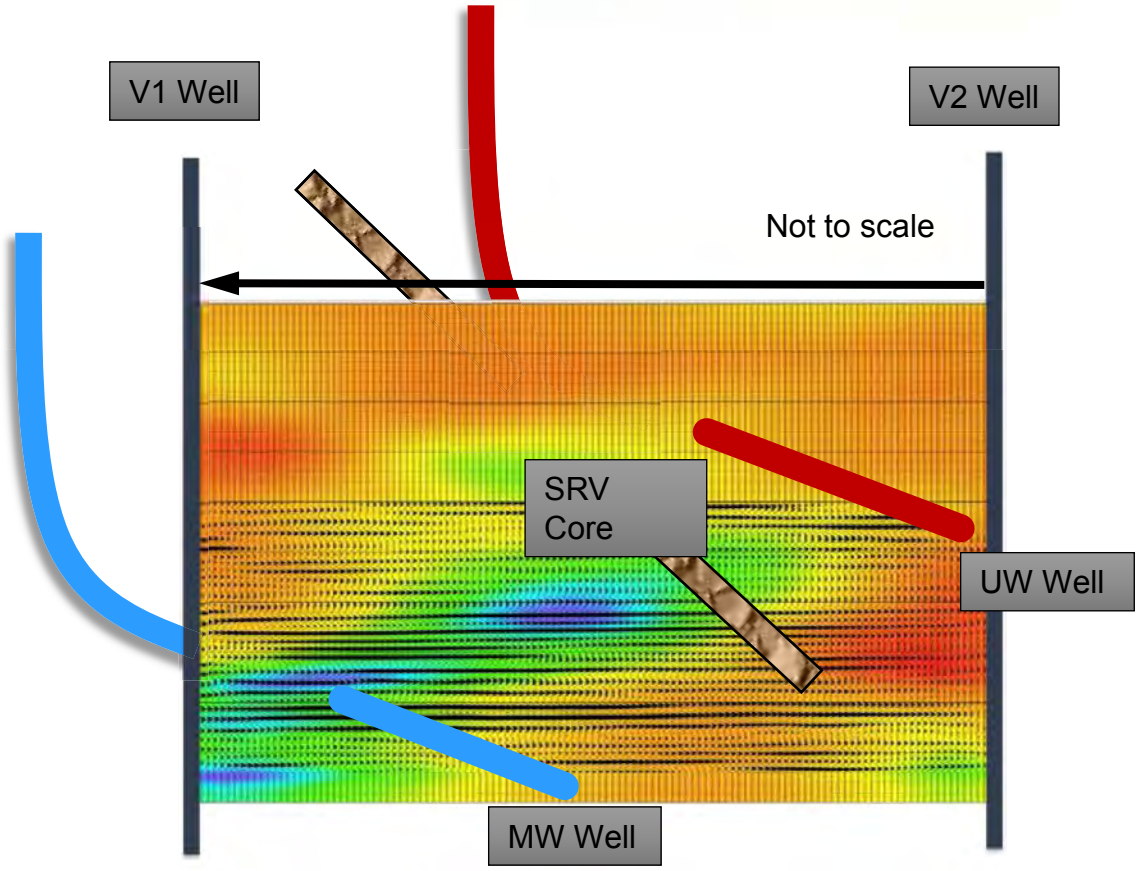
- 11 new horizontal test wells +2 refrac wells
  - 450+ fracture stages
  - Advanced OH horizontal logs
  - DFIT's in horizontals
- Vertical pilot below lower WC
  - Advanced OH logs and 110 sidewall cores
  - 14 OH micro DFIT's
  - Complete core analysis: petrophysics, geochem, petrography, advanced rock imaging, etc.
- Fracture Diagnostics
  - RA, oil and water tracers, dual array microseismic, tilt-meter surveys
  - 5 different colored proppants next to core well



Field Data Acquisition, Con't.

- Environmental monitoring
  - Air and water sampling before, during, and after hydraulic fracturing
- Pre and Post frac X-Well Seismic
  - 3 profiles between 4 vertical wells
- VSP – Zero Offset
- BH pressure gages in all HZ wells
- Production interference testing
    - After 6 and 18 months
- SRV core through well

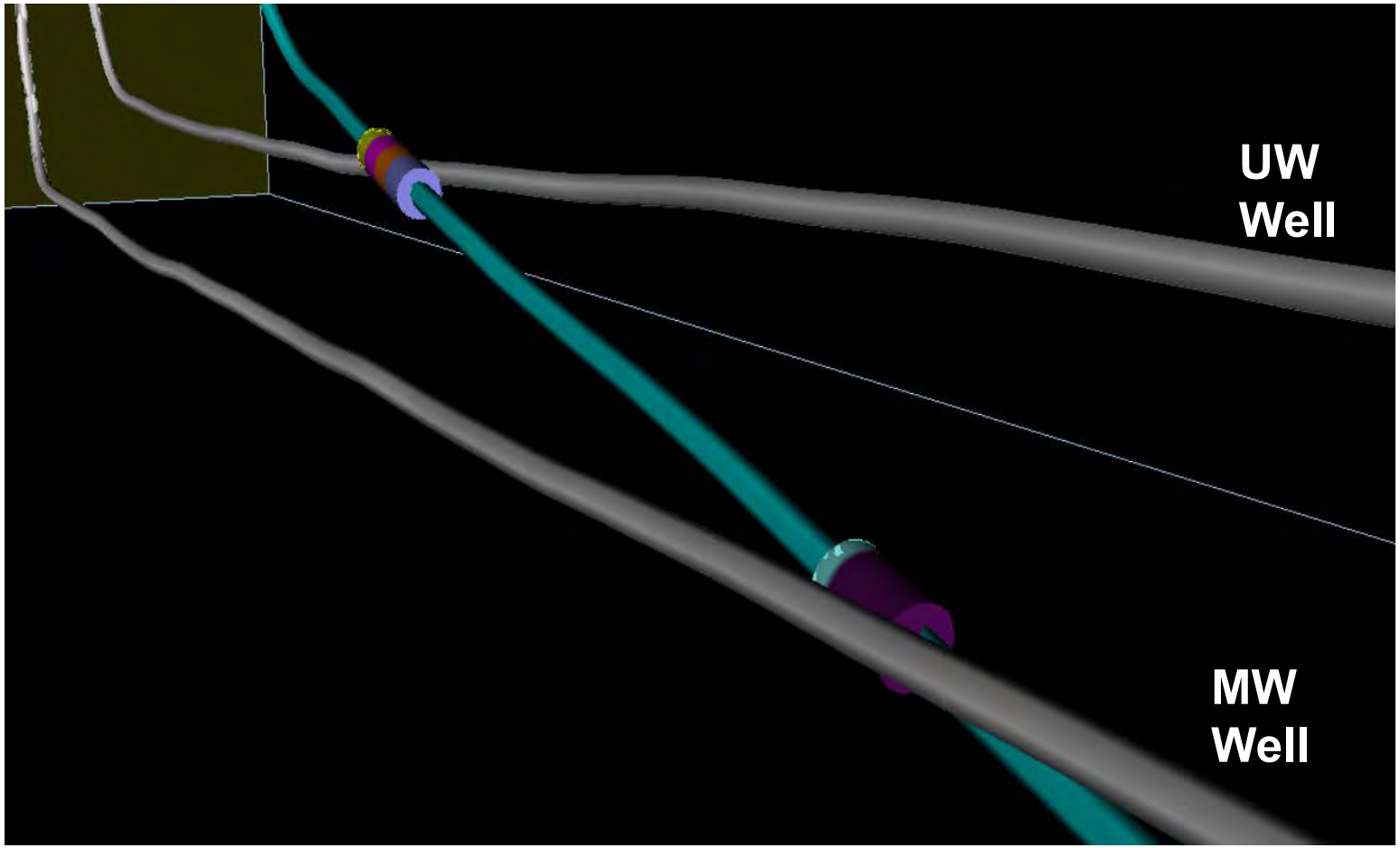




X-Well Compressional velocity difference

SRV Core Through Well

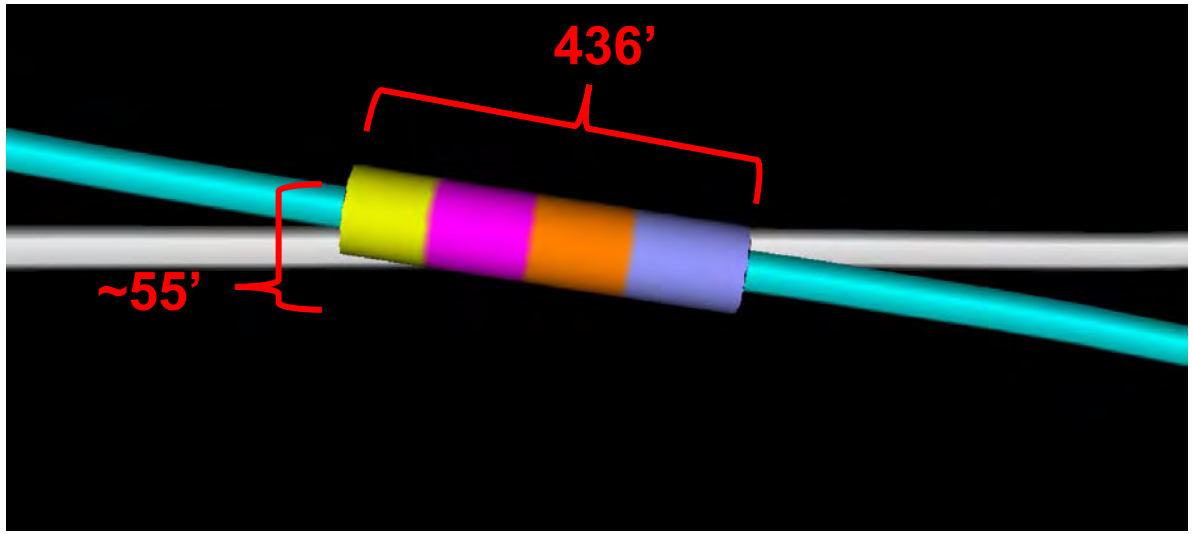
- Nearly 600 feet of SRV core
  - Upper & middle Wolfcamp
  - Core description – 2 teams
  - Proppant analysis
  - CT scanned entire core
- 5,100’ final lateral length
- Advanced open hole logs
  - Quad Combo, including spectral gamma and image log (OBMI)
- Discrete pressure gages



Core Summary – Upper Wolfcamp

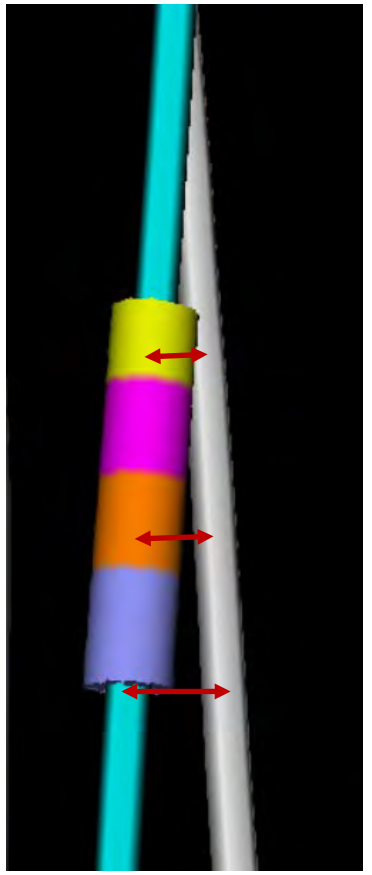
- Recovered ~436 feet of core in Upper Wolfcamp in 4 coring trips
  - Core 1 – 86’
  - Core 2 – 115’
  - Core 3 – 108’
  - Core 4 – 127’

Side View



Z-Distances
40’ above 6SU
15’ below 6SU

Plan View



X-Distances
40’ highest depth

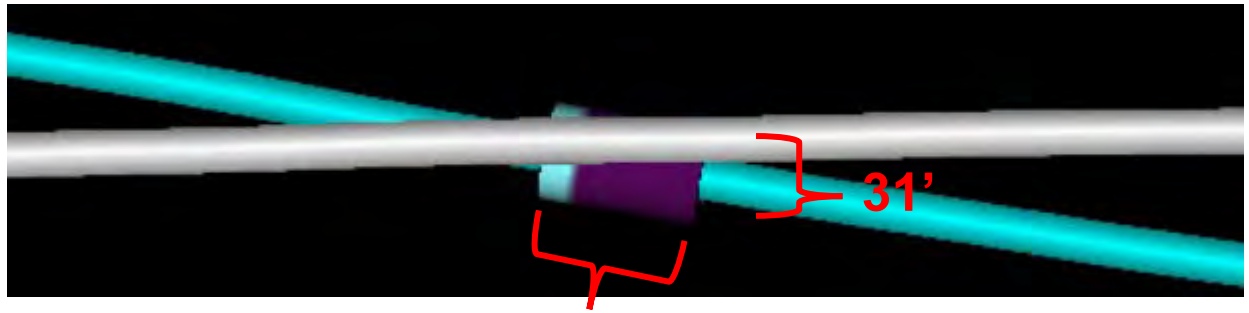
85’ same depth

105’ lowest depth

Core Summary – Middle Wolfcamp

- Recovered ~159 feet of core in Middle Wolfcamp in 2 coring trips
  - Core 5 – 34’
  - Core 6 – 125’

Side View

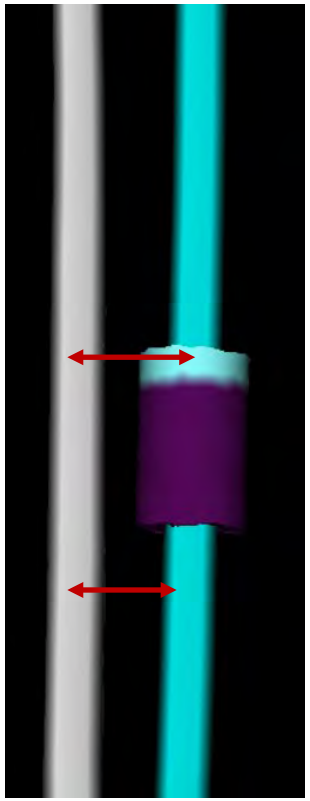


Z-Distances
1’ above 6SM
30’ below 6SU

X-Distances
105’ highest depth

93’ lowest depth

Plan View



HFTS 1 Slant Core Well #1 Highlights

- Over 700 fractures noted in core
- 323 HF's in the Upper Wolfcamp
- 51 HF's in the Middle Wolfcamp
- Recovered proppant in many HF's and also in core sludge collected in the core tubes
- Installed 8 isolated pressure gages to monitor reservoir pressure, 5 still work today

Image courtesy: Laredo Petroleum

Offset UW&MW Well Completion Comparison

- UW Well
  - 3 x 90', 1100 lb/ft
  - 2.5' cluster length with 15 shots @ 60° phasing
- Upper Wolfcamp core (436')
  - 323 HF's
    - 1 HF every 1.3 ft
  - 607 Total fractures
    - 1 fracture every 0.7 ft

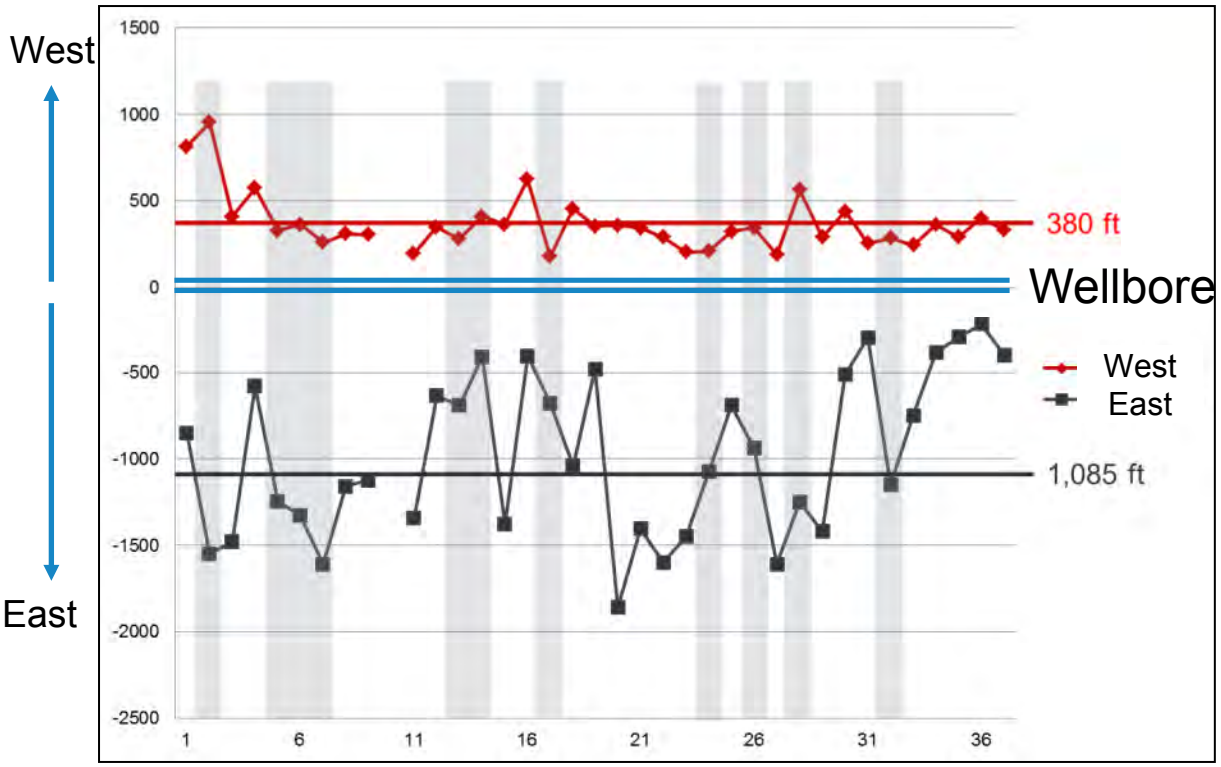
UW = 2.31xMW

UW = 2.35xMW

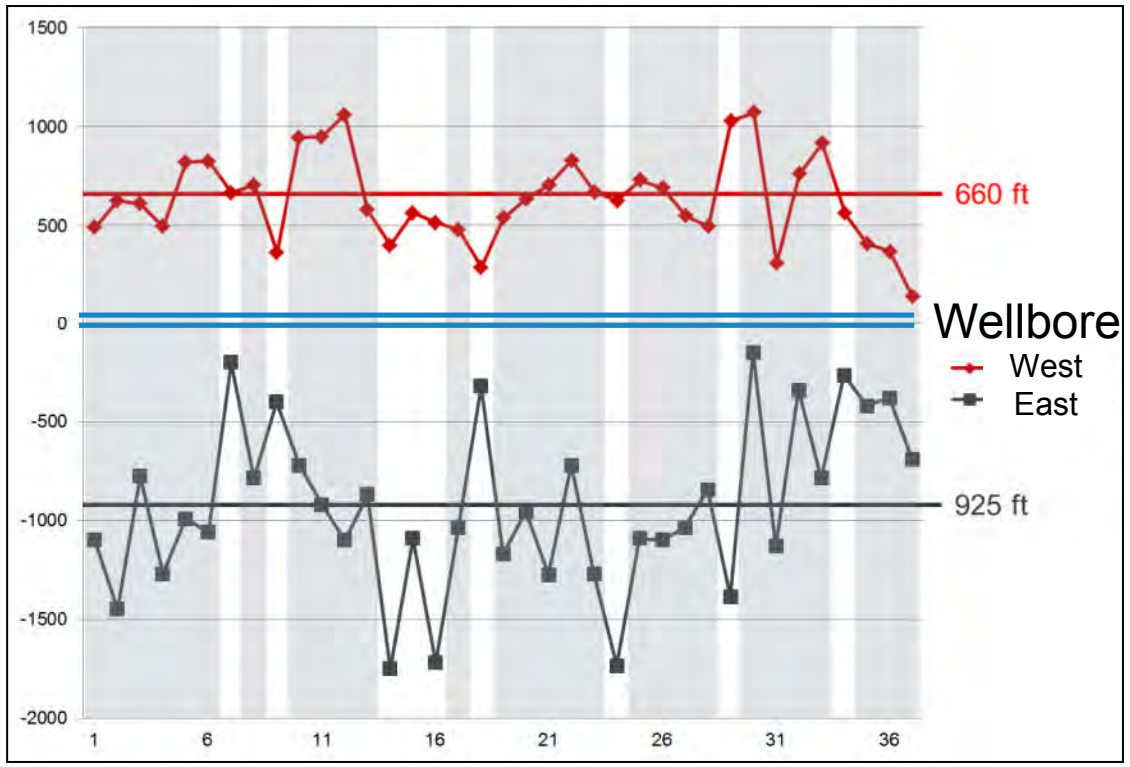
- MW Well
  - 3 x 90', 1100 lb/ft
  - 2.5' cluster length with 15 shots @ 60° phasing
- Middle Wolfcamp core (159')
  - 51 HF's
    - 1 HF every 3.1 ft
  - 94 Total fractures
    - 1 fracture every 1.7 ft

Implied Fracture Extension (Half Lengths) from MSM Data

UW Well



MW Well



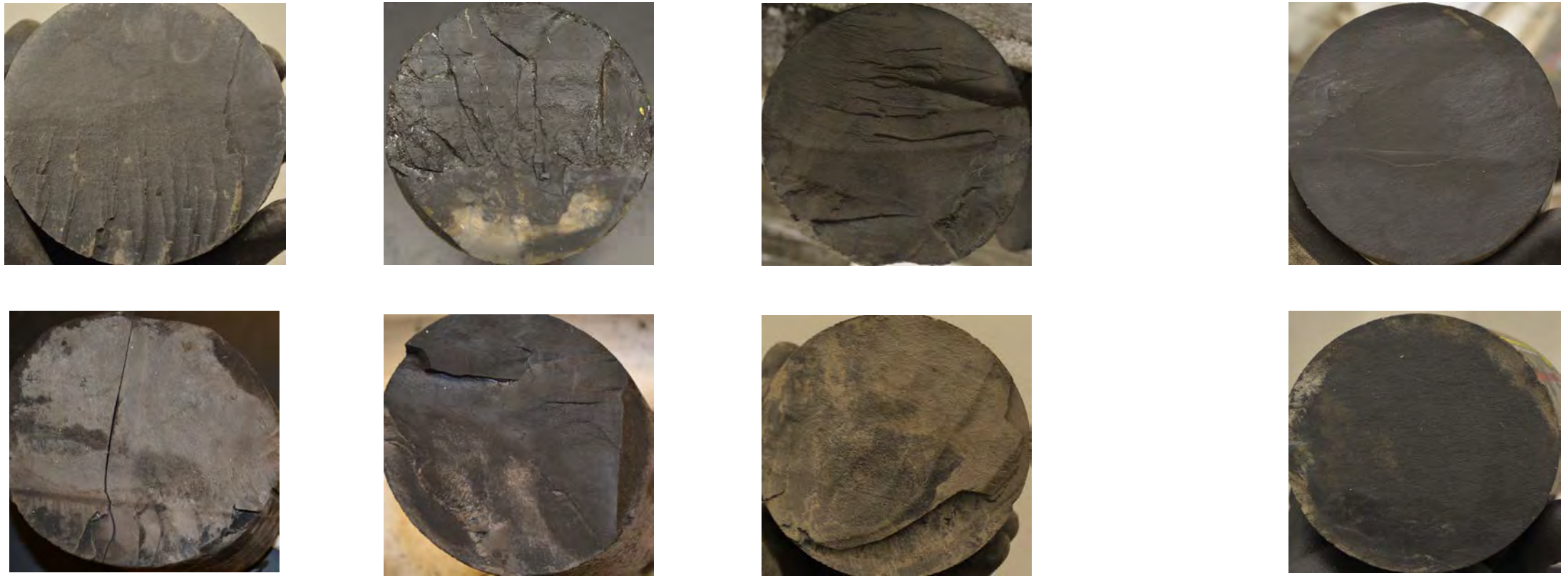
- UW Well fracture half-length much shorter in MW well, likely due to higher HF density
- Significant variability of half length to the east (negative black values) likely a result of observation bias, the horizontal monitoring array was in an adjacent hz. well to the west (top of each figure).

Selected Slant Core #1 Information

Hydraulic Fractures in Core – Variable Morphology

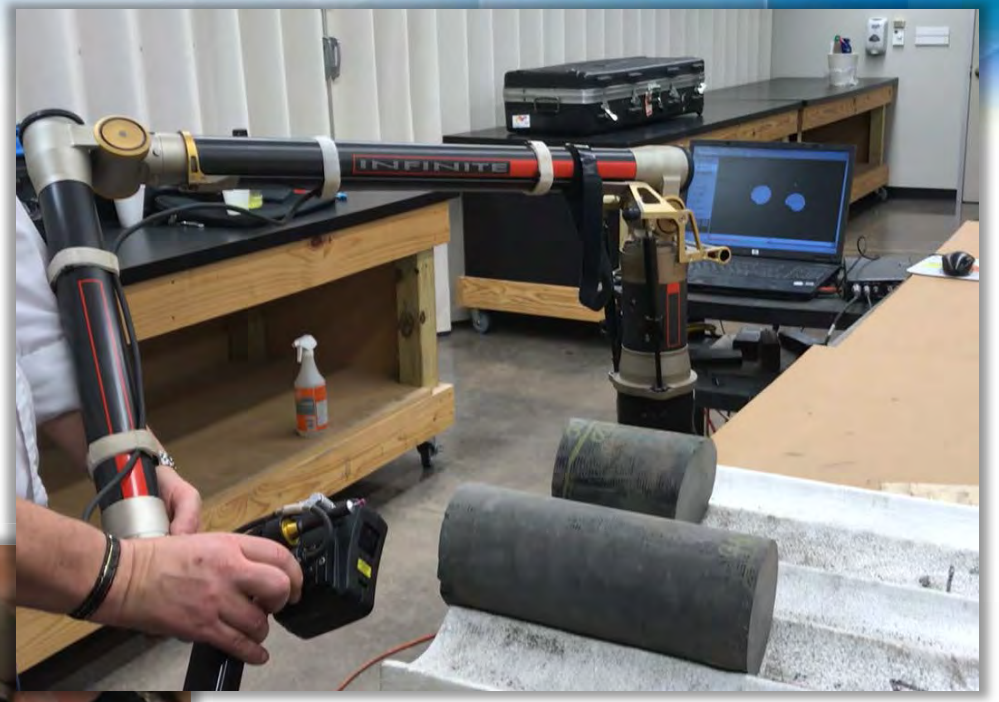
Complex breaks, irregular patterns, stepping planes

Smooth planar surfaces



3D Laser Scans of Fractures

- Permanently preserve fracture features, 50µm (human hair)
  - "Digital magnifying glass"
  - Scans can be used for systematic interpretation, either visual or machine learning
  - Fracture type including propagation direction and mechanism
  - Print core and fractures on 3D printer for future display, demonstrations



Example of Picture vs 3D Fracture Scan

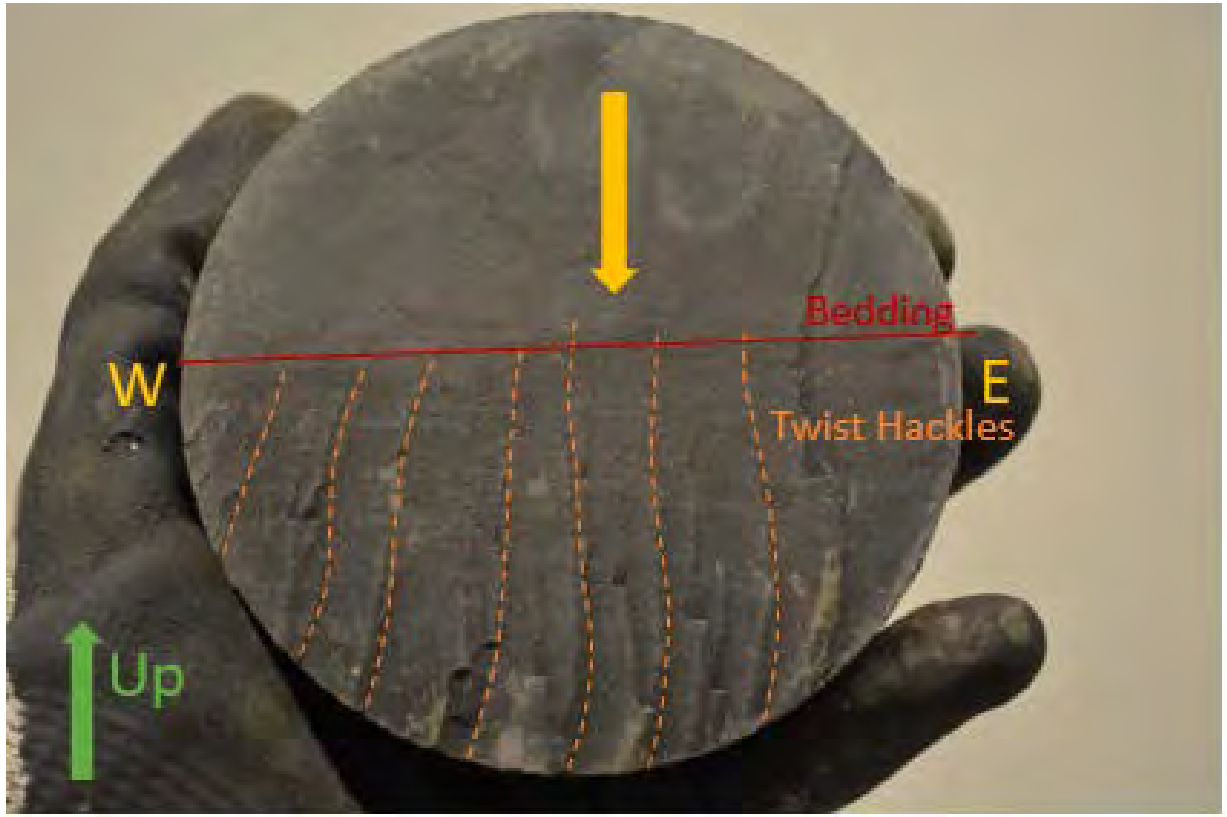
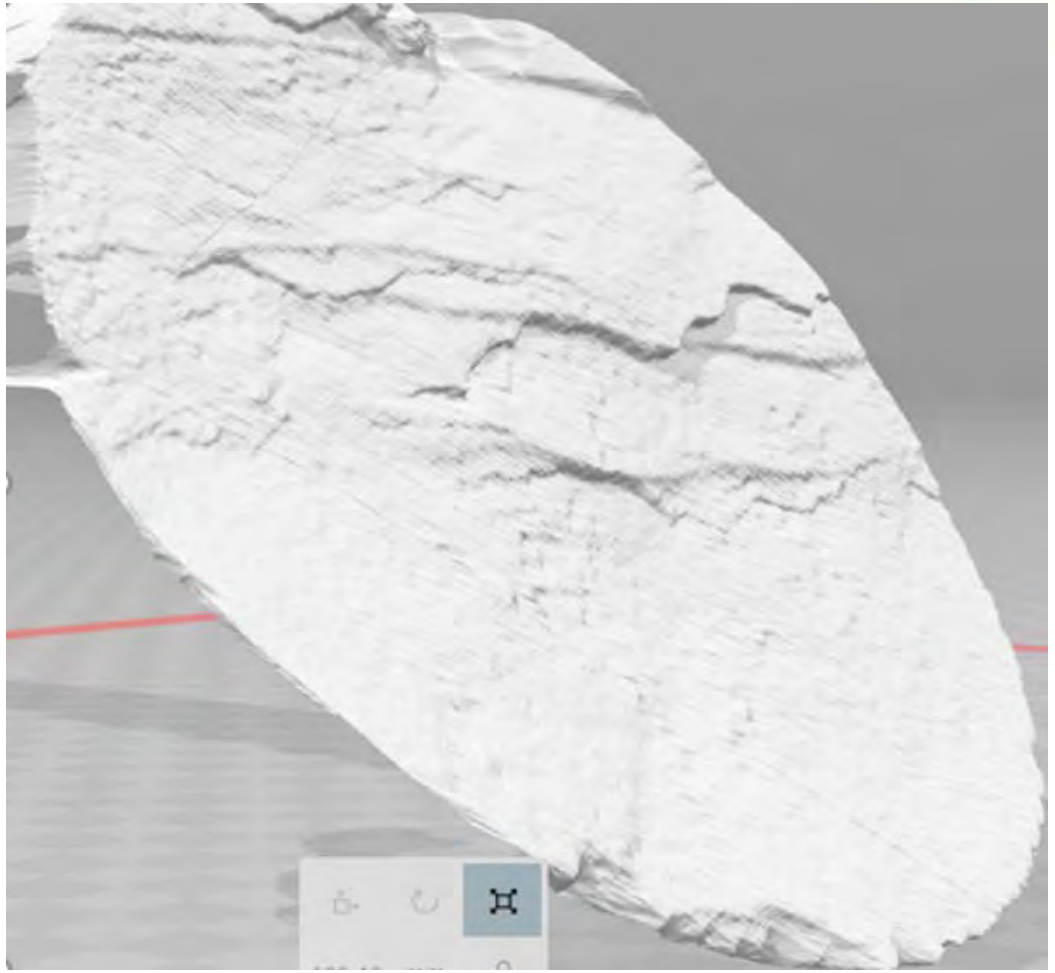
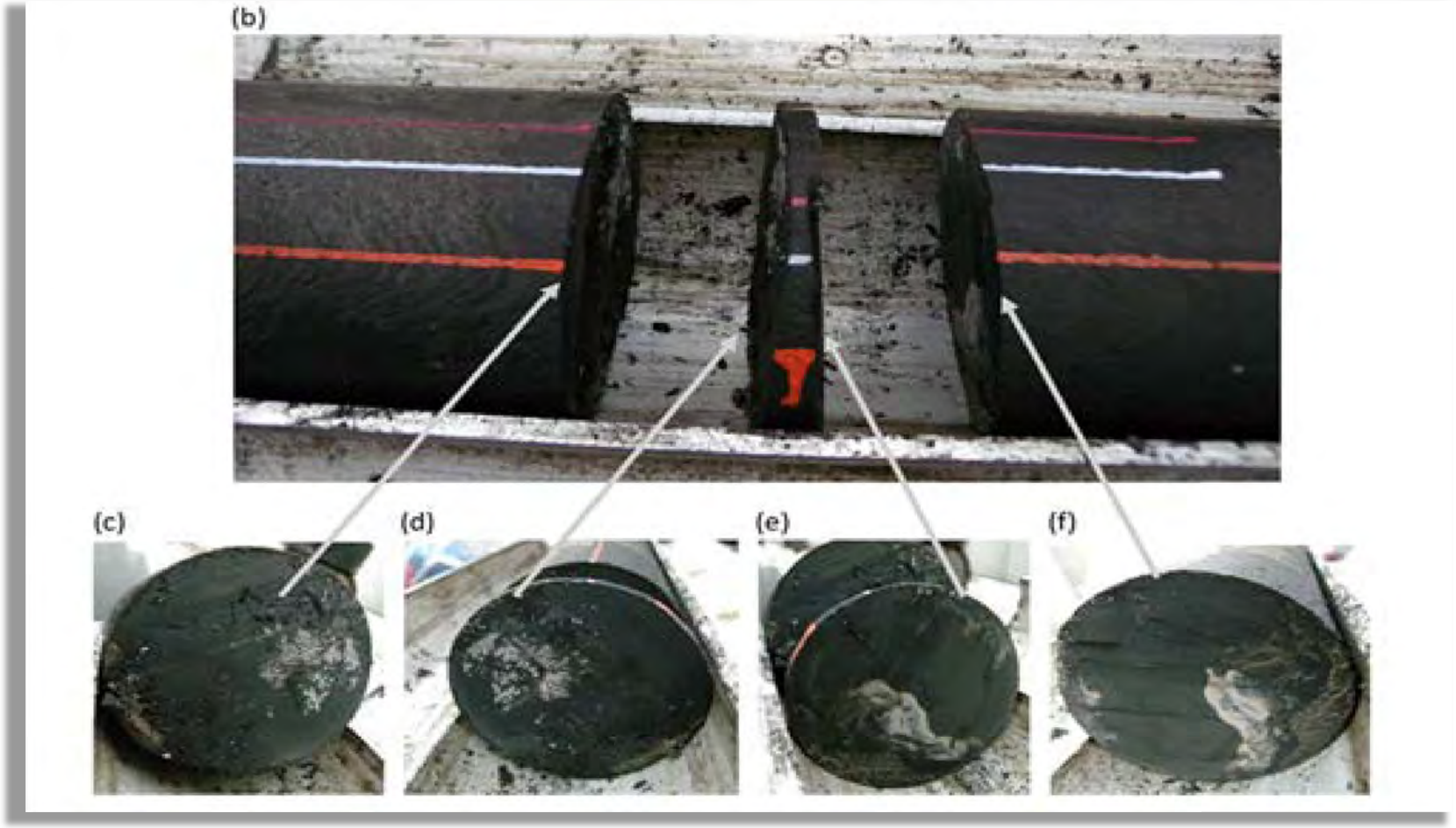


Image Courtesy ConocoPhillips



Hydraulic Fractures in Core

Doublet – 2 competing fractures



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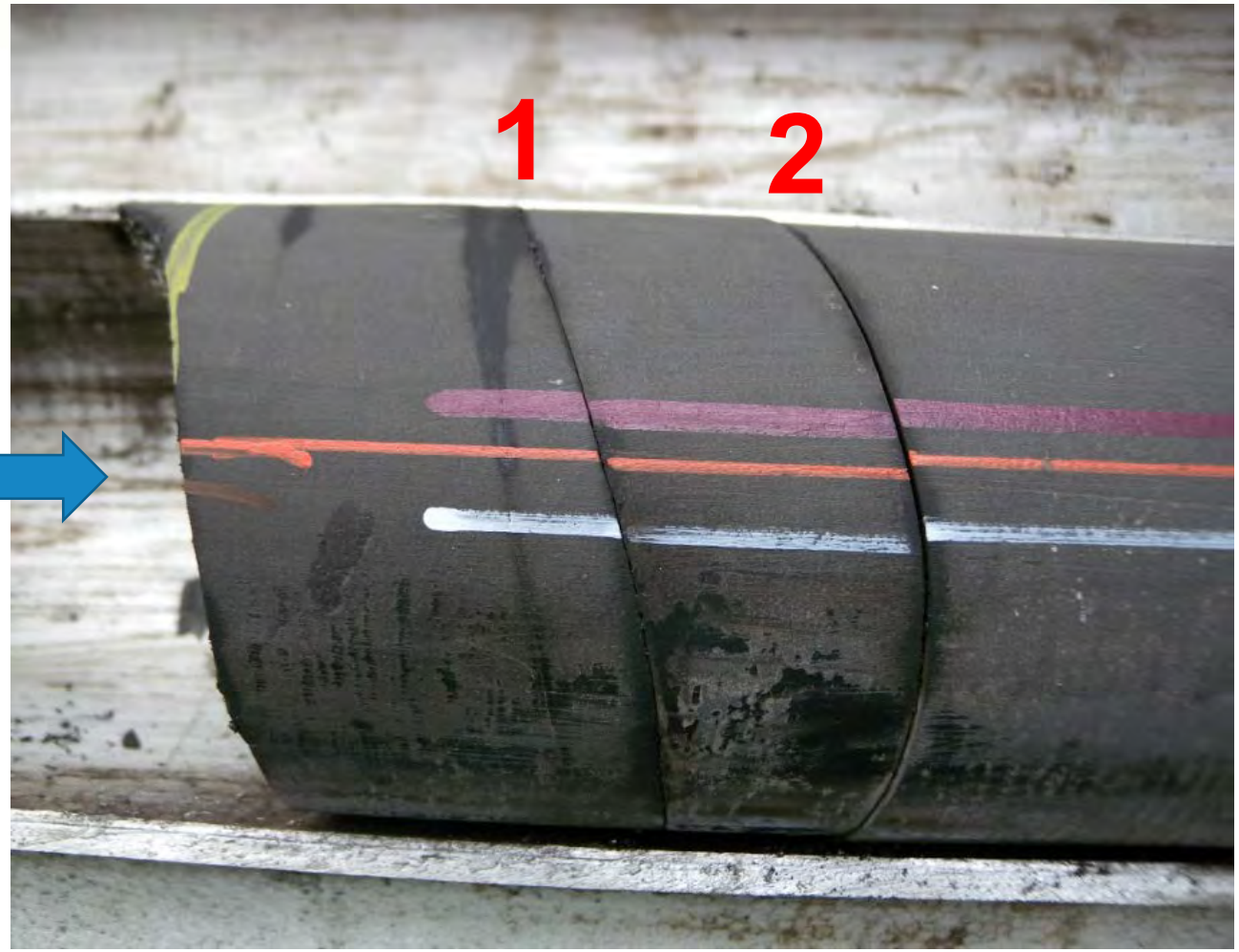
Hydraulic Fractures in Core

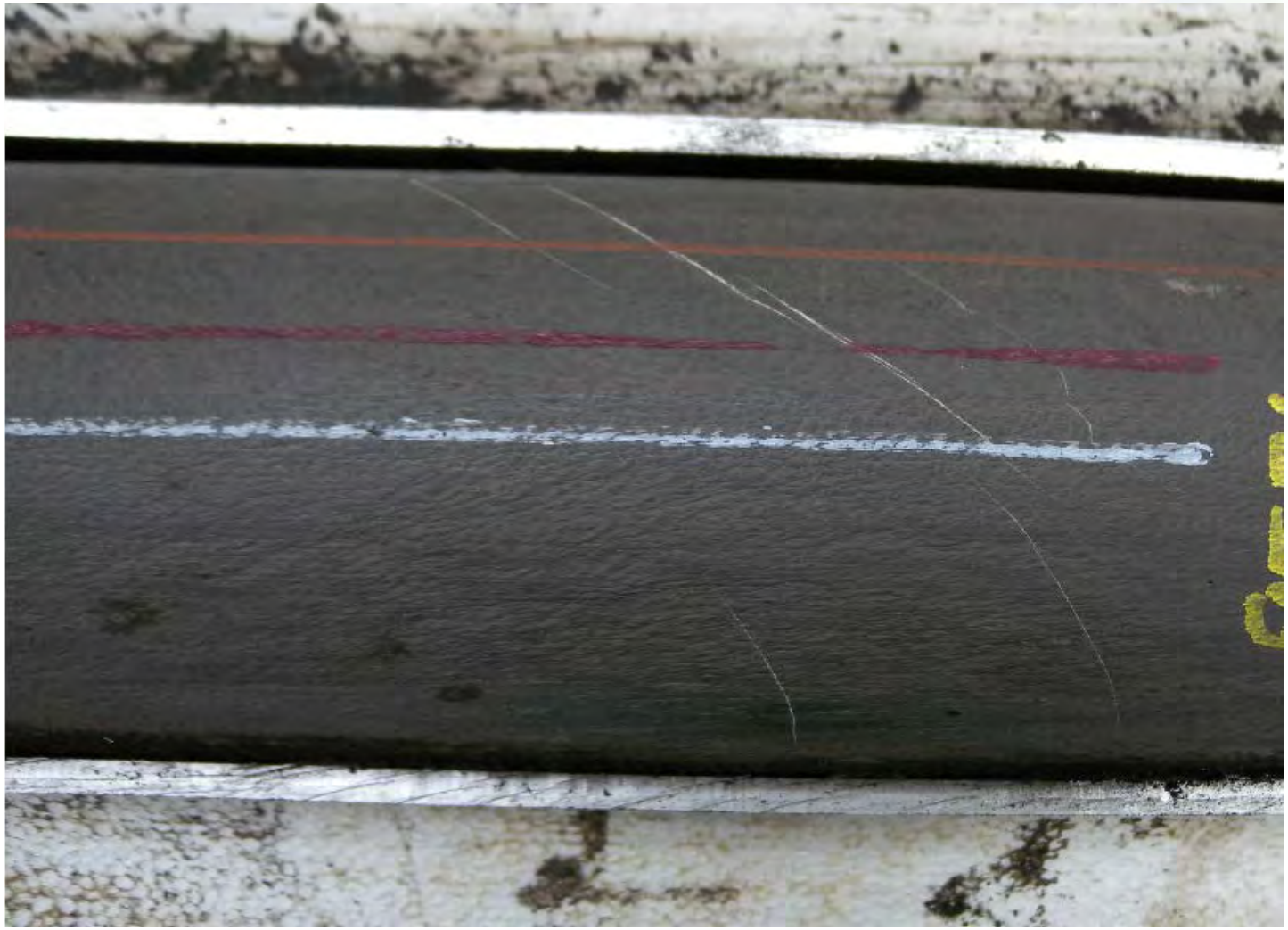
More competing fractures



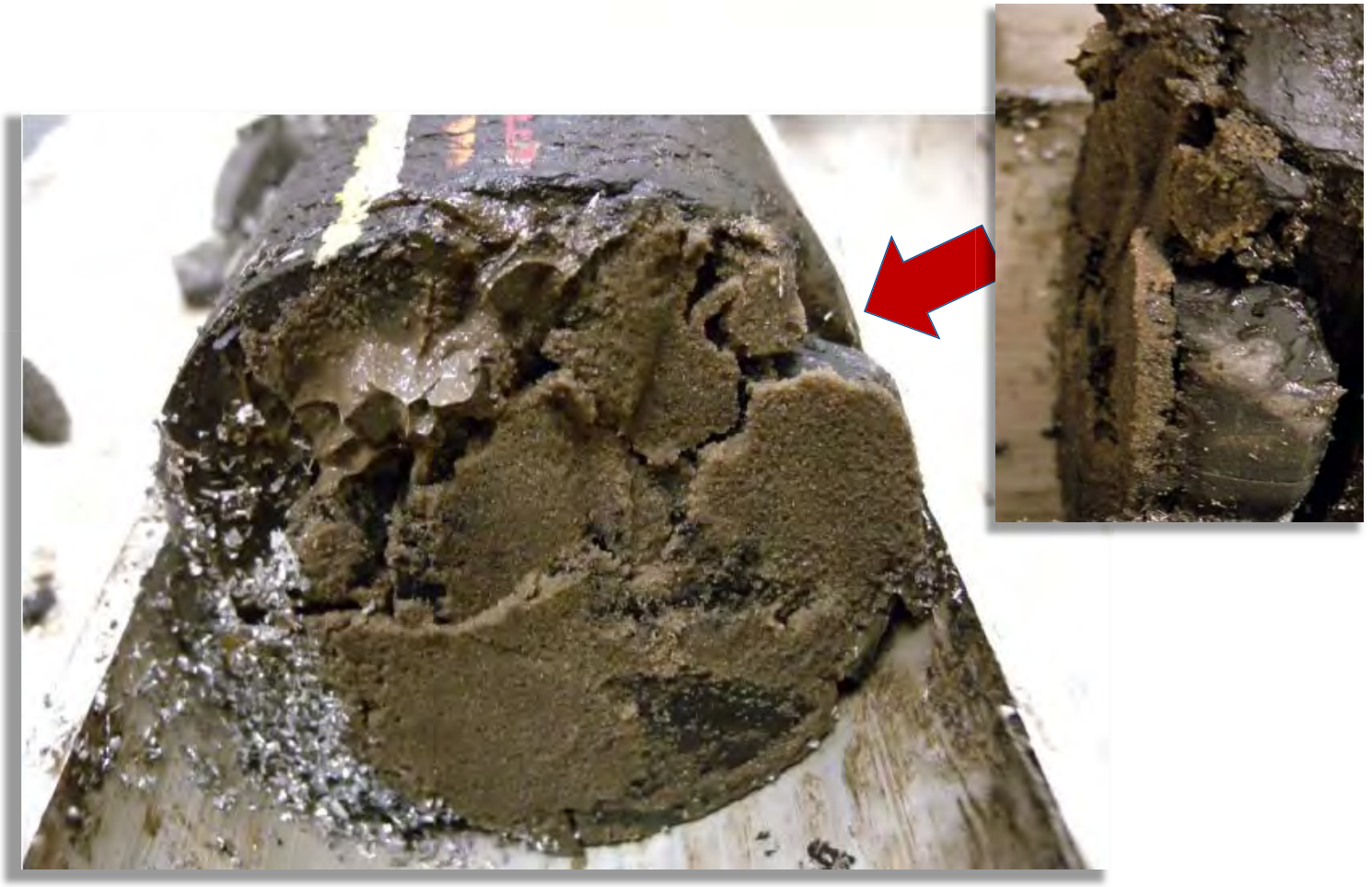
- Which fracture came first, second, third?
- Same time?
- How can we tell: orientation, surface features from 3D laser scan?

Natural Fractures in Core

- 5 discontinuous NF's
- Useful section for modeling discrete fracture network at this scale
- Useful section to calibrate & QC the image log,
- Compare to CT scans



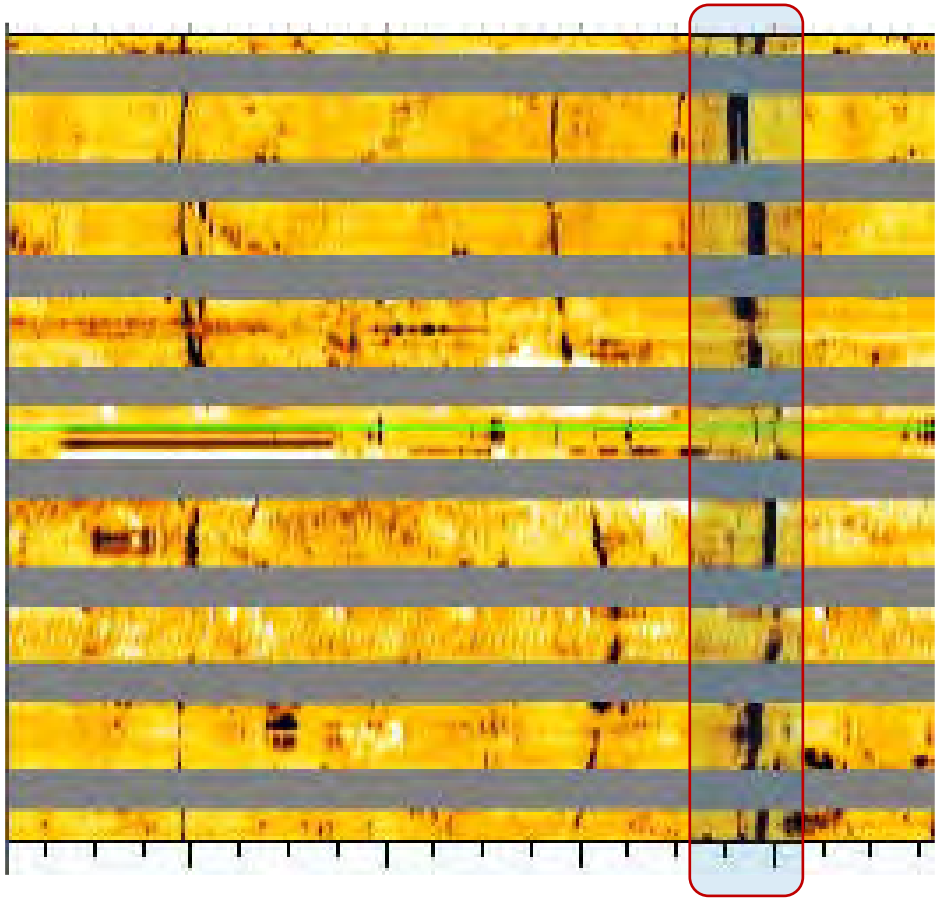
Fracture and Proppant Features Captured in Core



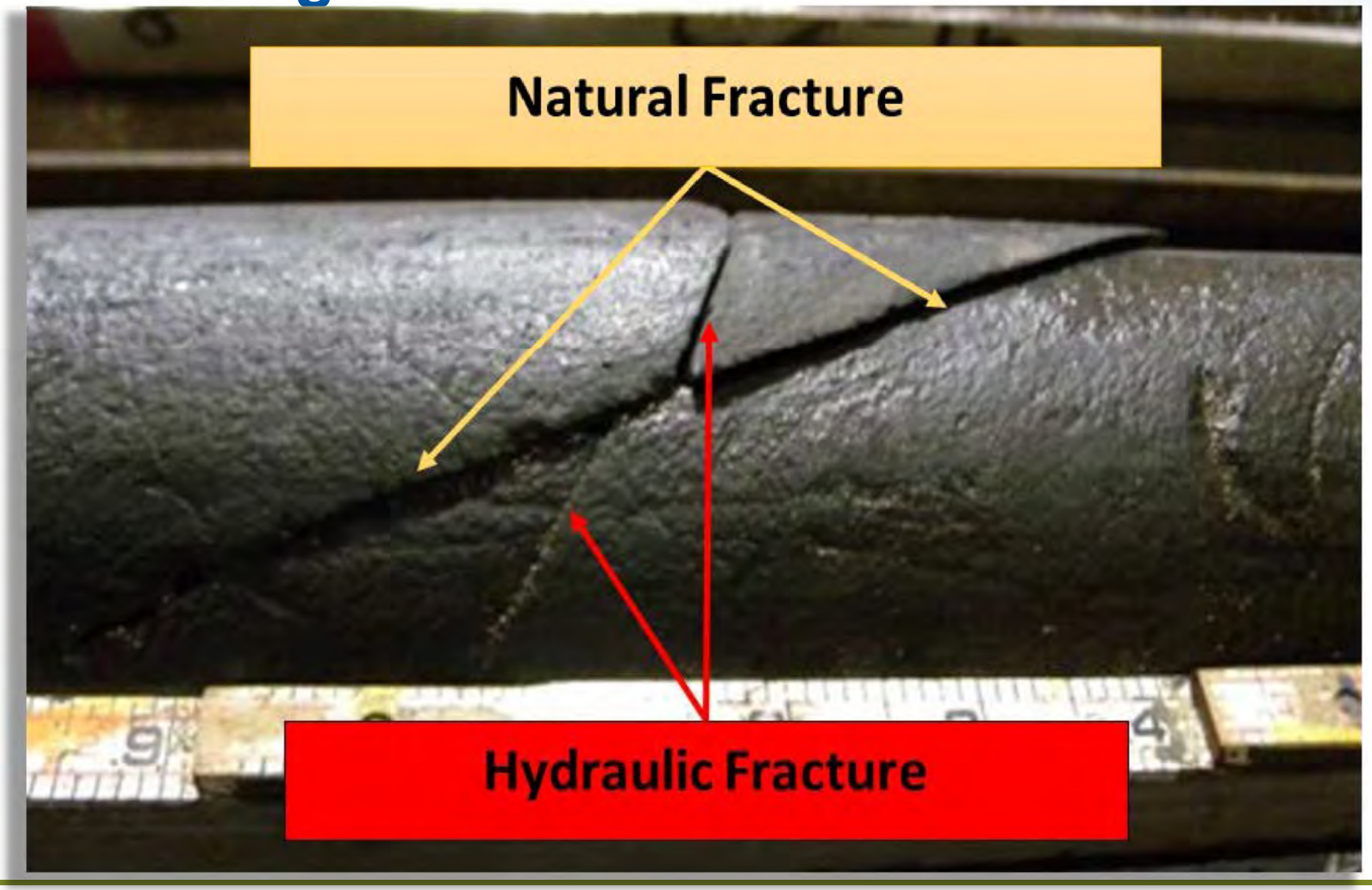
Tortuous path for proppant

Proppant Pack in Image Log

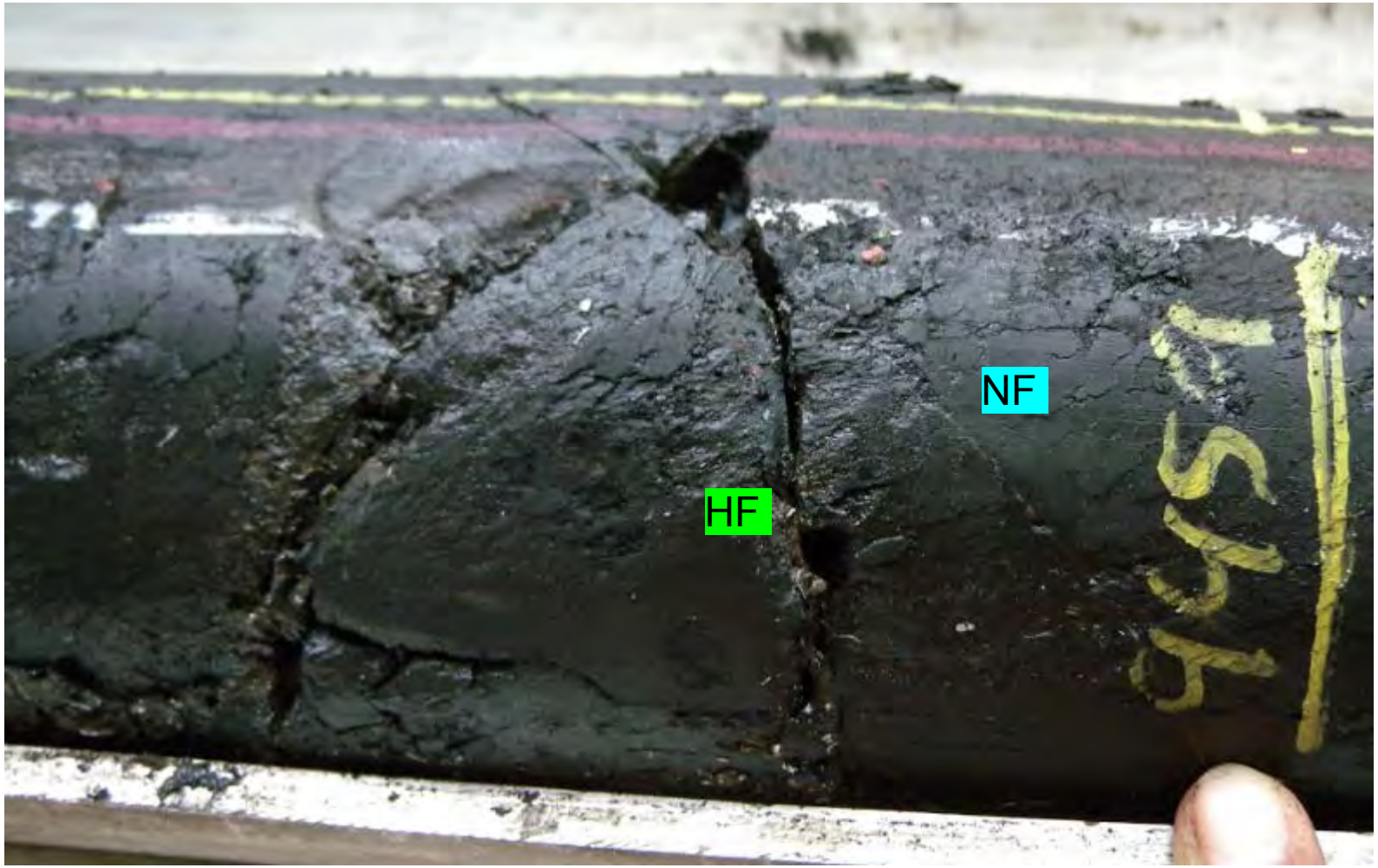
Many open fractures captured in image log
Sealed fractures difficult to discern



HF Intersecting NF

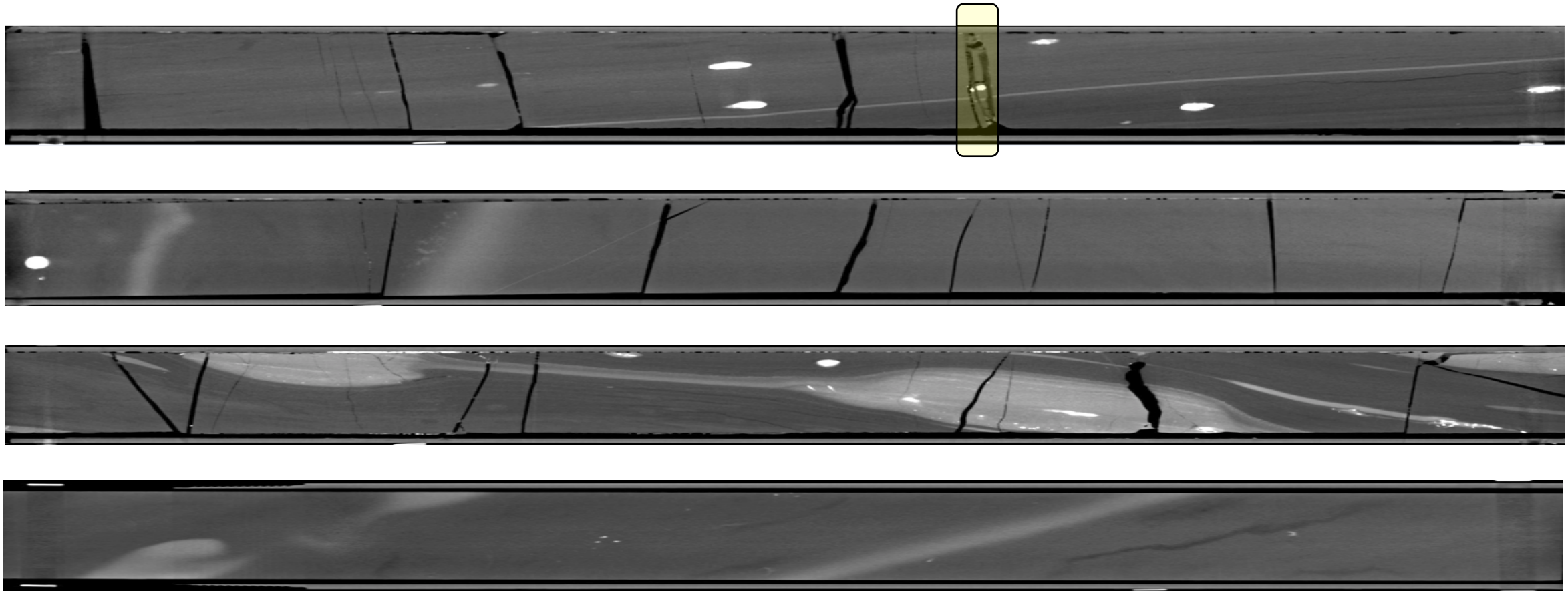


Proppant in HF/NF Complex



SRV Core CT Scans – Non Uniform Fracture Spacing

3 foot sections – some with >12 fracs, others 0



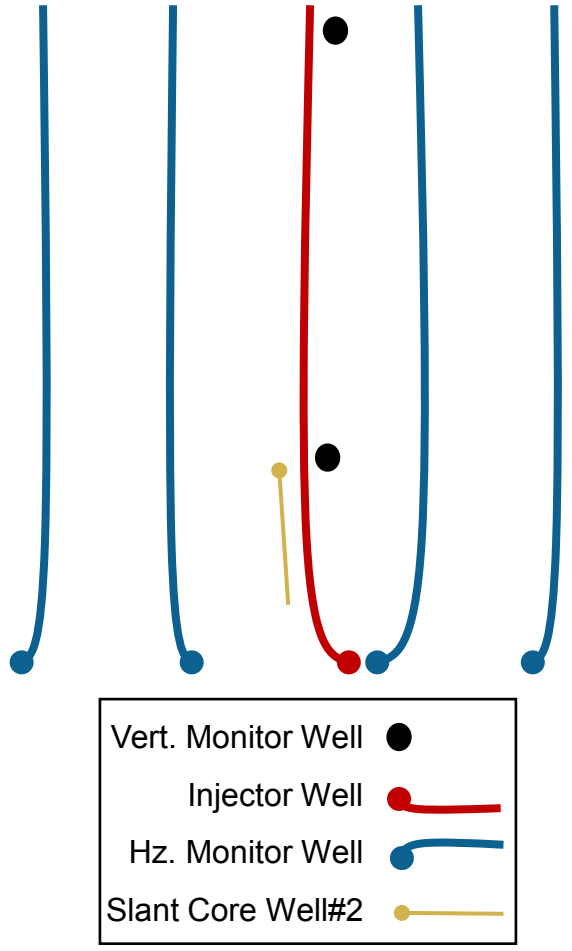
HFTSI Phase 2 – EOR – Huff-and-Puff Pilot

H-n-P Pilot Details

Determine the effectiveness of cycling gas injection (huff-and-puff) in increasing oil recovery from the Wolfcamp shale. Tasks:

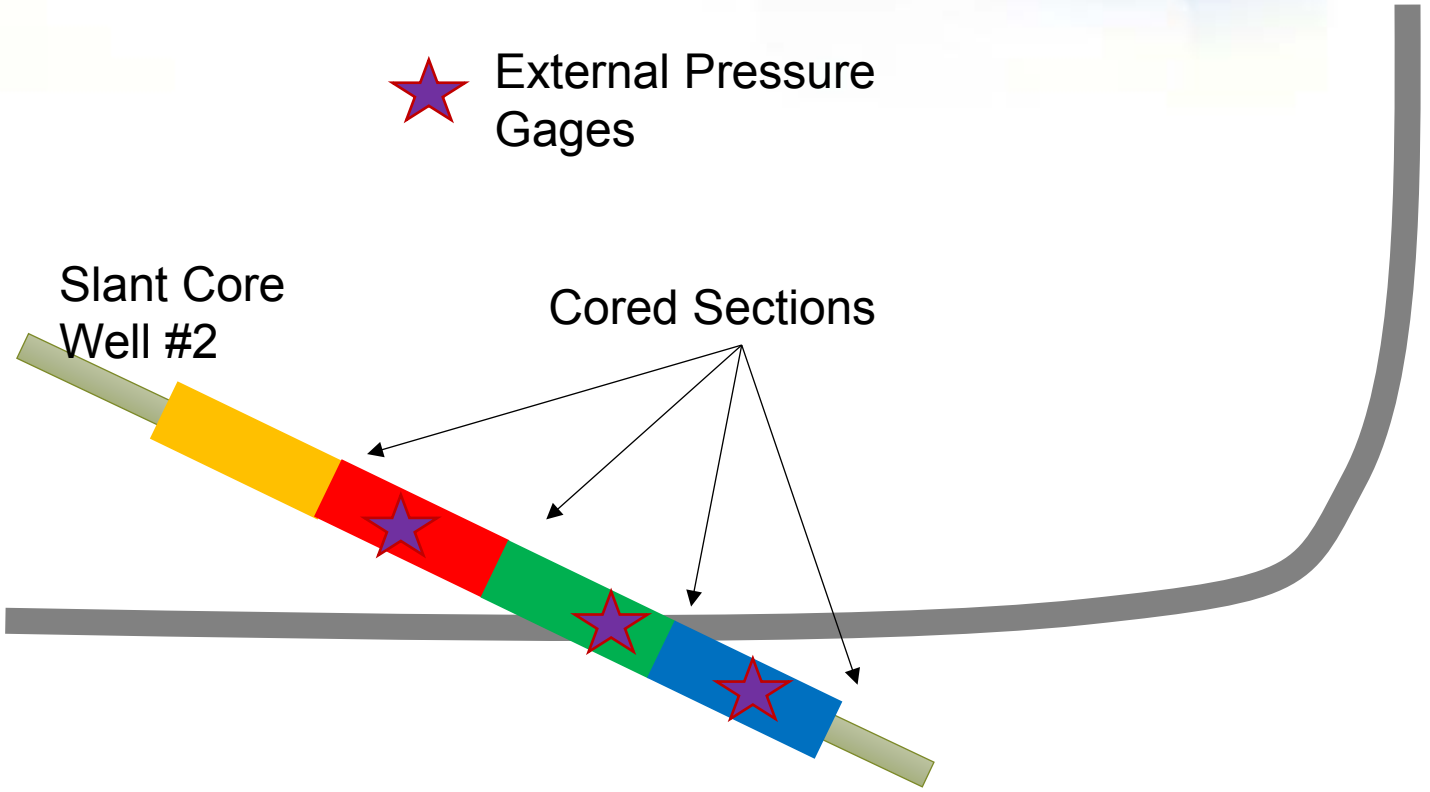
- Perform laboratory experiments to determine PVT behavior, MMP slim tube analysis, swell testing, etc.
- Perform a series of core flow experiments using slant core well plugs to determine incremental oil recovery, varying injection fluids, varying pressure conditions
- Perform a series of cyclic gas injections to determine if additional oil can be recovered, quantify the results

- New slant core well adjacent to injector well
  - Capture fractures in SRV
  - Water-based mud image log, OH quad combo logs
  - Multi horizon pressure gauges
  - Repeat PNLs through time to monitor oil saturation changes before, during, and after each gas injection



Slant Core Well #2

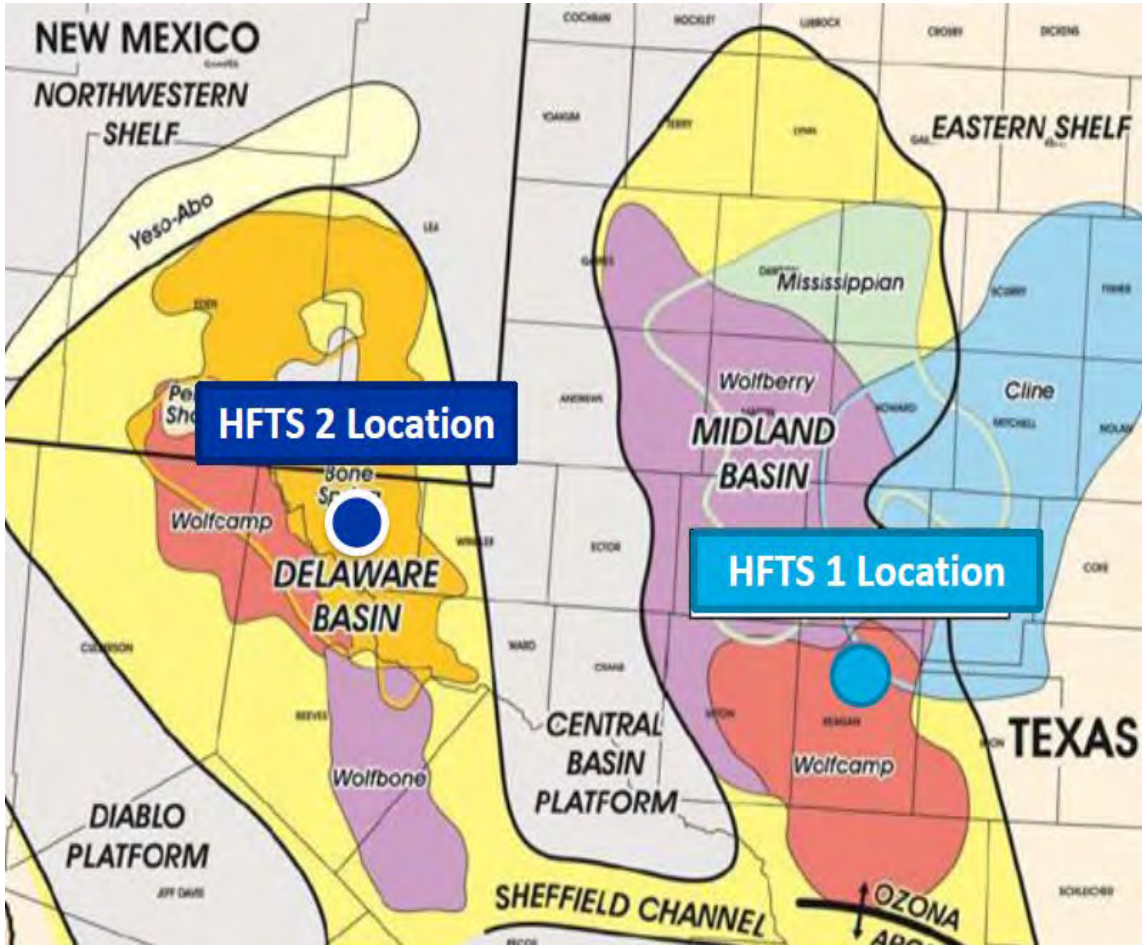
- Drilled in December 2018
- Adjacent to HnP well
- Collected 260’ of SRV core
- Installed 3 external, isolated pressure gages
  - Above, even, below injector
- Fracture description ongoing
- Collected samples for proppant analysis, ongoing



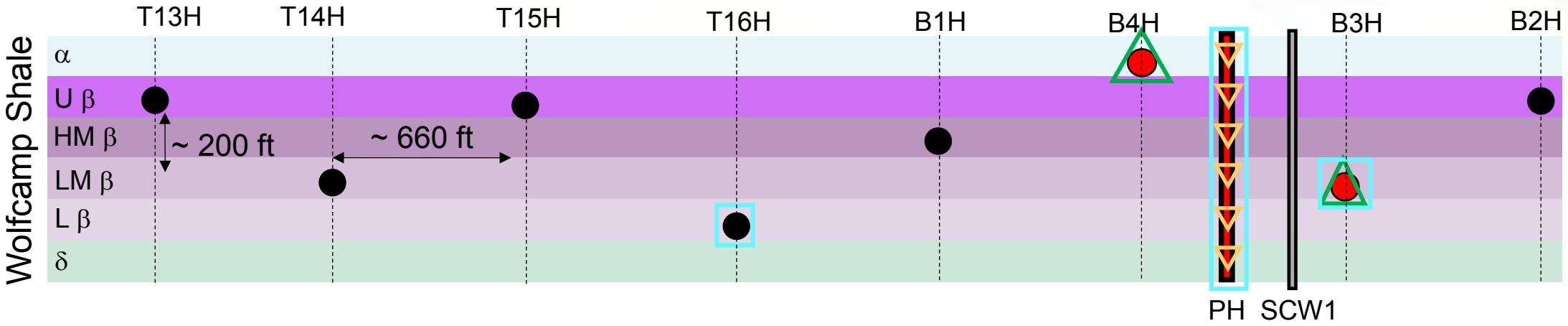
HFTS 2 – Delaware Basin

HFTS 2 Project Underway

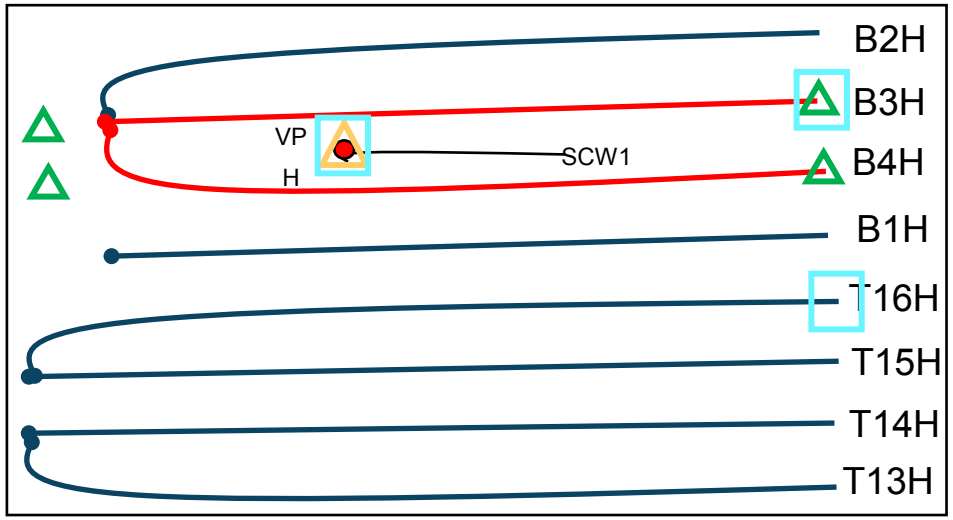
- Permian Delaware Basin, $25MM experiment
  - Anadarko/Shell test site host
- Leverage HFTS 1 learnings and experience
- Similar Objectives to HFTSI with upgraded experiments and diagnostics
  - **Permanent fiber optic monitoring in multiple wells, 2 horizontal and 1 vertical**
  - **Multi well, multi array BH microseismic, MTI capable**
  - **Test 5 producing targets, 2 tested in HFTS 1**
  - SRV coring, **fall 2019**
- Currently bringing wells on production, monitoring with BHG, FO
- Open to additional industry participants



HFTS 2 Project Well and Diagnostic Details



- *Vertical Pilot Hole with Permanent Fiber Optic and P/T Gages*
- *Production Horizontal Test Well*
- *Producing Horizontal Test Well with Permanent Fiber Optic*
- *Permanent P/T Gage at Toe and Heel of Horizontal Well*
- *Permanent P/T Gage in Vertical Well*
- *Conventional MSM Array in Vertical and Horizontal wells*
- *Planned Slant Core Well*



*Slant core well trajectory is notional at this time.

Final Thoughts

- The HFTS represents one of the most comprehensive hydraulic fracturing research projects (datasets) to date
- Public Private Partnerships leverage funding and expertise, and allow for fast dissemination of learnings and technology adoption
- Teamwork among the consortium was essential to the successful execution of the project

Thank YOU - HFTS I Members

Site Host

Thank YOU - HFTSII Members

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Thank You! For more info please contact:

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