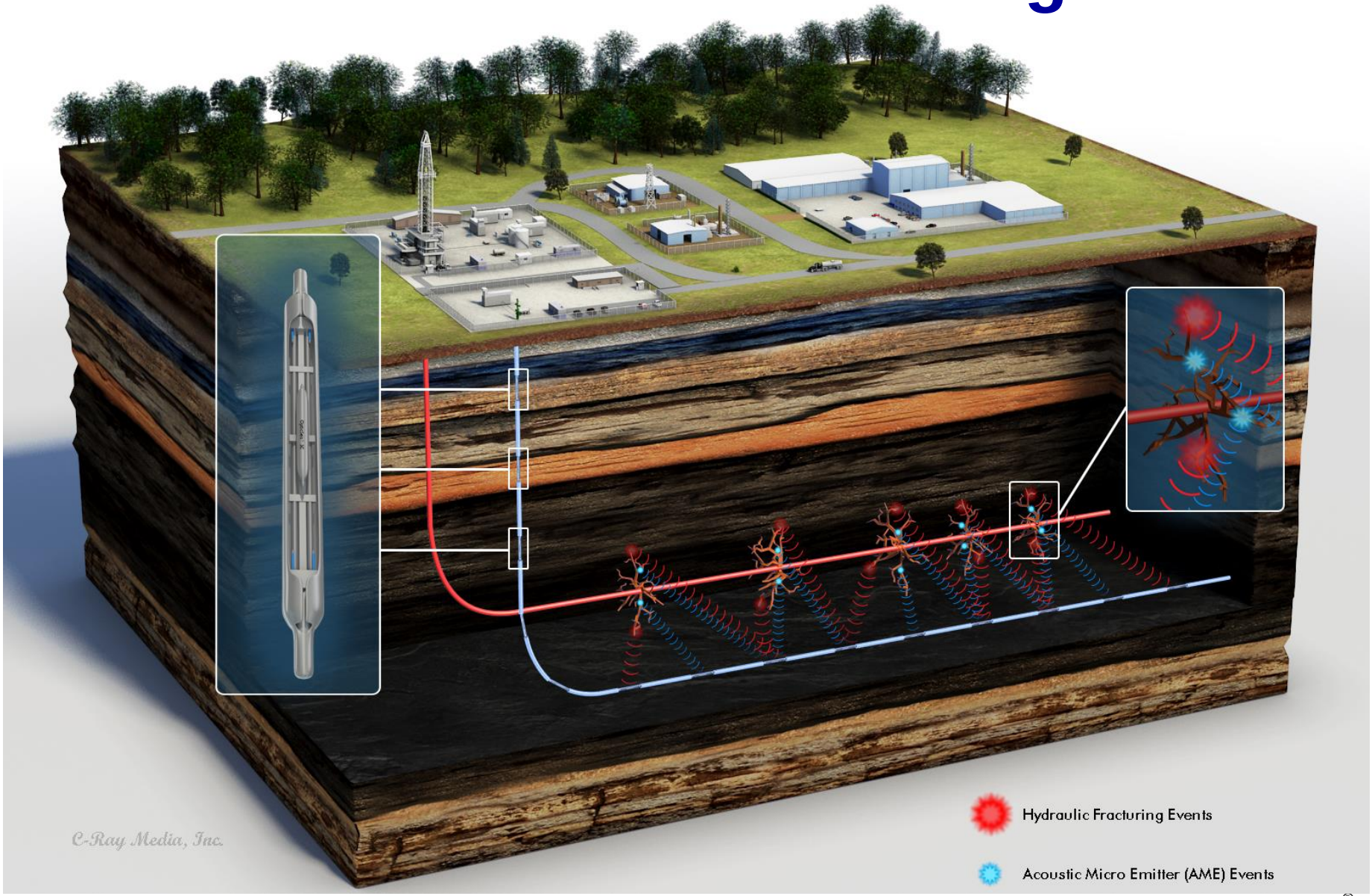
Paulsson, Inc. (PI)

Fiber Optic Seismic Vector Sensor (FOSVS)
tracking of
Acoustic Micro Emitters (AME)
to Optimize
Unconventional Oil and Gas (UOG) Development

August 1-3, 2017

Effective & Accurate Monitoring of UOG

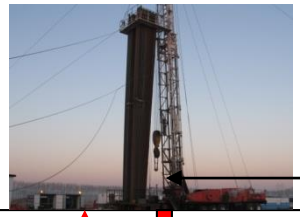


Key Technologies Presented

- **Large Seismic Array Technology**
  - **Key to Record and Track small Seismic Events**
- **Fiber Optic Seismic Sensors**
- **Acoustic Micro Emitters**

Borehole Seismic Imaging with Ultra long arrays

More Receivers = Better Images



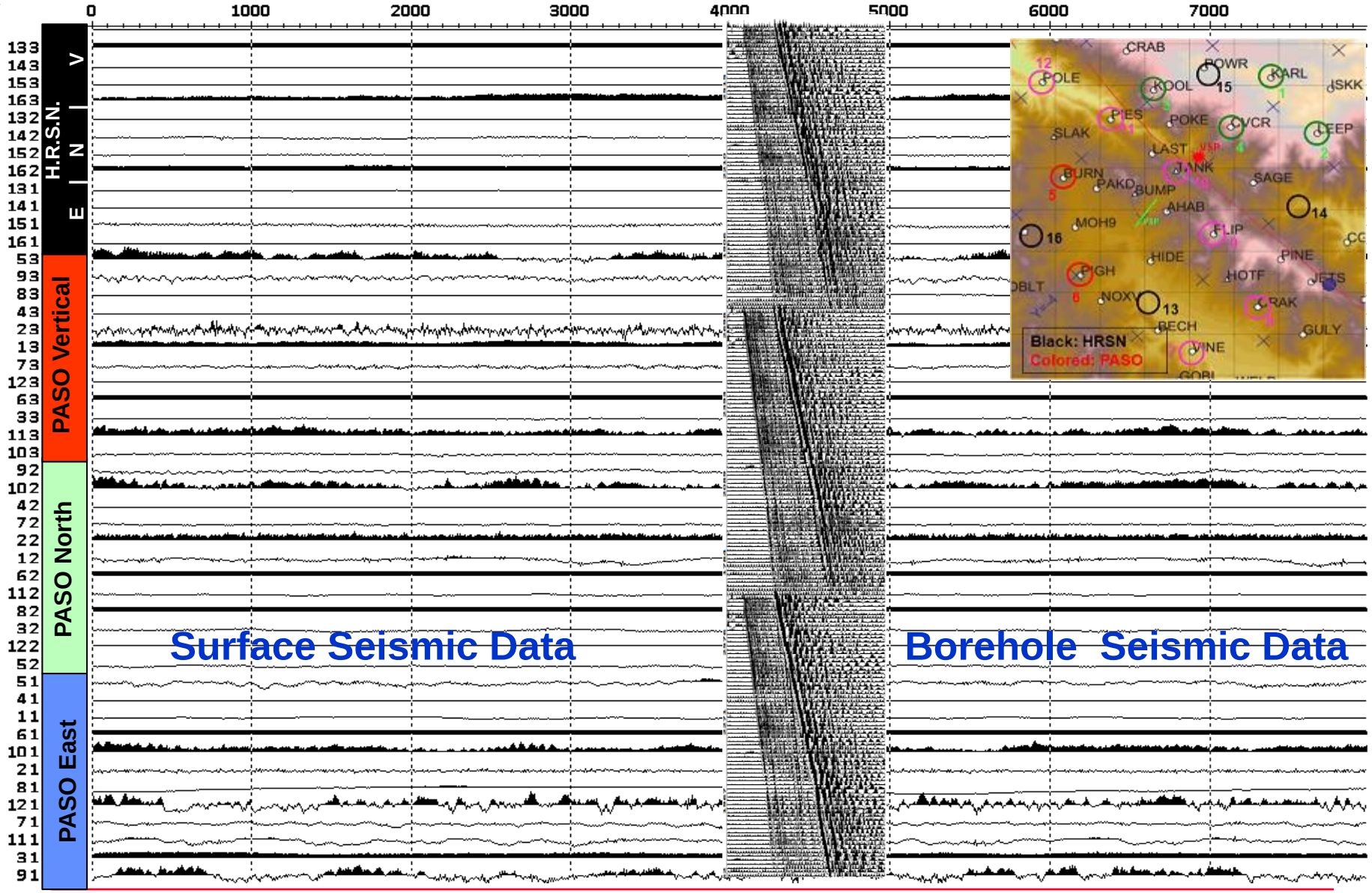
Interferometric Imaging using receivers below weathering layer

Long arrays provide the large reflection angle range needed for inversion of data

Interferometric Imaging of faults and fractures (sub) parallel to vertical or horizontal wells

PI: M-1.3

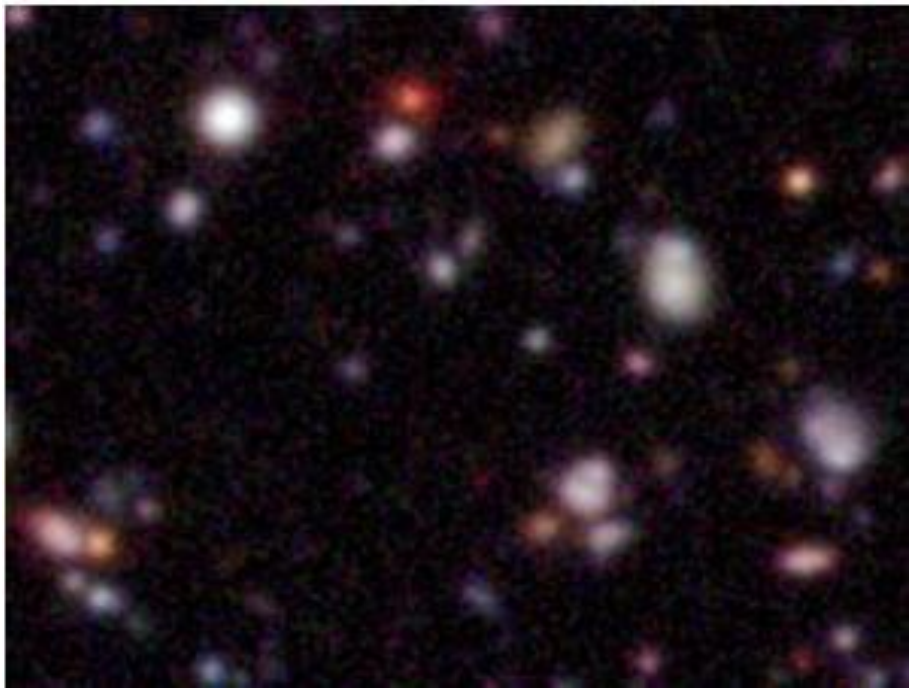
Micro-earthquake Event at SAFOD (4/30/2005 18:49:59)



Focus:
Develop Better Sensors
and
Deployed The Sensors Below The Noise!

Example From Space Exploration: Images From Same Region in Space

Earth Telescope

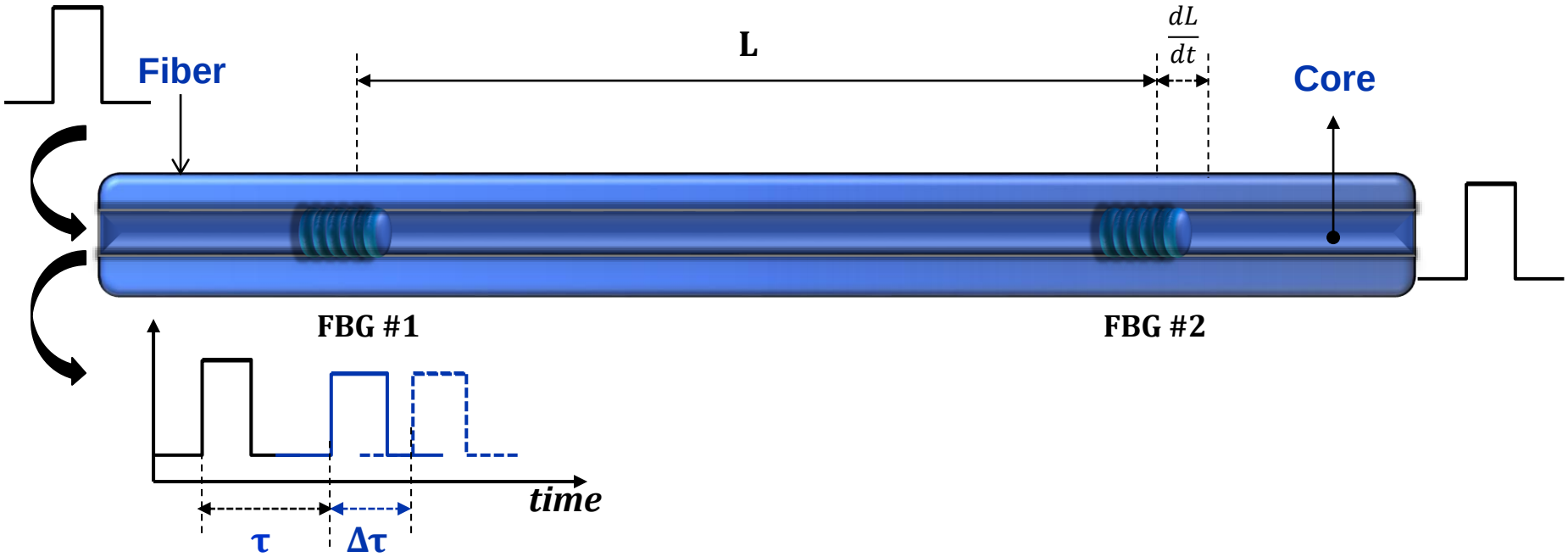


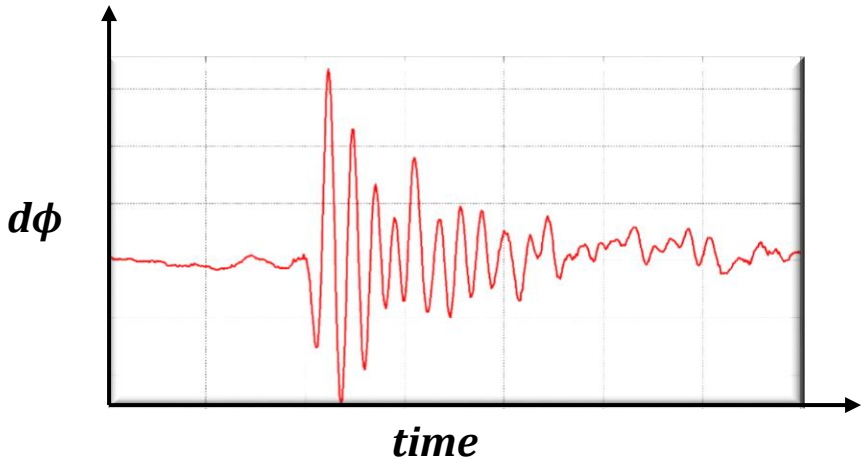
Hubble Space Telescope

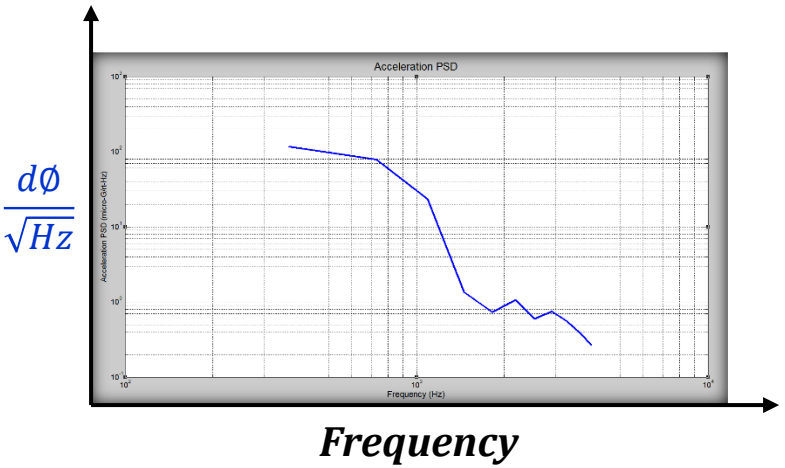
Borehole Seismology

- Large Seismic Array Technology
- Fiber Optic Seismic Sensors
- Acoustic Micro Emitters

Fiber Bragg Grating: Theory







Laboratory Test of Acoustic Micro Emitters using Fiber Optic Seismic Sensors

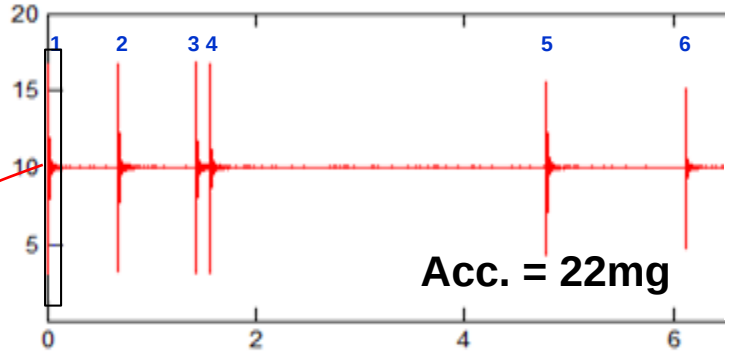
AME Test using Fiber Optic Seismic Vector Sensors (FOSVS)

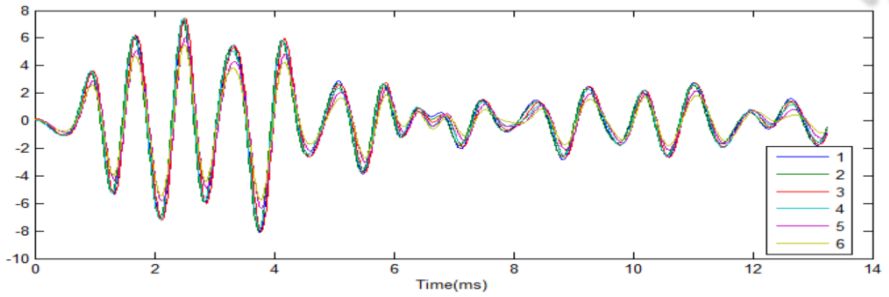
Pressure cell and sensor plate placed on a metal plate sitting on a foam mat on a metal table

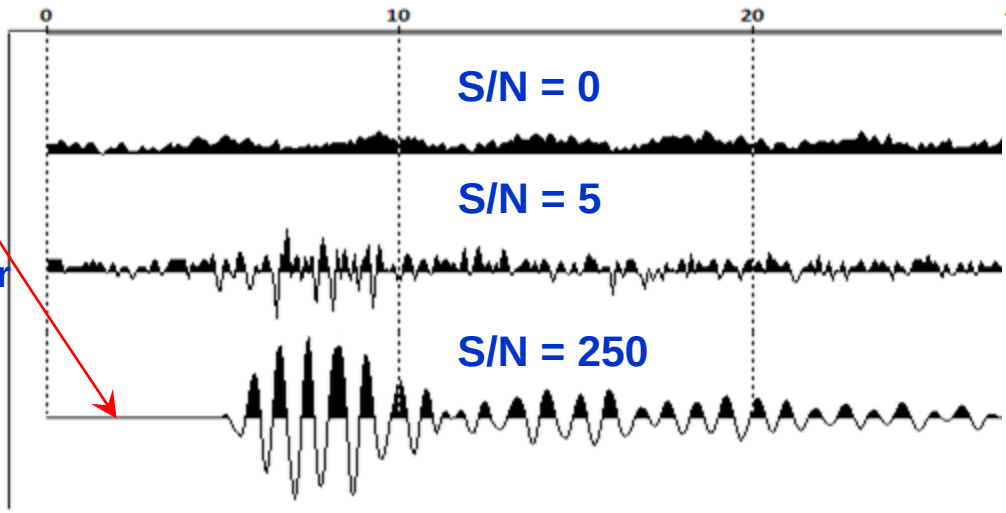
Fiber sensor, geophone and accelerometer are placed approximately 20 cm (8 inches) from the pressure vessel with AMEs

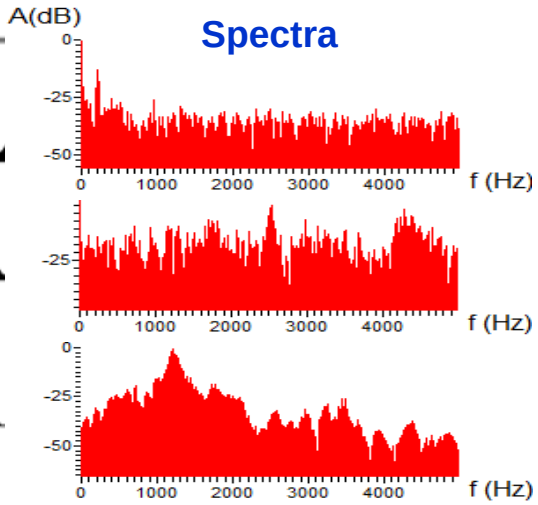
Repeatability Test: 6 AME's recorded on FOSVS: Outstanding Repeatability. Allow extraction of arrivals in high noise environ

Energy ~2J = M-2.9

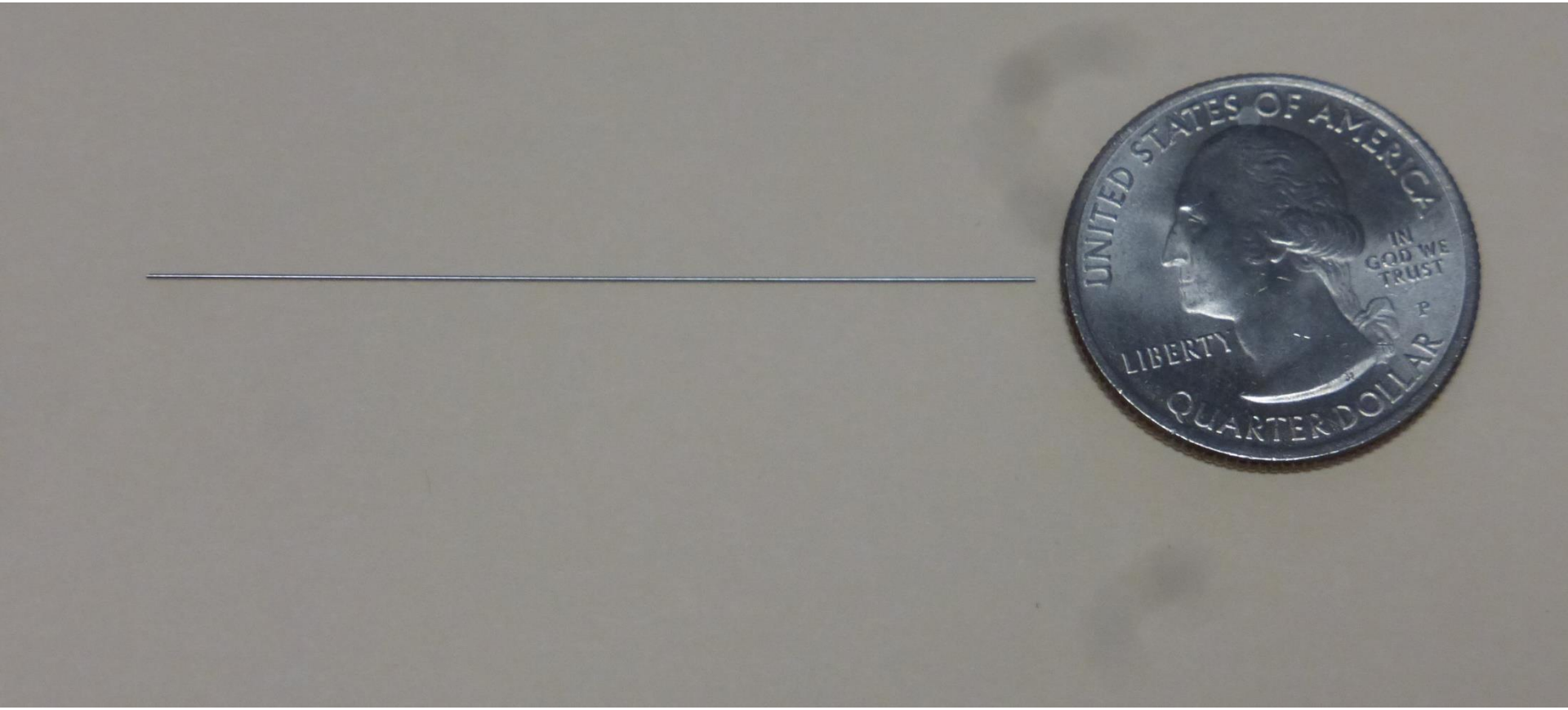






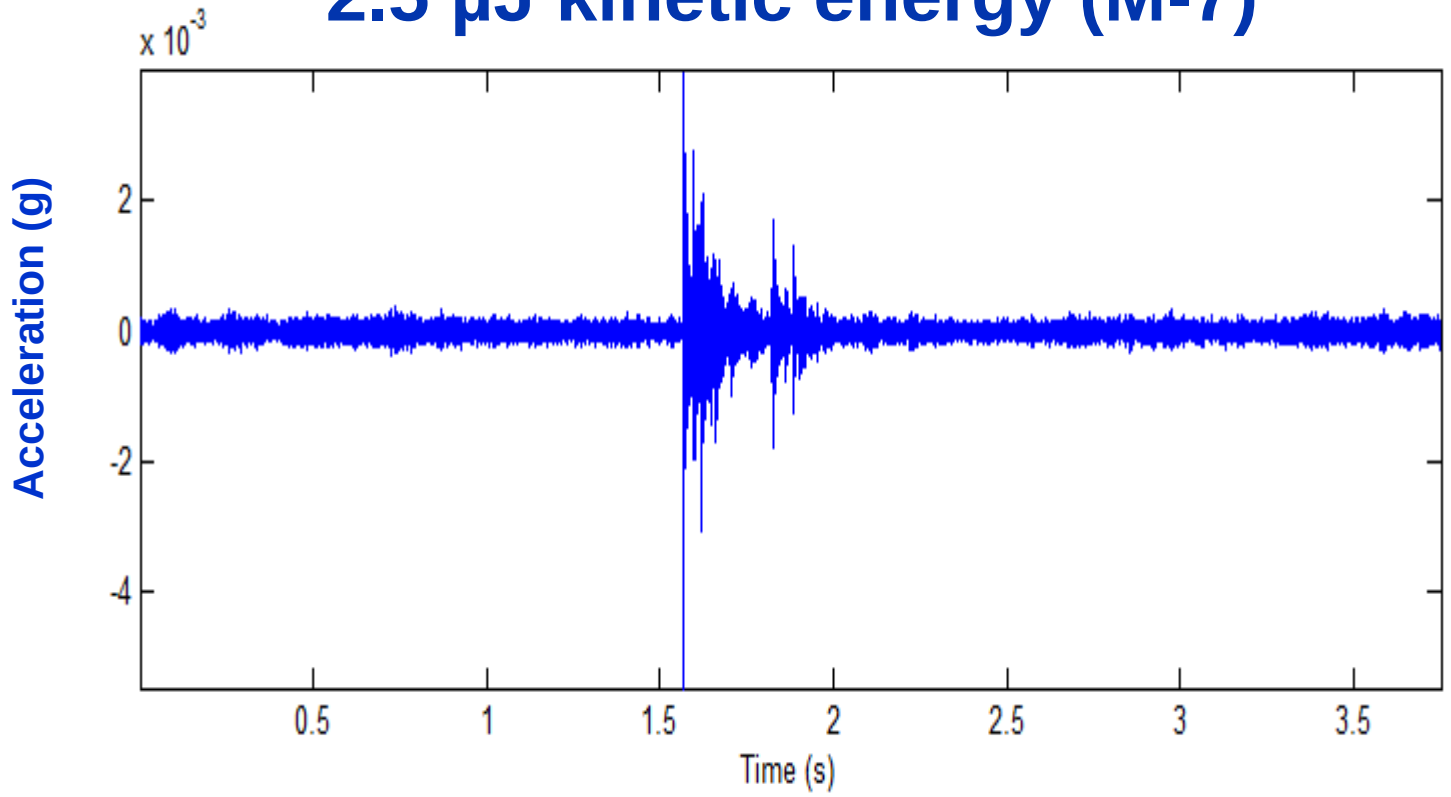


Can You Hear a Pin Drop?
Test Object: OD: 0.011”, 2” long, 24.8 mg



FOSVS Test: OD: 0.011”, 24.8 mg Pin Drop 1 cm:

2.5 µJ kinetic energy (M-7)



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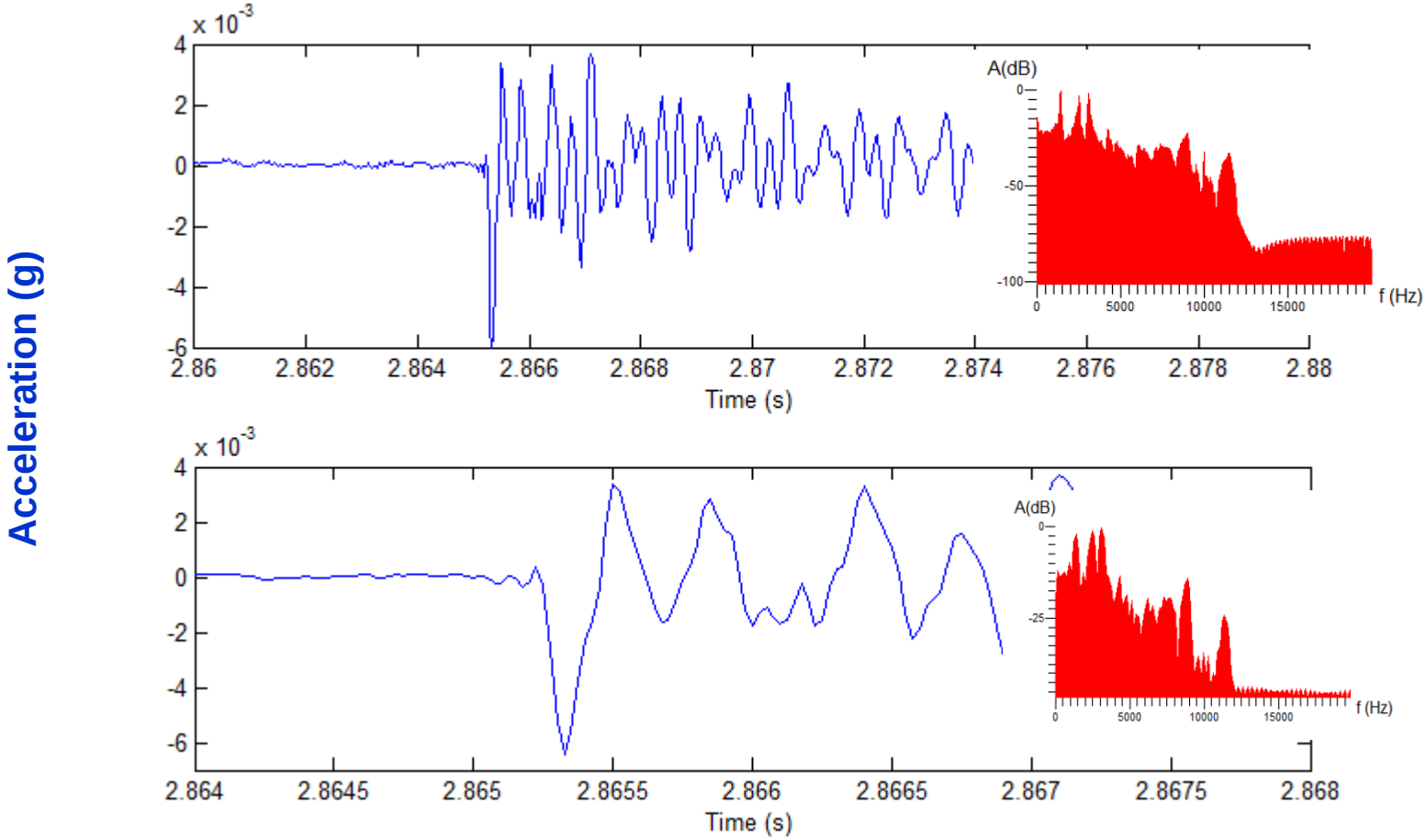
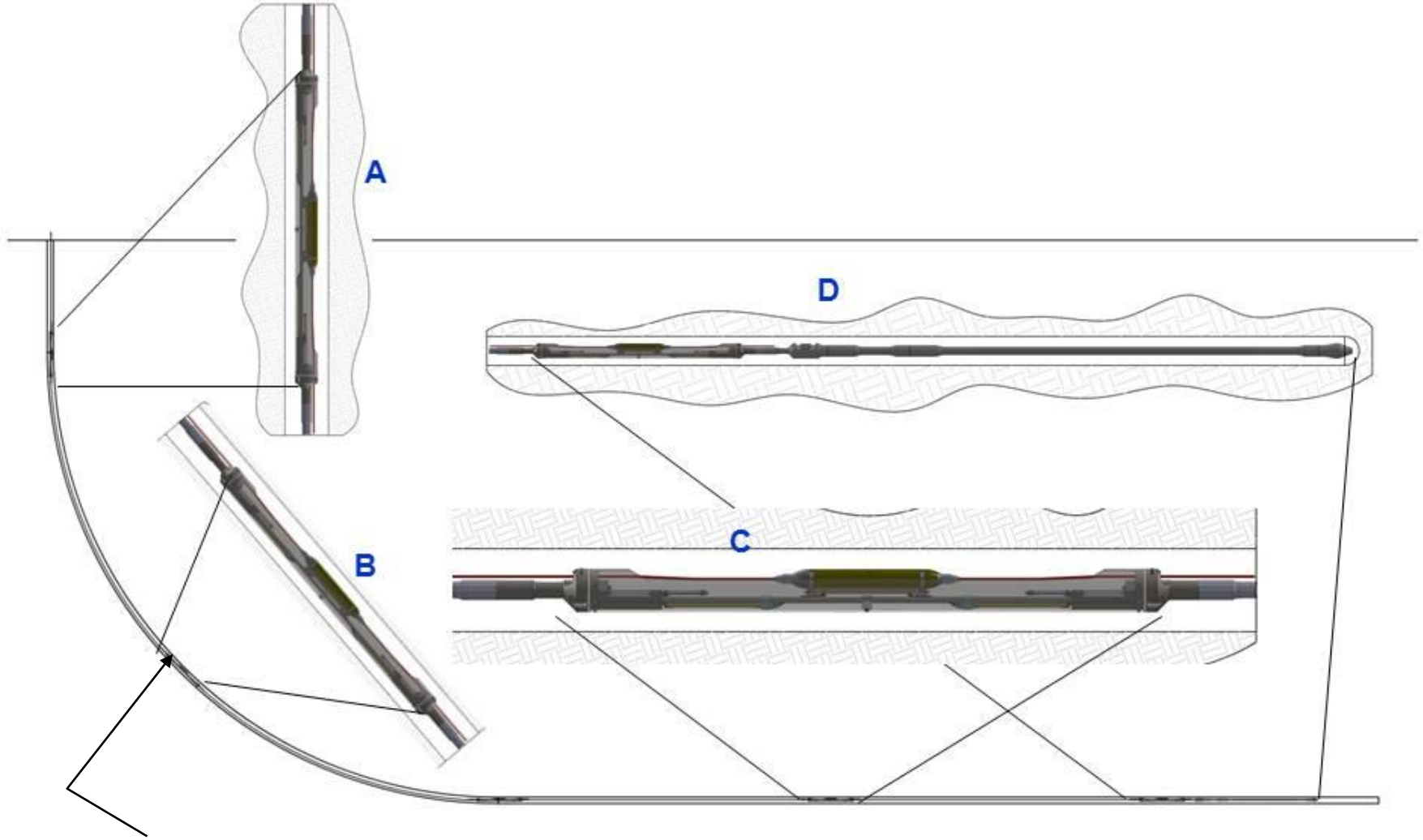


Deployment System Development

Drill Pipe Deployed System – Housing and Clamping



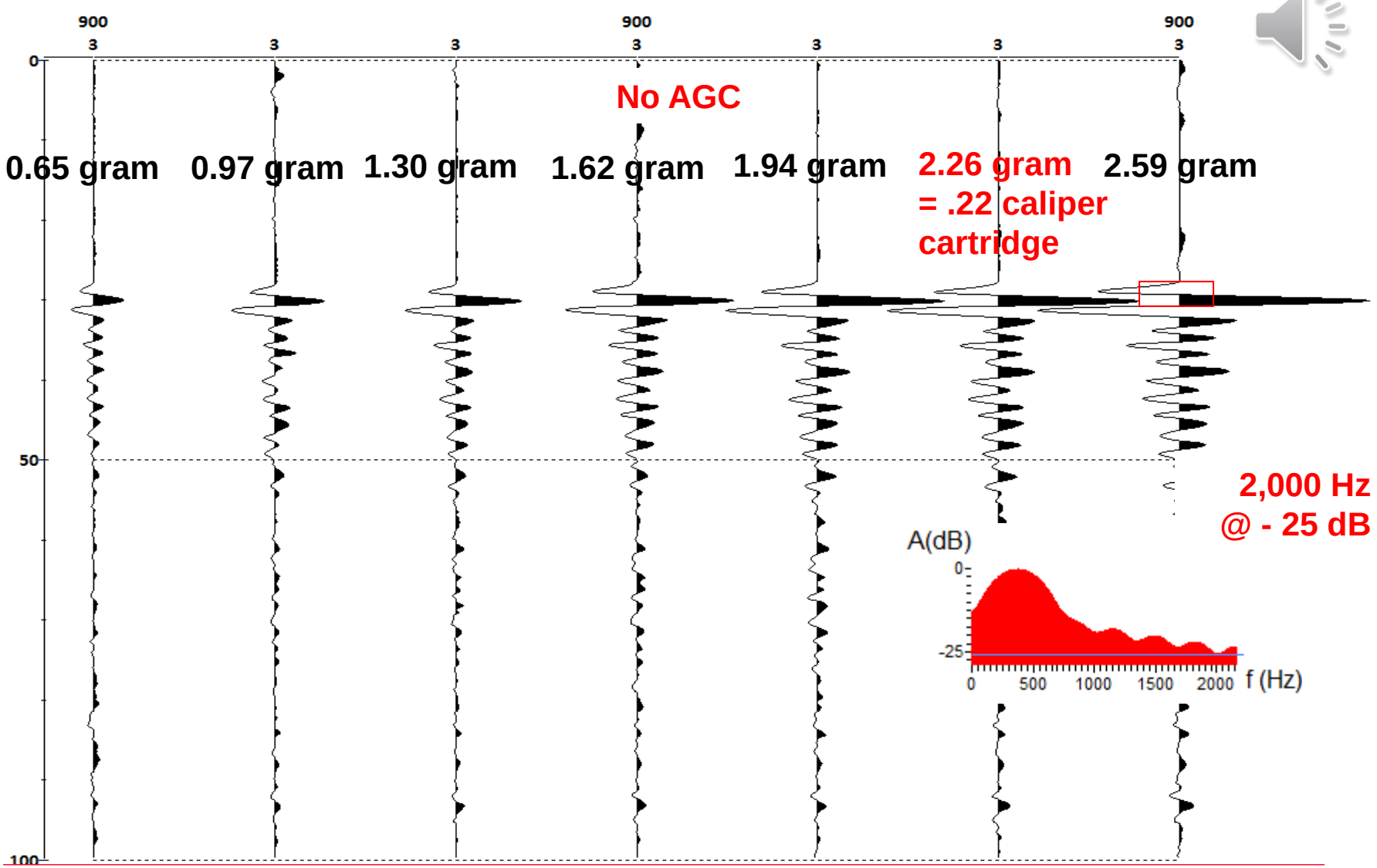
Clamping system operates by increasing the pressure inside the drill pipe and manifolds and uses the bore hole fluid as a medium

Field Tests
of
Fiber Optic Seismic Sensor (FOSVS)™
System

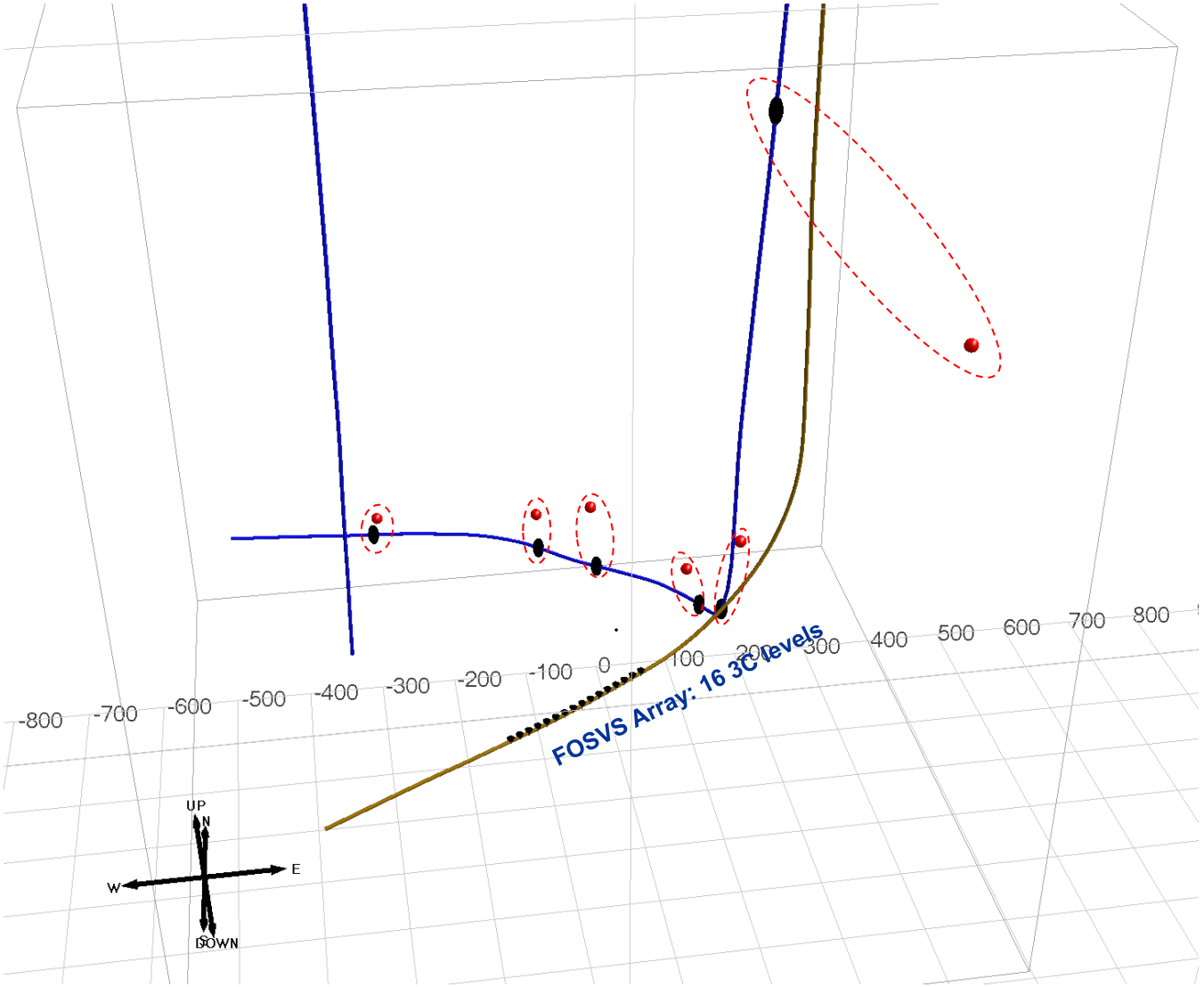
Fiber Optic Seismic Sensor System Deployment

Field Test Data Recorded with Fiber Optic Seismic Sensor (FOSVS)™ System

Shots Recorded by Principle Component @ 1,200 ft (400 m) (Filter: 80-100-1500-2000 Hz)

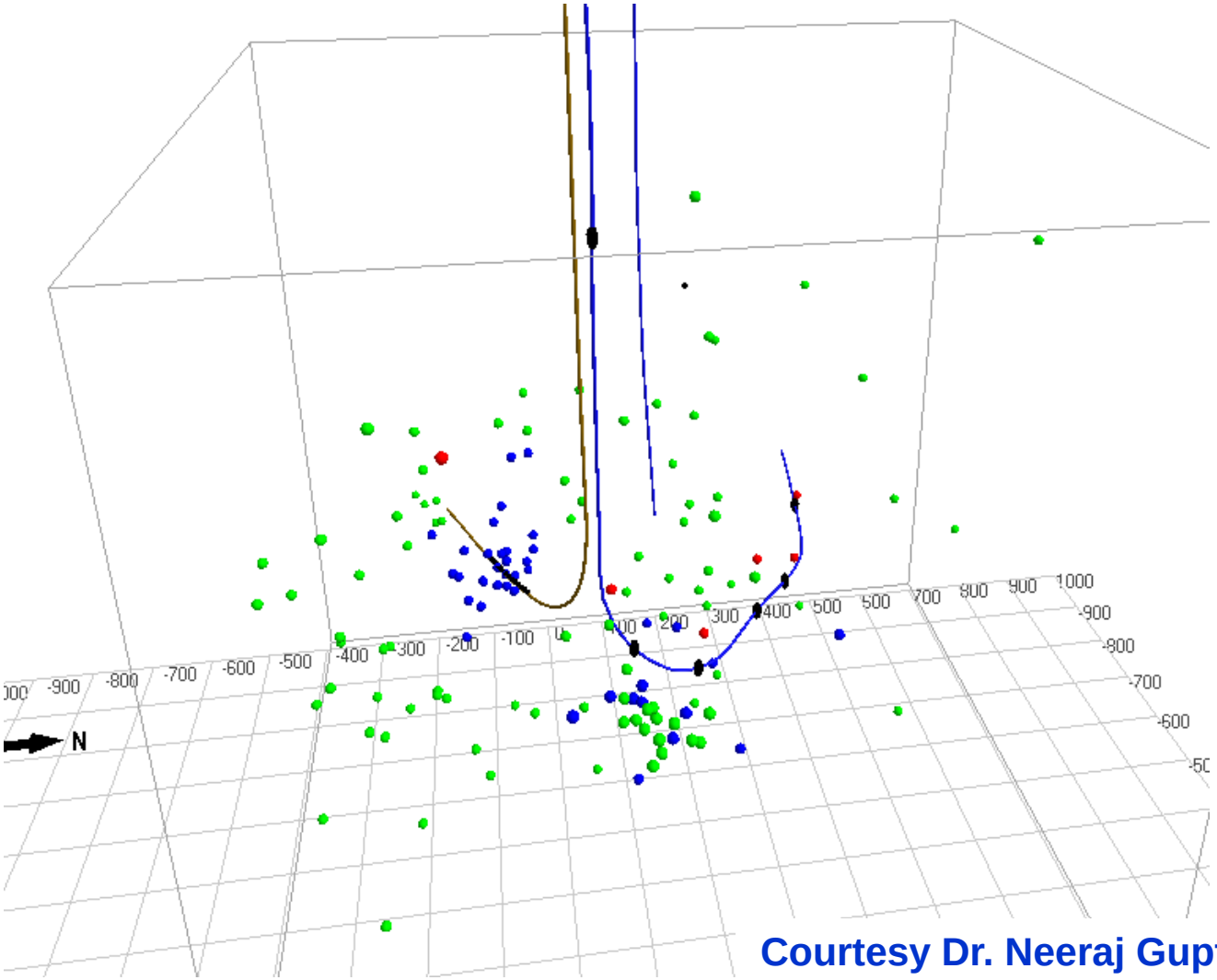


Results from Locating String Shots during a survey for Battelle in June 2016



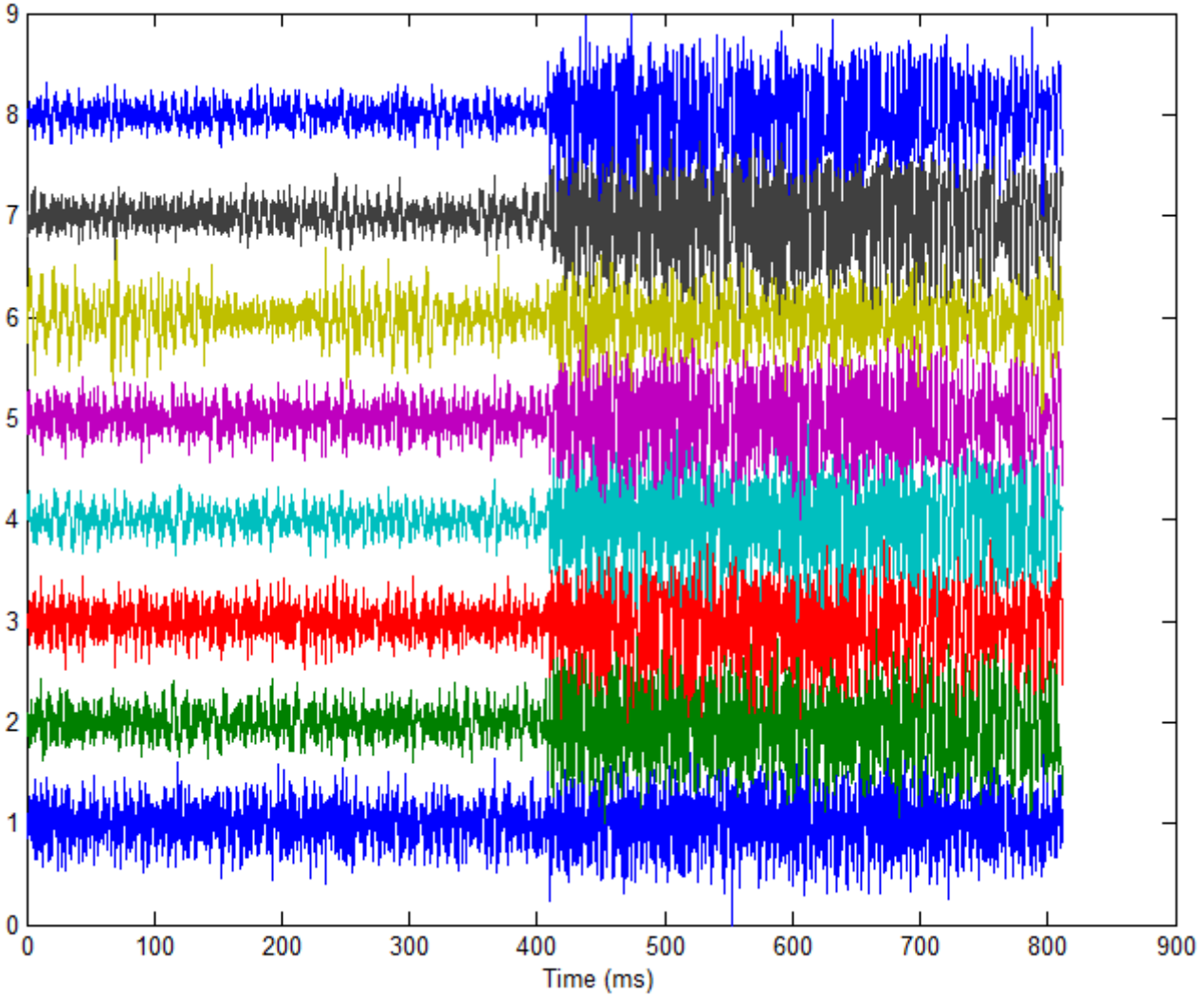
Locating String Shots and Micro Seismic Events – Work in Progress
Recorded 11,000 events in four weeks. Displayed here are 130 events.

Red: String Shots; Blue: Focused Micro Seismic; Green: "Distributed" Events

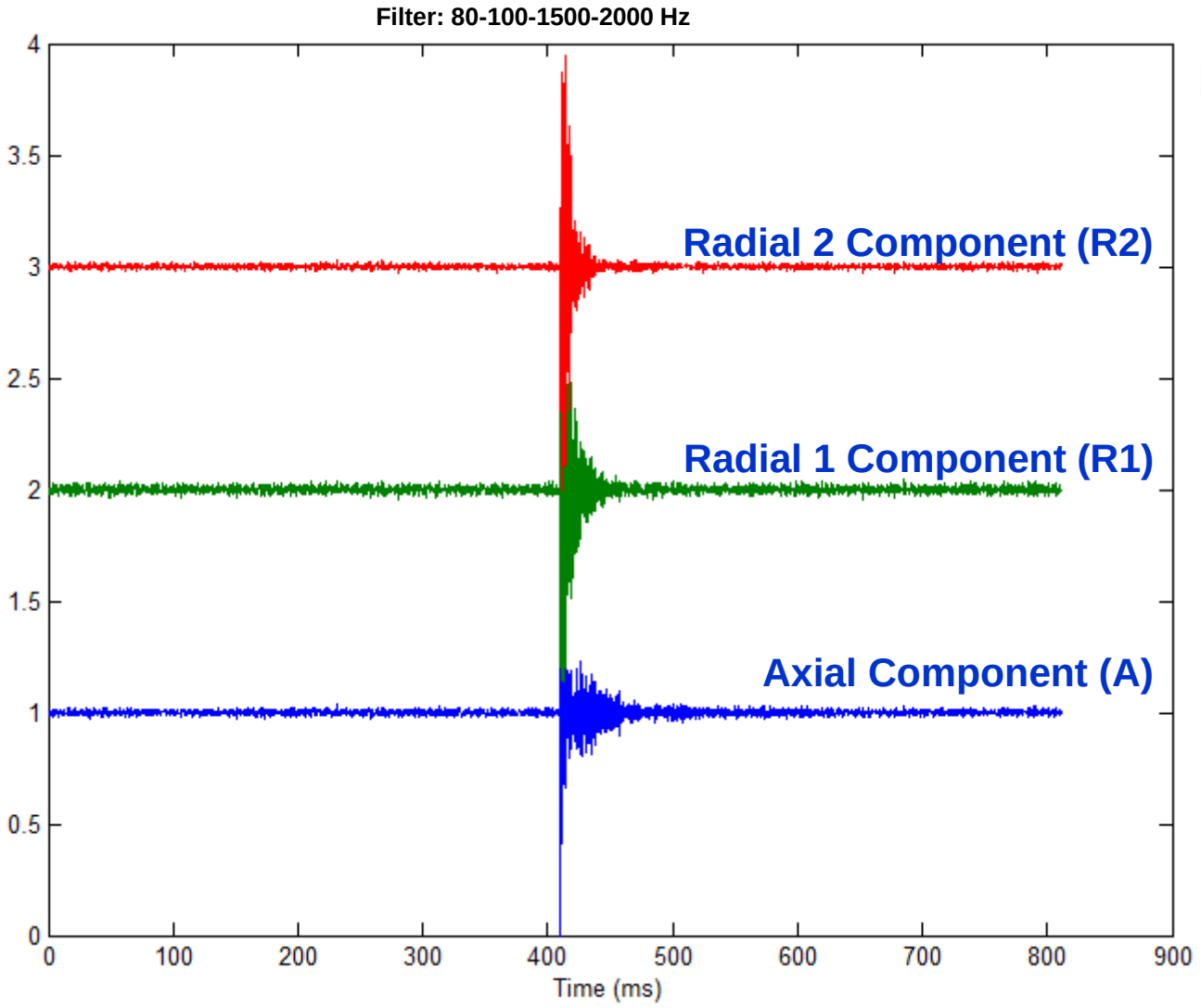


Courtesy Dr. Neeraj Gupta, Battelle

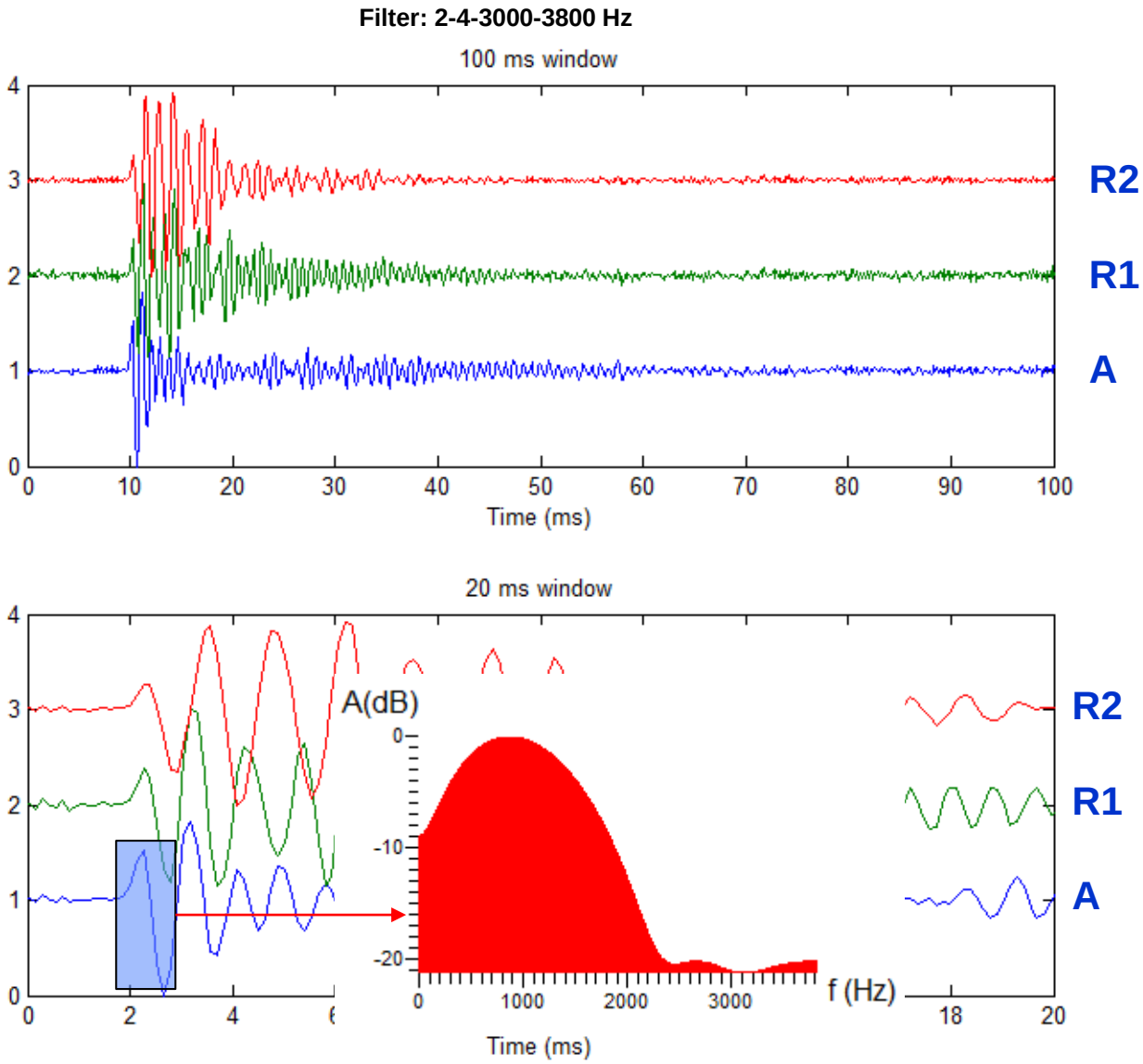
Sound of A Distributed Event



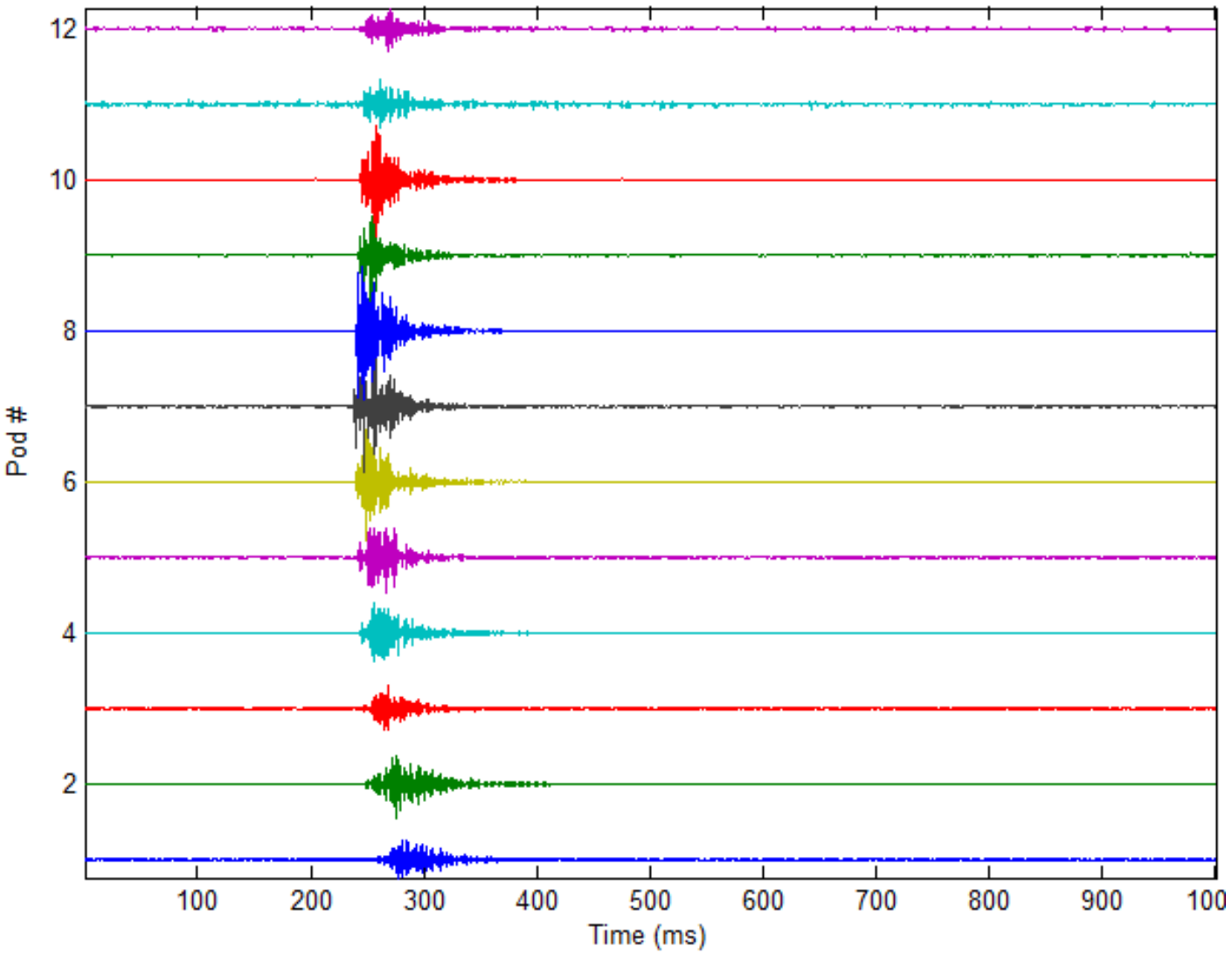
Sound of A Focused MS in 3C, Survey for Battelle, June 2016



Zoomed-In Focused MS in 3C- Filter: 2-4-3000-3800 Hz



A Microseismic Data (Axial) – Magnitude < M-2.9



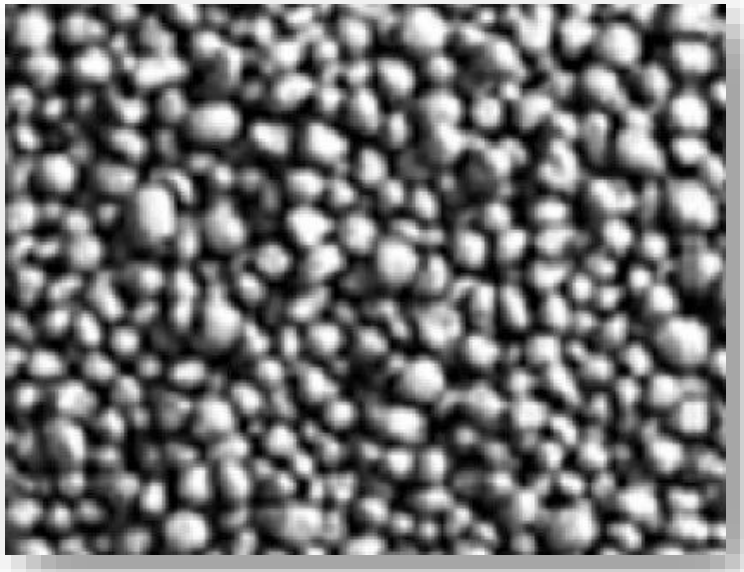
Borehole Seismology

- Large Seismic Array Technology
- Fiber Optic Seismic Sensors
- Acoustic Micro Emitters
- Joint testing of FOSVS & AME technology

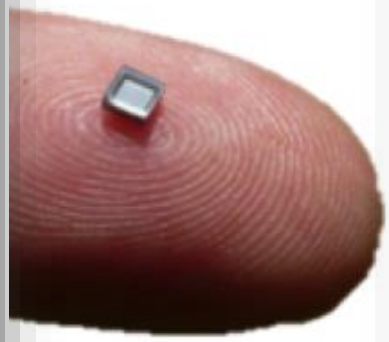
Getting most out of fracture monitoring

Problem: Need to know where fractures are propagating, their number, width, extent.

Answer: Injecting SMART microsystems along with proppant



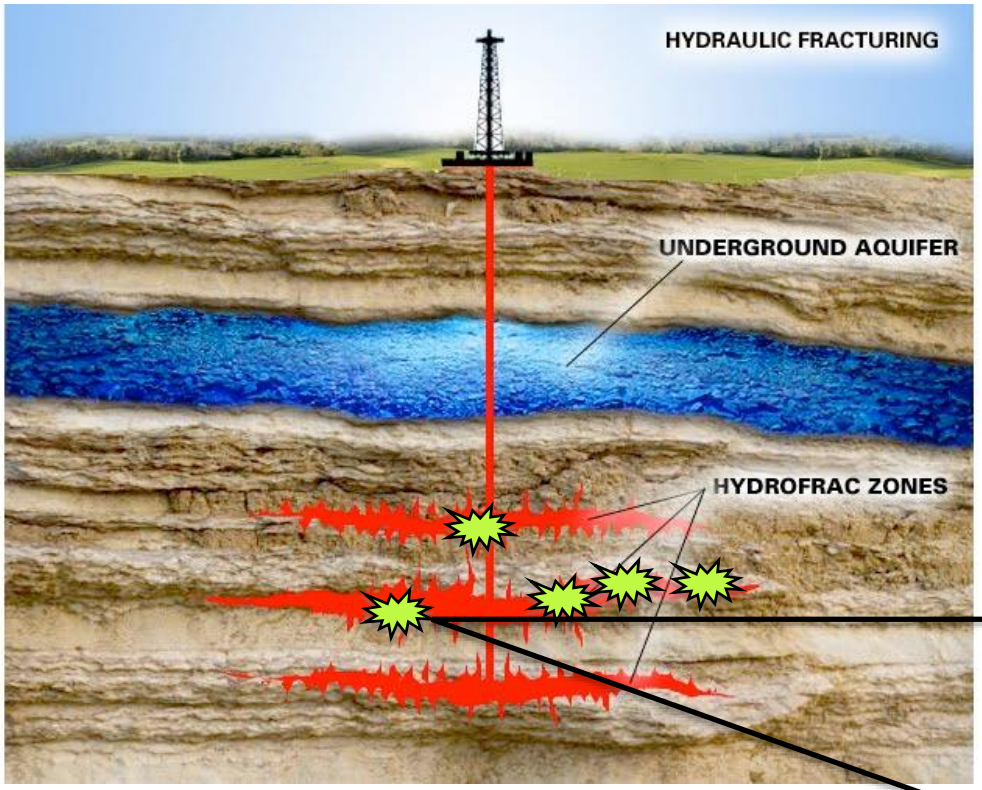
Typical ceramic proppant 20/40



fluidion smart micro-emitter (prototype stage)

www.fluidion.com

Using smart Acoustic Micro Emitters (AME)

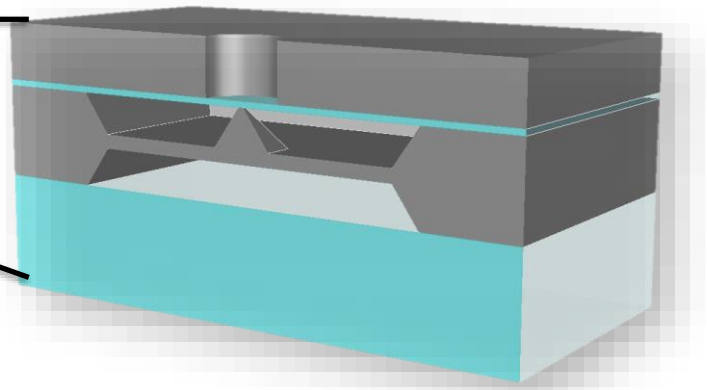


Simple logistics:

1. Injected in well along with proppant
2. Detected using fiber optic sensor array

High added value:

Delayed acoustic emission – high S/N
Guaranteed in-fracture signal
Specific acoustic signature
Various sizes – mapping fracture width



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fluidic intelligence

AME Simulation Flow Setup

Dynamic visualization of proppant and AME positioning

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Previous work

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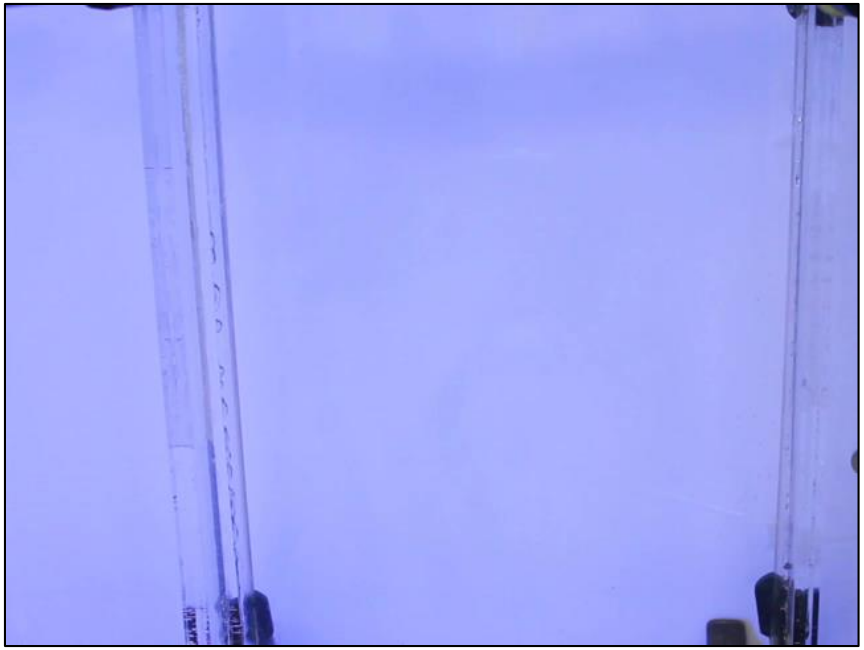
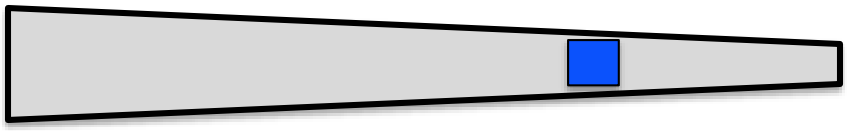
Lateral fracture view

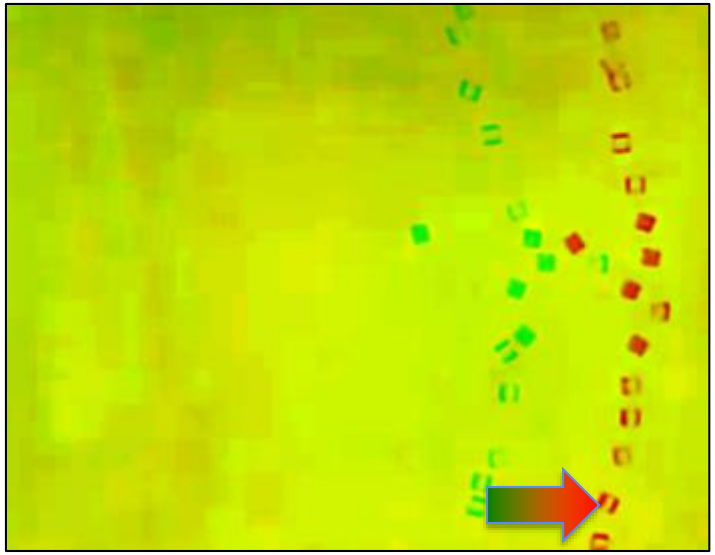


4mm 2mm



Top fracture view

Fracture proppant transport
Dynamic fracture opening tracking
Multiple-size proppant: wedge angle



Increasing pressure

www.fluidion.com

Borehole Seismology

- Large Seismic Array Technology
- Fiber Optic Seismic Sensors
- Acoustic Micro Emitters
- Joint testing of FOSVS & AME technology

500 psi AME – to FOSVS: Experimental Parameters

1. Receivers
    a. 3C Fiber Optic Seismic Sensor (FOSVS)
    b. Fiber Optic Hydrophone
    c. Optical sampling rate: 152,439.03 Hz
    d. 3C Geophones
    e. Geophone sampling rate: 40,000 Hz

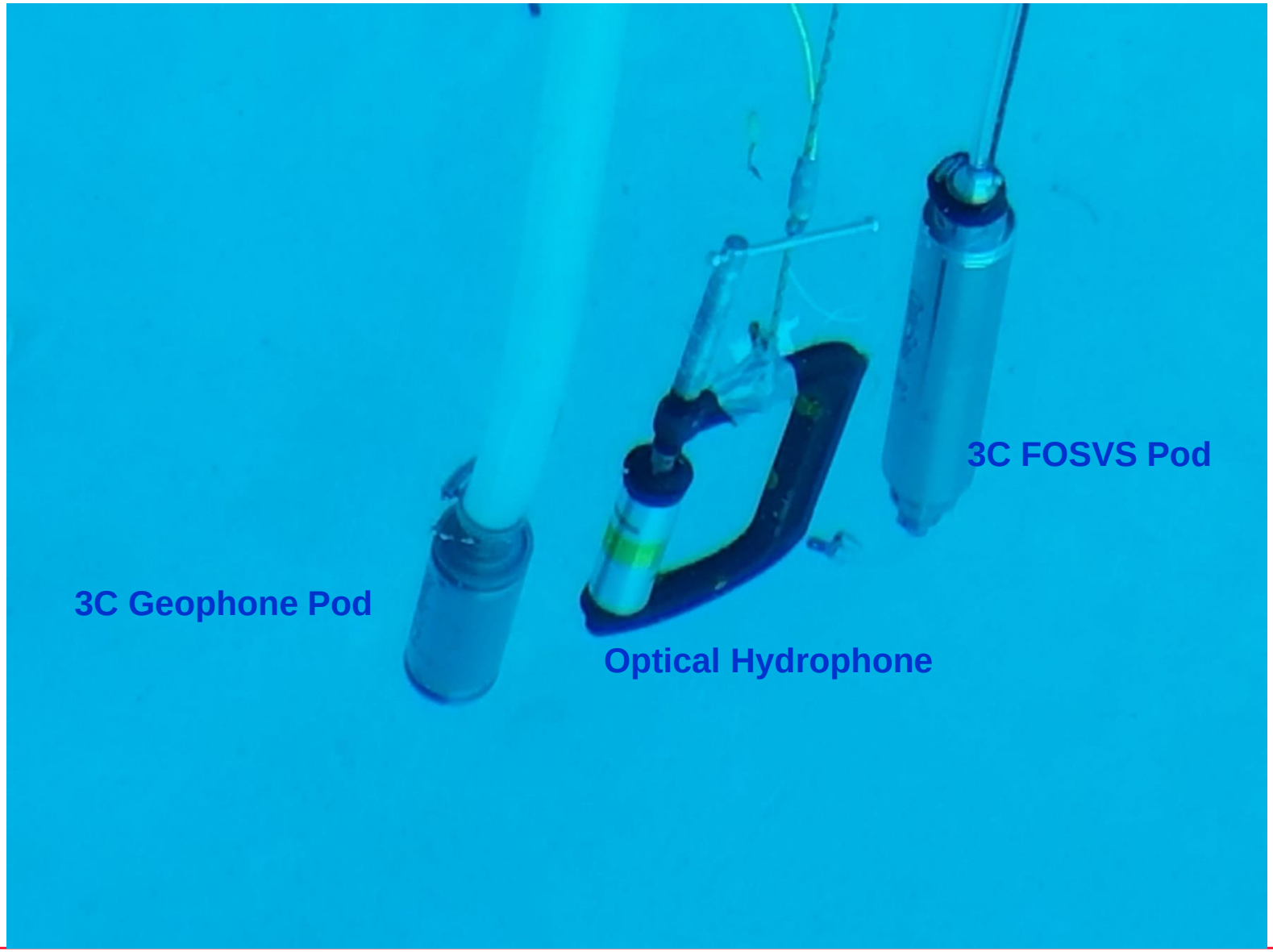
2. Sources: 4 x 4 mm Acoustic Micro Emitters (AME), 500 psi collapse version. Estimated energy 2J.

3. Offset: 20 feet

4. Processing
    a. Filter: 400-500-4000-5000 Hz

500 psi AME to FOSVS Experimental Set Up

500 psi AME to FOSVS Experimental Set Up

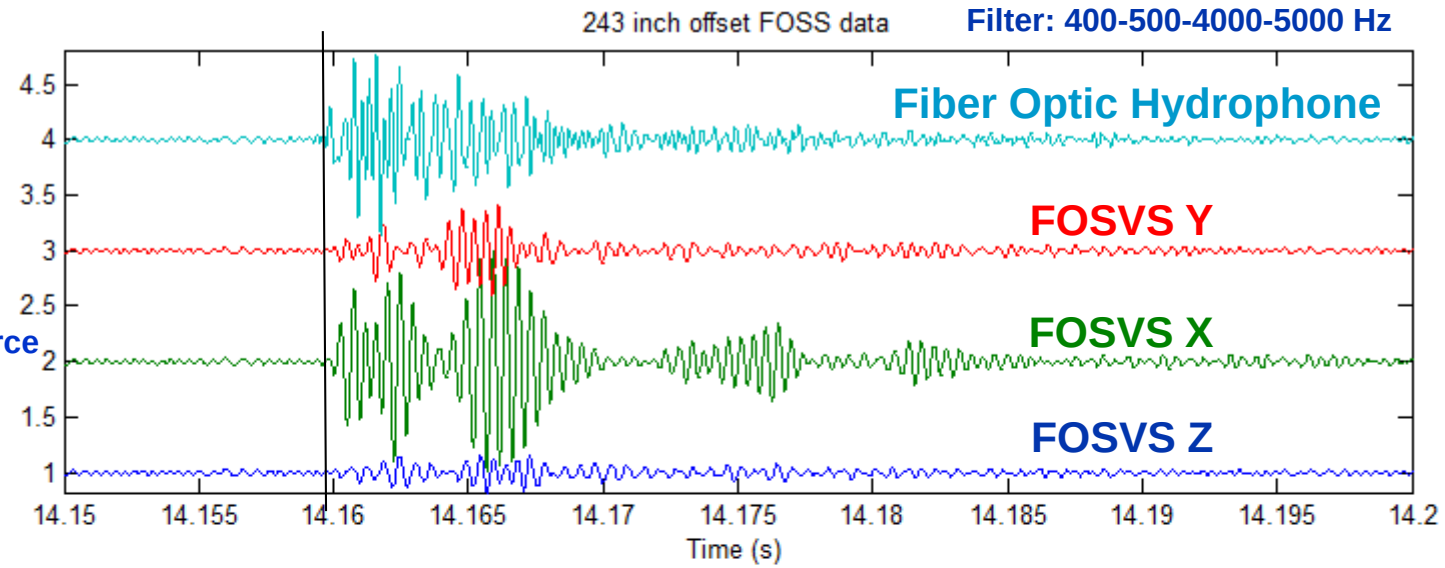


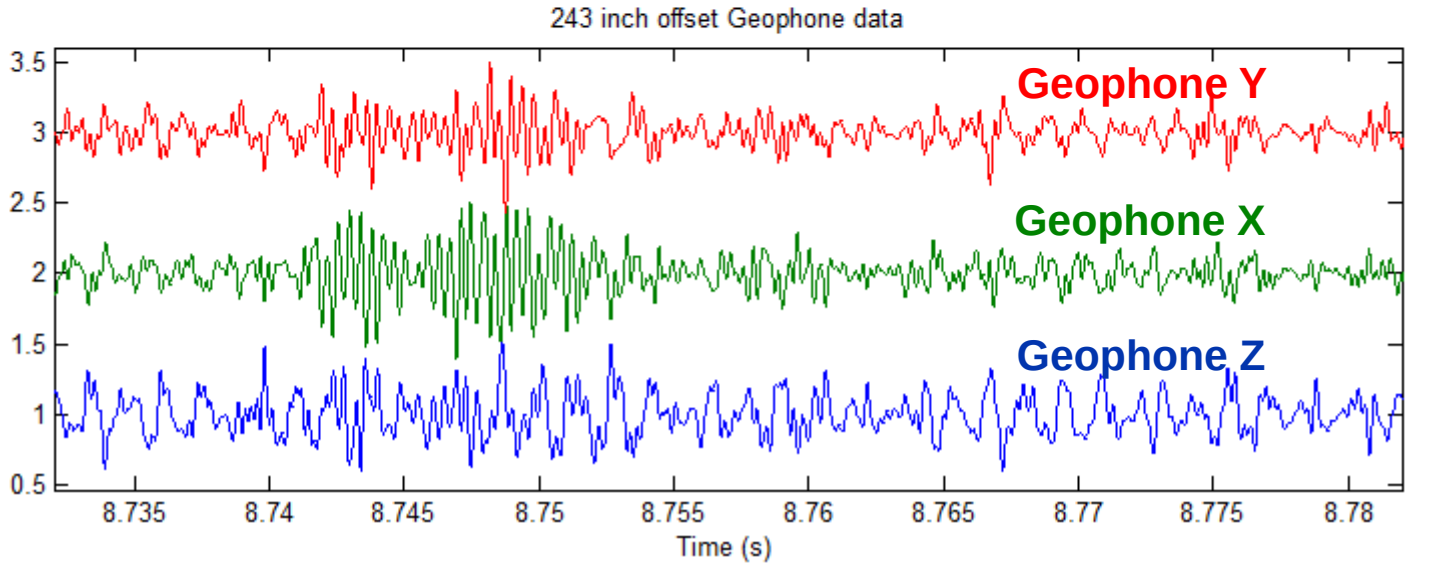
500 psi AME to FOSVS Experimental Set Up

Small Pressure Vessel used for the AME's
AME's collapse at 500 psi

500 psi AME to FOSVS - 20 ft Offset - Filtered Data - Zoom In

Note:
Coherent Pre arrival Energy from An external acoustic Source





500 psi AME to FOSVS - 20 ft Offset - Filtered Data - Zoom In

Filter: 400-500-4000-5000 Hz

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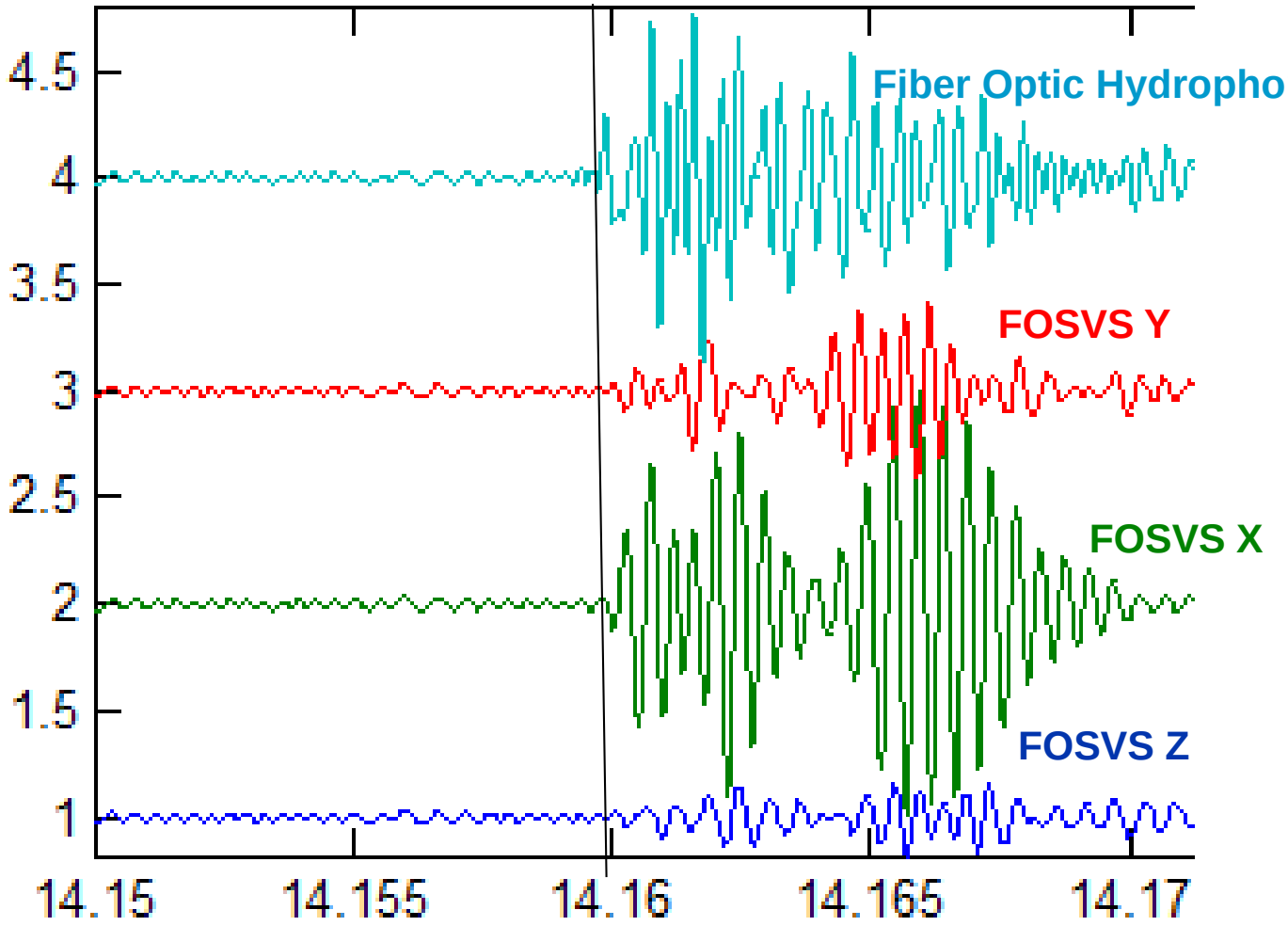
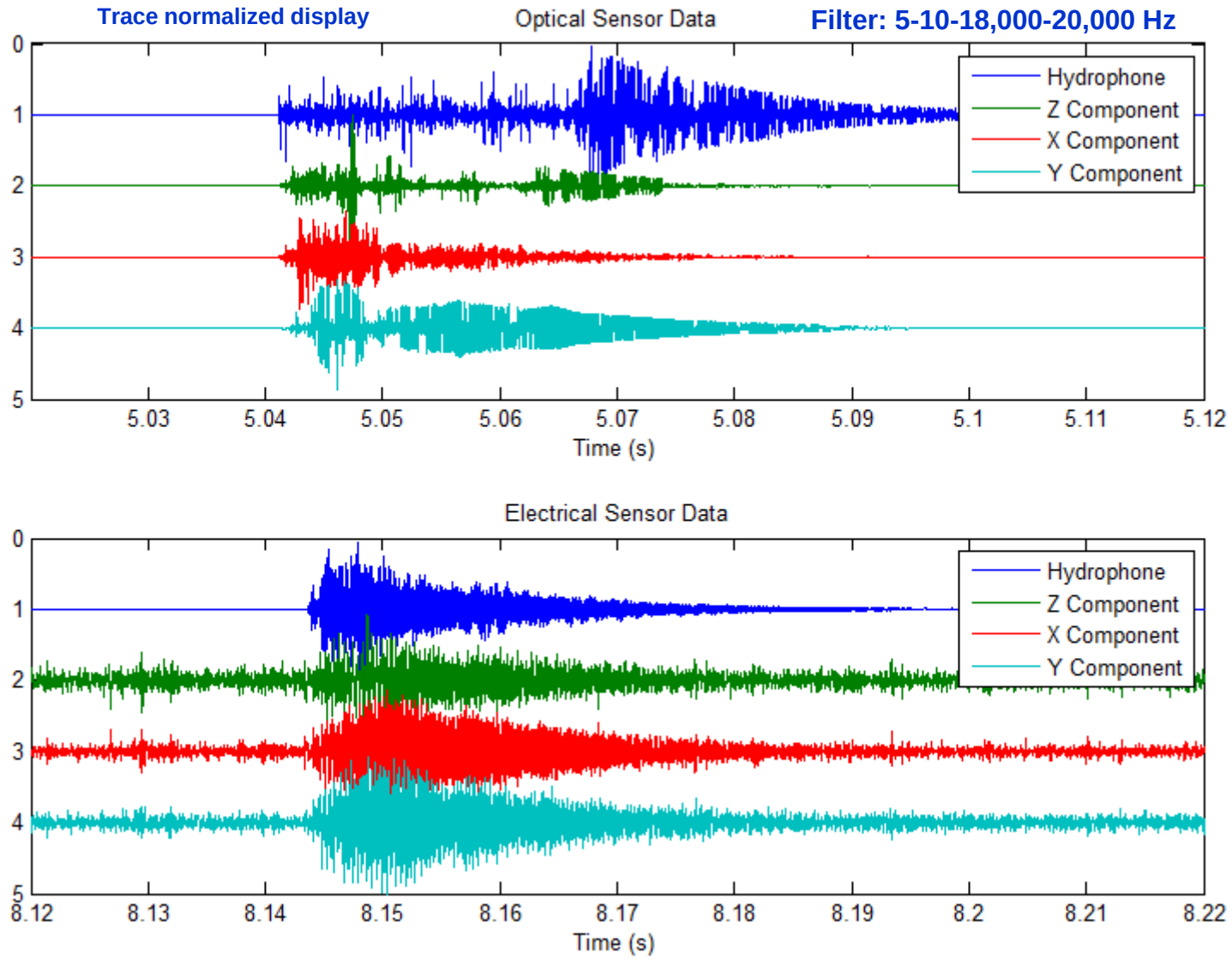


4,000 and 8,000 psi AMEs Test Summary

- Date: Dec. 9, 2016
- Location: Pool
- Source-Receiver Distance: 20 ft
- Receivers:
  - Optical: FOSVS and optical Hydrophone
    - Sampling rate: 152,439.03 Hz
  - Electrical: Geophone and Hydrophone
    - Geophone: Omni-2400
    - Hydrophone: Aquarian Scientific AS-1
    - Sampling rate: 40,000 Hz
- Sources:
  - AME, 4,000 psi and 8,000 psi

Test 1: Two AMEs at 4,000 & 8,000 psi



Observations

1. From the same AME the Fiber Optic Seismic Vector Sensors (FOSVS) generate much higher signal to noise (S/N) ratio than the electronic geophones.

2. The Fiber Optic Hydrophone (FOH) generate much higher S/N ratio than the electronic geophones.

3. A second test using 4,000 and 8,000 psi AME's generated much higher S/N than the 500 psi AME's

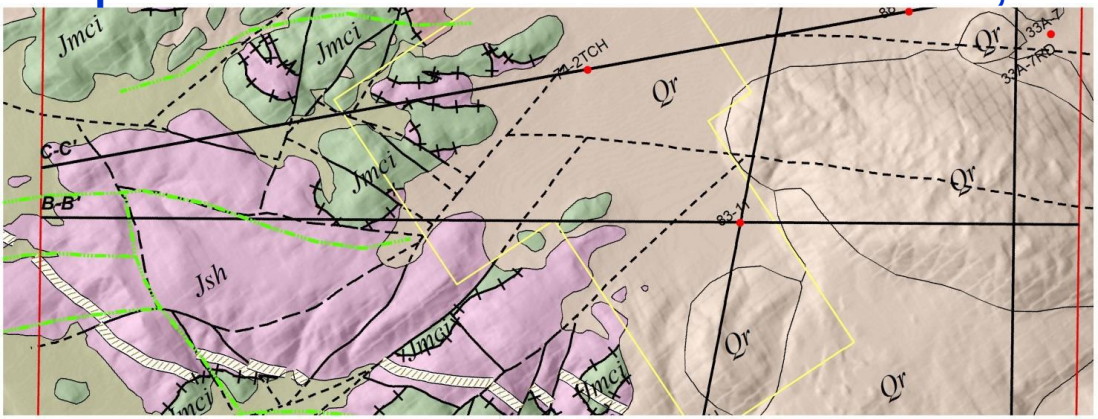
Other Projects and Applications where the FOSVS and AME Combination Can be Applied

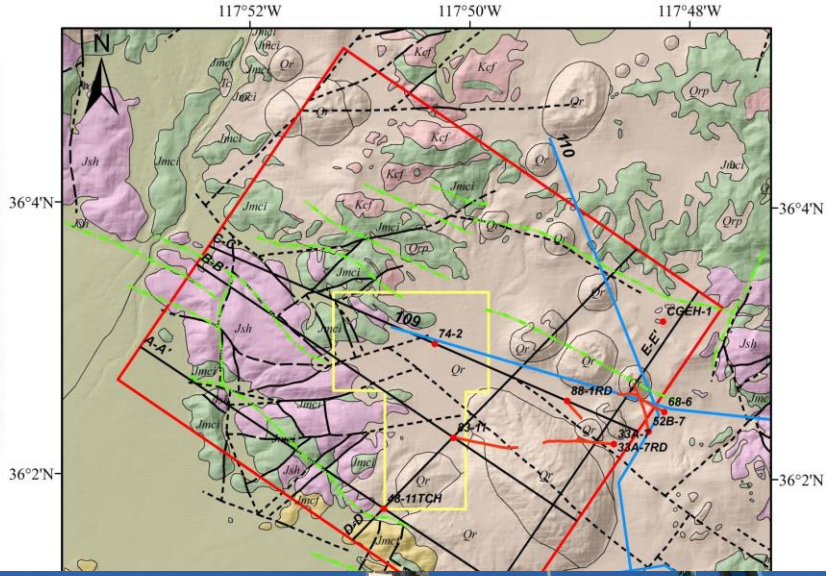
FORGE Applications

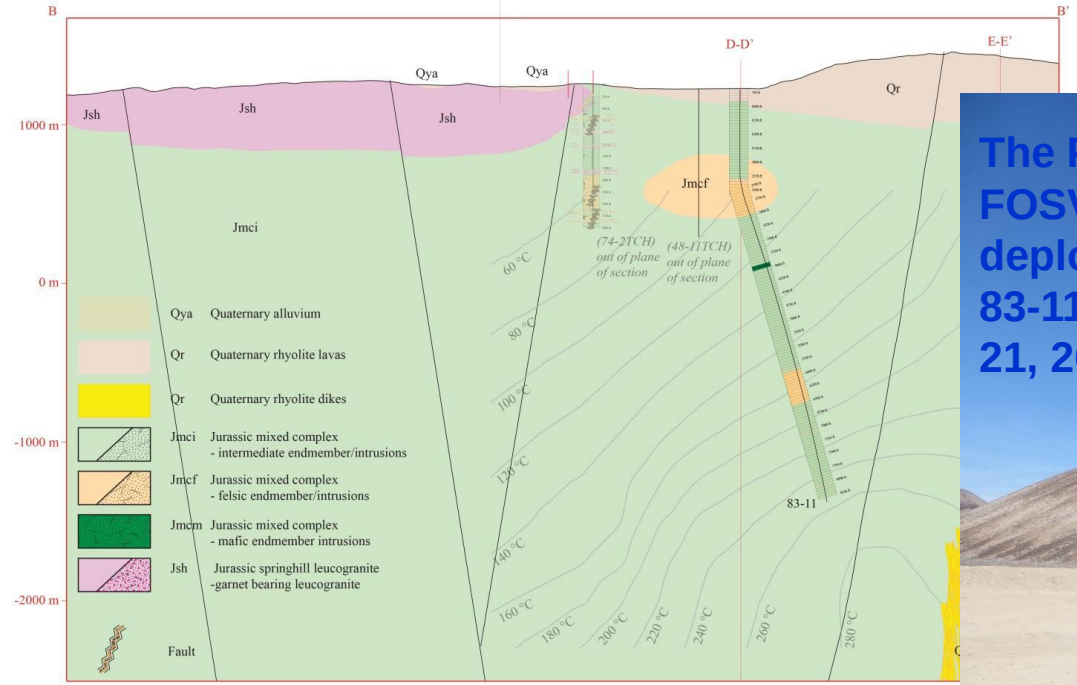
- Inject AME's into EGS fractures
- Use FOSVS to monitor the location of the AME's to map the fractures to improve productivity through guided drilling

The West Flank FORGE Site

Maps from FORGE Phase 1 West Flank of Coso, CA





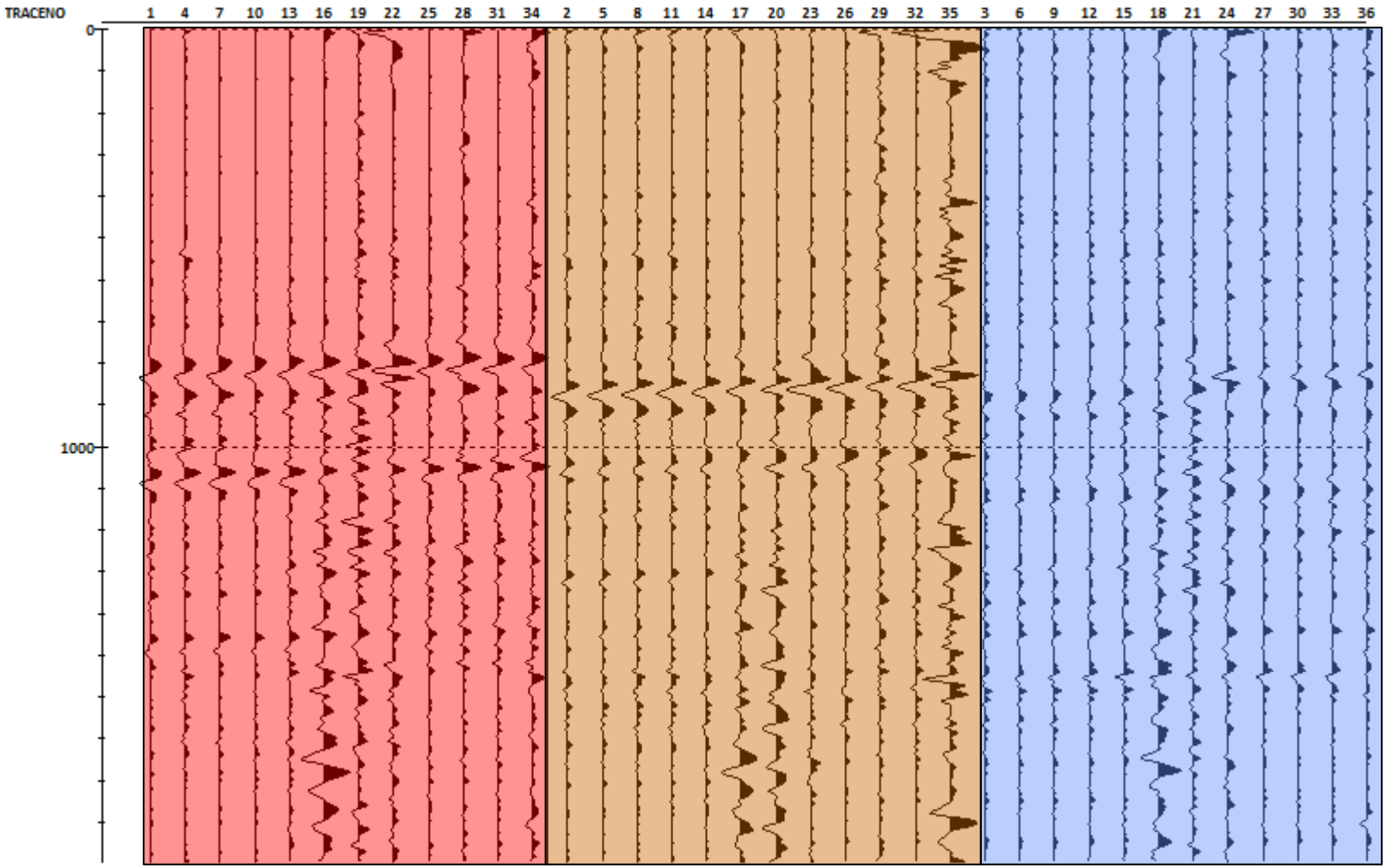


An Earthquake 3.4 Miles Away M1.9

3C Rotated

PT: 2017-03-15 23:19:47

Filter: 5-10-200-300 Hz



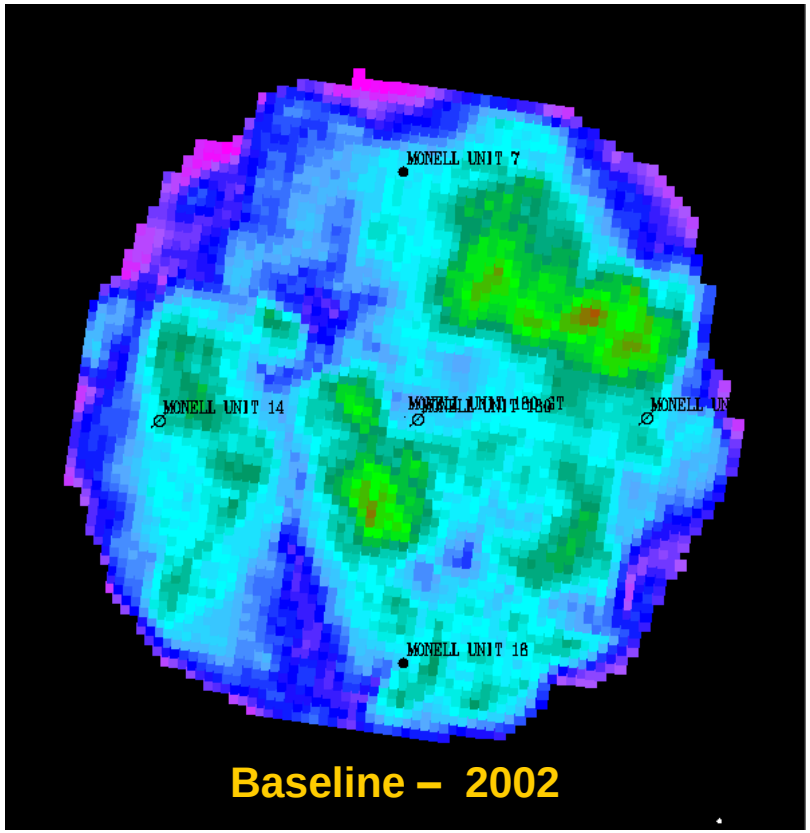
Primary Shear Wave R T

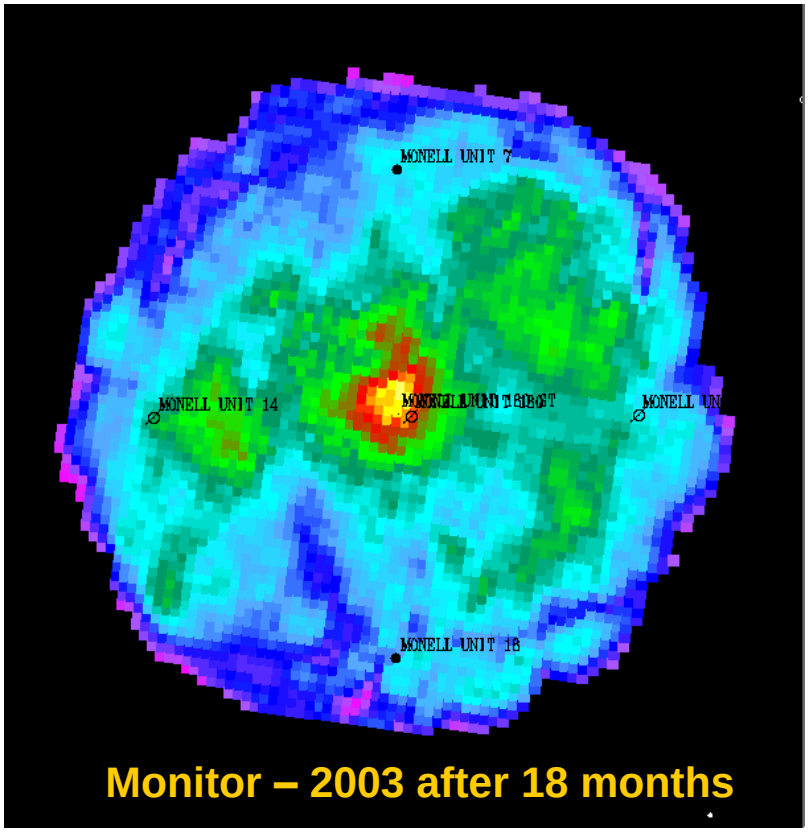
P is the primary energy direction; R is the radial minimum energy direction; T is the transverse direction

Time Lapse Data Monitoring of CO2 injection for Enhanced Oil Recovery in 2002 - 2003

Time lapse surveys to monitor CO2 Injection
Depth Amplitude Maps at 4,800 ft showing the CO2 Plume

Simultaneous imaging and monitoring possible using FOSVS and AME in combination.





Increased reflectivity in the Monitor Survey 2003 at a depth of 4,800 ft at the well is due to the injected CO2. Also seen is the increased reflectivity around the water injector wells.

O'Brien et al., 2004

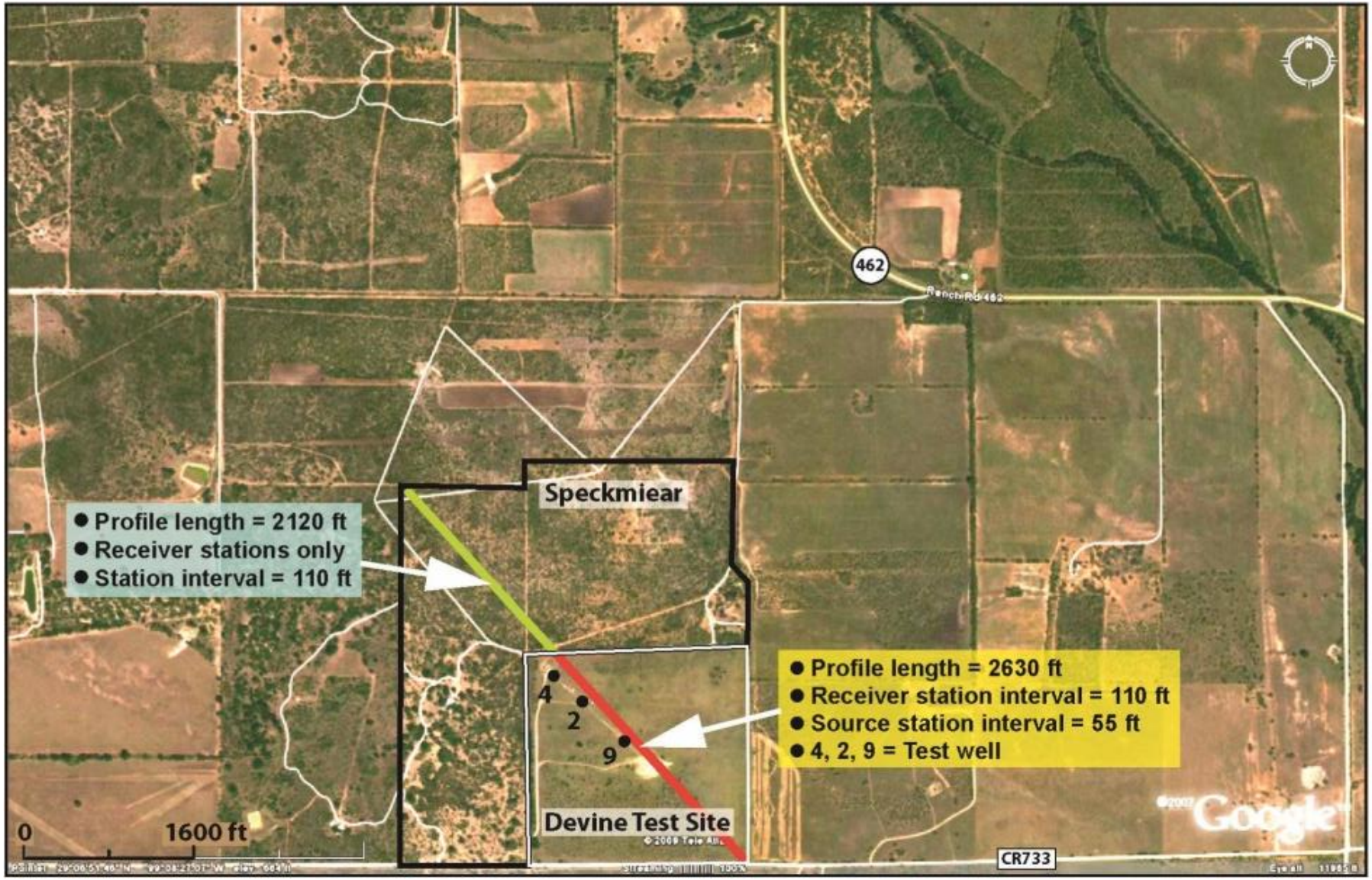
Borehole Seismology

- Large Seismic Array Technology
- Acoustic Micro Emitters
- Fiber Optic Seismic Sensors
- Field Testing & Calibration
- Offshore Applications

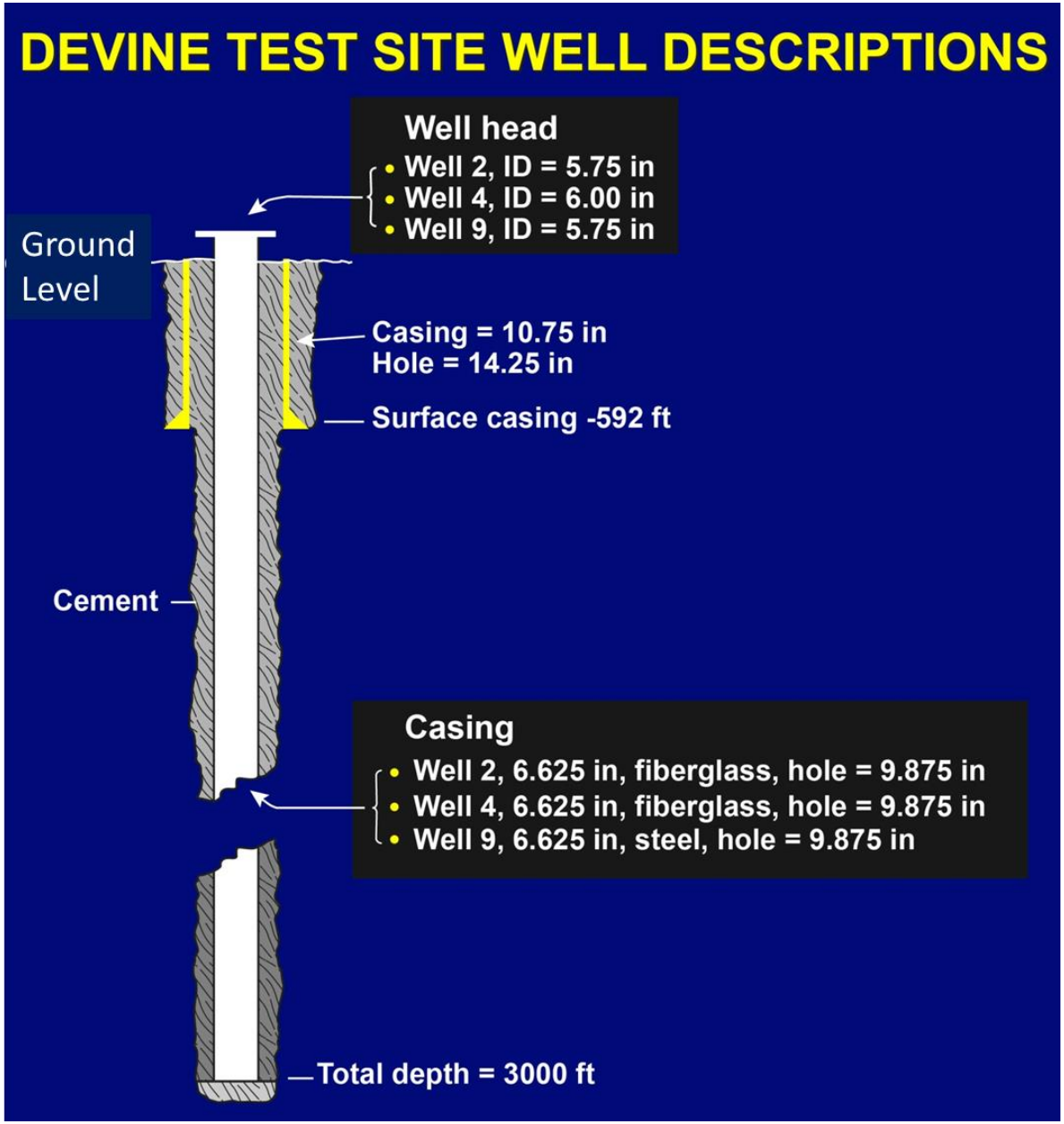
Devine Test Objectives

- Perform a test at a known field laboratory
- Calibrate and document the FOSVS ability to record data from the AME under controlled conditions

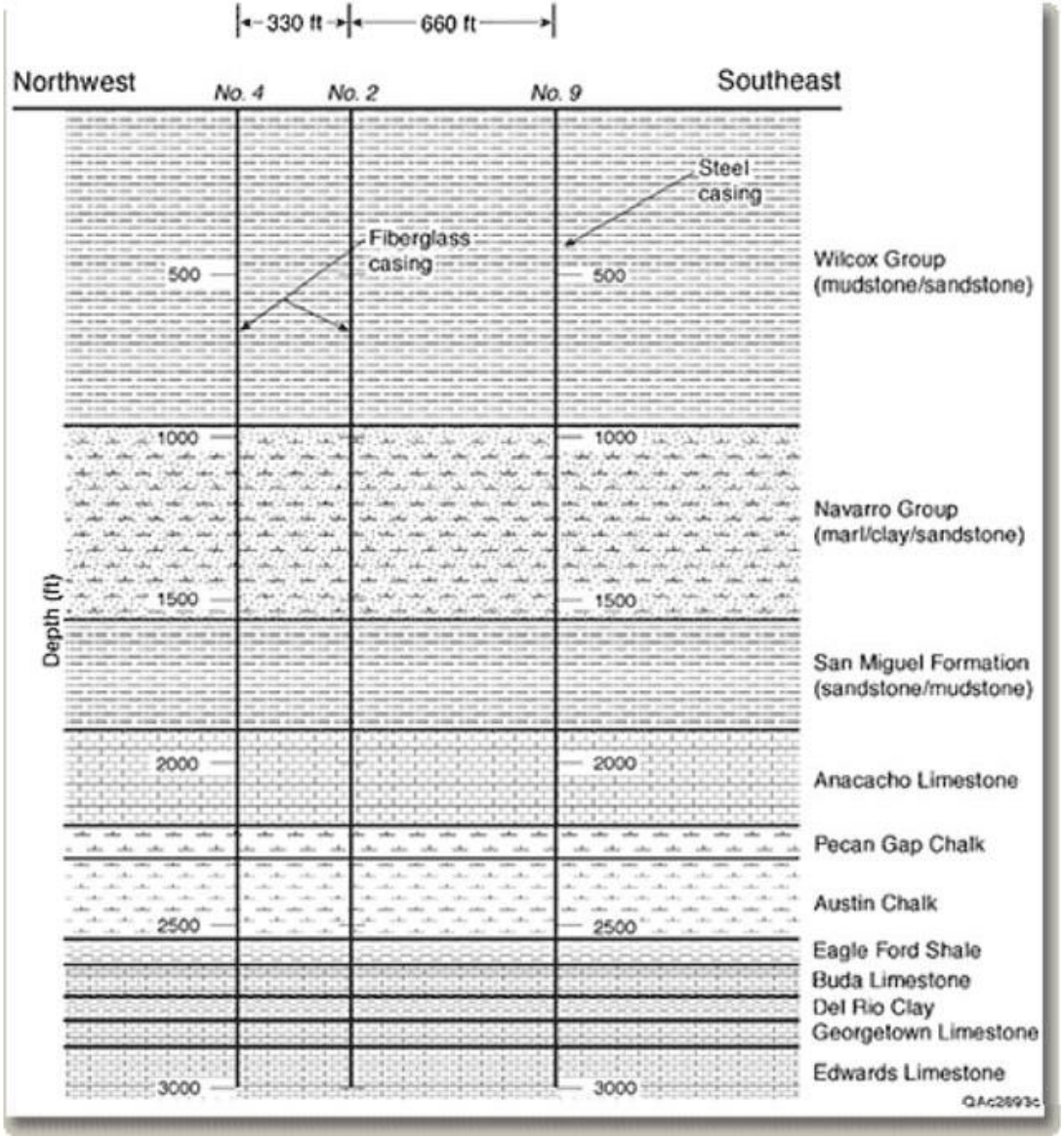
Devine Test Site Map



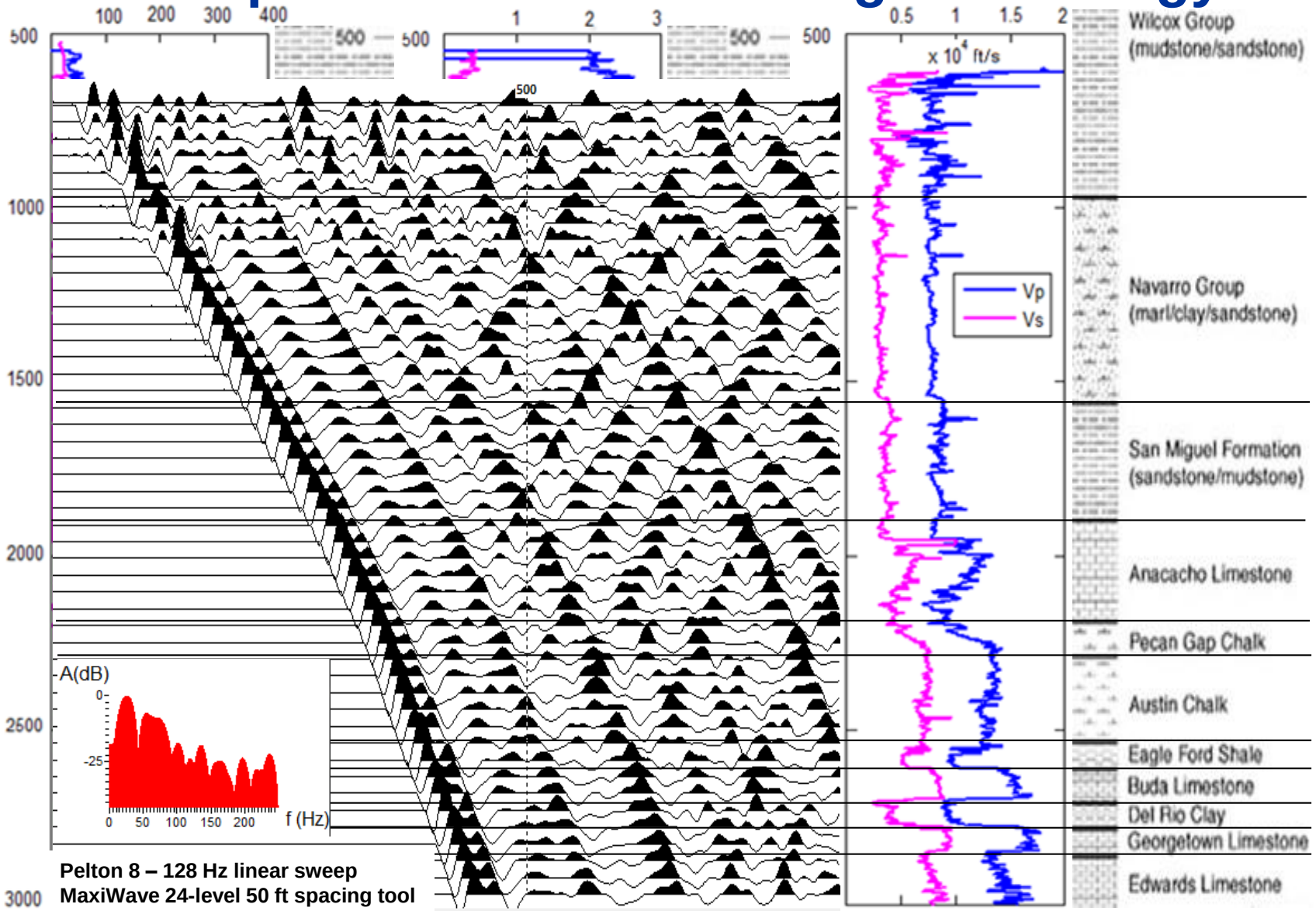
DEVINE TEST SITE WELL DESCRIPTIONS



Geology Profile @ the Devine test site

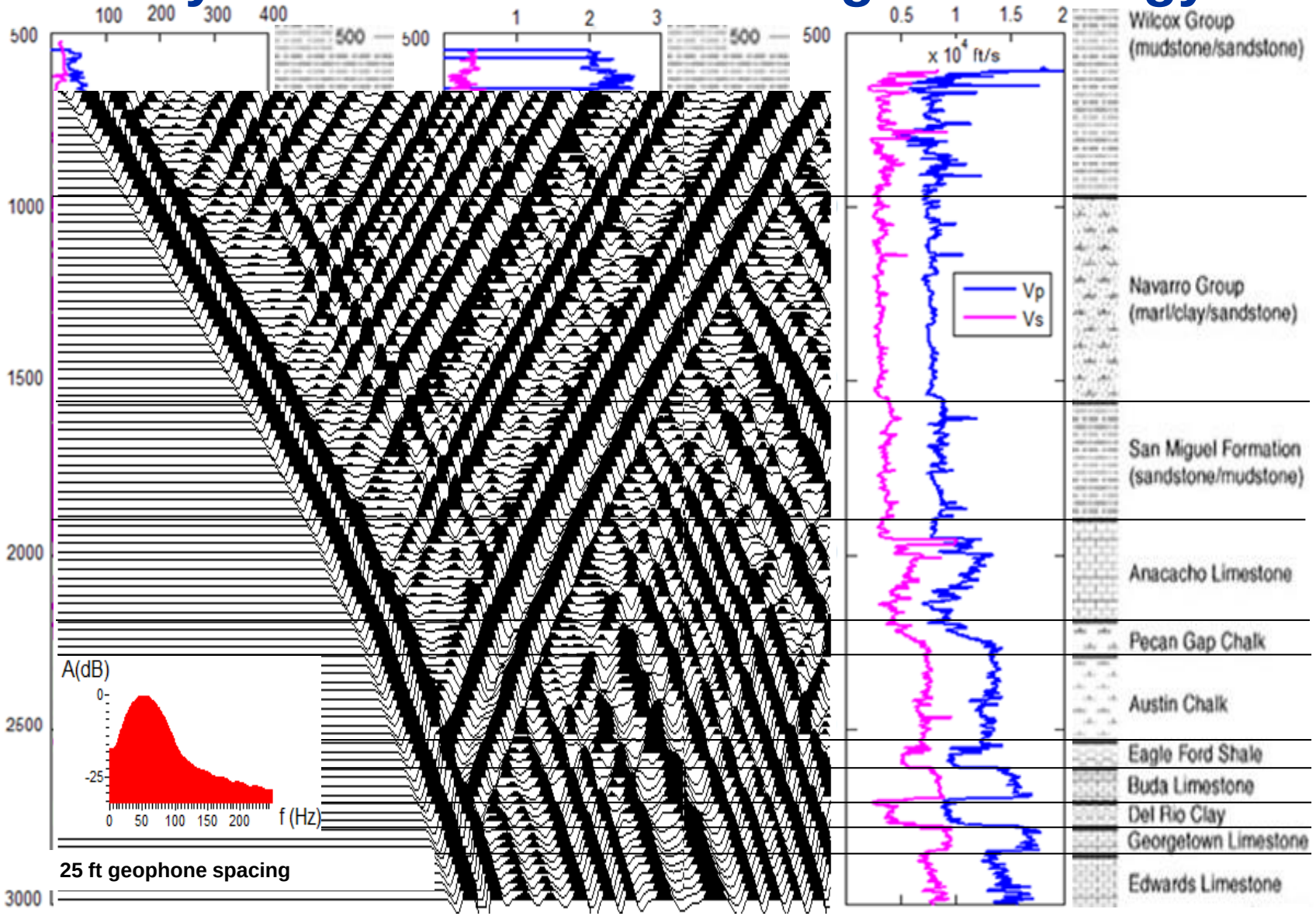


Geophone VSP vs Well Log Vs Geology

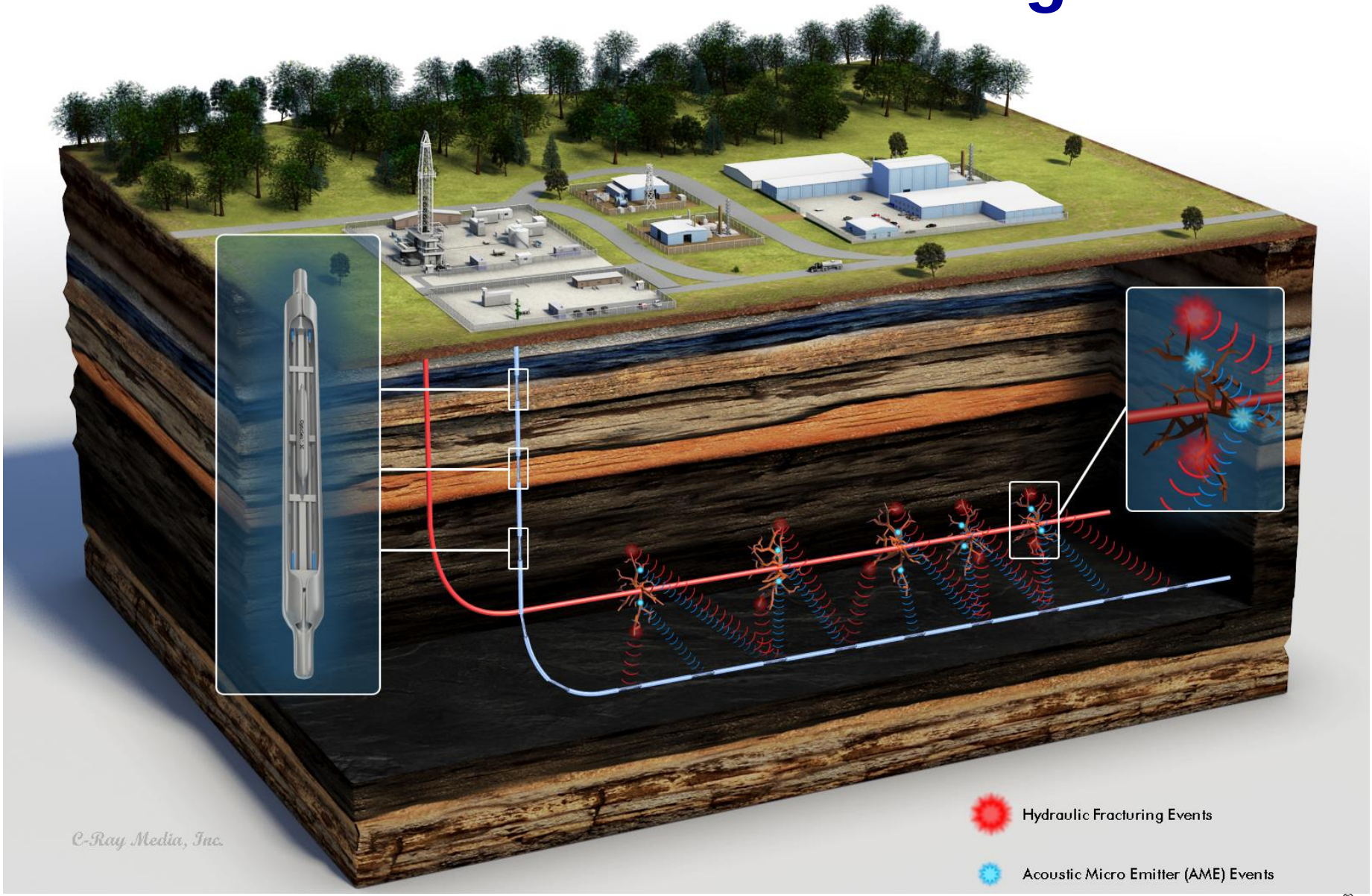


Pelton 8 – 128 Hz linear sweep
MaxiWave 24-level 50 ft spacing tool

Synthetic VSP vs Well Log Vs Geology



Effective & Accurate Monitoring of UOG



Borehole Seismology

- Large Seismic Array Technology
- Acoustic Micro Emitters
- Fiber Optic Seismic Sensors
- Field Testing & Calibration
- Offshore Applications – stay tuned

What can we learn from the “New Signals”

- High Resolution images – much better than surface seismic
- Large volume images – much larger volumes than well logs
- 3D Velocity model to be used for surface seismic processing
- Anisotropic velocity information to focus imaging
- Outstanding structural/stratigraphic images
- Volumetric rock-mass stress distribution – not just at the well
- 3D Maps of Faults & Fracture distribution and directions
- Type of fluids in the reservoirs:
  - Gas vs Oil vs Water vs CO2 vs Steam
- Map fluid flow and fluid boundaries
- Map permeability in reservoirs
- Temperature distribution
- With AME’s - Monitor Hydro Fracturing (Fracking) Operations including mapping the location of the proppant – game changer
- Much better understanding of the dynamic processes of producing and injecting liquids and gases

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Thank You!

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