SCOPE: INJECTION AND TRACKING OF MICRO SEISMIC EMITTERS

OBJECTIVE: TO OPTIMIZE UNCONVENTIONAL OIL AND GAS (UOG) DEVELOPMENT

DE-FE0024360

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U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 13-16, 2018

“Mastering the Subsurface ..”

I want to provide a Perspective what is Technically Needed and the Economical Market for High Resolution Imaging and Monitoring Technologies

Presentation Outline

- Subsurface Applications
- Commercial Markets
- Technology

Effective & Accurate Monitoring of UOG

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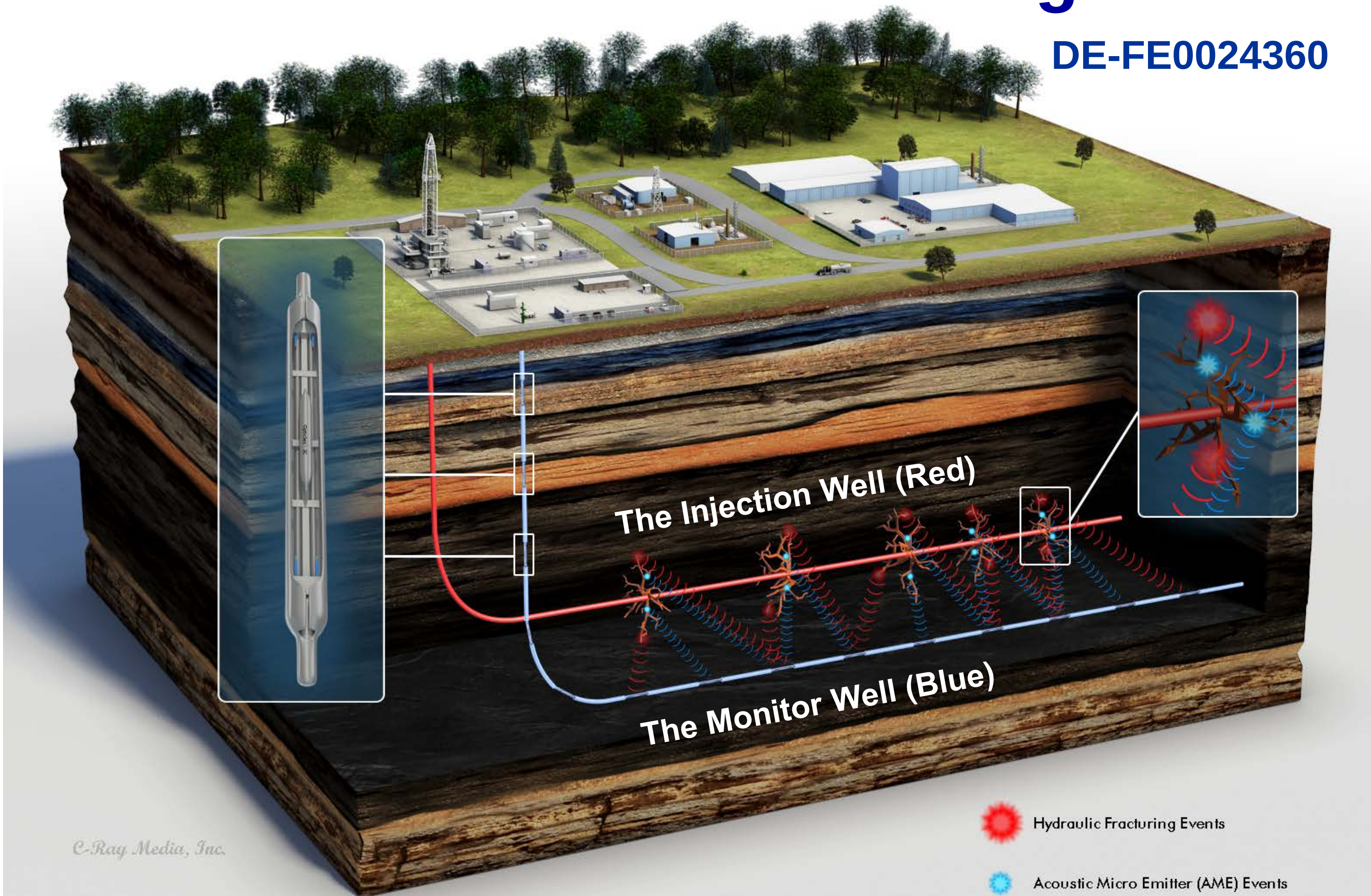
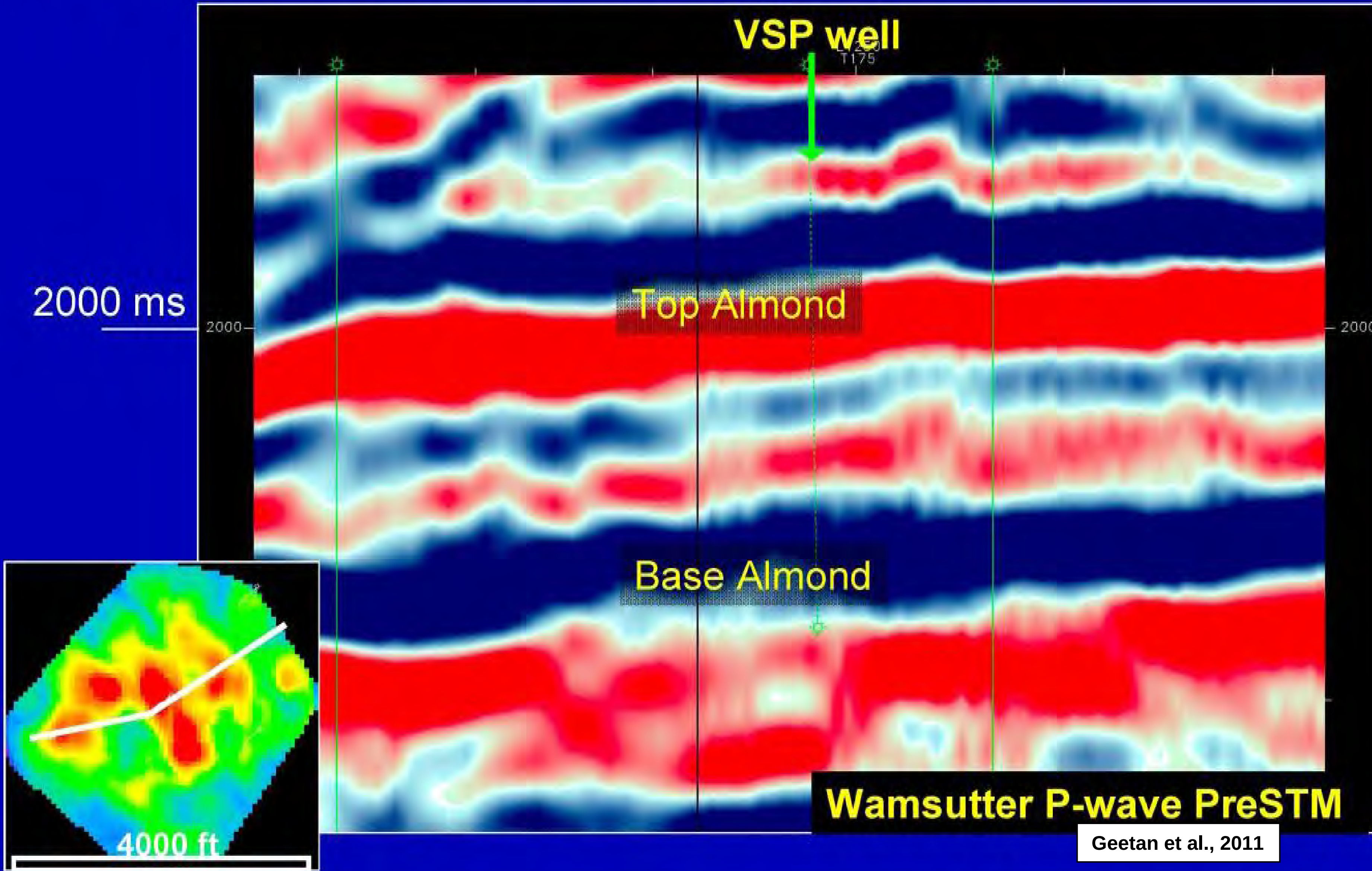


"Earth Angiography"

3D/4D Imaging Results Using Long Borehole Seismic Arrays

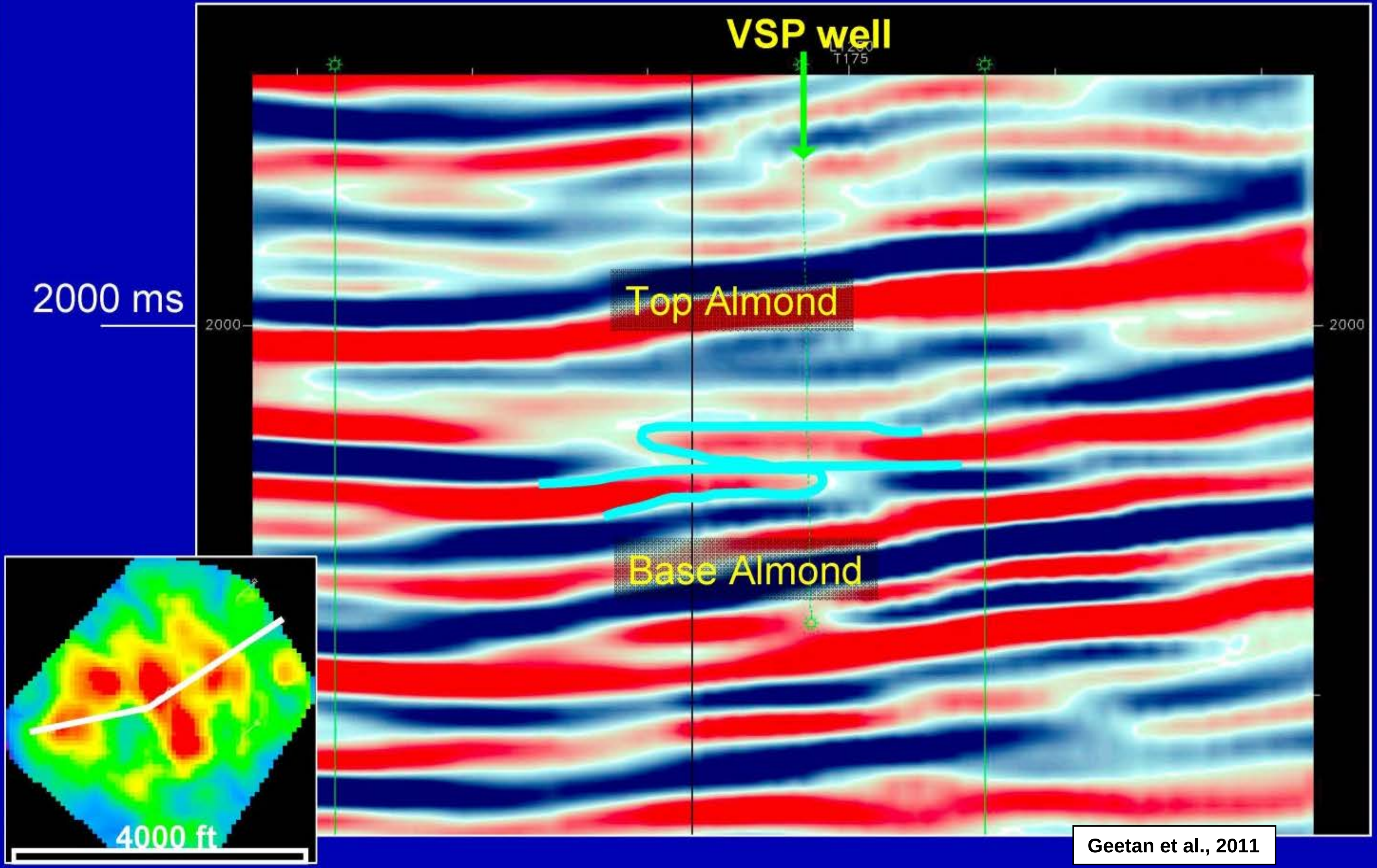
A look at the data- comparison to surface seismic data



Geetan et al., 2011

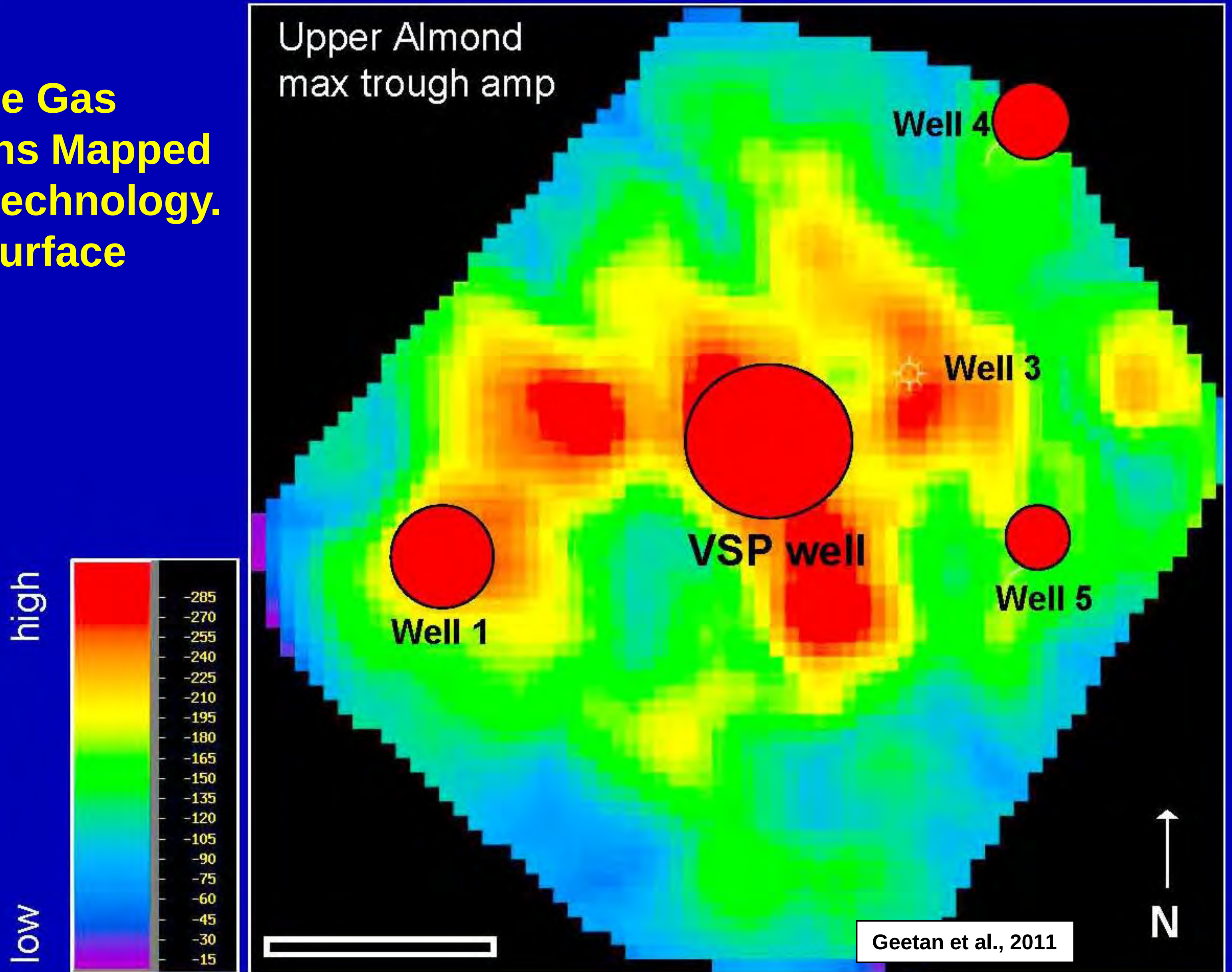
VSP Data

clearly visible terminations that tie into the depositional framework



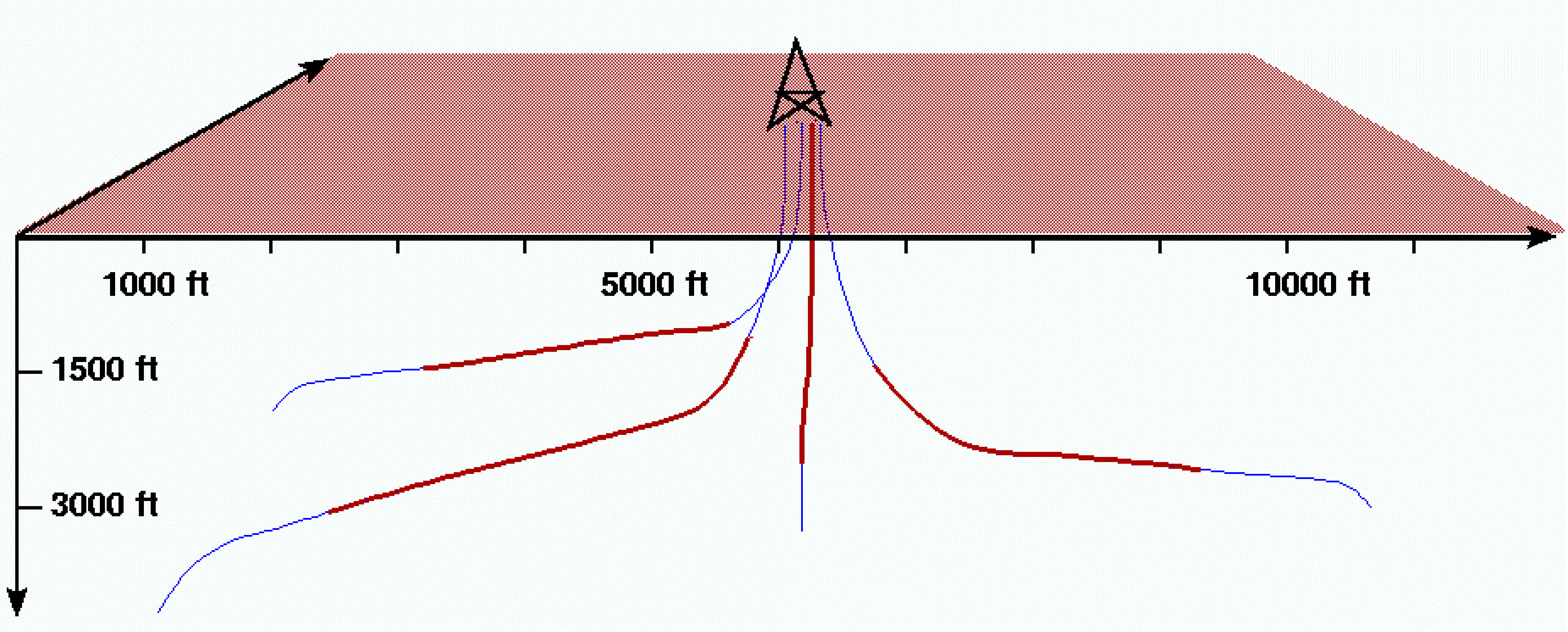
Almond reservoir 3D VSP and Production overlay

Areas of Large Gas Concentrations Mapped with 3D VSP technology. Not seen of Surface Seismic.



3D VSP survey using four 80 level 3C borehole arrays simultaneously: 960 channels Largest number of borehole sensors deployed

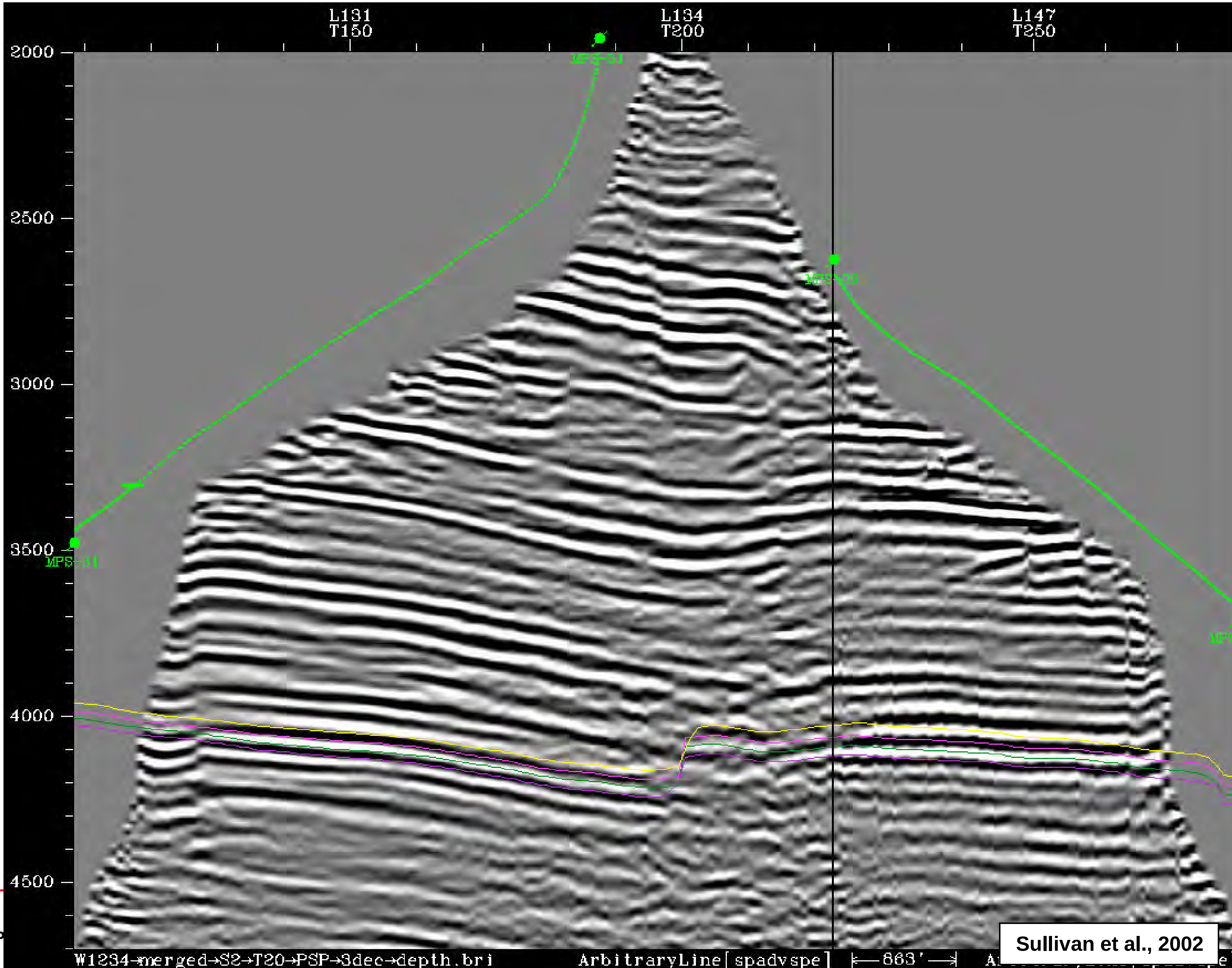
Surface Seismic Failed to Image the Reservoir



The well trajectories are shown as blue lines and the position of the four arrays is indicated by the red lines.

Paulsson et al., 2004

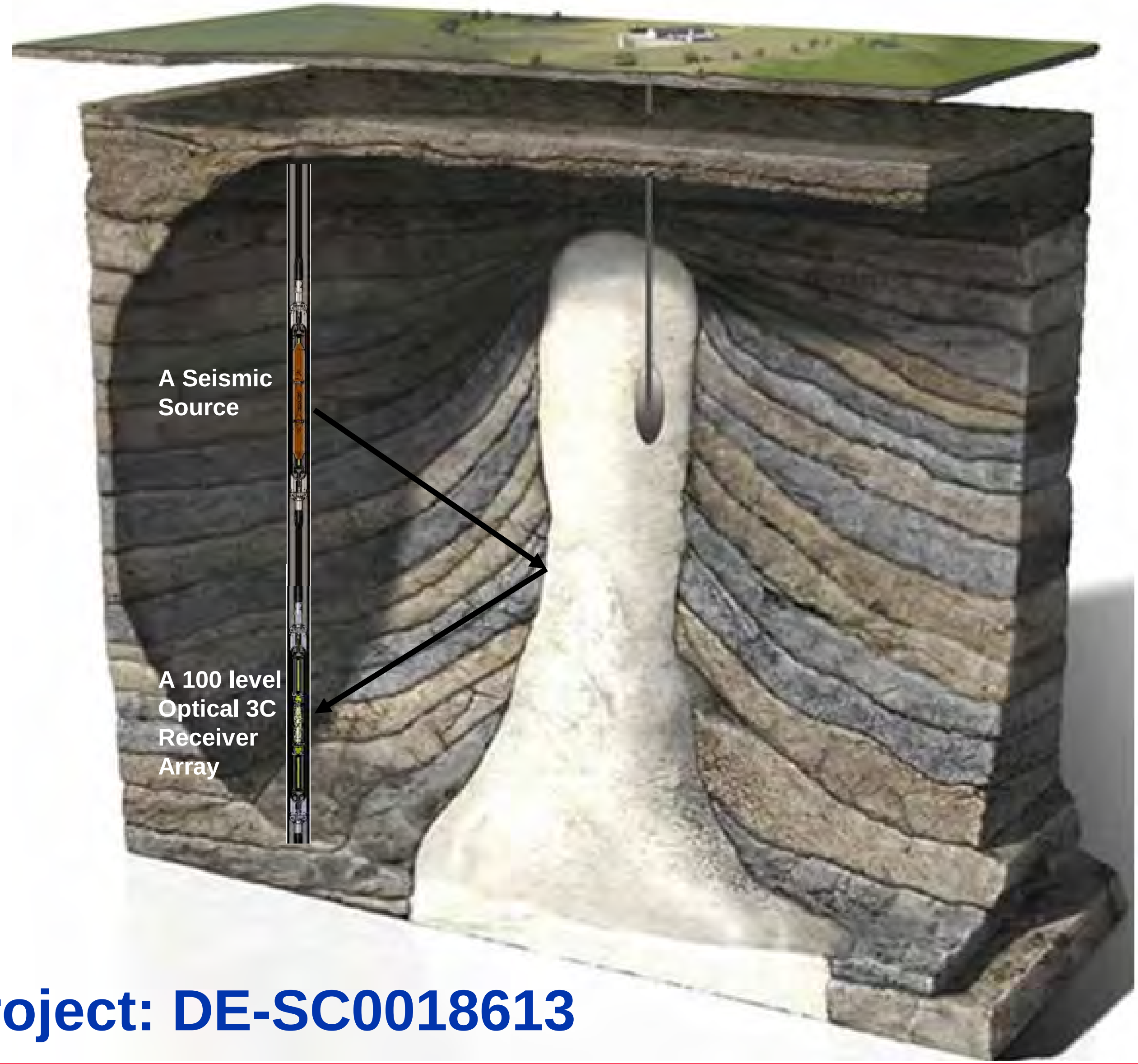
Massive 3D VSP / W-E Profile



Sullivan et al., 2002

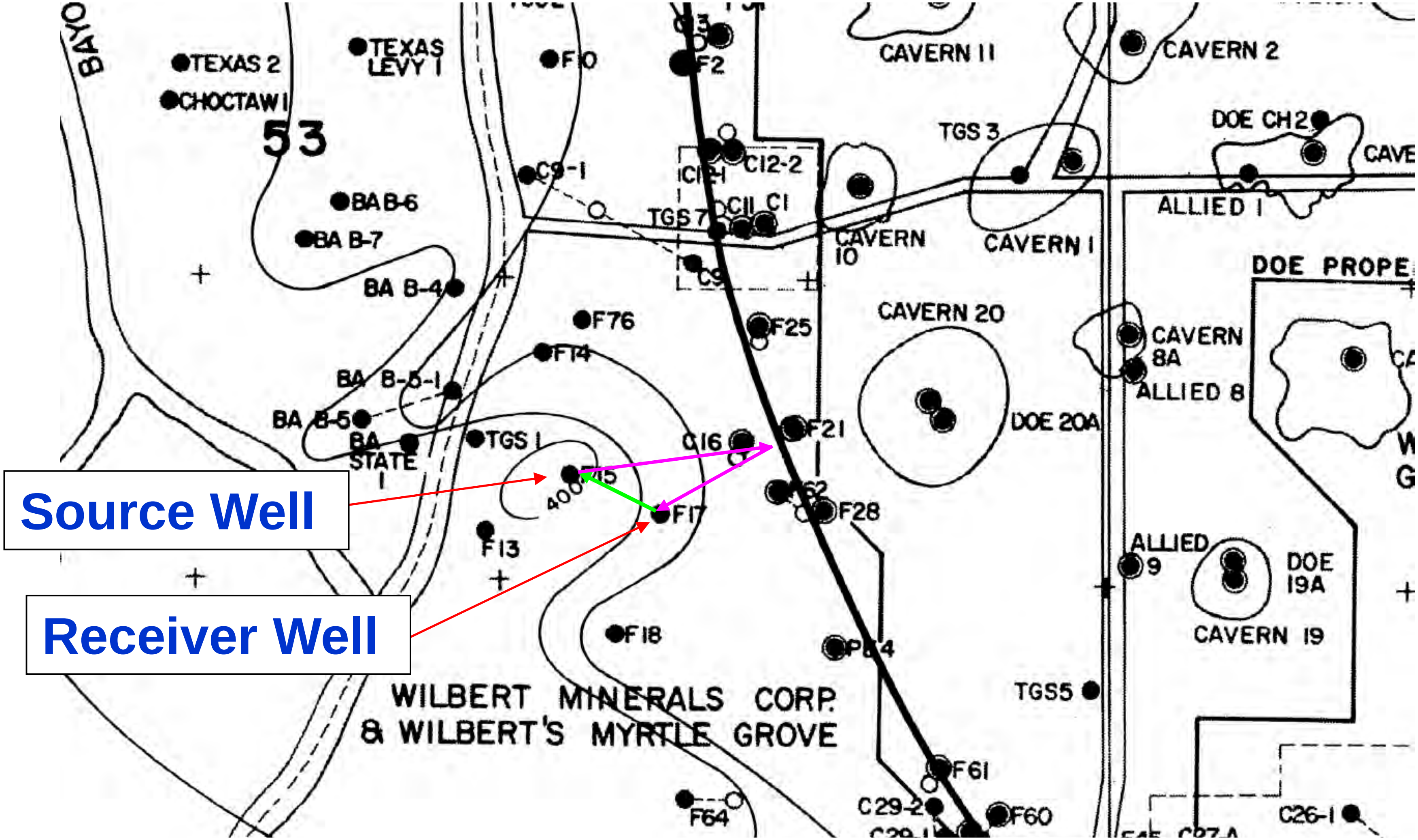
Salt Flank Imaging

Imaging a Salt Dome using Single Well Seismic

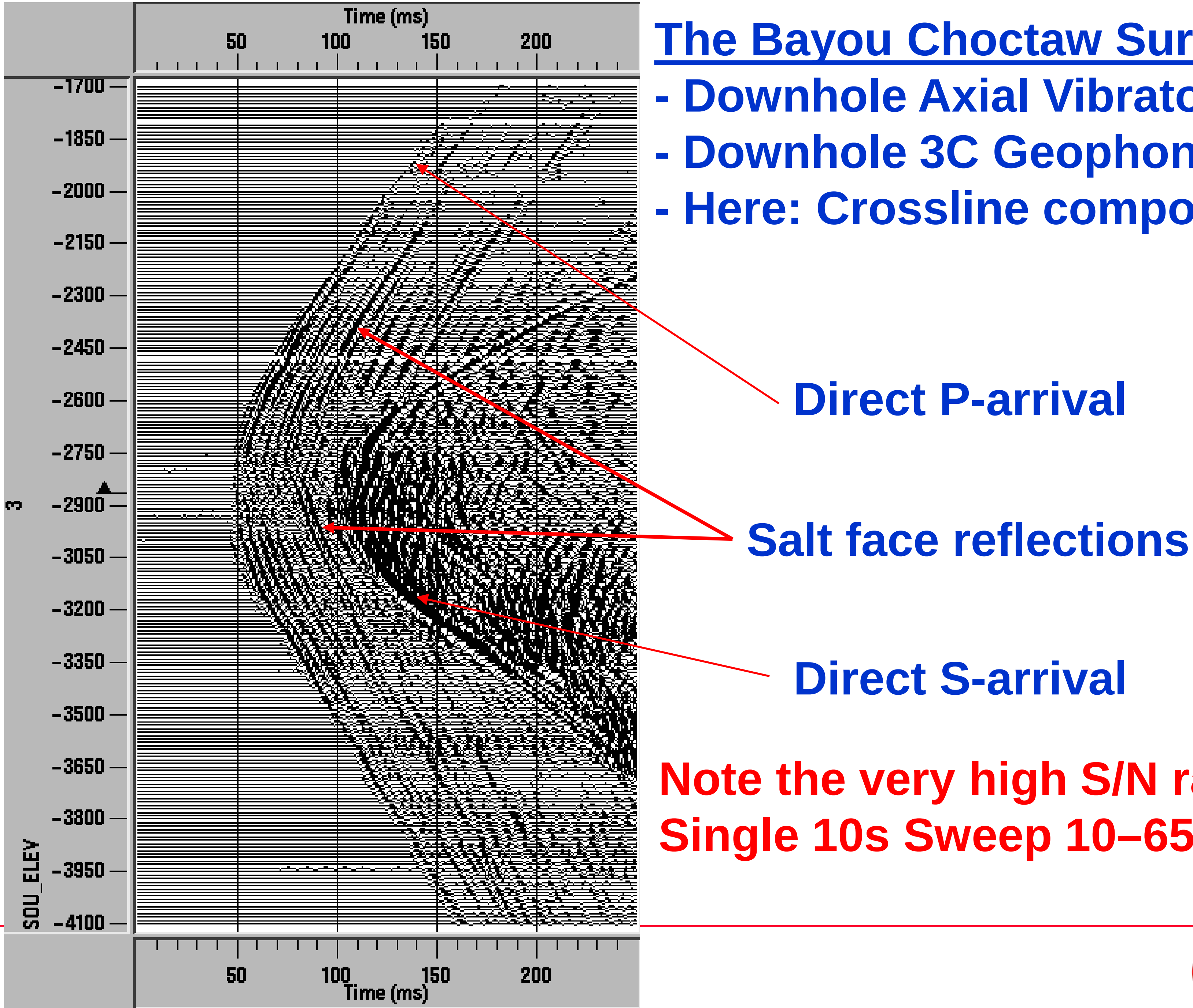


SBIR I Project: DE-SC0018613

The Bayou Choctaw Borehole Seismic Survey (DOE+Industry)



This map shows the location of the source well, receiver well, and approximate location of the salt dome. The green arrow shows the orientation of the inline horizontal component. The purple arrows show the approximate orientation of reflection ray paths that would come from the salt face. The orientation of reflections in a horizontal plane hodogram would be about 45 degrees from the inline component. A horizontally traveling event would cause horizontal motion in the vertical plane hodogram. The motion of a reflection from the salt face should be about 45 degrees left of the direction of the first arrivals.

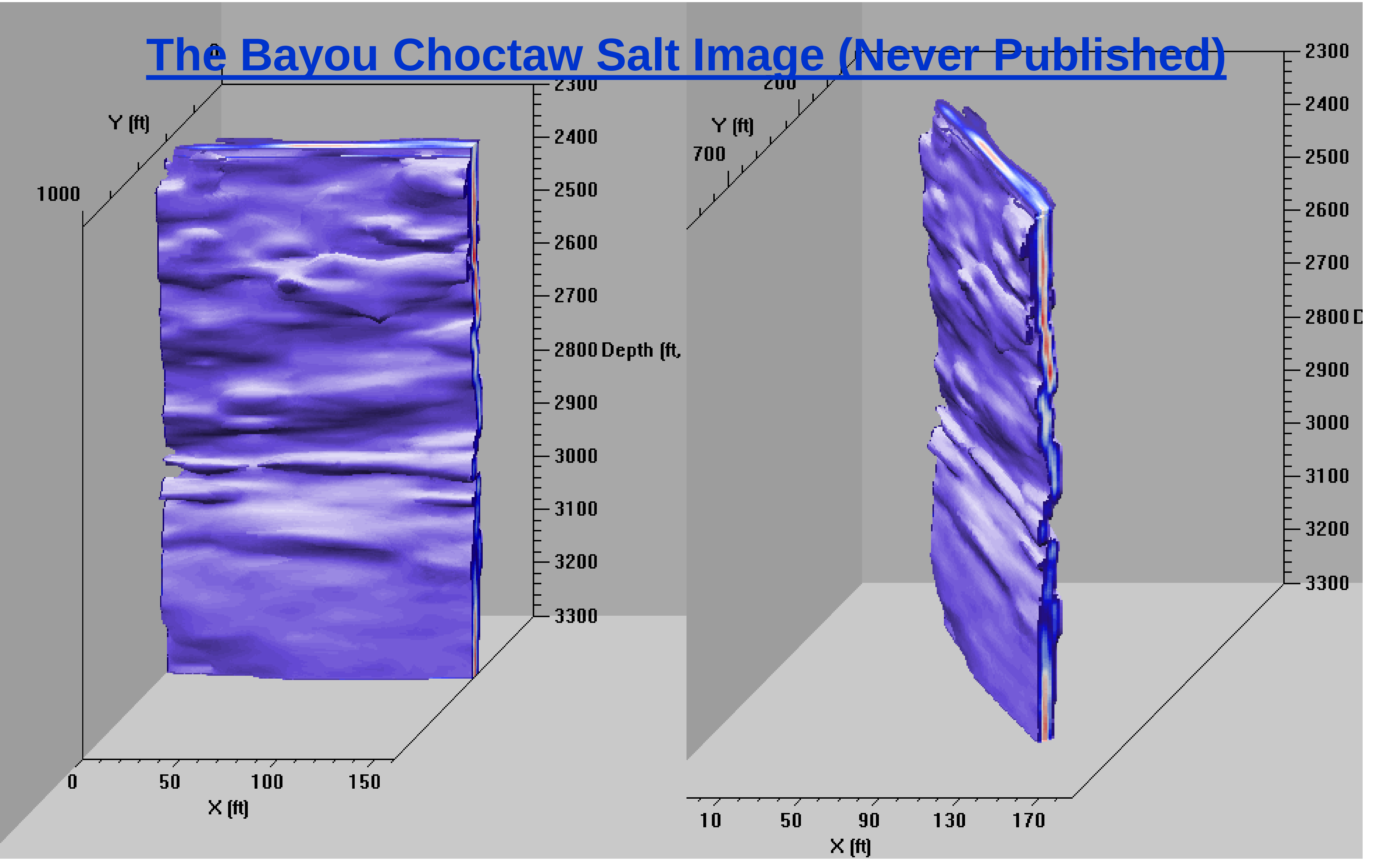


The Bayou Choctaw Survey

- Downhole Axial Vibrator
- Downhole 3C Geophones
- Here: Crossline component

Note the very high S/N ratio
Single 10s Sweep 10–650 Hz

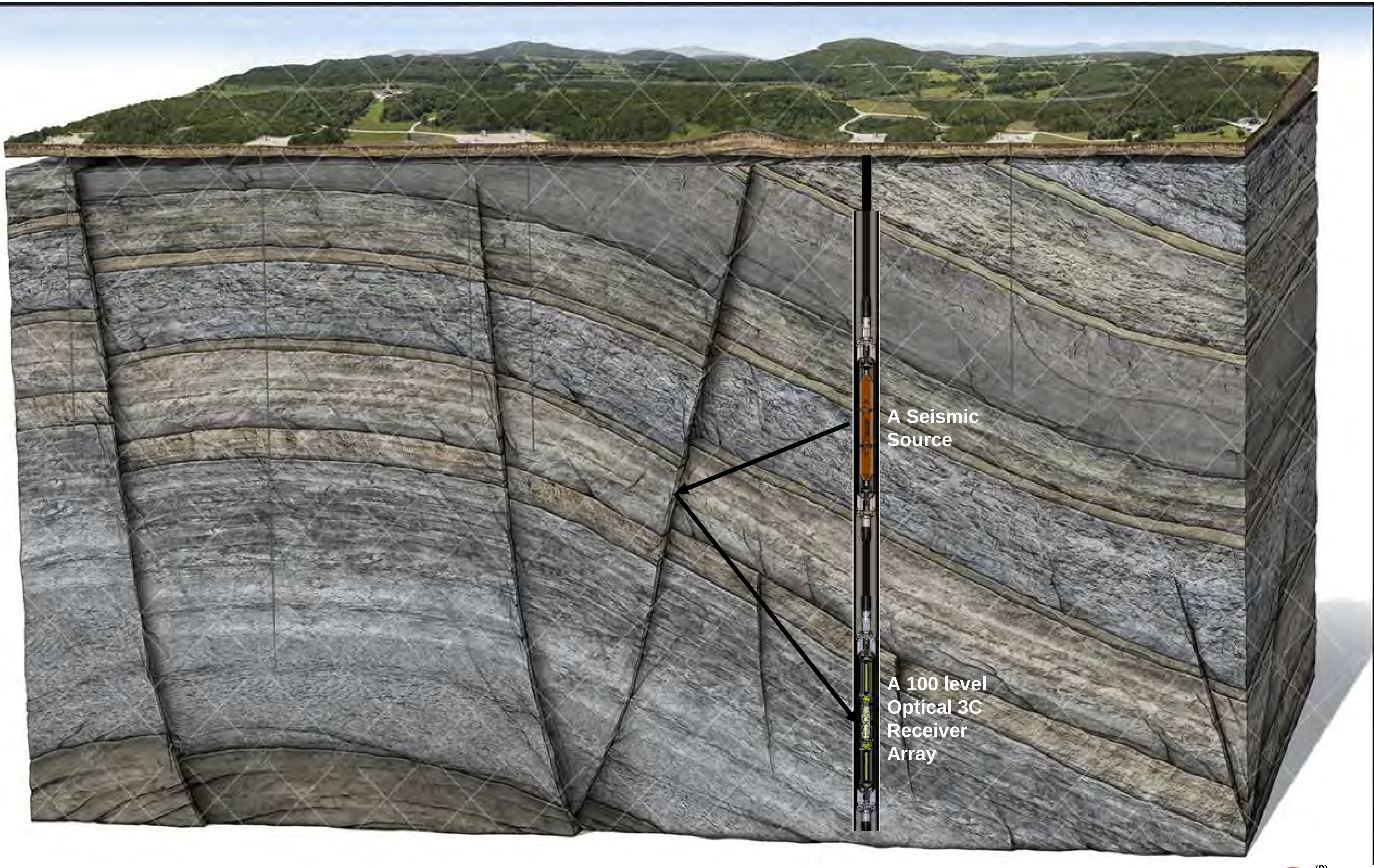
The Bayou Choctaw Salt Image (Never Published)



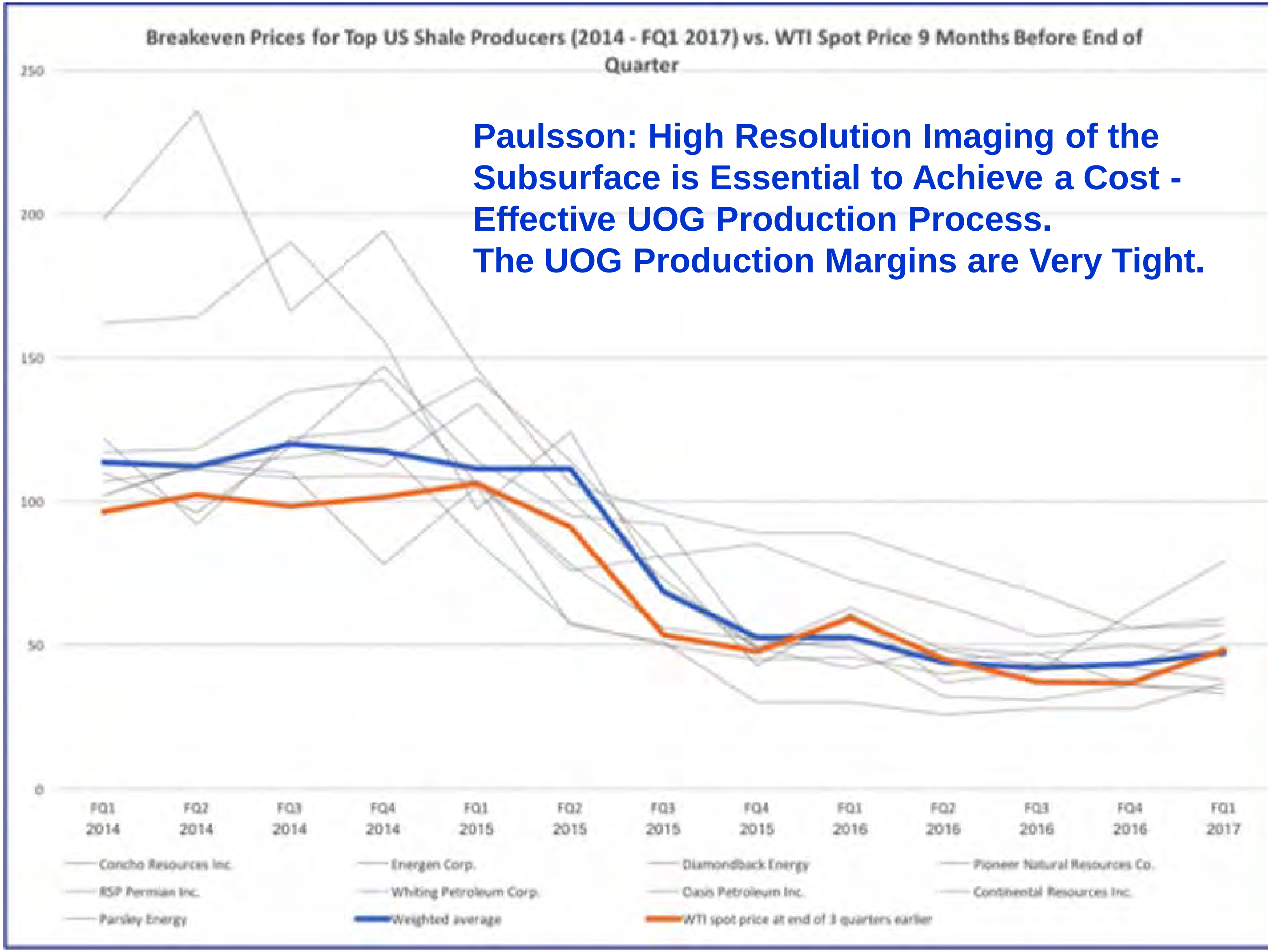
This is the image of the vertical face from a Pseudo Single well Seismic Survey

Fault Imaging

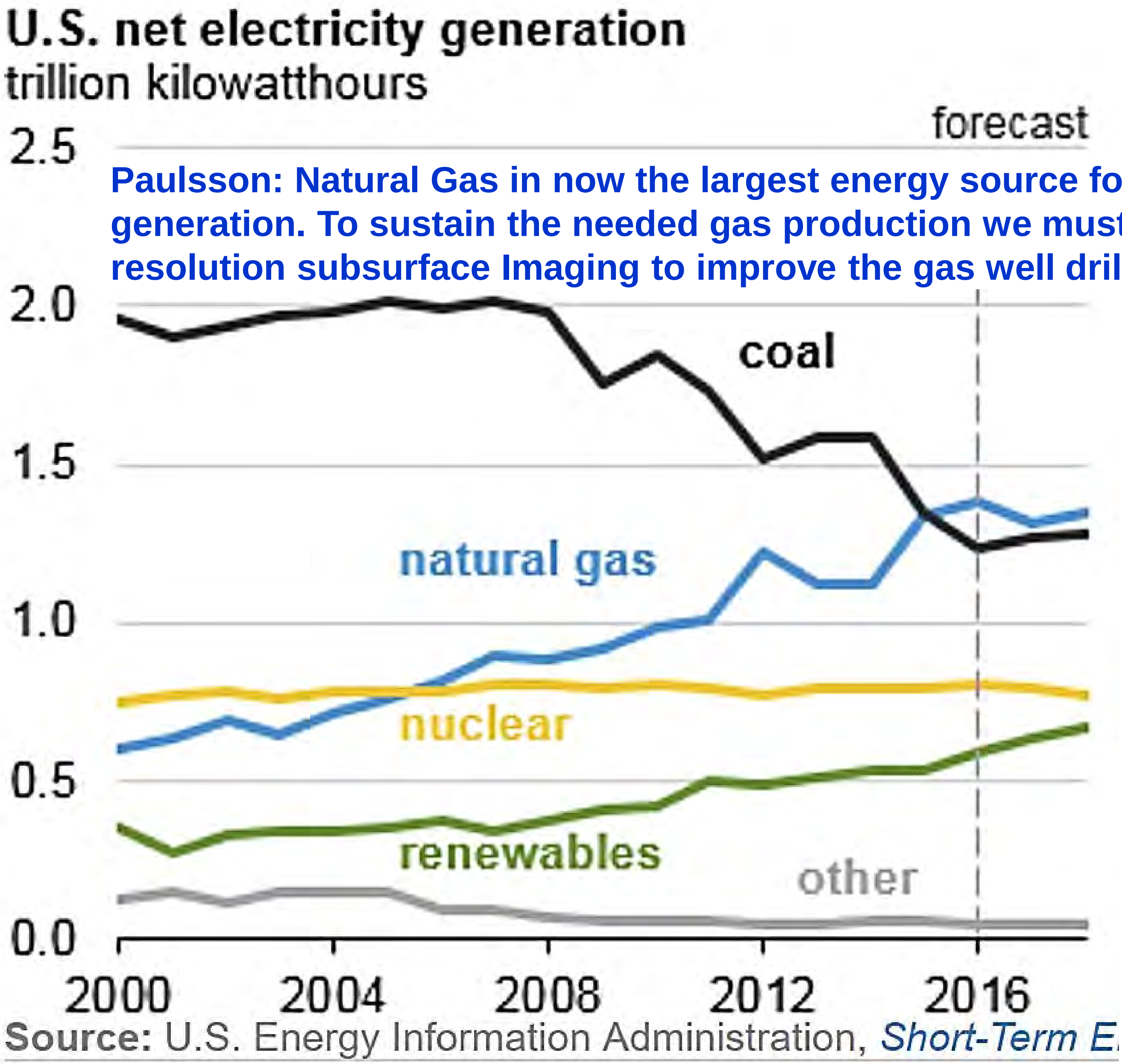
Subsurface Fault Imaging



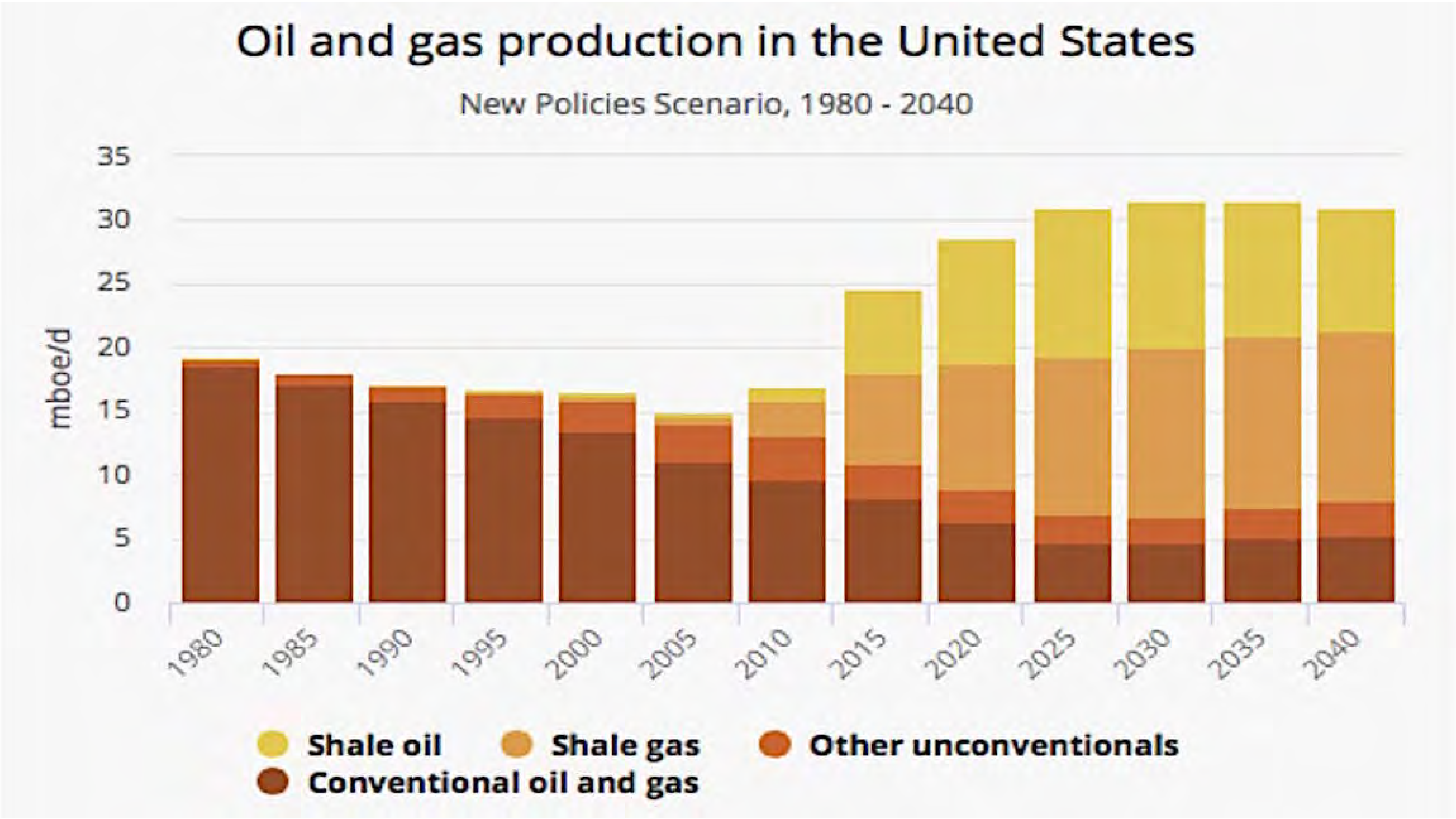
Why is High Resolution Subsurface Imaging Important from a Financial Point of View ?



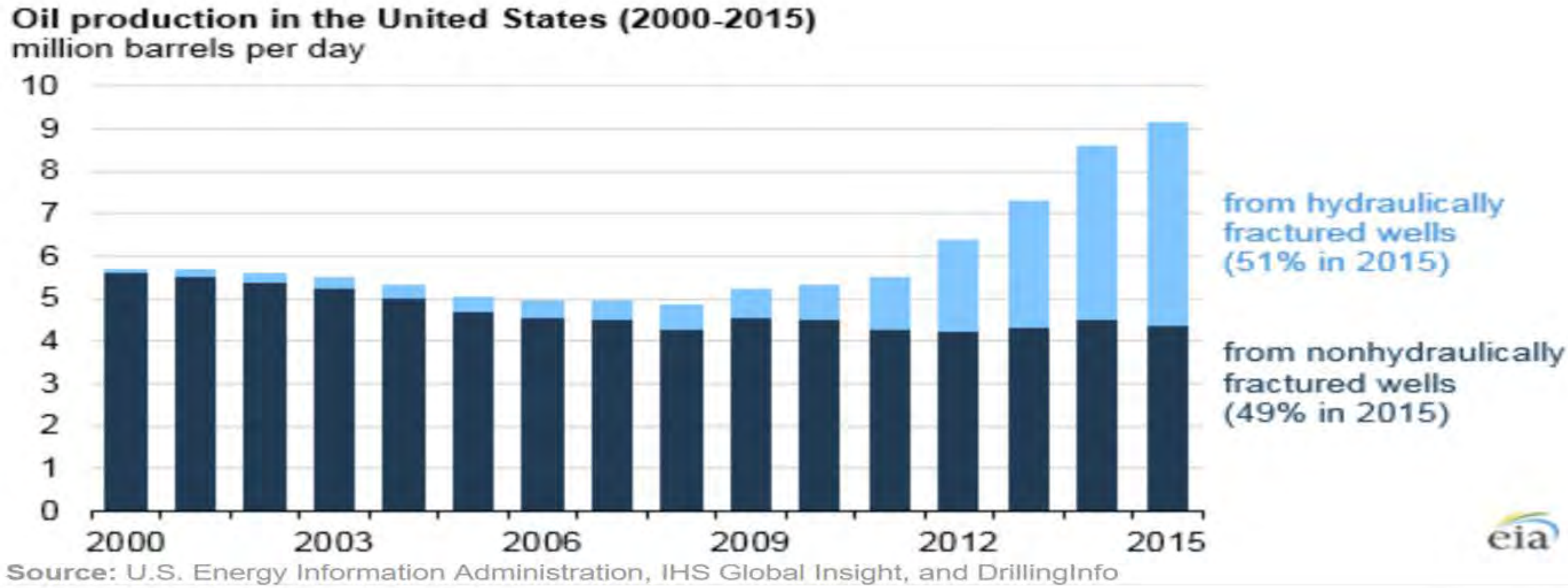
Based on data compiled by Dr. Anas Alhaji and Al Rajhi Capital and data sourced from EIA.

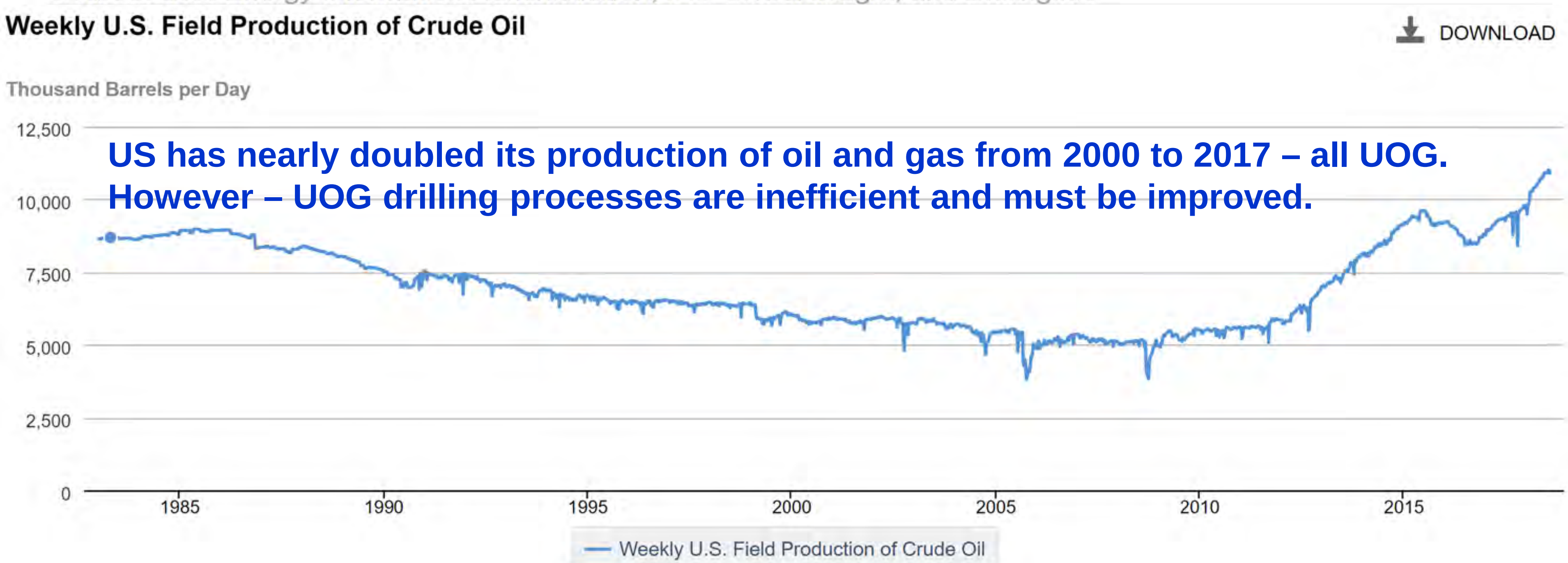


Paulsson: Natural Gas in now the largest energy source for electrical generation. To sustain the needed gas production we must apply high resolution subsurface Imaging to improve the gas well drilling results.



Paulsson: There is a radical transformation underway of the source for our oil and gas from conventional to unconventional oil and gas (UOG) reservoirs. To sustain this process we must achieve a better understanding how to improve image driven drilling.





US has nearly doubled its production of oil and gas from 2000 to 2017 – all UOG. However – UOG drilling processes are inefficient and must be improved.

The Subsurface Target for Conventional Oil & Gas

Alain Labastie, then President of Society of Petroleum Engineers (SPE), wrote in 2011:

"The current ultimate average recovery factor for oilfields, on a worldwide basis, is about 35%. This means that about two-thirds of the oil that has been discovered is left within the reservoir. We have under our feet, in well-known locations, enormous prospects for booking new reserves. Increasing the average ultimate recovery factor from 35% to 45% would bring about 1 trillion barrels of oil!".

Target: 1 trillion barrels of oil!

Fiber Optic Seismic Vector Sensors (FOSVS)
&
Acoustic Micro Emitters (AME)

Applications Include

- Monitor UOG Fracturing Operations
- Monitor Production of Oil & Gas
- Monitor Water, Steam, CO2 Injection
- Monitor Geothermal Operations

DOE 24360 Project: Goals and Objectives

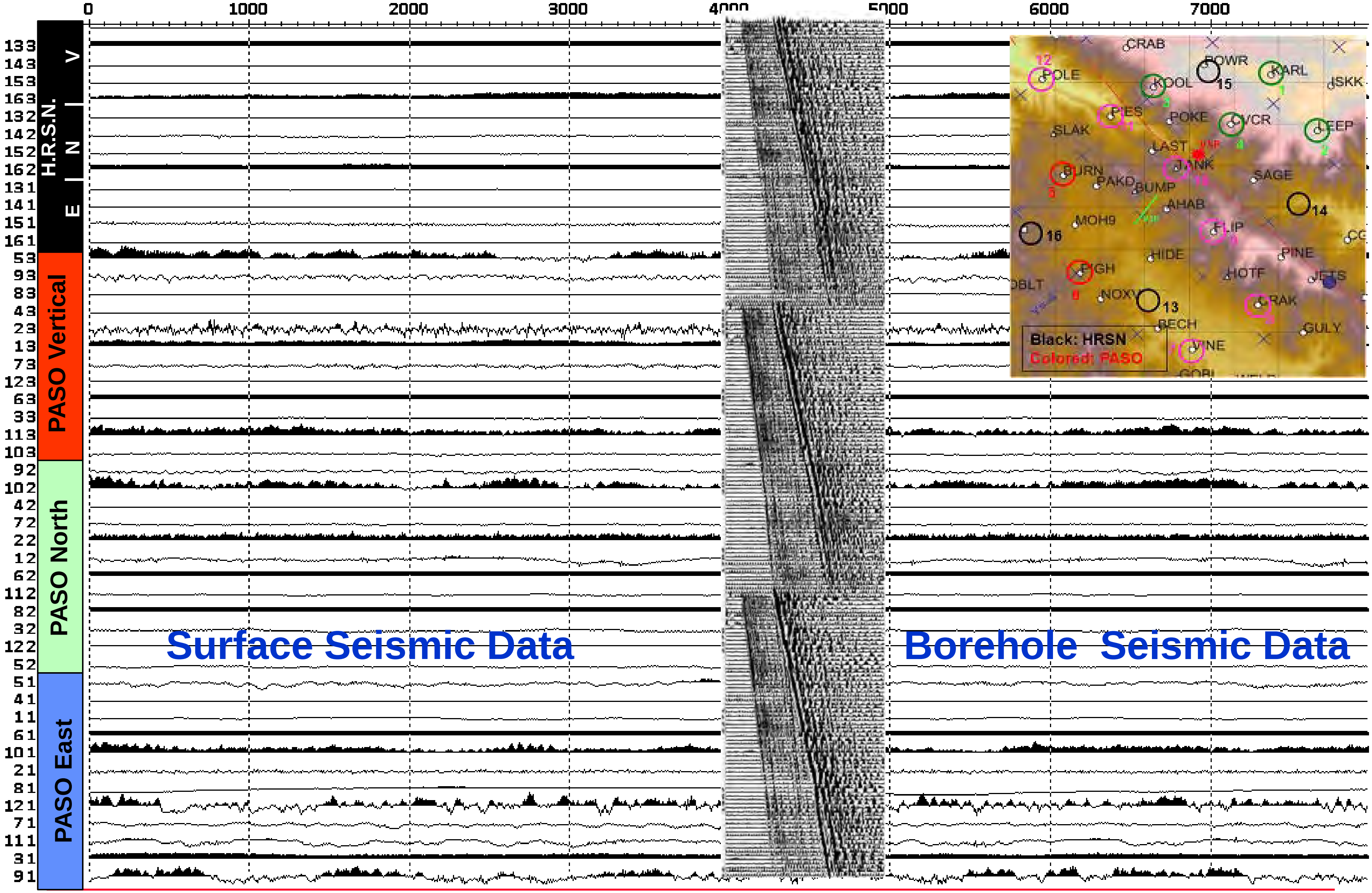
- **Main Objective:** Design, build and deploy an UOG borehole based reservoir evaluation and monitoring system
  - **Goal A:** Build a 100 station 3C Fiber Optic Seismic Vector Sensor (FOSVS) System.
  - **Goal B:** Develop injectable smart Acoustic Micro Emitters (AME's)
  - **Goal C:** Test the combined FOSVS and AME systems in the lab and in several field tests.

Key Technologies Presented

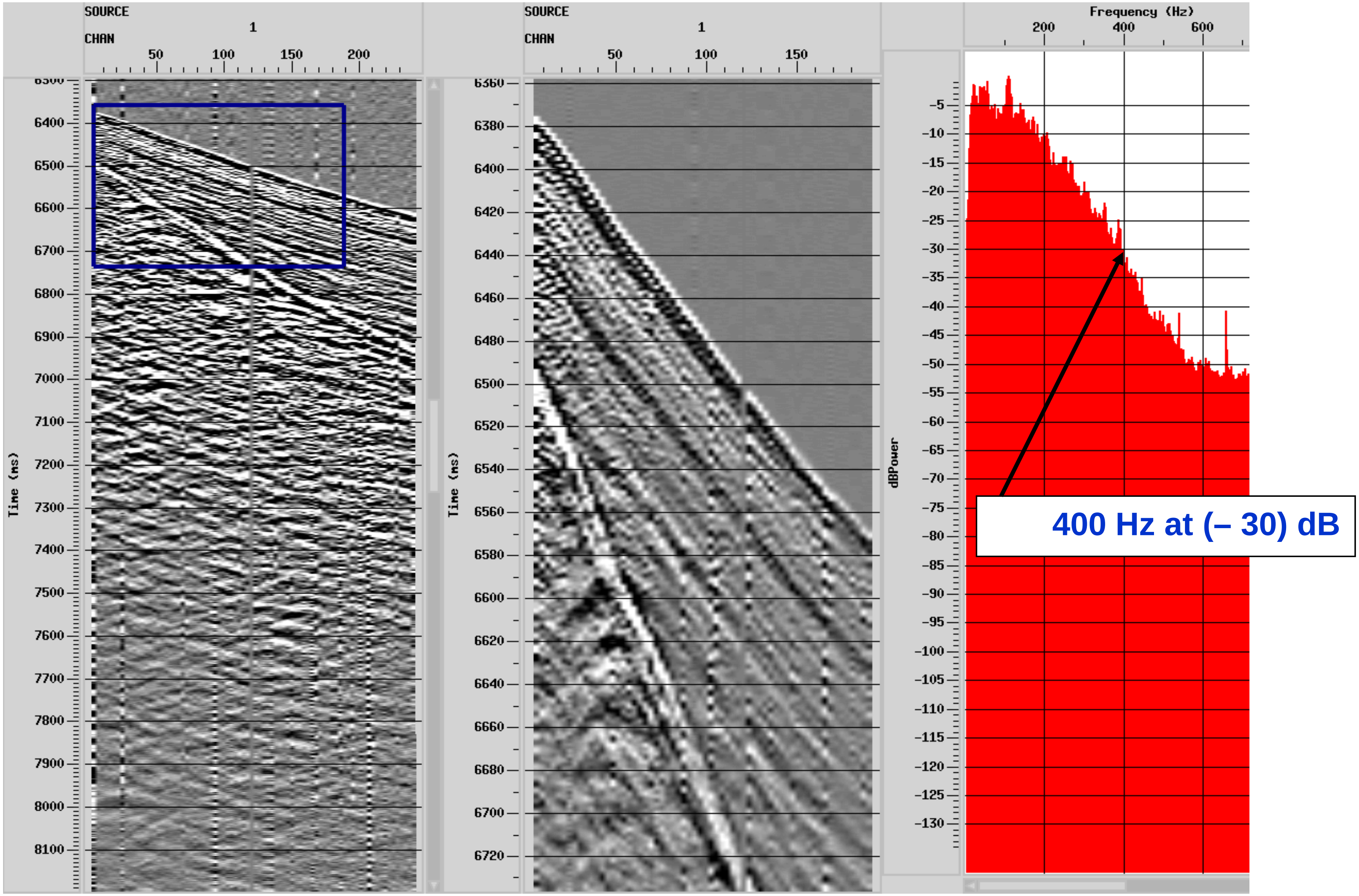
- Large Seismic Array Technology
  - Key to Record and Track small Seismic Events
- Fiber Optic Seismic Sensors
- Acoustic Micro Emitters

PI: M-1.3

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



M0.0 Micro Seismic Event recorded May 5, 2005 at 18:41 UTC – axial components

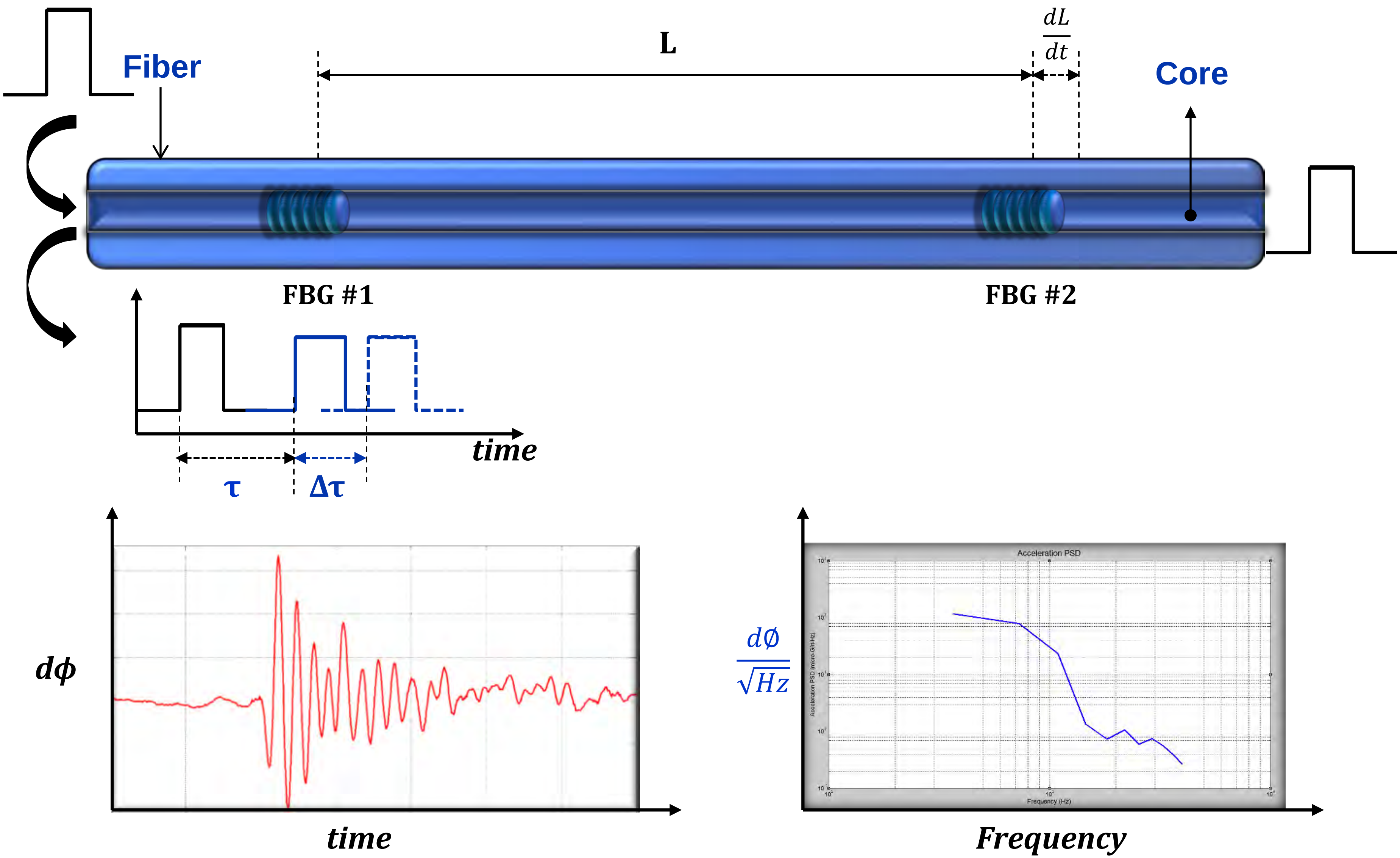


Key Technologies Presented

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

Develop Better Sensors!

Fiber Bragg Grating: Theory



Laboratory Test of

Acoustic Micro Emitters (AME)

using

Fiber Optic Seismic Vector Sensors

(FOSVS)

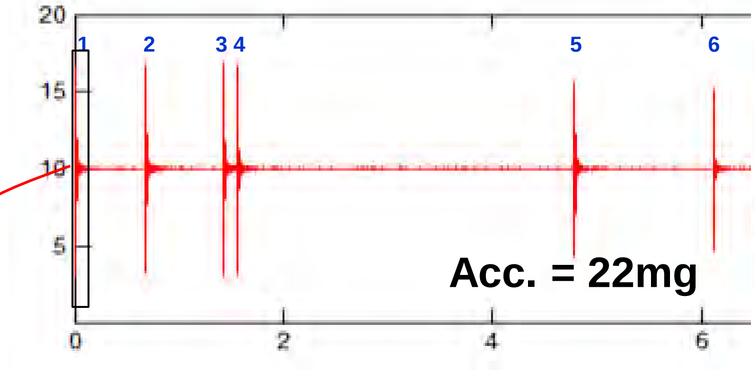
AME Test using Fiber Optic Seismic Vector Sensors (FOSVS)

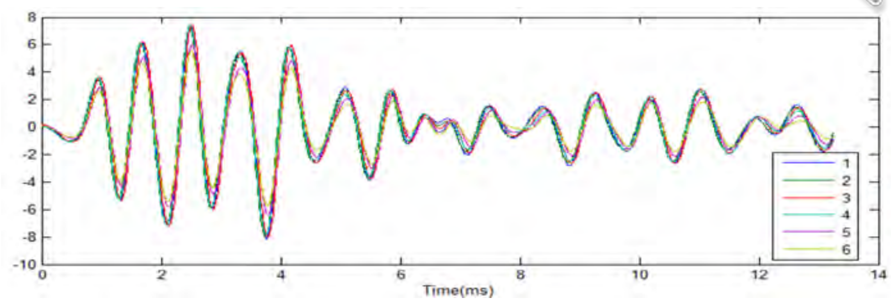
Pressure cell and sensor plate placed on a metal plate sitting on a foam mat on a metal table

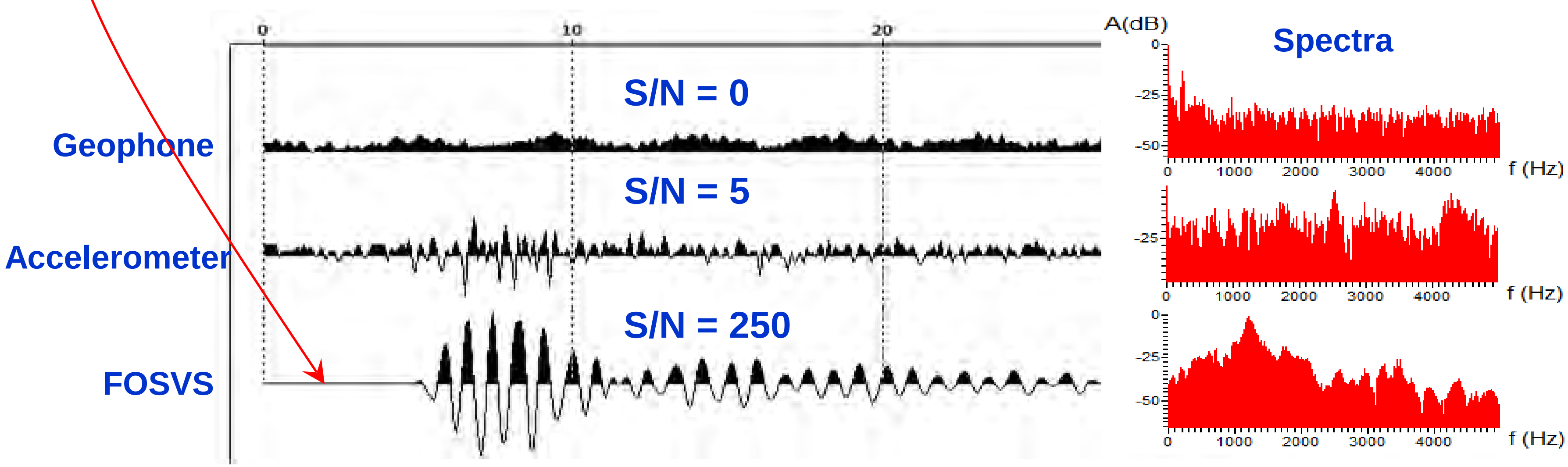
Fiber sensor, geophone and accelerometer are placed approximately 20 cm (8 inches) from the pressure vessel with AMEs

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

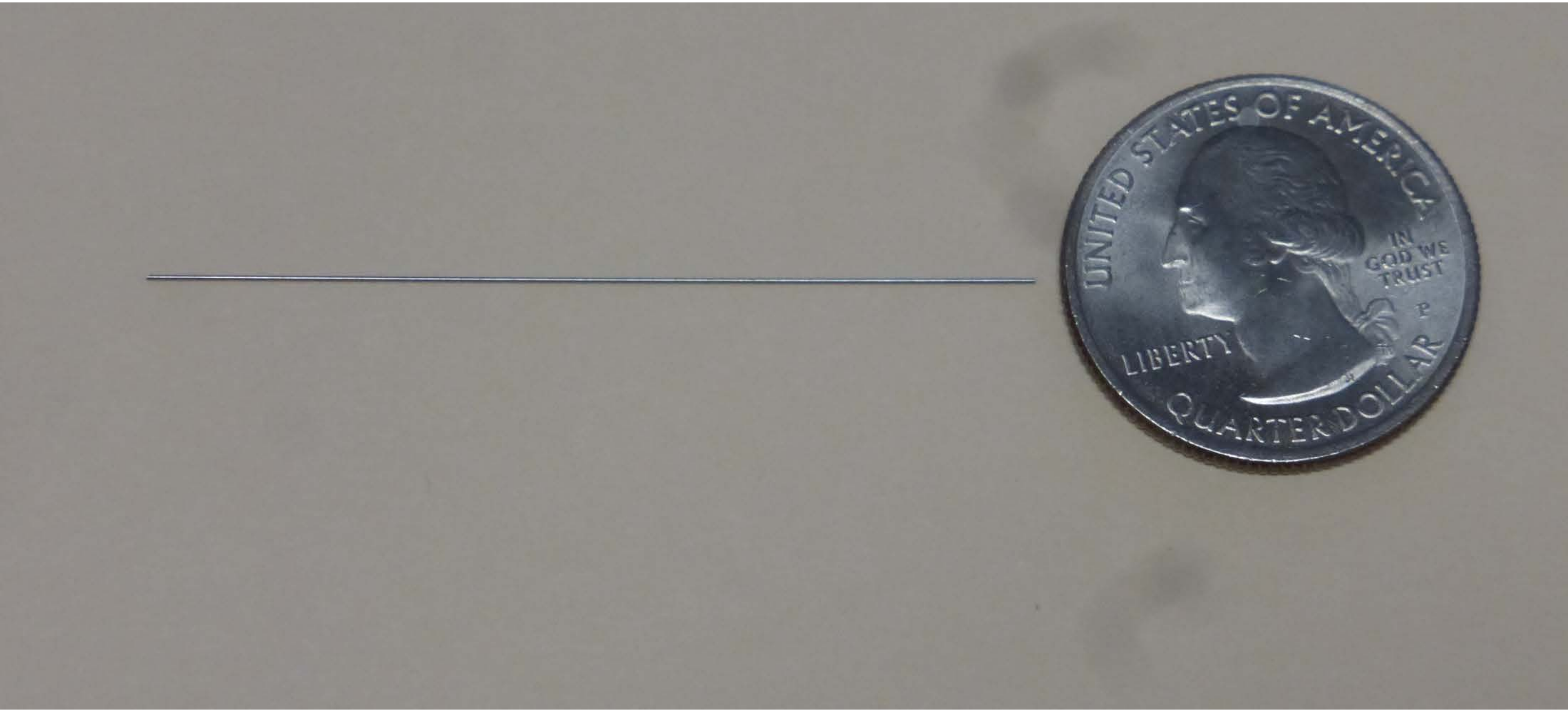
Energy Released: ~0.1 J = M-3.5





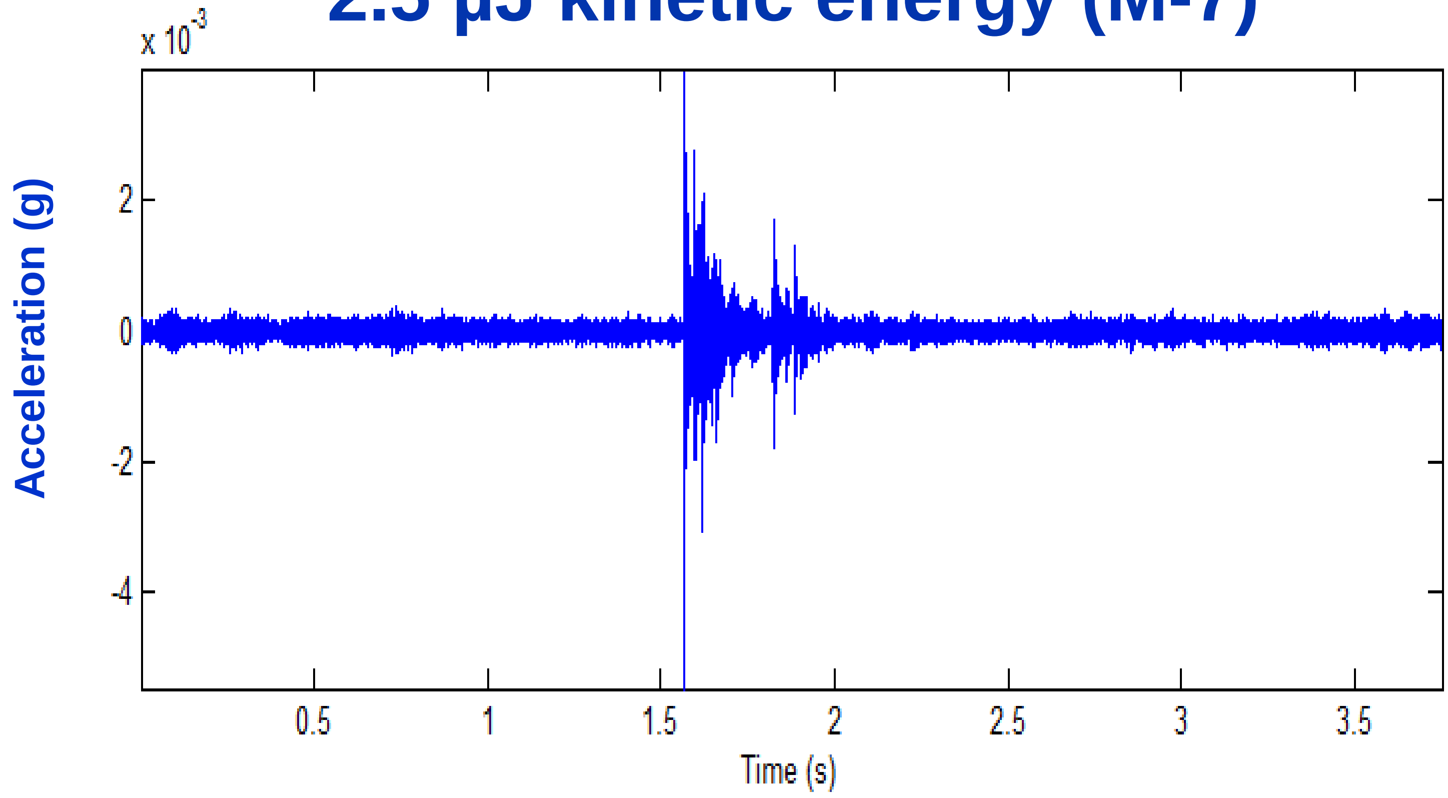


Can You Hear a Pin Drop?
Test Object: OD: 0.011", 2" long, 24.8 mg



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

2.5 μJ kinetic energy (M-7)



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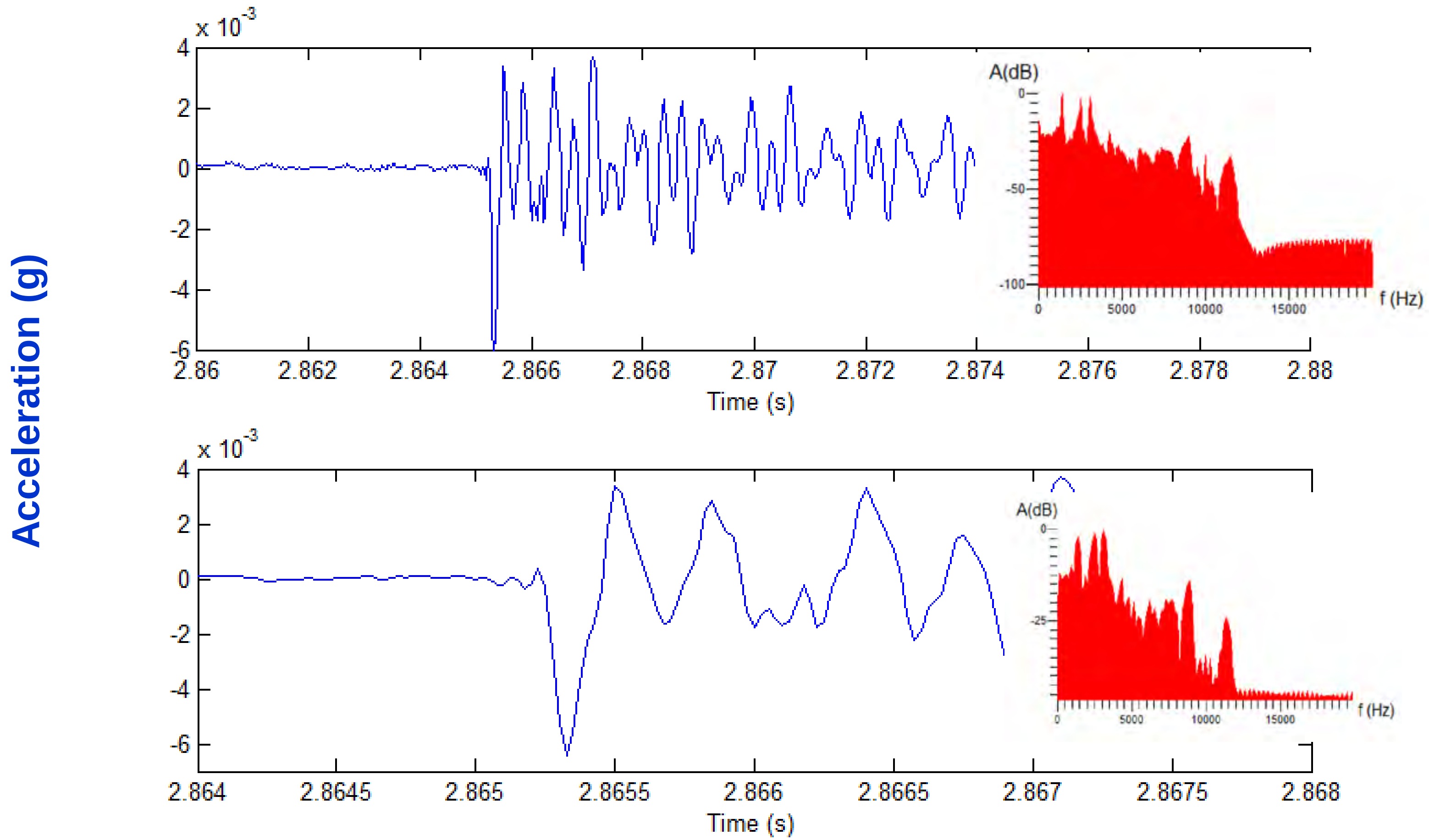
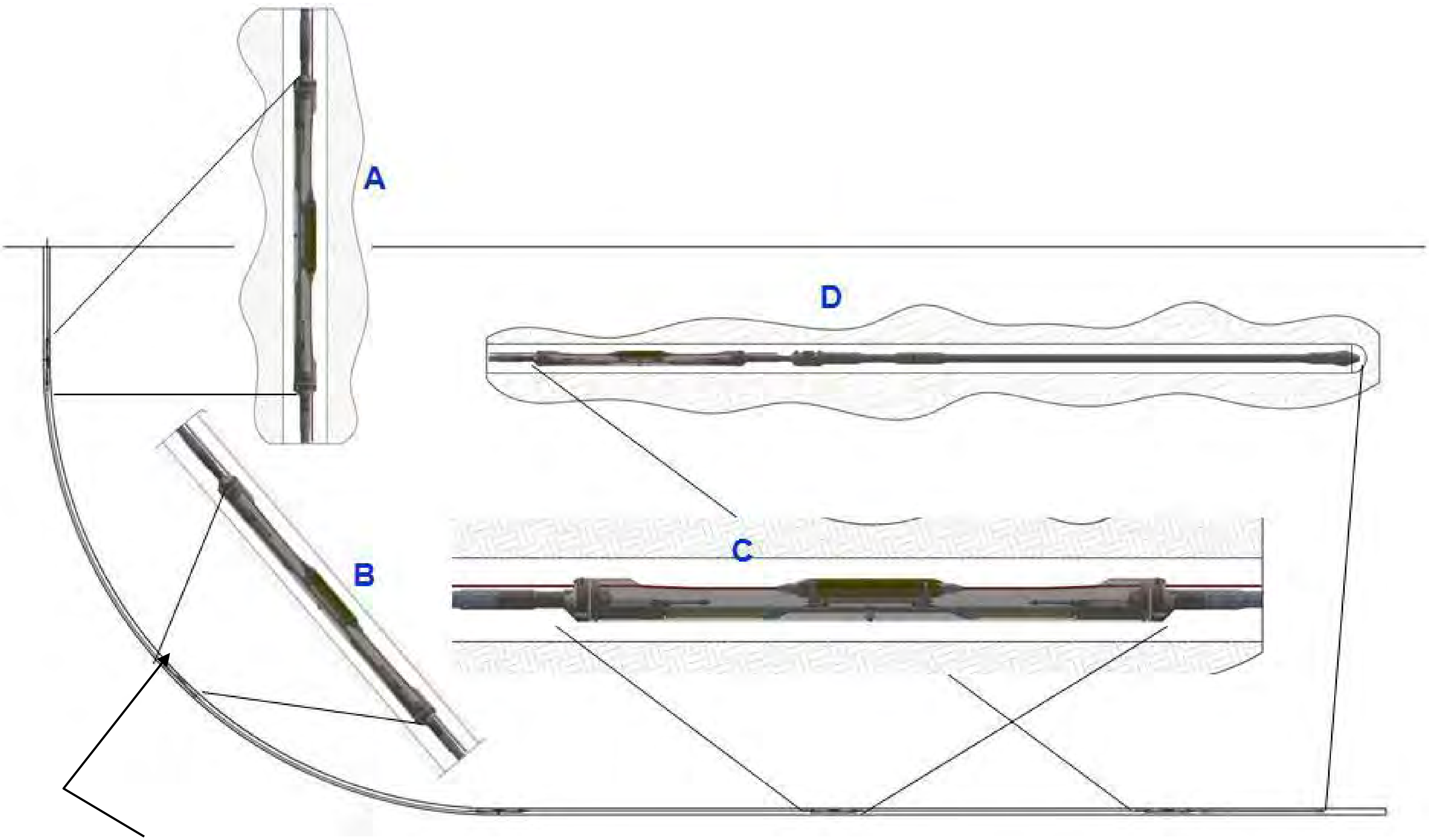


Deployment System Development

Drill Pipe Deployed Sensors Allowing Horizontal Well Deployment

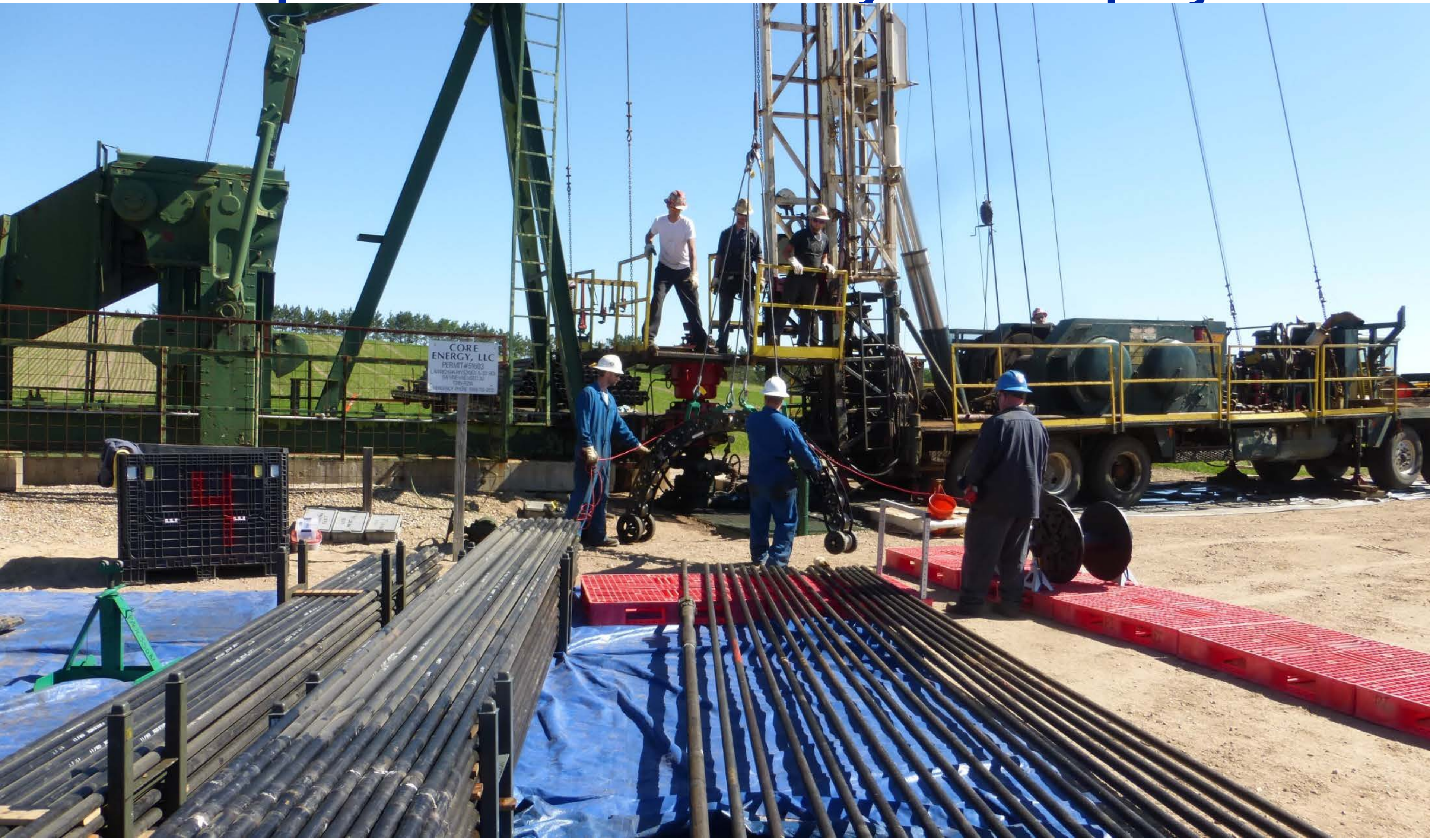


Clamping system operates by increasing the pressure inside the drill pipe and manifolds and uses the bore hole fluid as a medium

Field Tests
of
Fiber Optic Seismic Sensor (FOSVS)™
System
Deployed into a Near Horizontal Borehole

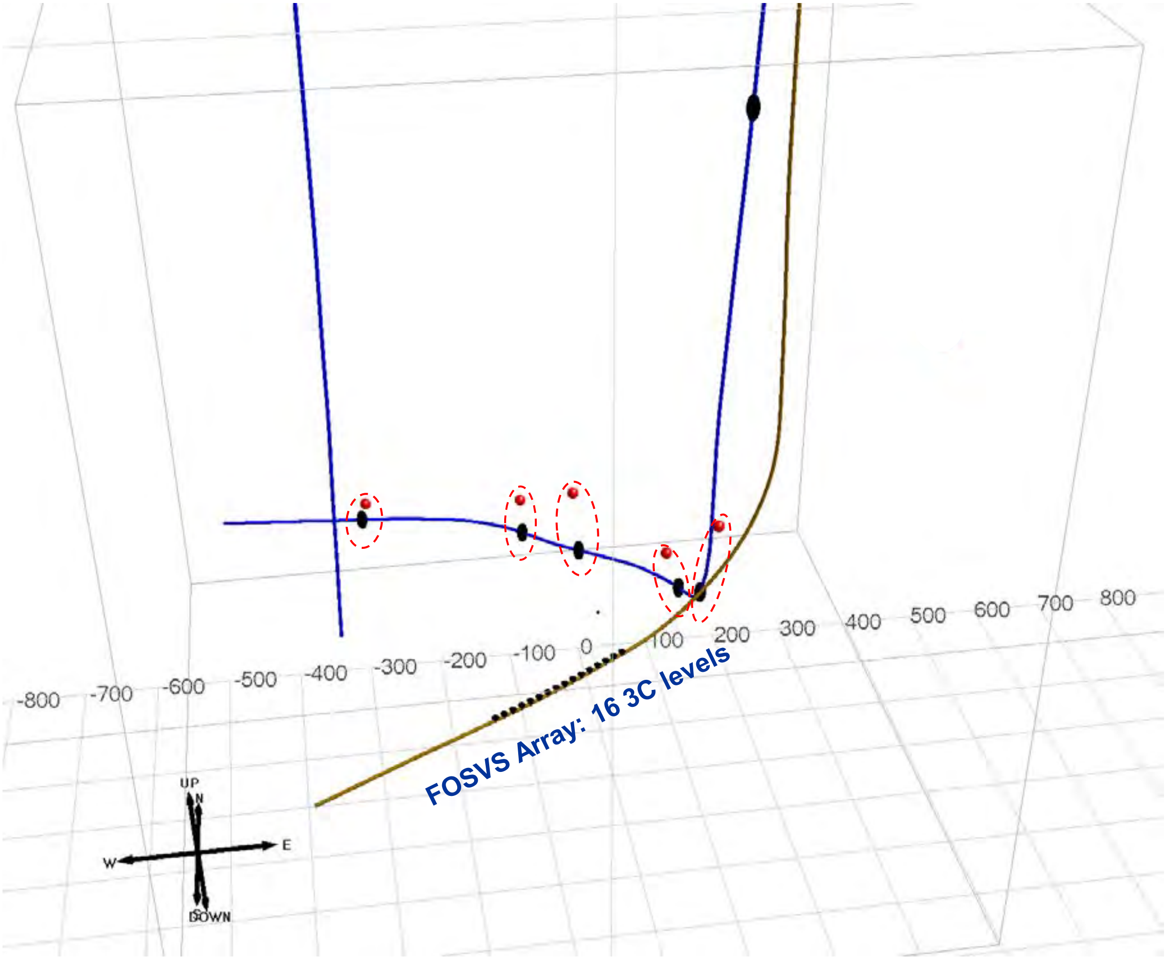
Fiber Optic Seismic Sensor System Deployment

Fiber Optic Seismic Sensor System Deployment



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

Results from Locating String Shots During a Survey Recorded for Battelle in June 2016

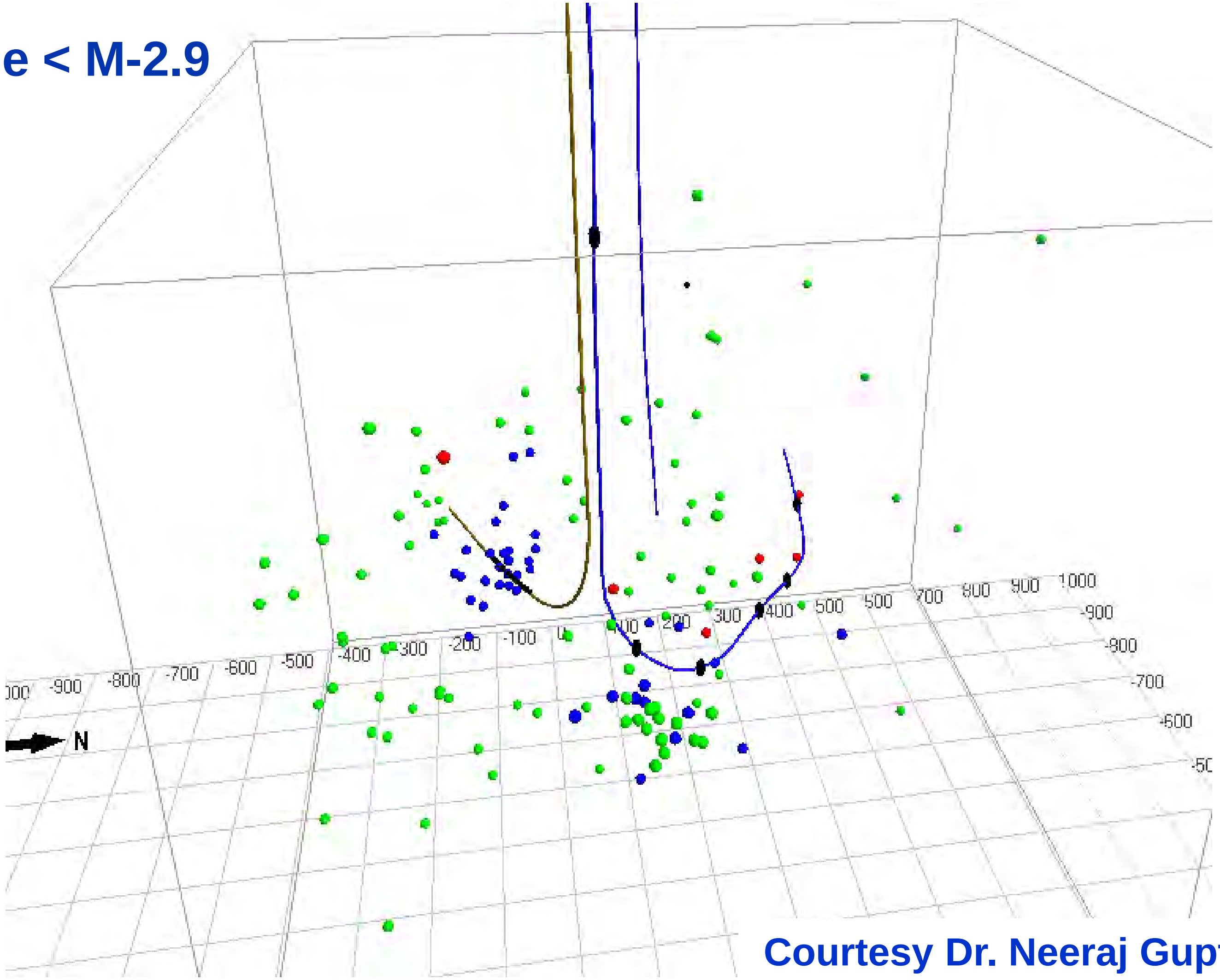


Courtesy Dr. Neeraj Gupta, Battelle

Survey for Battelle - Locating String Shots and Micro Seismic Events
Recorded 11,000 events in four weeks. Displayed here are 130 events.

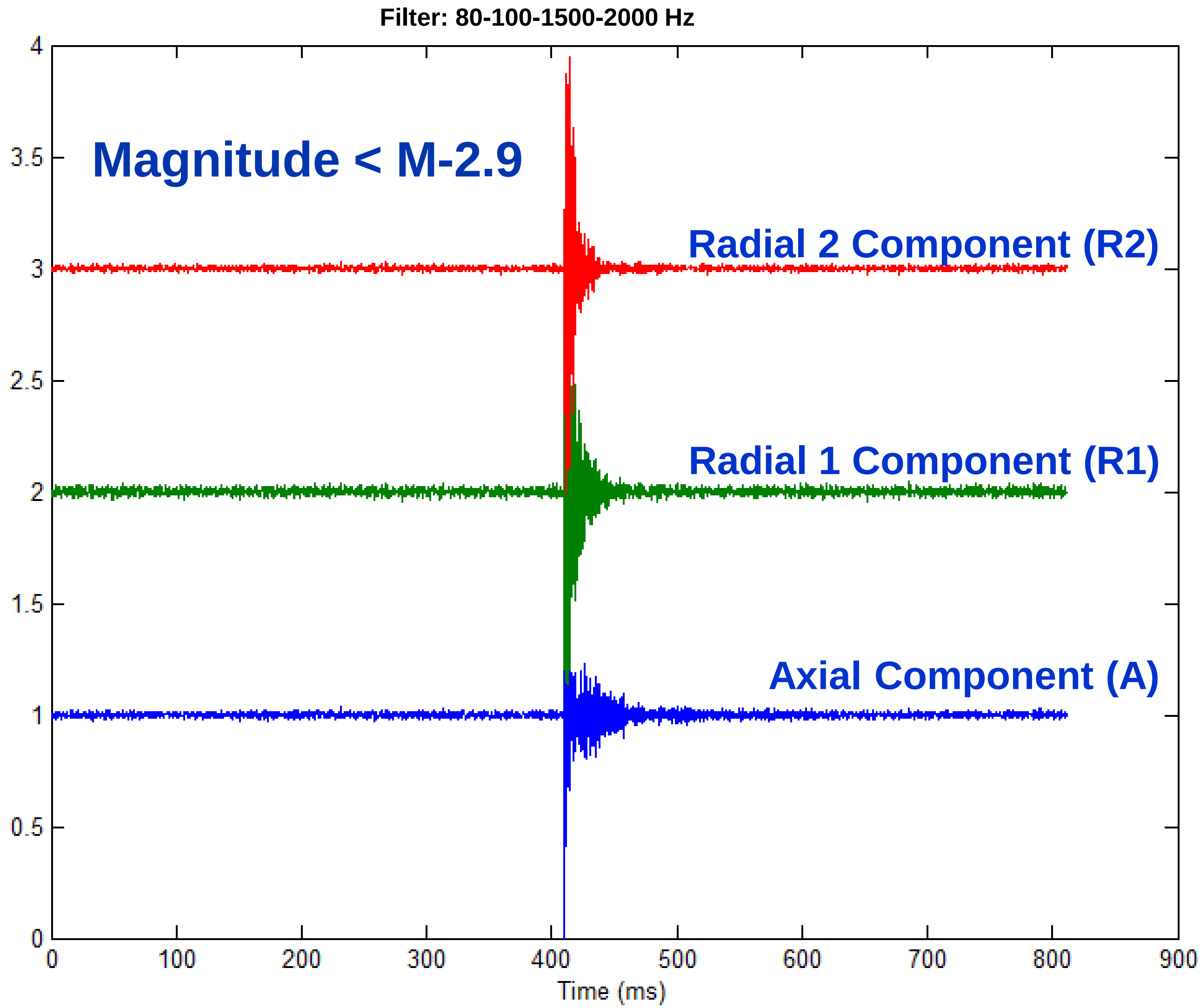
Red: String Shots; Blue: Classic Micro Seismic; Green: "Long Duration" Events

Magnitude < M-2.9

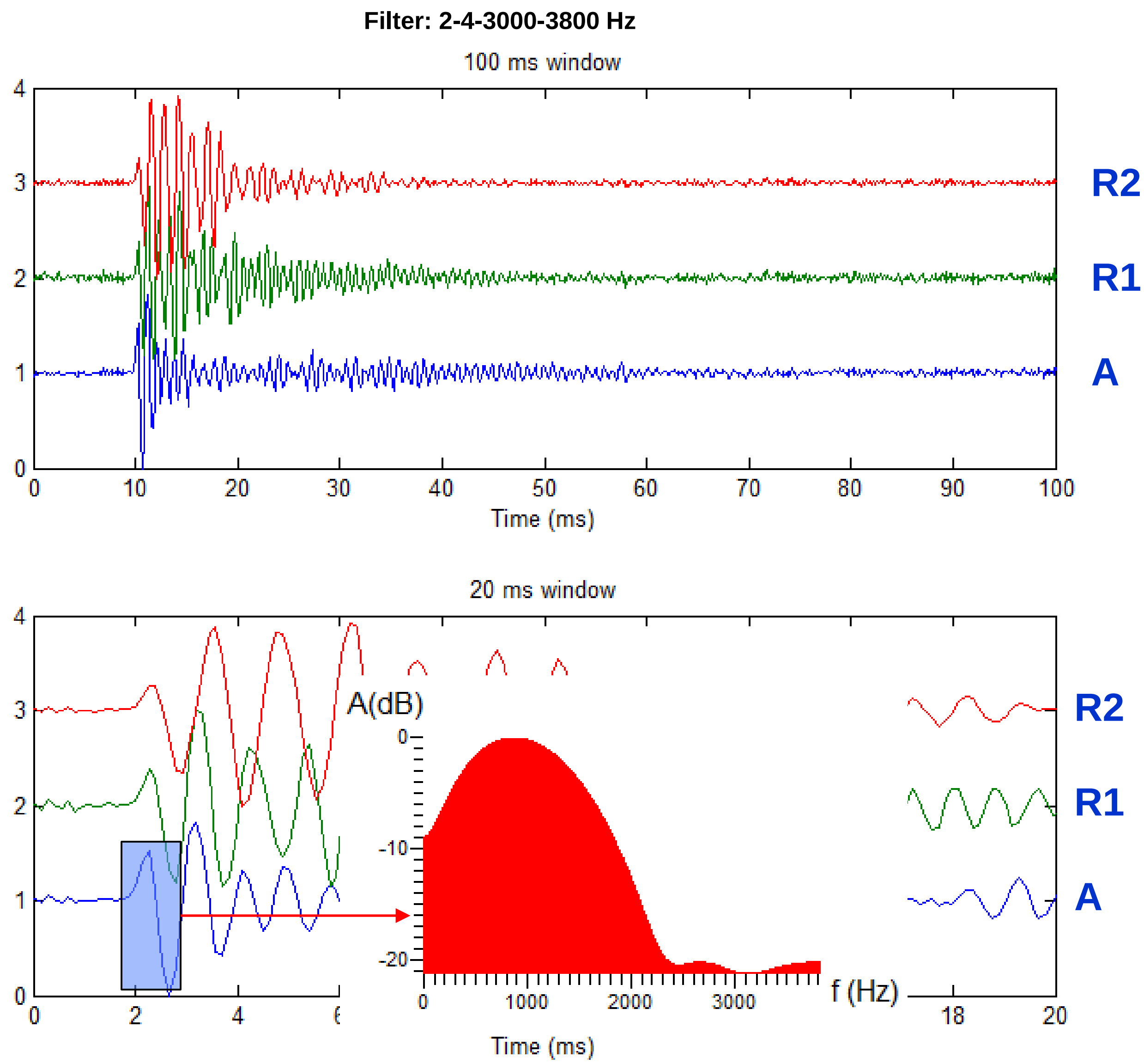


Courtesy Dr. Neeraj Gupta, Battelle

Sound of a Classic MS in 3C, Survey for Battelle, June 2016



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



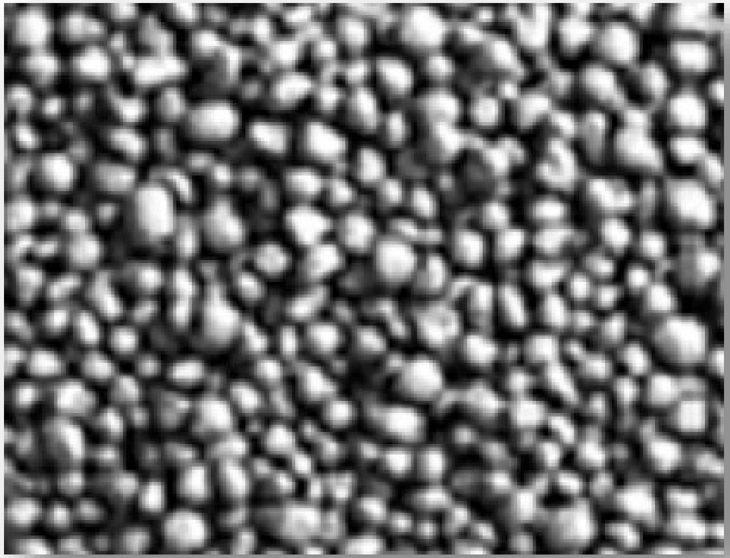
Borehole Seismology

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

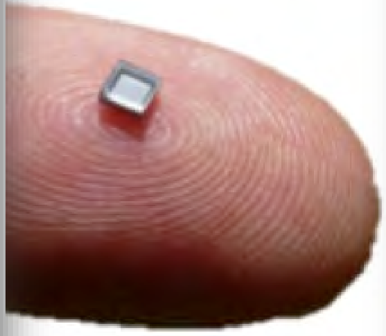
Fluidion Technology: The AME Concept

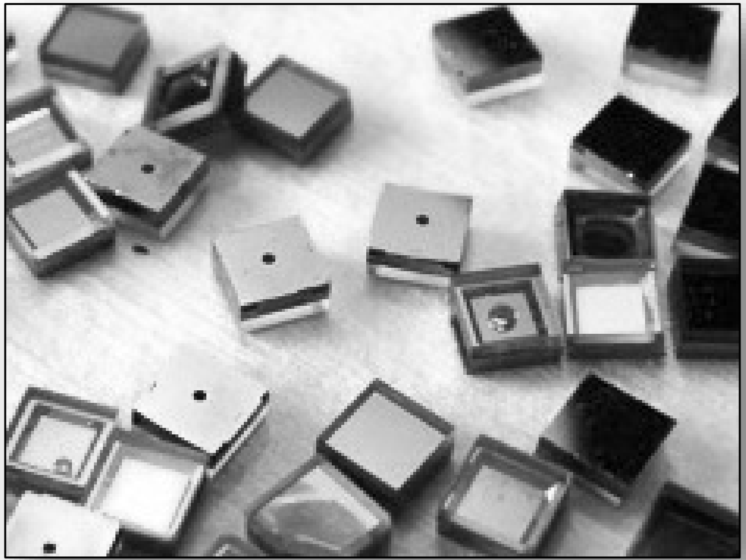
Problem: Need to know where fractures are propagating, their number, width, extent.

Answer: Injecting SMART microsystems along with proppant



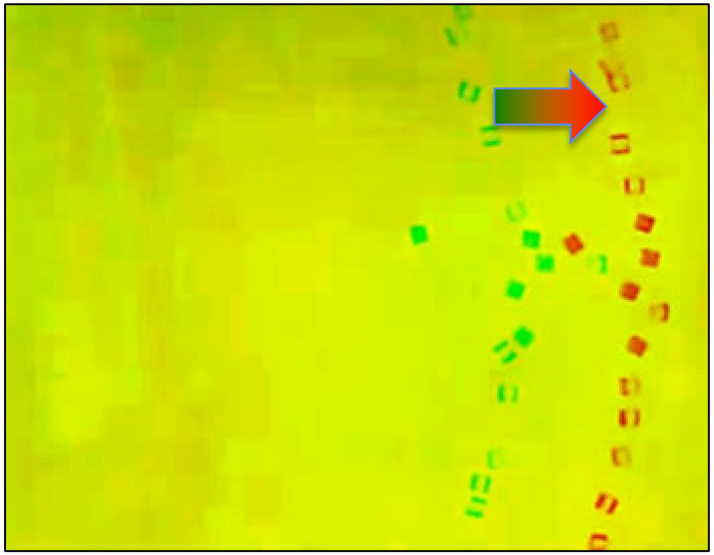
Typical ceramic proppant 20/40



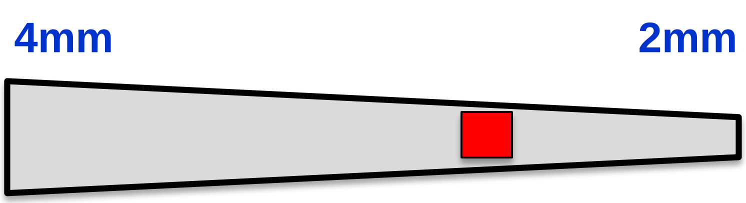


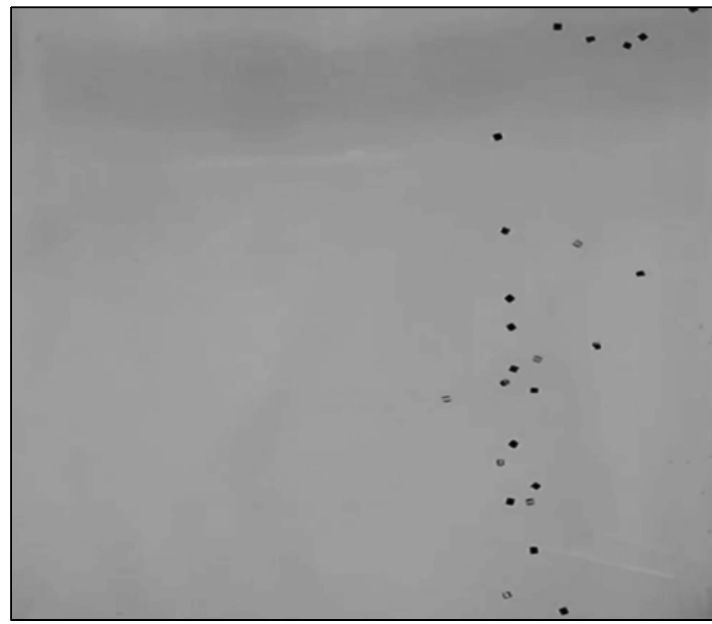
fluidion smart micro-emitter (prototype stage)

Fluidion Technology - Dynamic AME visualization



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





Borehole Seismology

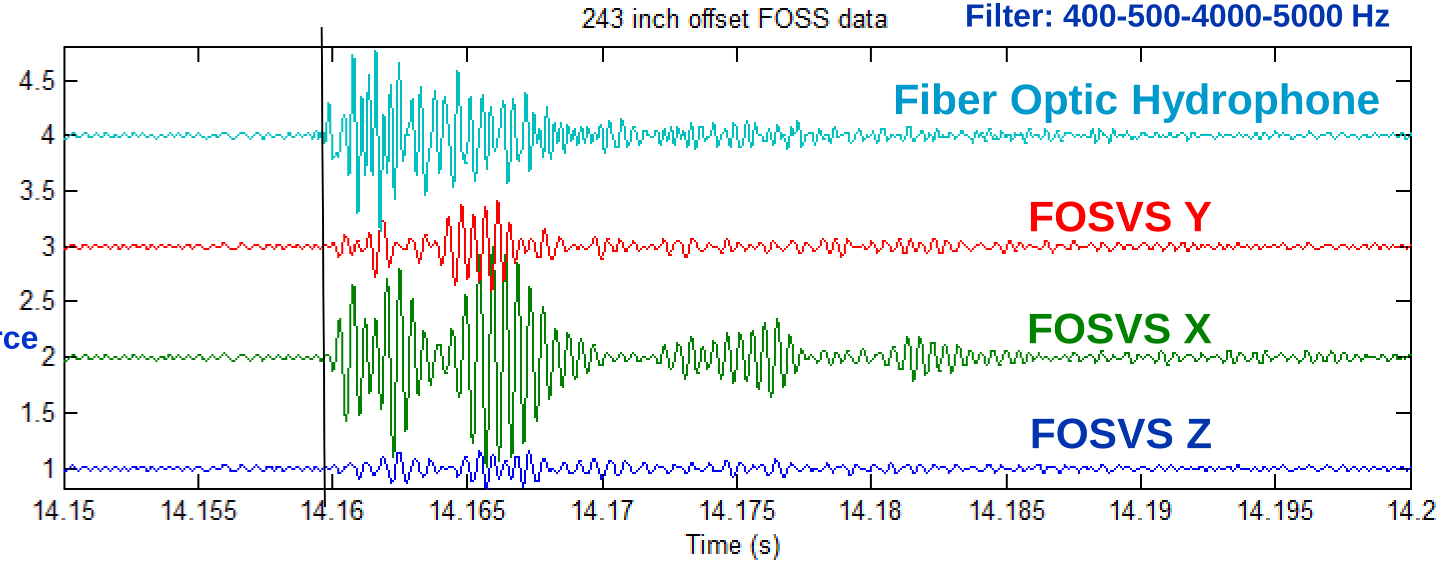
- Large Seismic Array Technology
- Fiber Optic Seismic Sensors
- Acoustic Micro Emitters
- Joint testing of FOSVS & AME technology

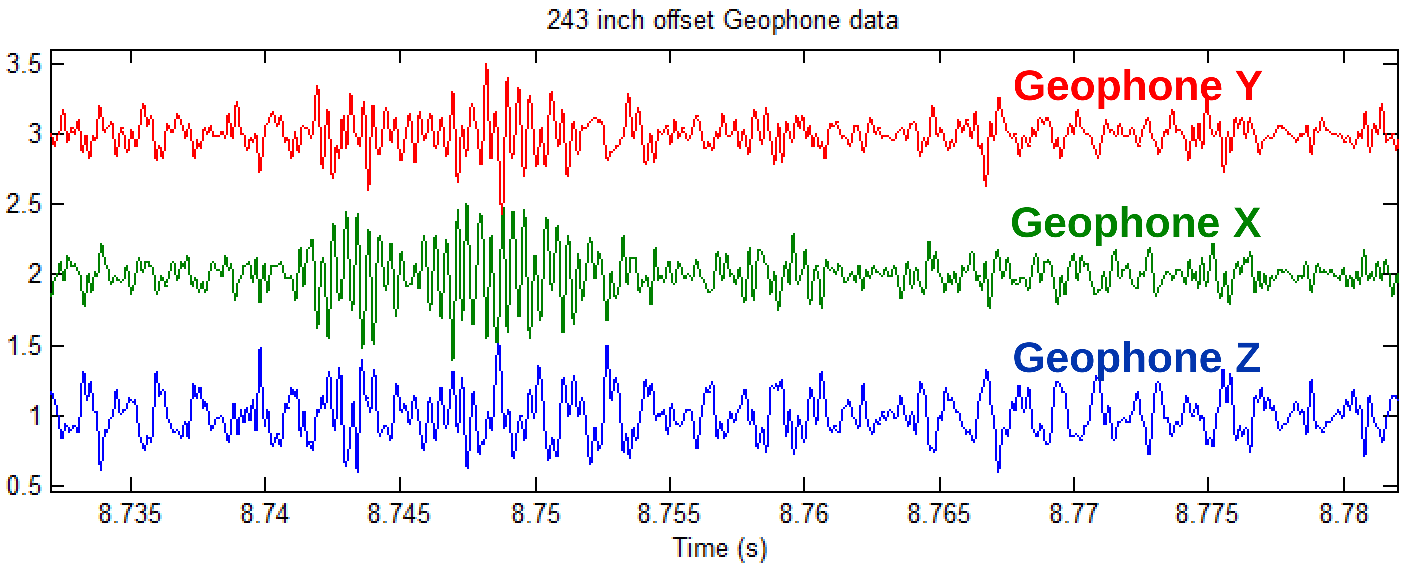
500 psi AME (Energy: ~0.1 J = M-3.5) Recorded by FOSVS

500 psi AME (Energy: ~0.1 J = M-3.5) to FOSVS:20 ft Offset

Note:
Coherent
Pre arrival
Energy from
An external
acoustic Source

Filter: 400-500-4000-5000 Hz





Devine Test Objectives

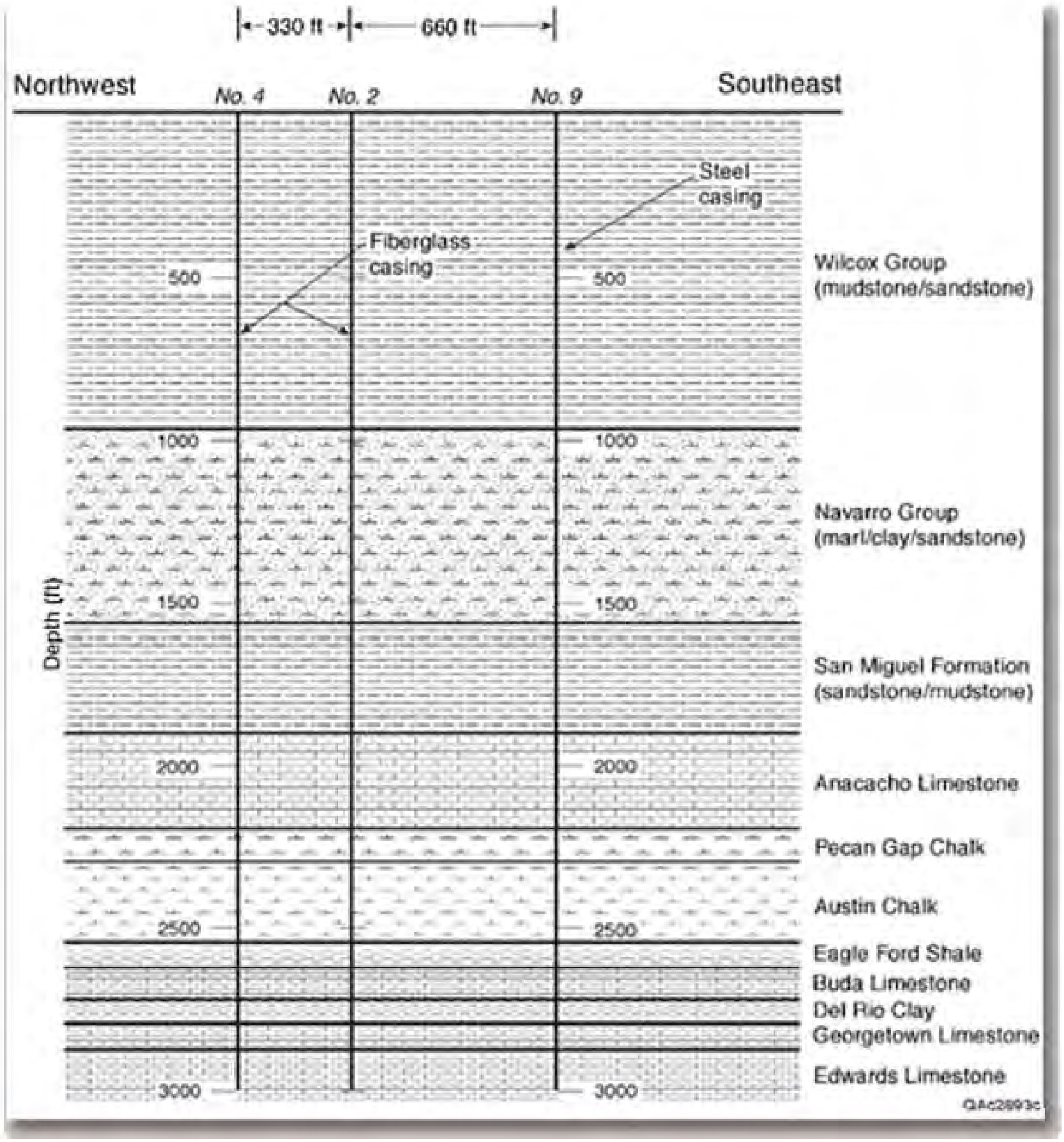
- Perform a test at a known field laboratory
- Calibrate and document the FOSVS ability to record data from the AMEs under controlled conditions

Devine test site - Geologic Profile

Plan using FOSVS & AMEs
- Record VSP Data
- Record Single Well Data
- Record Cross Well Data

Seismic Sources
- Use AMEs
- Small Explosives: 1-2 gr
- Mini High Frequency Vib

Objectives
- Test FOSVS with AMEs
- Calibrate AME Energy output in a real well



Effective & Accurate Monitoring of UOG

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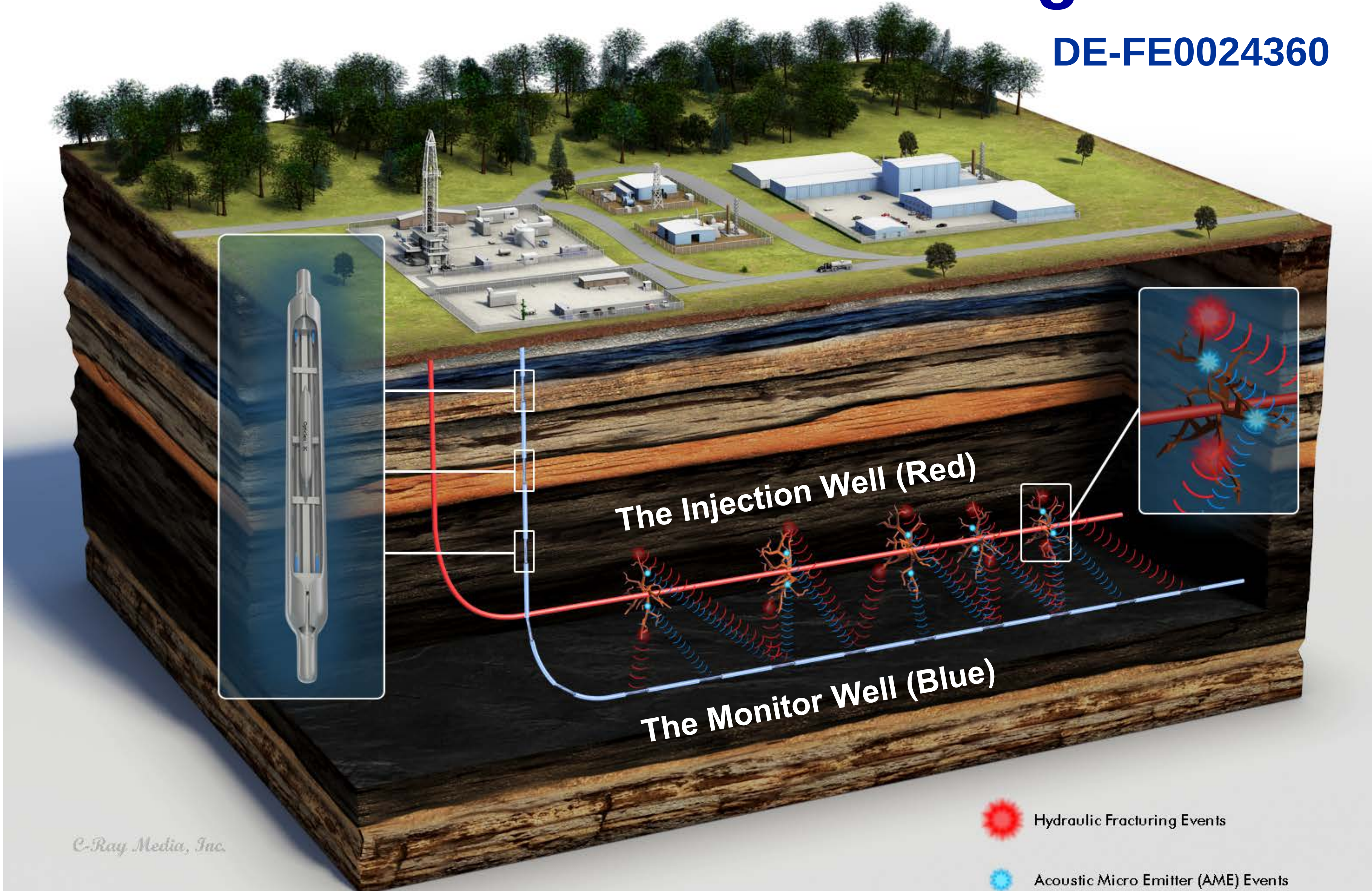


"Earth Angiography"

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 CO_2 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

Acknowledgement

- The research discussed in this presentation has been supported by the following grants:
  - DOE Contract DE-FE0004522 (2010)
  - RPSEA Contract 09121-3700-02 (2011)
  - DOE Contract DE-EE0005509 (2012)
  - California Energy Commission Contract GEO-14-001 (2013)
  - DOE Contract DE-FE0024360 (2014)

The support and assistance from these grants made it possible to develop the fiber optic sensor and deployment technology described in this presentation. The support from Karen Kluger for DE-FE0004522, Bill Head for RPSEA Contract 09121-3700-2, Bill Vandermeer for DE-EE0005509, Cheryl Closson for GEO-14-001 and Bill Fincham for DE-FE0024360 is gratefully acknowledged.

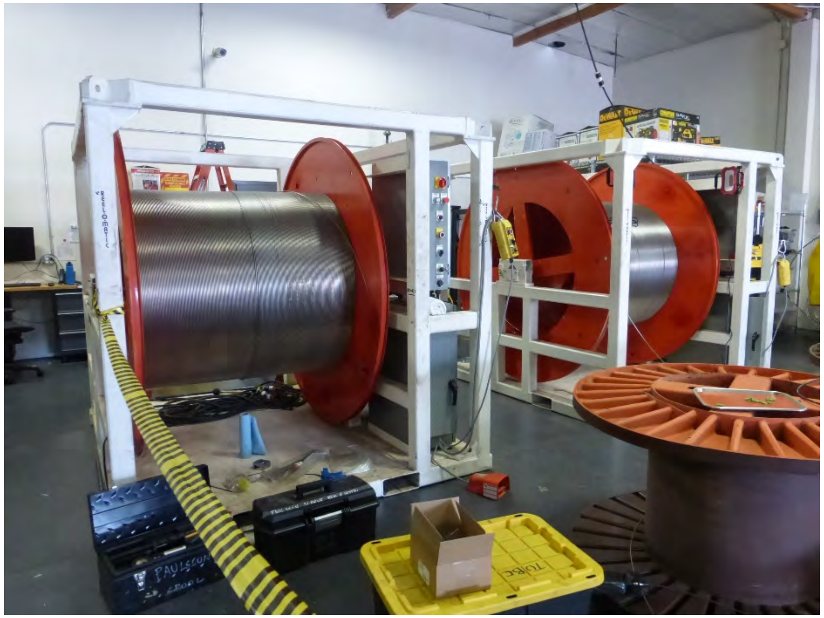
Paulsson, Inc. – The Company

12,000 sq. ft. facility in Van Nuys, CA

1,000 rated Clean Room for winding the sensors

Machine Shop – five new CNC machines

Fiber Optic Cable Spools for Operations



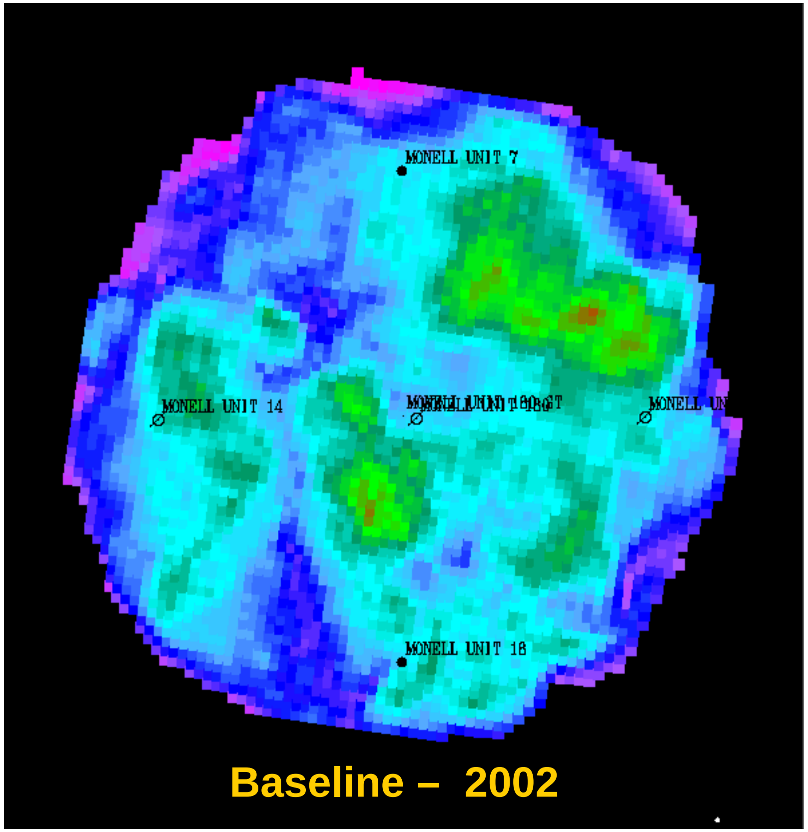
Thank You!

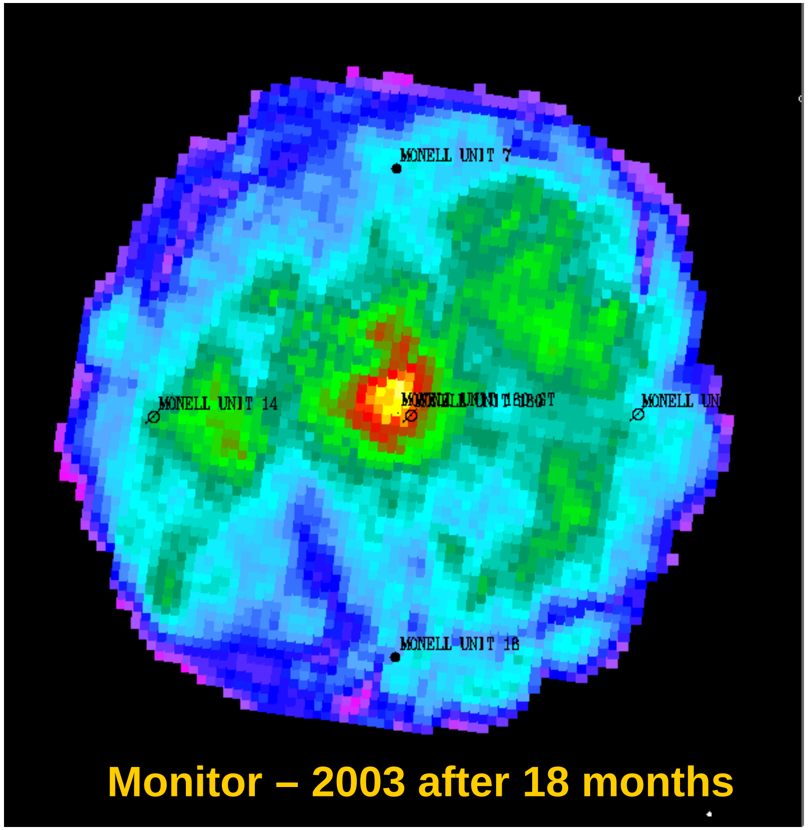
www.paulsson.com

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