Paulsson, Inc. (PI)

Single Well Seismic (SWS)™

(i.e. source & receivers in the same well)

October 14, 2020

Seismic & Sonic Techniques

A Spectrum of Techniques: Frequency Band:

- Surface Seismic: 2 Hz – (20–100) Hz
- Vertical Seismic Profiling: 2 Hz – (120-240) Hz
- Single Well Seismic: 10 Hz – (500–1,600) Hz
- Sonic Logging: 2,000 Hz – 10,000 Hz
- Ultra Sonic Laboratory Test: 100 kHz – 1 MHz

Resolution depends on the wavelength (λ) which is a function of velocity (v) and frequency (f): $v = f * \lambda$; $\lambda = v/f$ Generally a subsurface layer can be resolved at $\lambda/4$ and detected at $\lambda/20$. However – with sensors in boreholes, in addition to higher frequencies, we also record S waves.

The Oil and Gas Target for High Resolution Imaging

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!".

The Estimated Recovery from UOG fields is only 5-8% providing for a large potential upside using high S/N, high frequency robust data & state-of-the-art depth-imaging technologies.

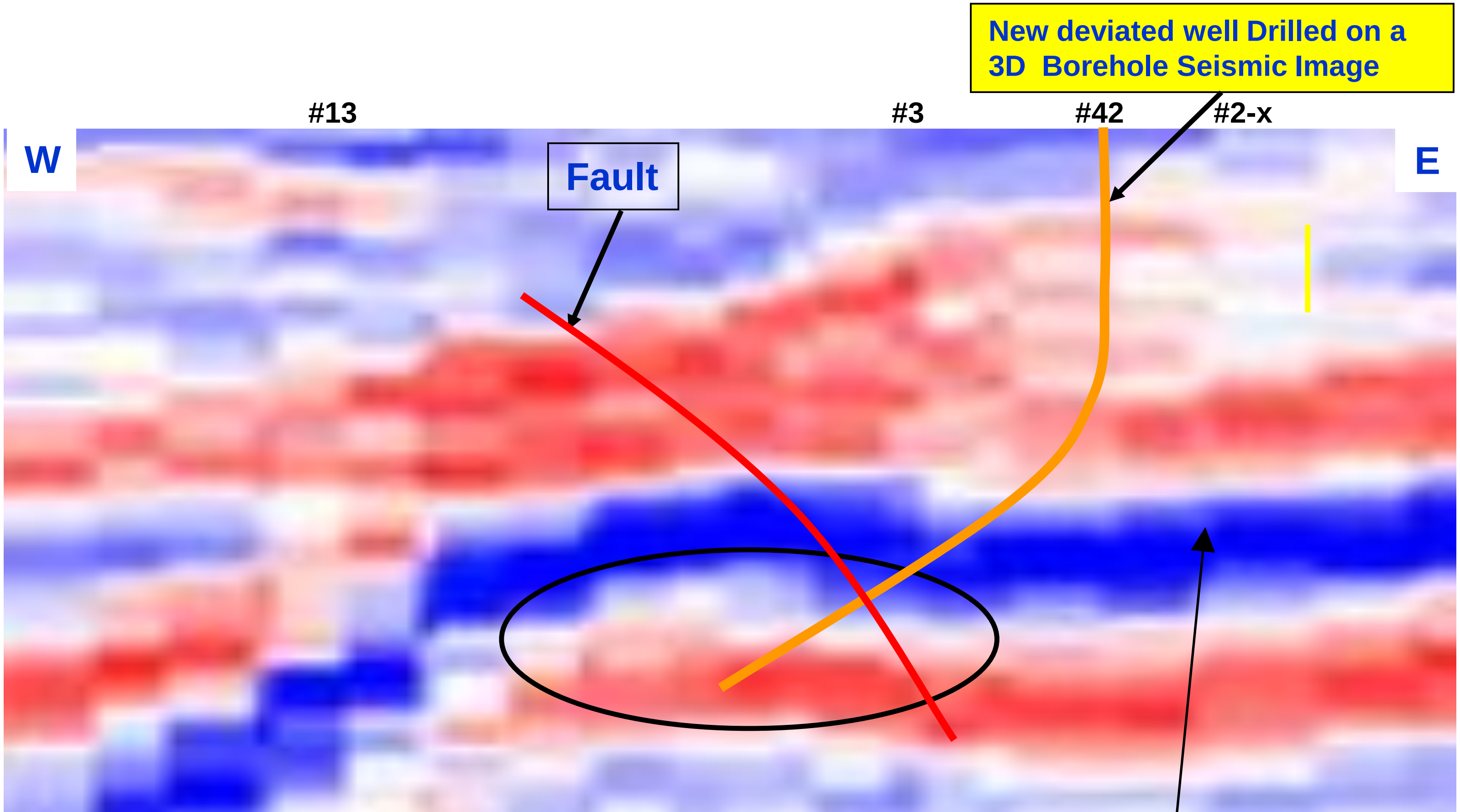
Target: >1 Trillion Barrels of Oil Worldwide!

Paulsson Experience

- Recorded over 65 3D VSPs around the world
- Recorded the largest 3D VSP in the world using a 960 channel system (4 wells x 80 x 3C)
- Recorded VSP's with the largest number of 3C clamped stations: 160 3C levels & 8,000 ft long
- Recorded the first multi-well (8 wells) 3D VSP
- Recorded 3D VSP data in the USA, Canada, China and Middle East

Drilling a Deviated Well in the Edison Field, California based on a 3D image from a Massive 8-well 3D VSP

3D Surface Seismic Technology (SST)

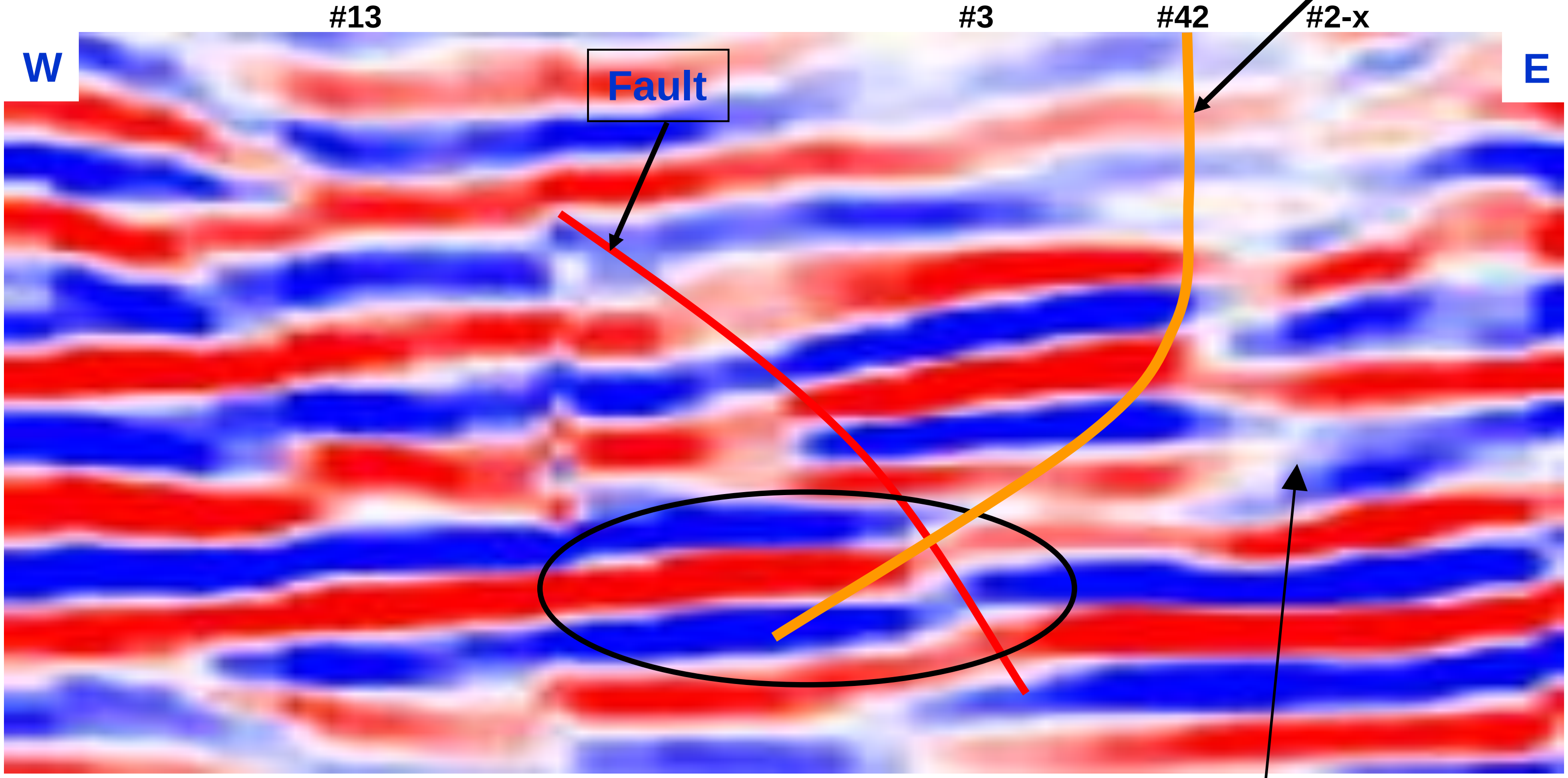


Drilling result: The new well encountered 300 ft of oil and became the biggest producer in the field

Oil Sands in DS #2-X well doesn't make it over to the DS #3 well.

3D Vertical Seismic Profiling Technology (VSP)

New deviated well Drilled on a 3D Borehole Seismic Image



Drilling result: The new well encountered 300 ft of oil and became the biggest producer in the field

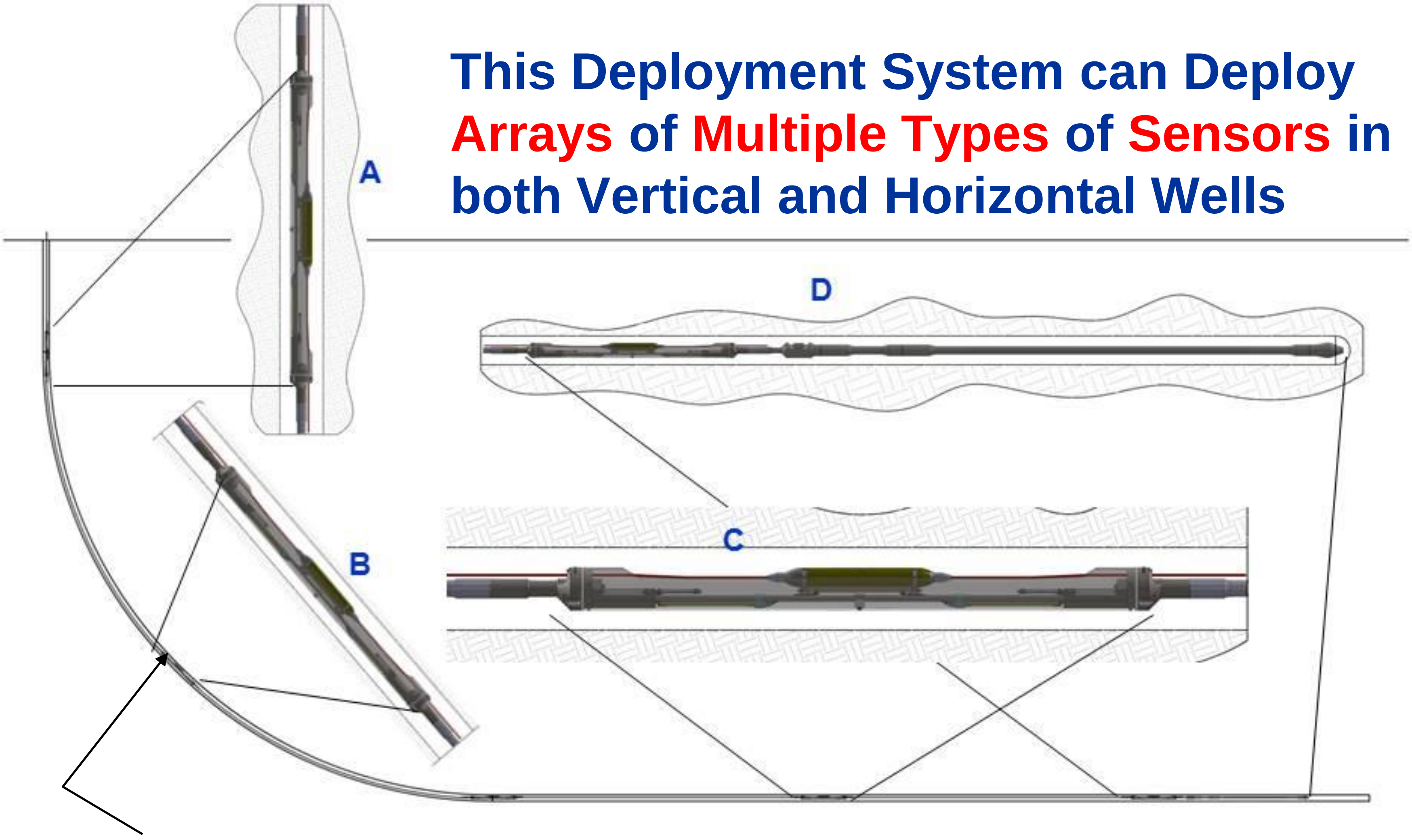
Oil Sands in DS #2-X well doesn't make it over to the DS #3 well.

Fiber Optic Seismic Vector Sensors (FOSVS) Field System was Funded under DE-FE00024360

The FOSVS System is the Base for our Single Well Seismic System

Drill Pipe Deployed System – Housing and Clamping

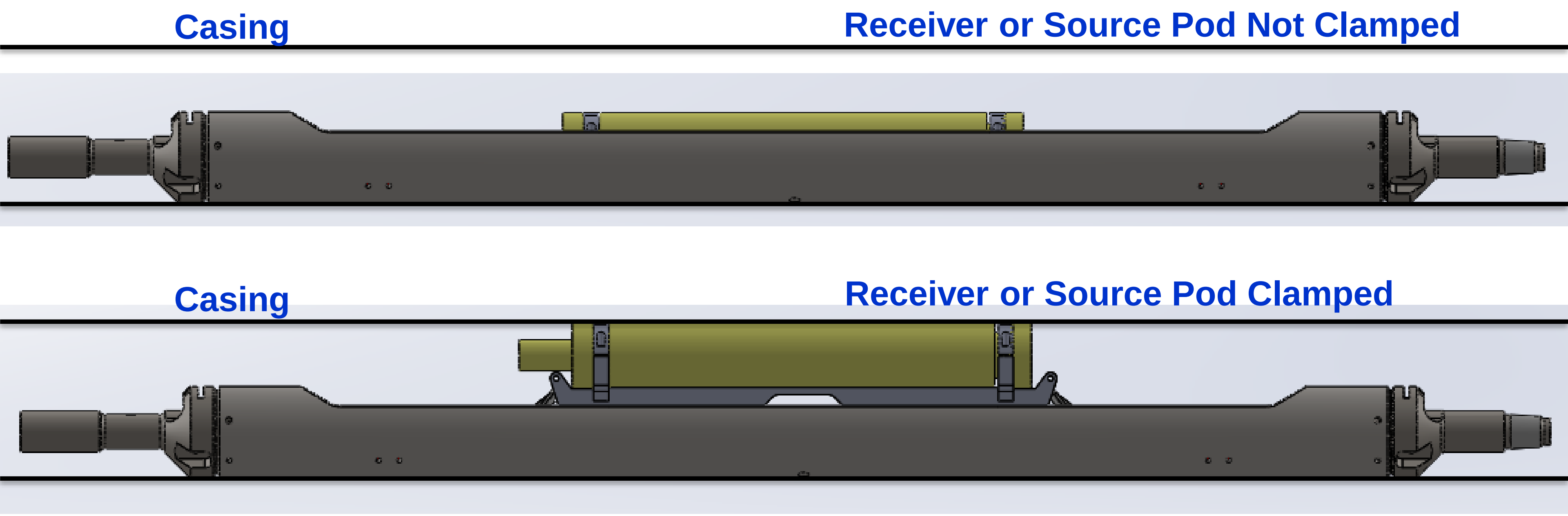
This Deployment System can Deploy Arrays of Multiple Types of Sensors in both Vertical and Horizontal Wells



Clamping system operates by increasing the pressure inside the drill pipe and manifolds using the borehole fluid as the pressurized medium

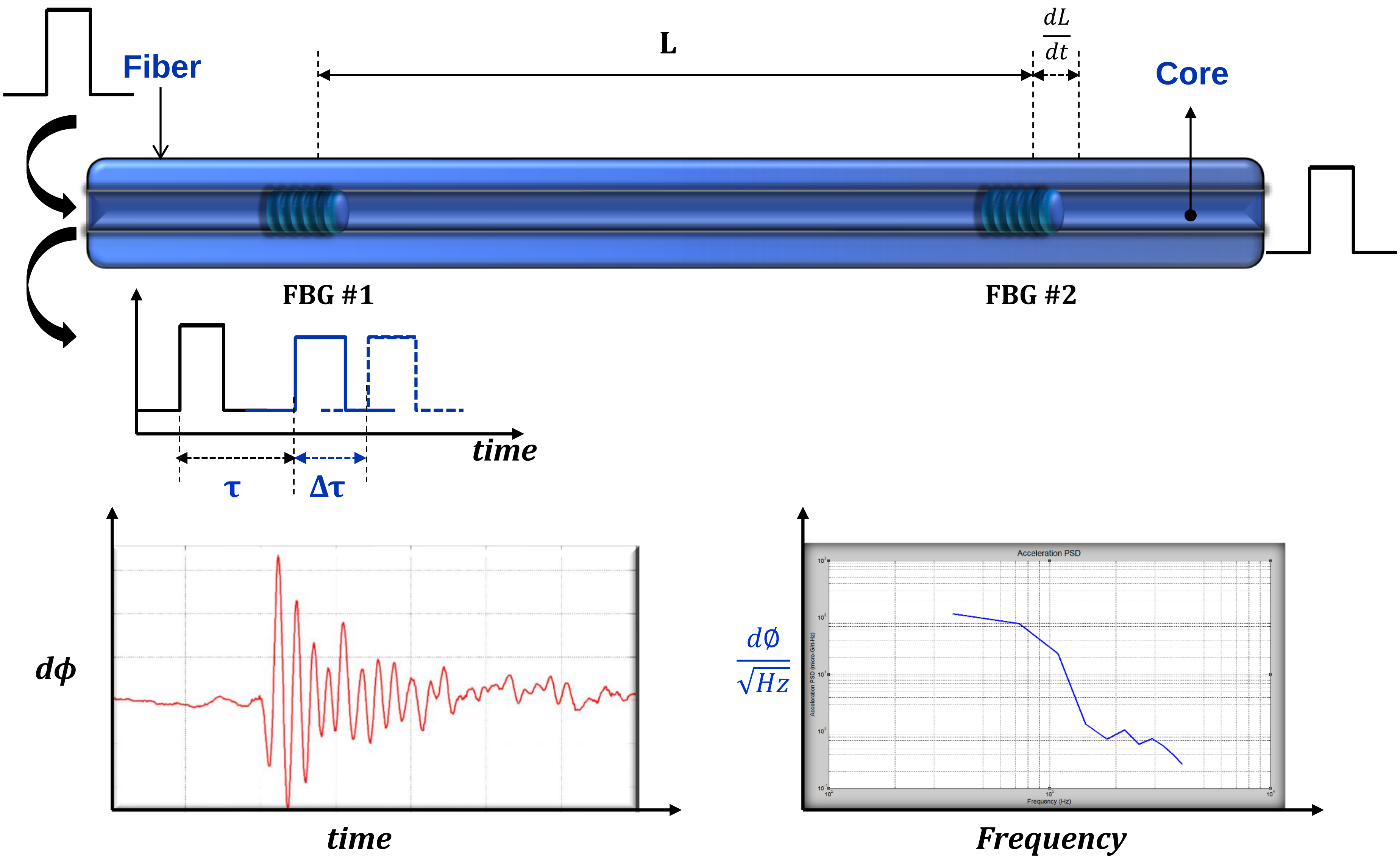
Fiber Optic Seismic Sensor System Deployment Battelle, Michigan June 2016

Borehole Seismic Receiver & Source Deployed On a Sensor Pod Housing System



Fiber Optic Seismic Vector Sensors

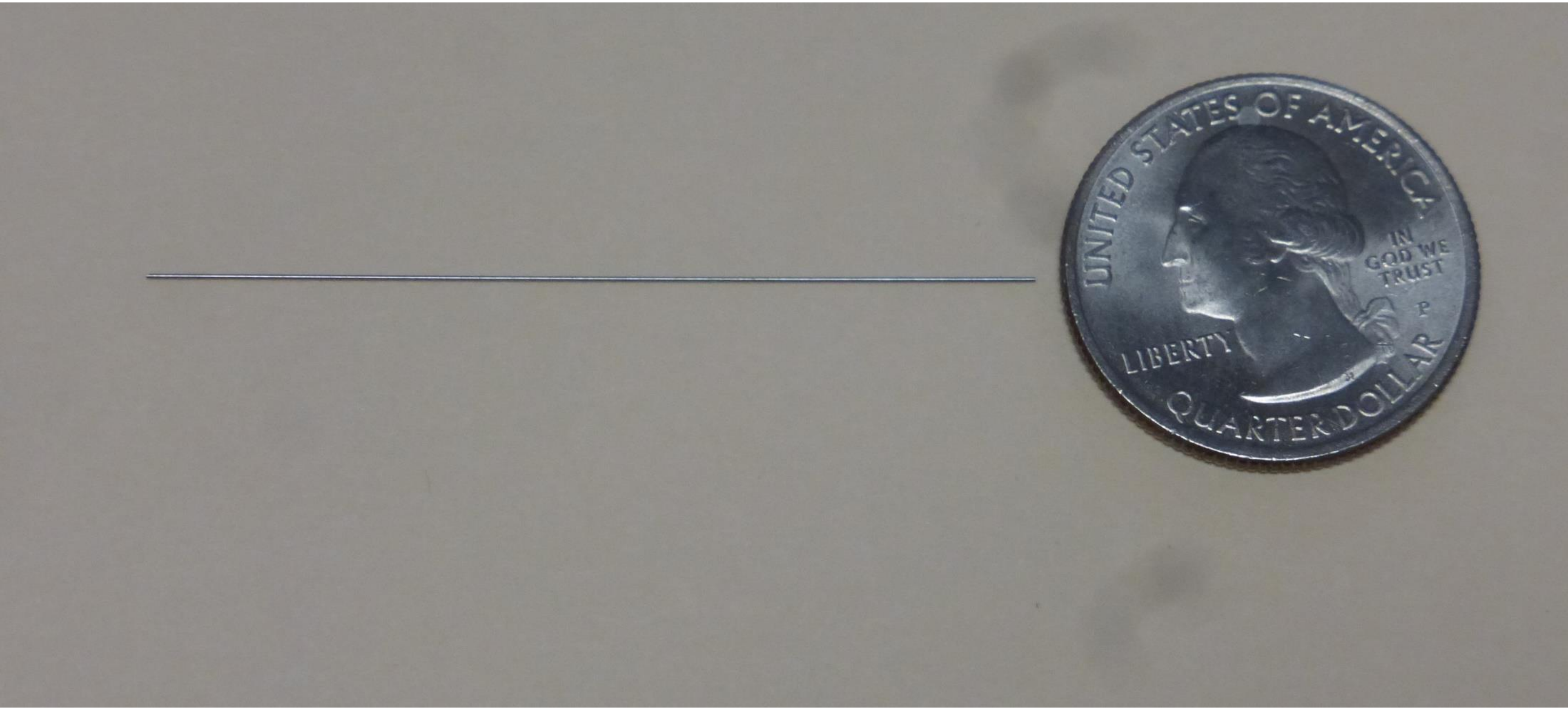
Fiber Bragg Grating: Theory



Laboratory Test of

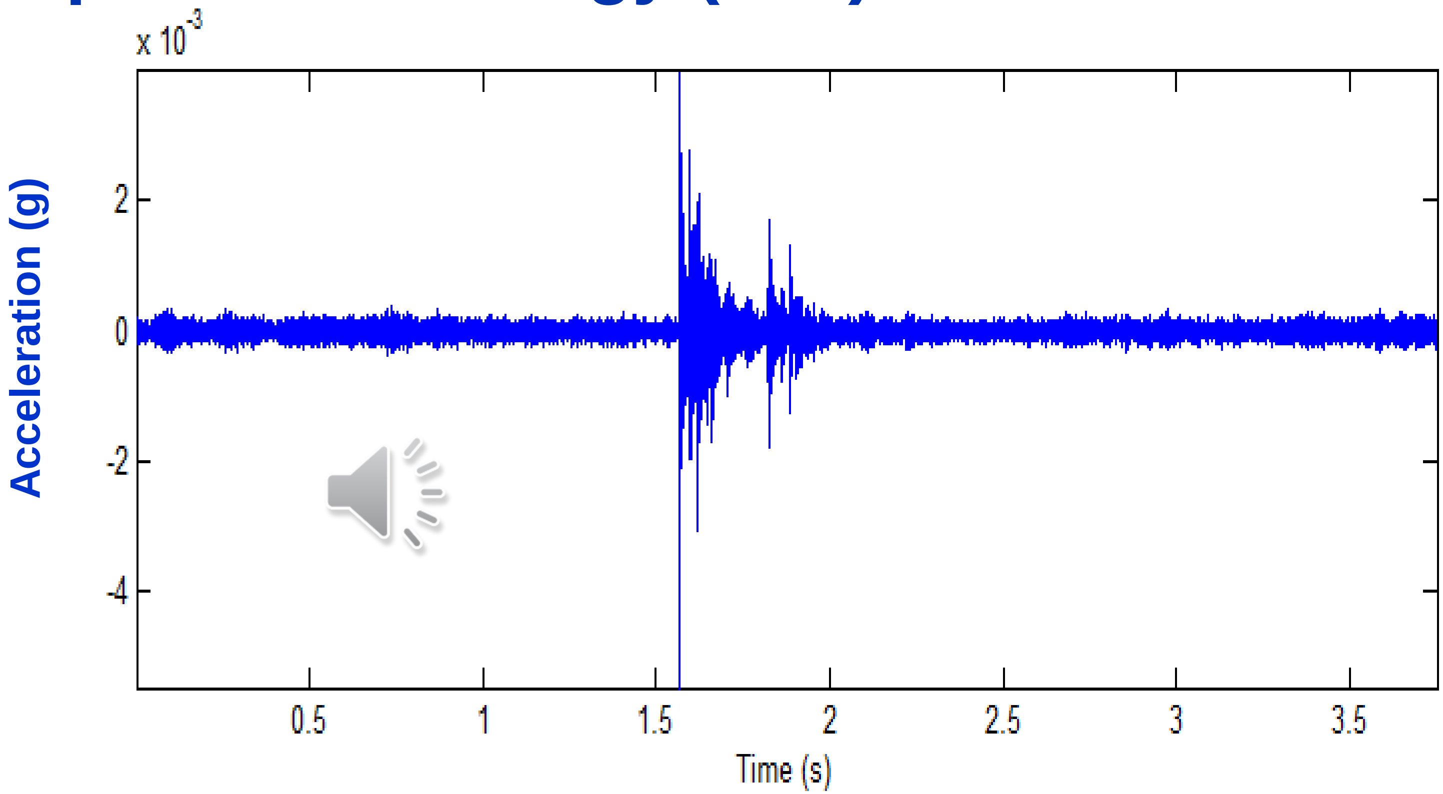
Fiber Optic Seismic Vector Sensors

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:

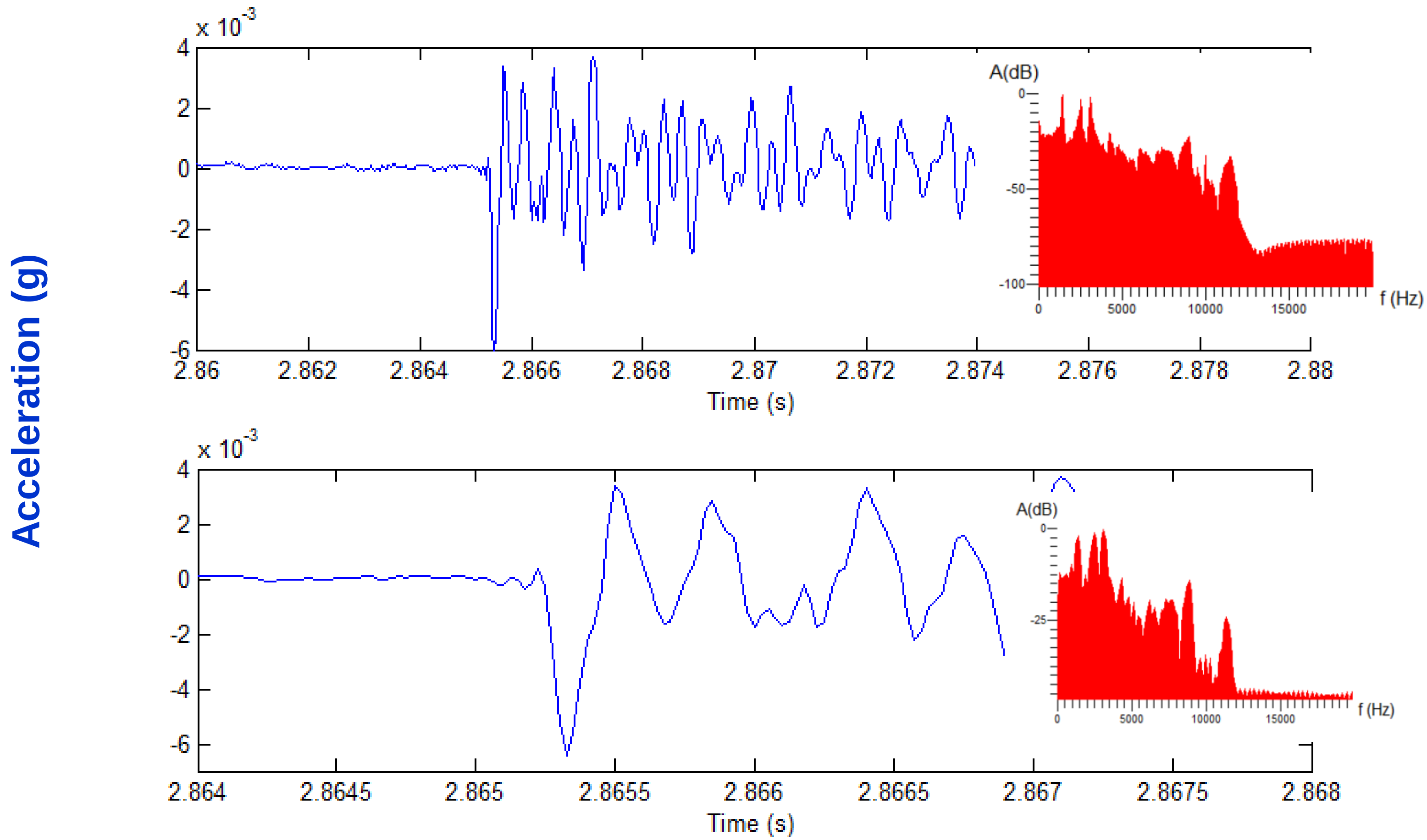
2.5 µJ kinetic energy (M-7) for 1st of 8 hits of Pin



The FOSVS recorded 8 bounces of the pin = <<M-7

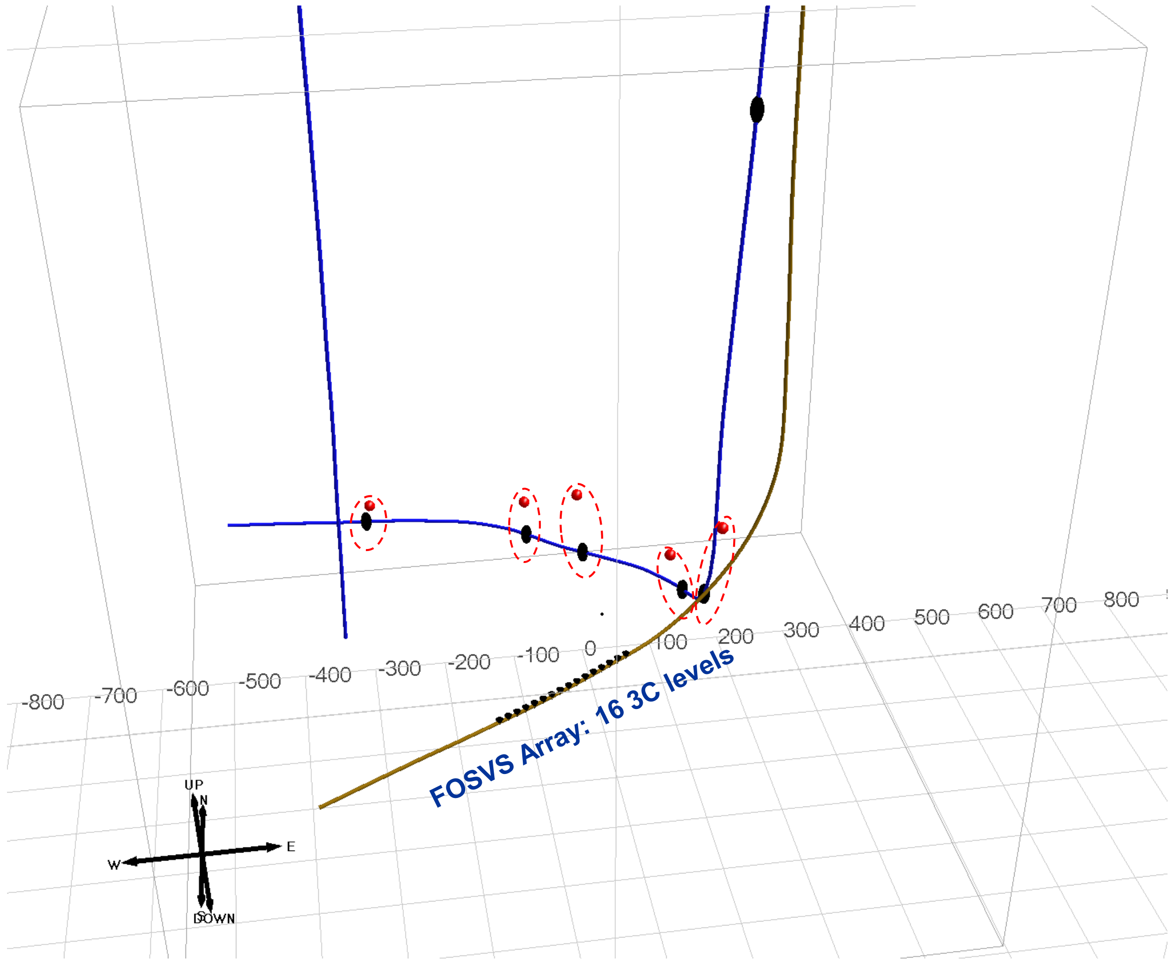
FOSVS Test: OD: 0.011”, 24.8 mg Pin Drop 1 cm:

2.5 µJ kinetic energy (M-7) for 1st of 8 hits of Pin



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

Results from Locating 0.5 gram String Shots During a Survey Recorded for Battelle in June 2016

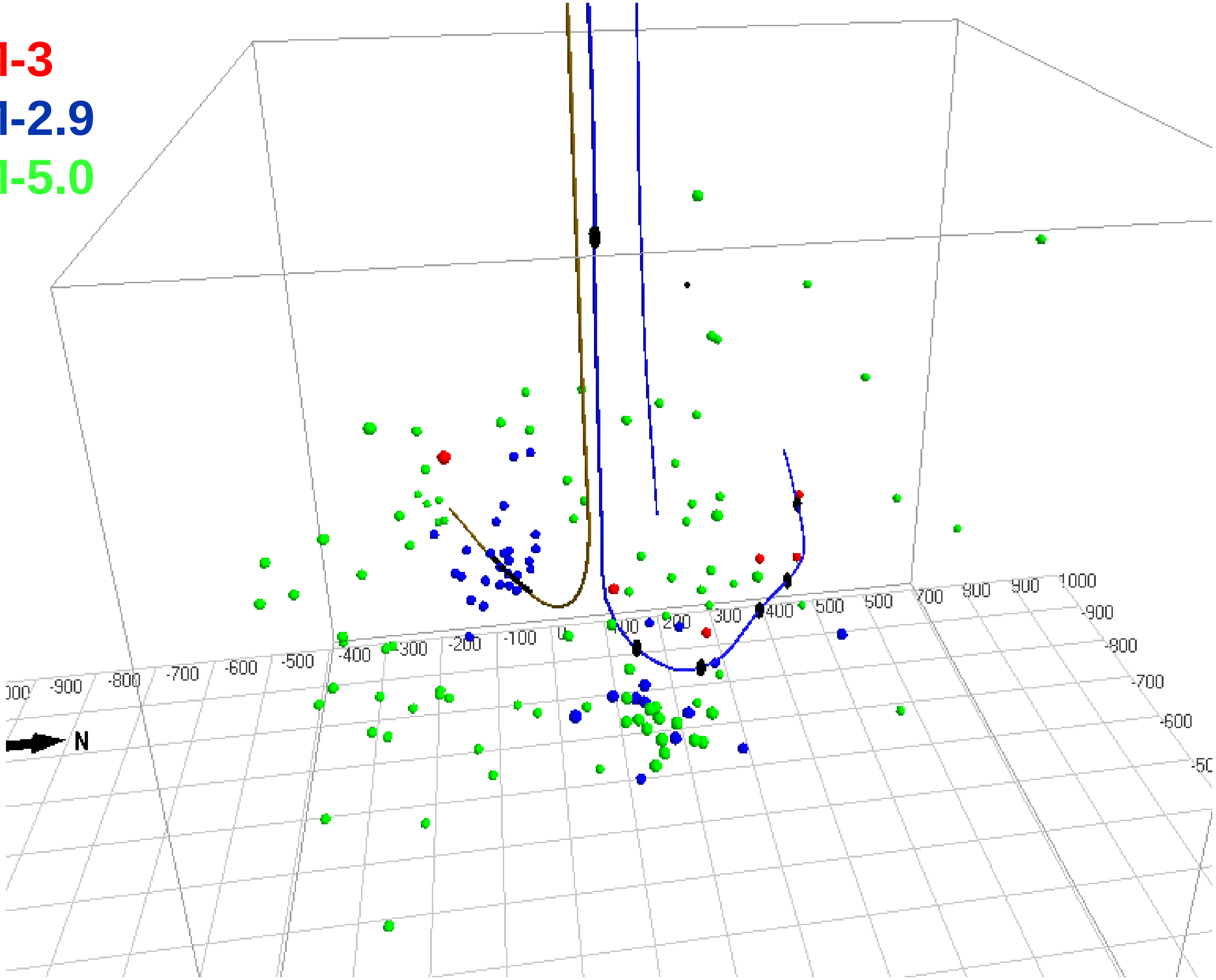


Survey for Battelle - Locating String Shots and Micro Seismic Events

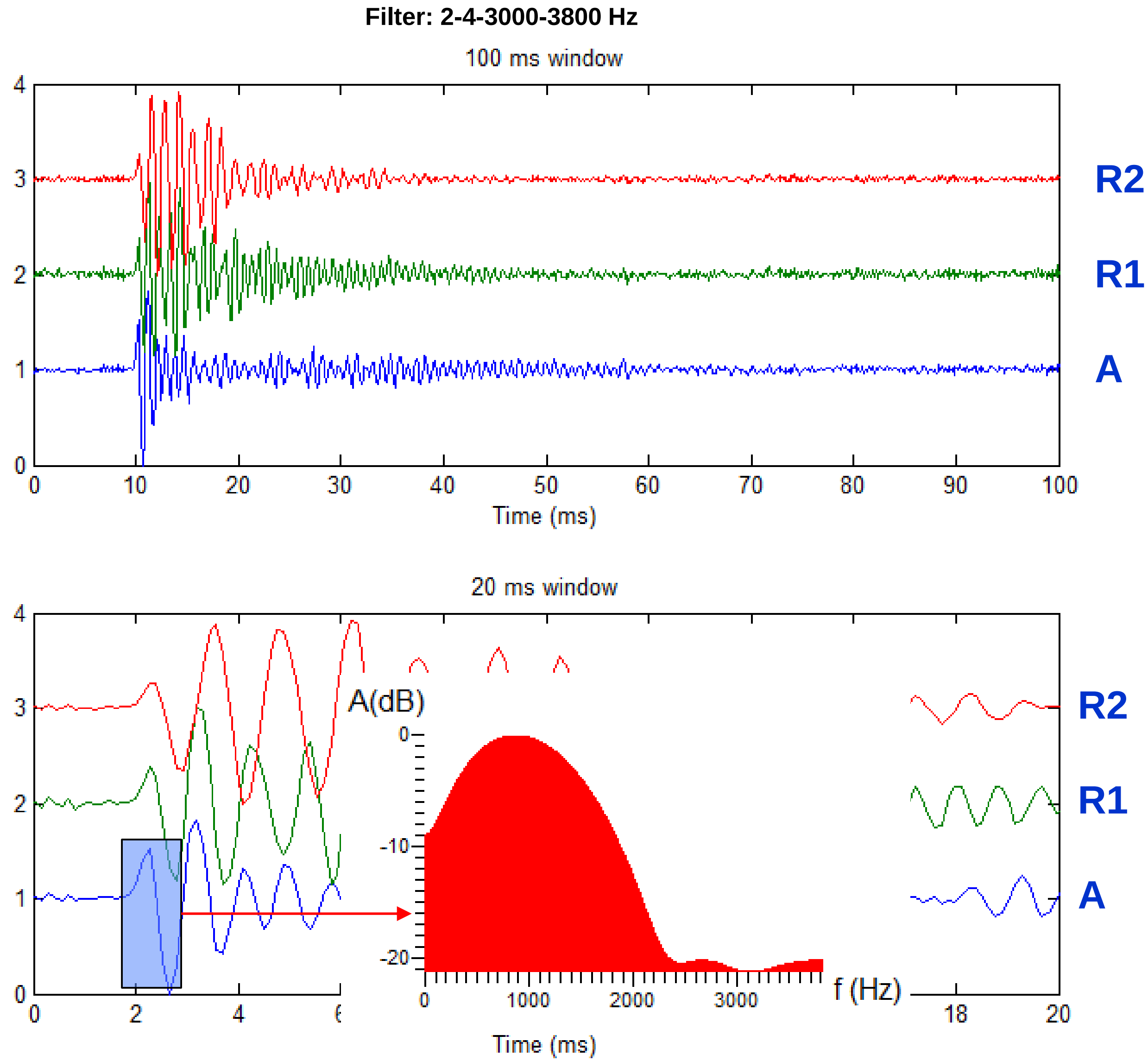
Recorded >20,000 events in four weeks. Displayed here are 130 events.

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

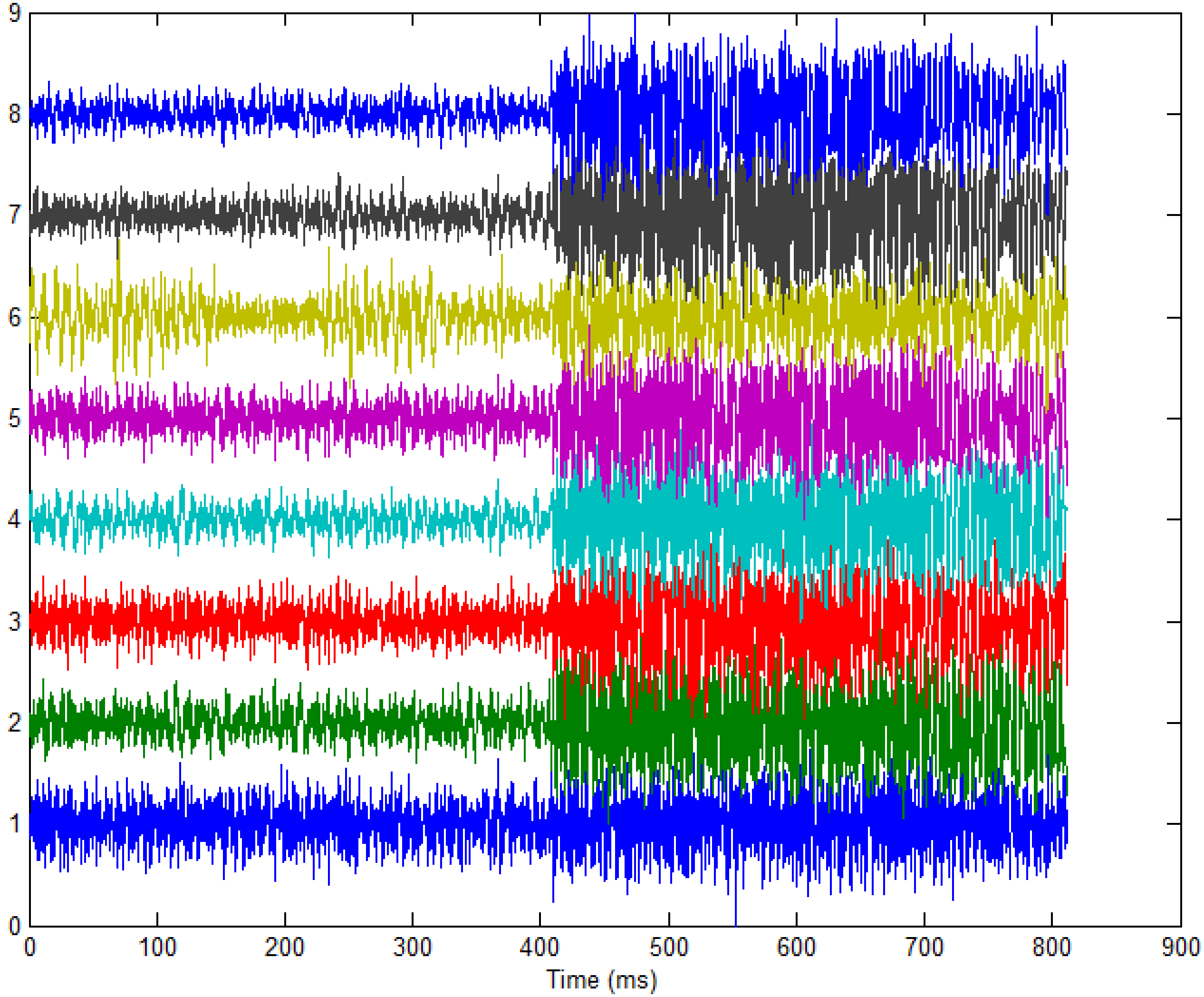
Magnitude < M-3
Magnitude < M-2.9
Magnitude < M-5.0



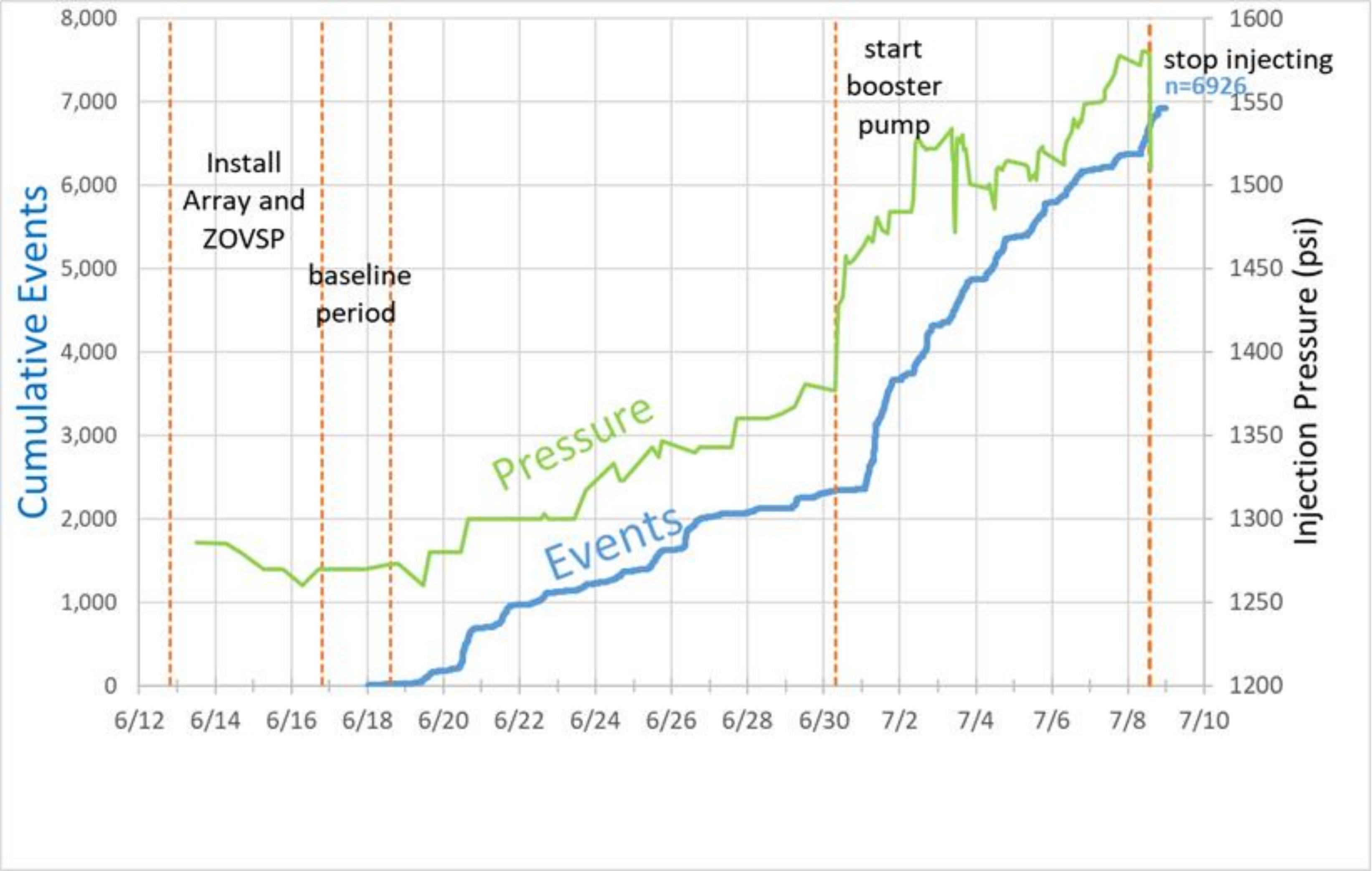
Zoomed-In Focused MS in 3C- Filter: 2-4-3000-3800 Hz



Sound of A Long Duration Event (~M-5.0) –Fluid Flow



Micro Seismic Events as Function of Injected CO2



Courtesy Mark Kelley, Battelle, 2019

Why Develop
Single Well Seismic Technology?

Single Well Seismic

- Much (>20x) Higher Frequencies than Surface Seismic and VSP (>10x)
- Different View Perspective – Radial to Borehole
  - Horizontal Perspective from Vertical Boreholes
  - Vertical Perspective from Horizontal Boreholes
  - Image high angle faults not visible from surface
- Closer to the imaging targets
  - Avoid the Near Surface Noise and Attenuation
- P and S waves
  - Multi Component S waves: SV & SH

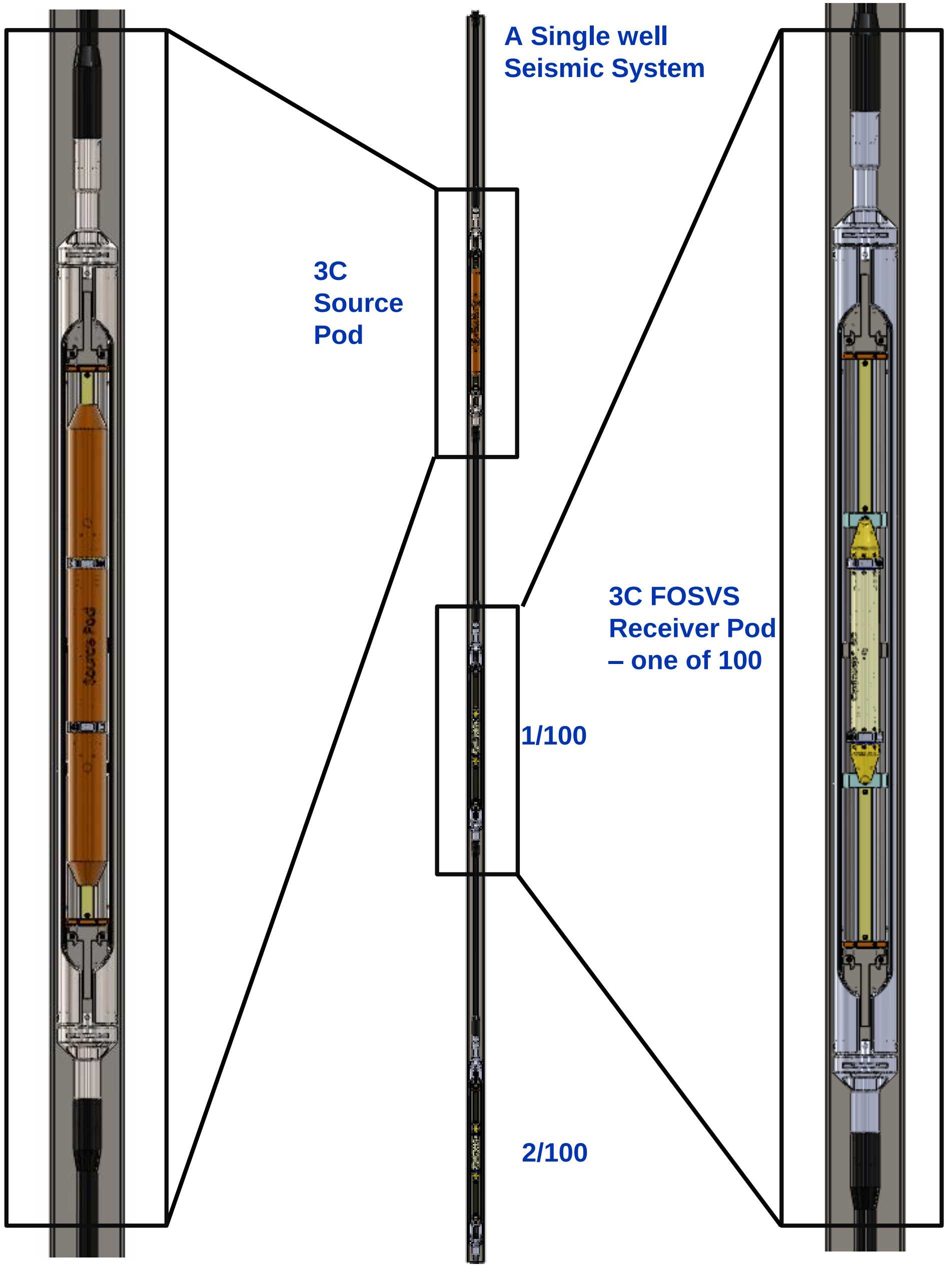
The Single Well Seismic Technology will Address the Need to Map and Monitor:

- Map The Detailed Geology using Single Well Seismic
- Monitor The Primary Fracturing with High Fidelity Vector Sensors
- Monitor the Injection of the Proppant
- Monitor the Injection of Acoustic Micro Emitters (AMEs)
- Monitor The Fluid Flow of the Injected Fluids
- Monitor The Fluid Flow of the Produced Fluids

A Single Well Seismic System: Deploying the Source and the Receivers in the same well.

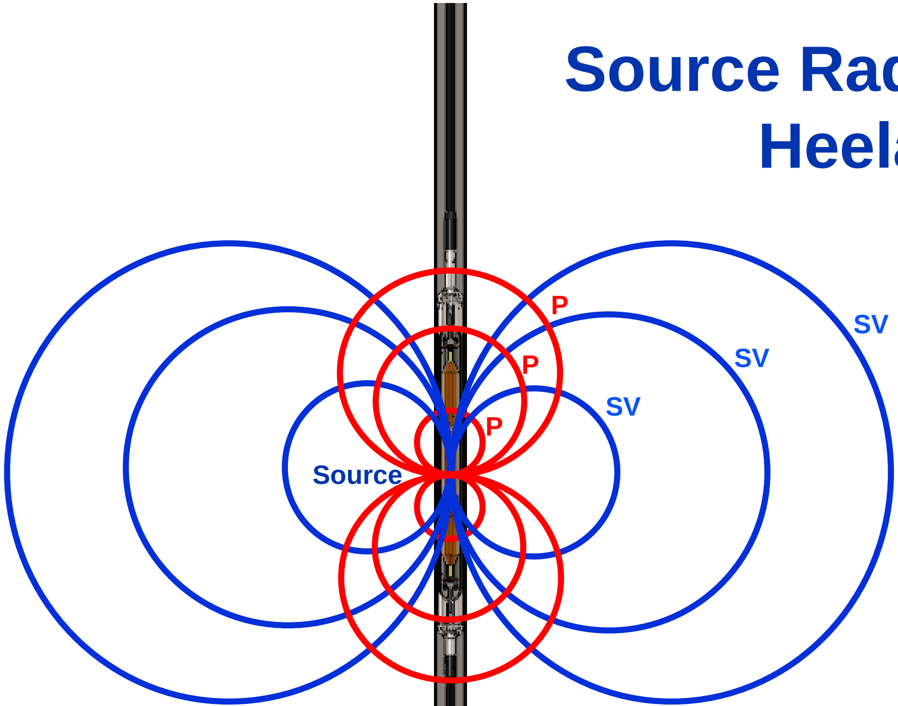
This is NOT a well Logging System – this is a Seismic System with a 10 – 1,600 Hz Operating Frequency.

This system will be able to image to a radius of 1,000 m (3,000 ft) or more.



Single Well Seismic
Test, Modeling & Processing

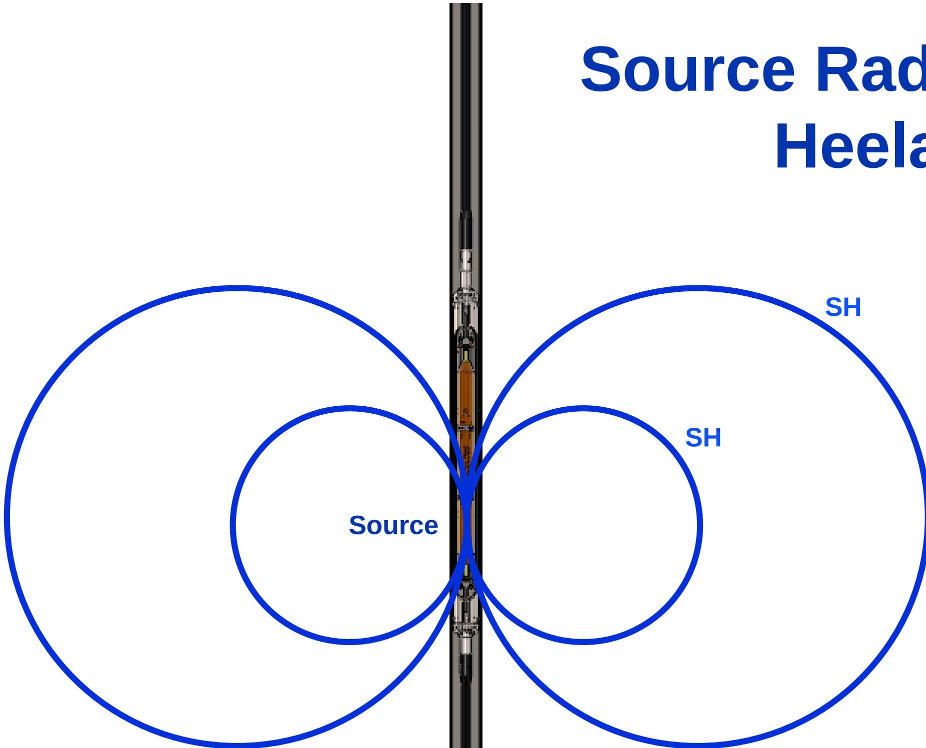
Source Radiation Patterns
Heelan (1953)



1. **Axial Source**
2. **Torsional Source**
3. **Radial Source**

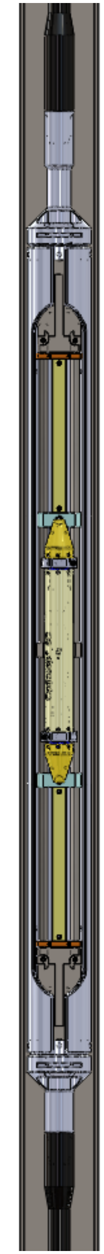
Variation of P and SV amplitudes with φ, when the source is subjected to shearing stress q(t) only

Source Radiation Patterns
Heelan (1953)

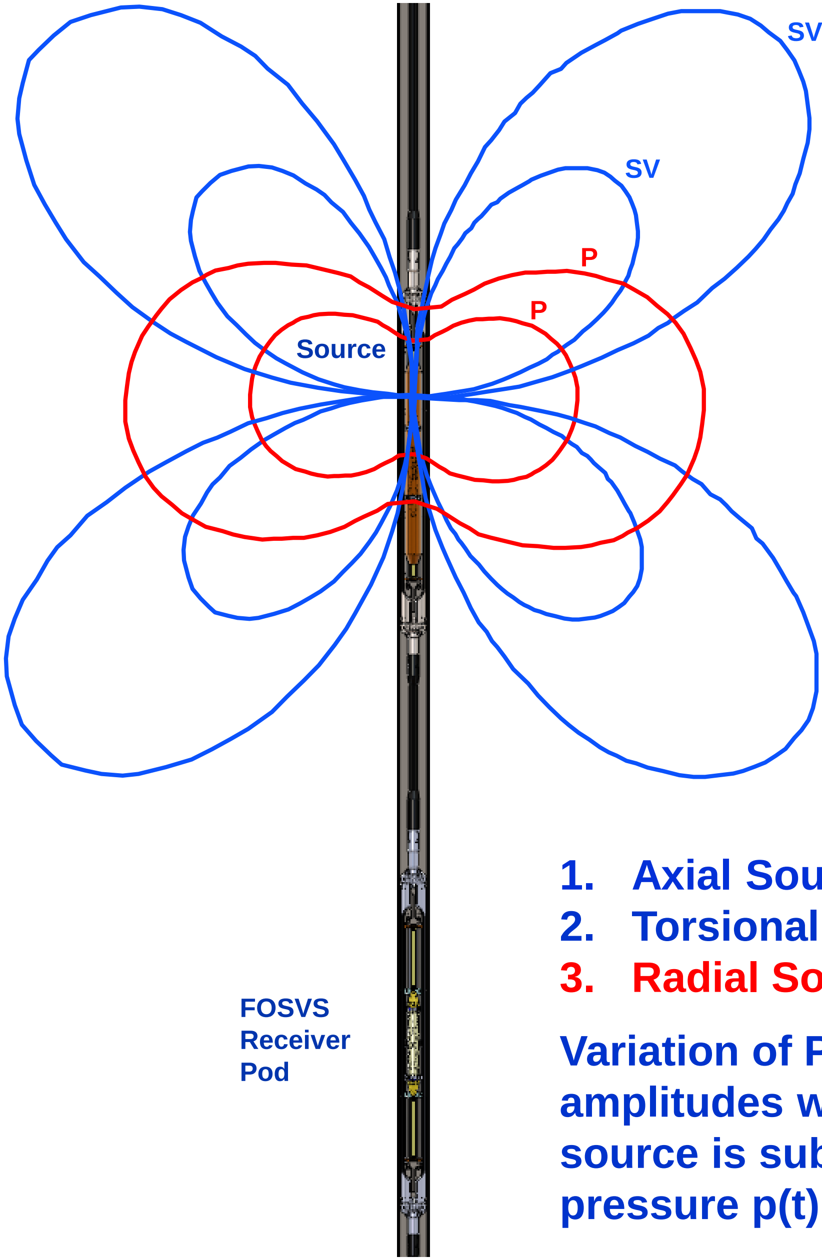


1. **Axial Source**
2. **Torsional Source**
3. **Radial Source**

Variation of SH amplitudes with φ when the source is subjected to a horizontal shearing stress s(t) only



Source Radiation Patterns Heelan (1953)



1. Axial Source
2. Torsional Source
3. Radial Source

Variation of P and SV amplitudes with φ when the source is subjected to a pressure p(t) only

FOSVS
Receiver
Pod

A Small Scale Field Test of Axial Vibrator Unit Developed under the SBIR I Grant

Source and Receiver On-Ground Experiment

- **Sources:**
  1. **Impulsive source (The Piston): 50 kg (110 lbs.). ~100 g measured acceleration at impact.**
  2. **Vibratory Axial Source: 10-410 Hz, 10 sec, 13.6 Vpp drive, Custom Sweeps.**

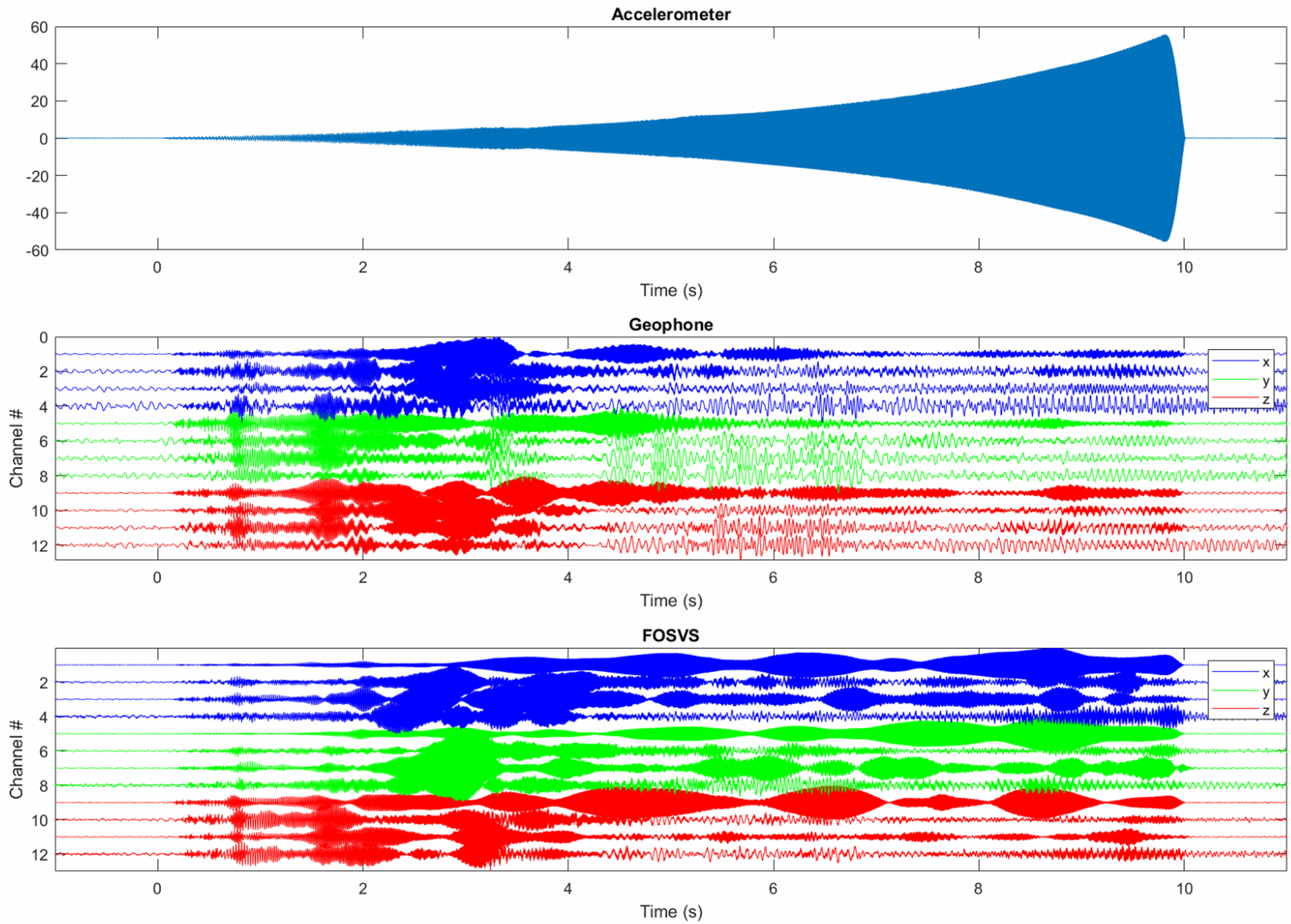
- **Receivers:**
  1. **VR Accelerometer: 75 kHz sampling rate to monitor the mass & baseplate**
  2. **Geophone: 4 kHz sampling rate, 5ft, 15ft, 25ft, 35 ft offsets displayed**
  3. **FOSVS: 80 kHz sampling rate, 5ft, 15ft, 25ft, 35 ft offsets**

- **Processing:**
  1. **All data filtered with 5-10-410-500 Hz Ormsby filter**
  2. **All vibrator data correlated with custom correlation function to reduce ringing.**

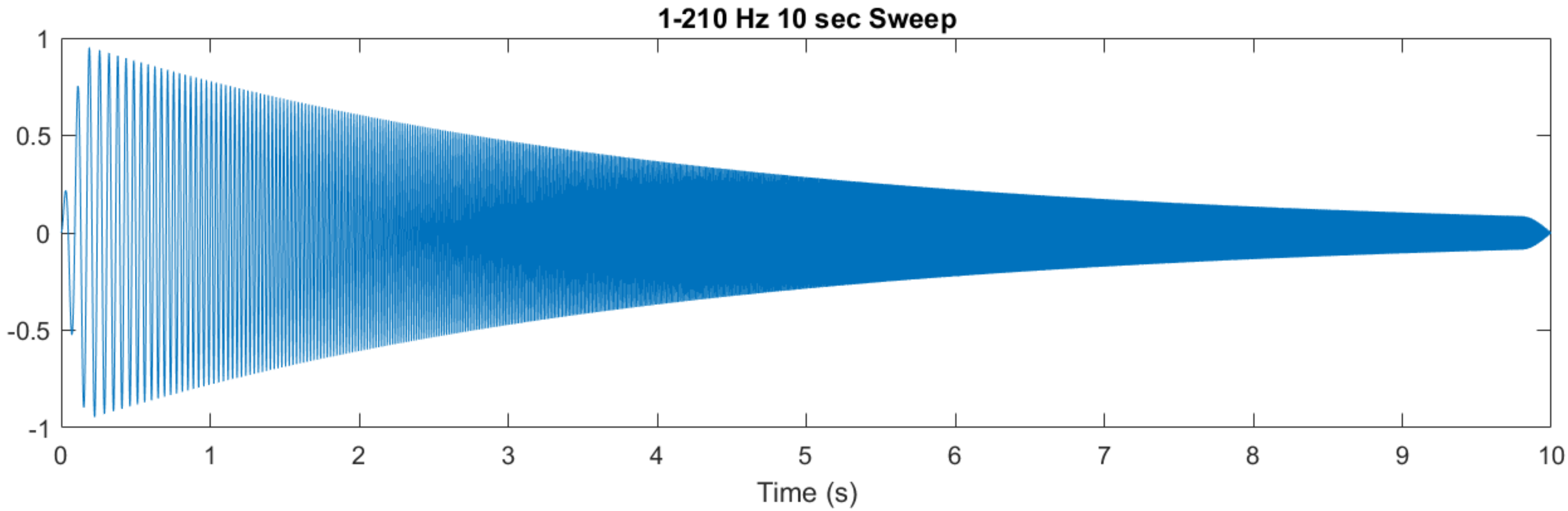
Test Fixture for a Downhole Seismic Vibrator

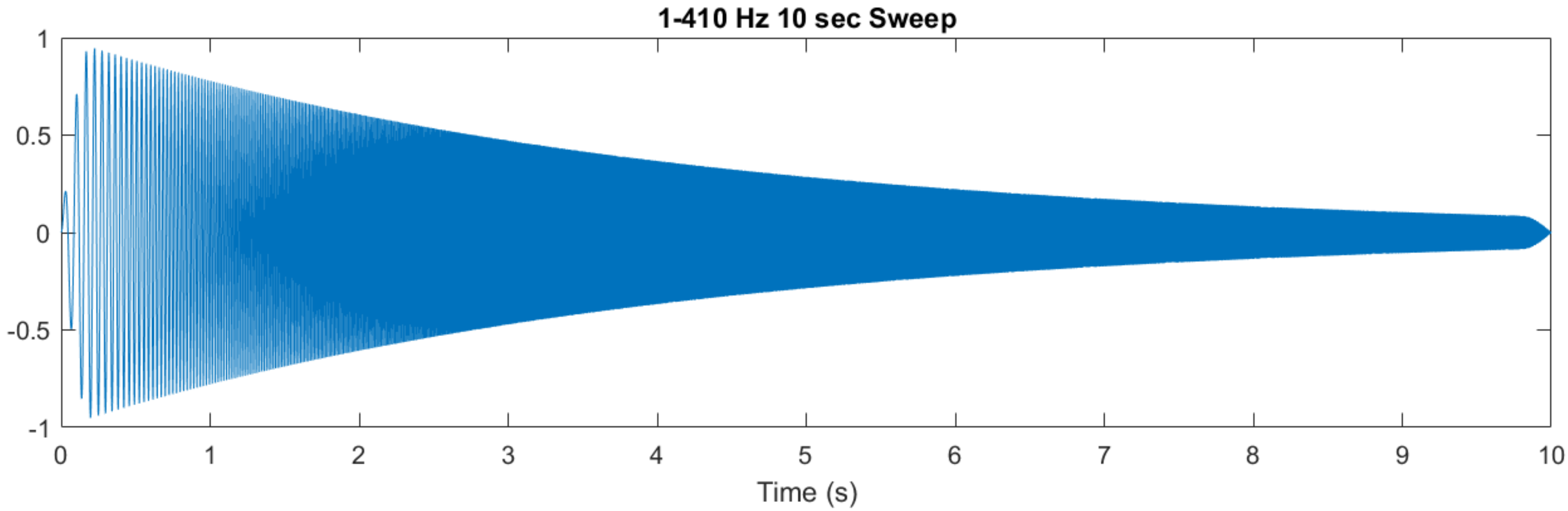
10-410hz, 10sec, 10vpp (200Vpp), 3.2kg
Custom Sweep w/ $A=e^{x/8}$

Vibrator Uncorrelated Data: 10-410 Hz, 10 sec sweep, 13.6 Vpp drive

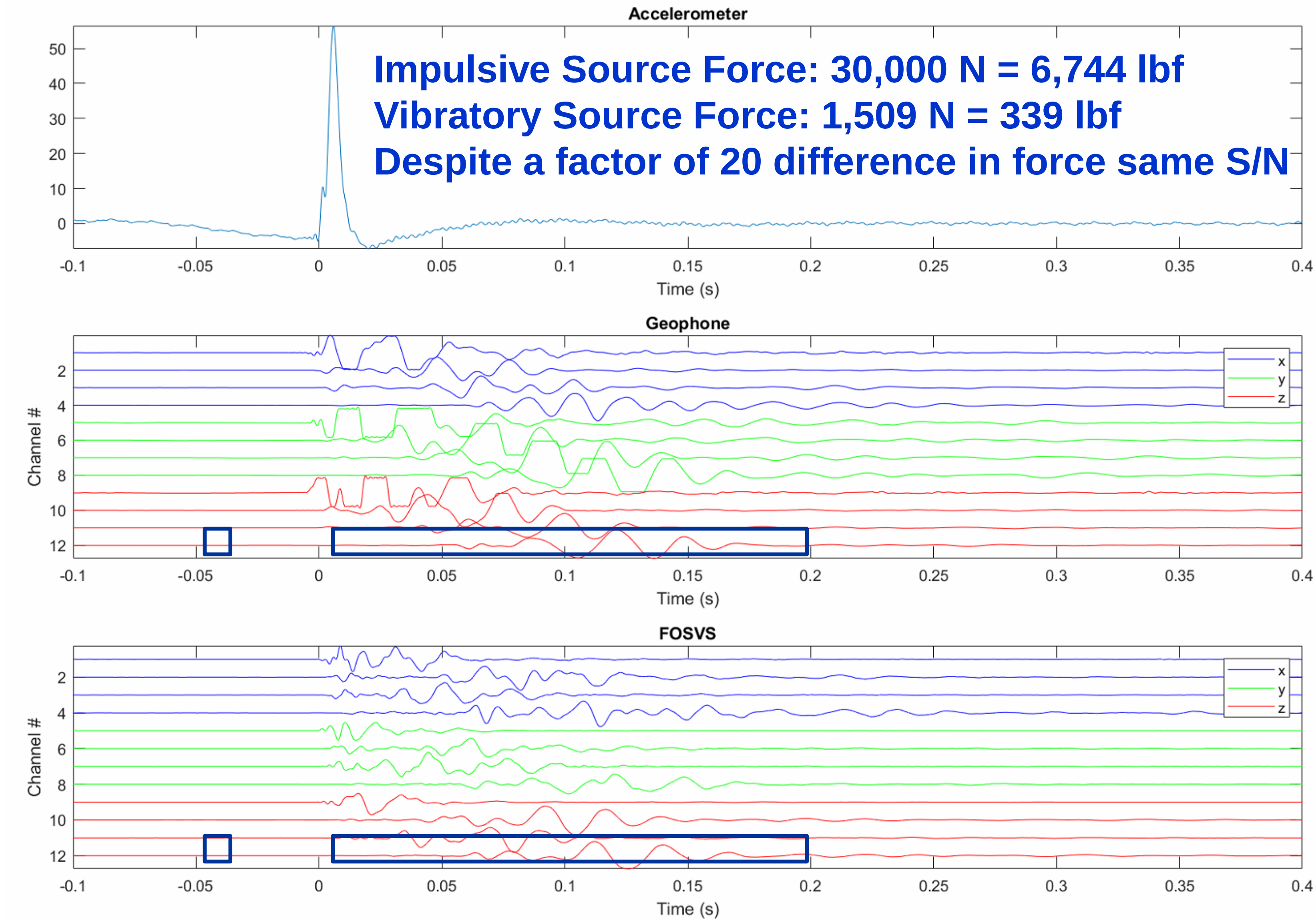


Theoretical 10 Second Sweeps used for Correlation - Case 4

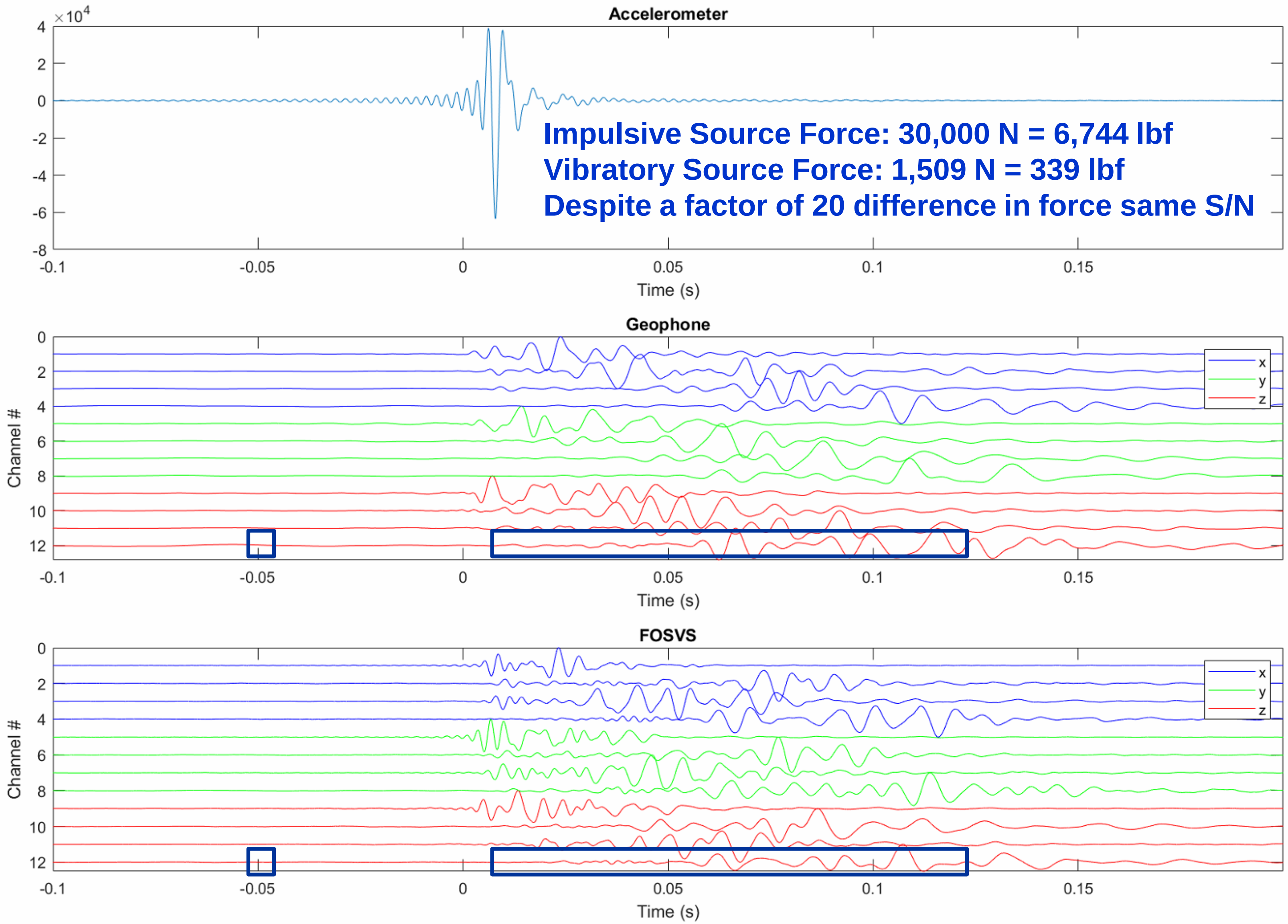




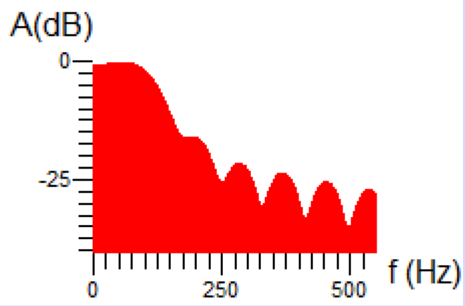
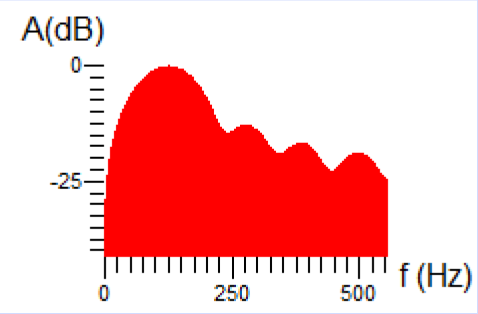
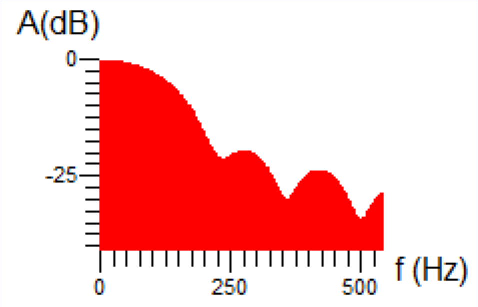
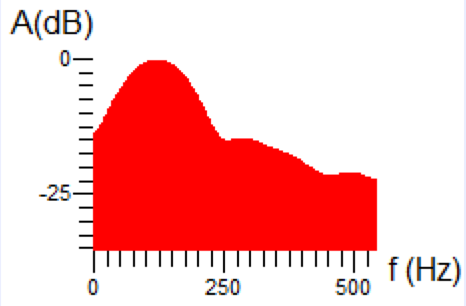
Impulsive Source: 50 kg (110 lbs) @ 60g. Hit Data – Zoomed In



Vibrator Correlated Data: 10-410 Hz, 10 sec, 13.6 Vpp - Case 4

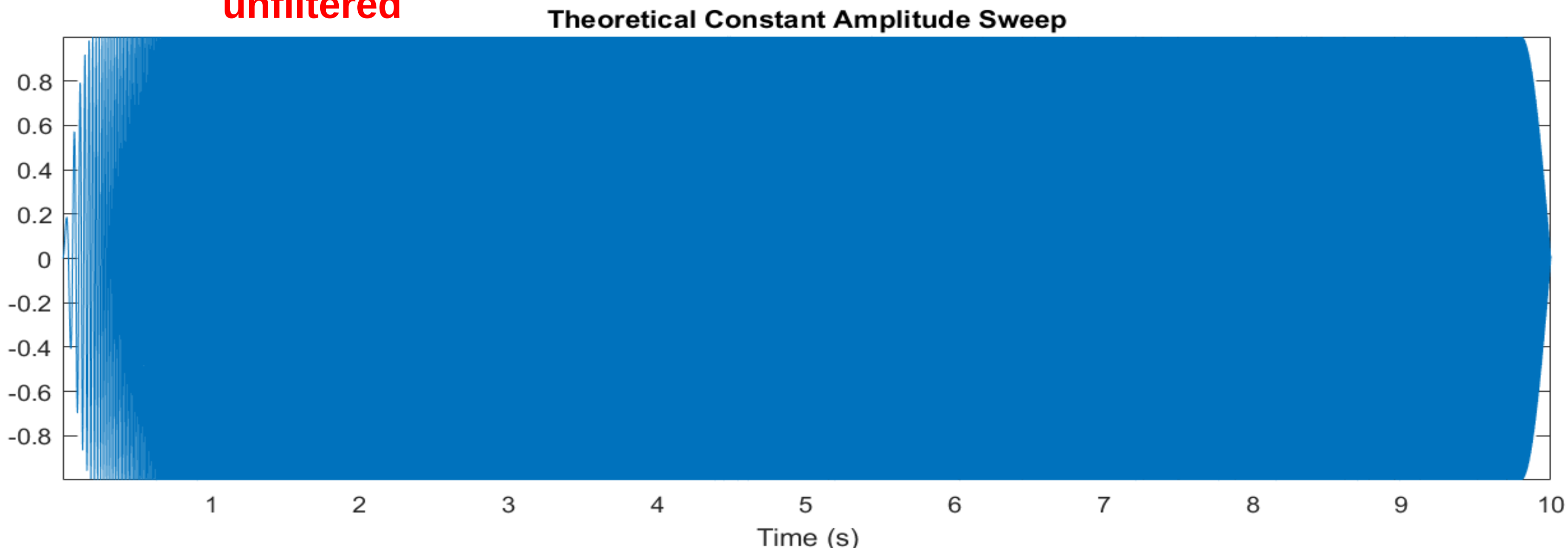


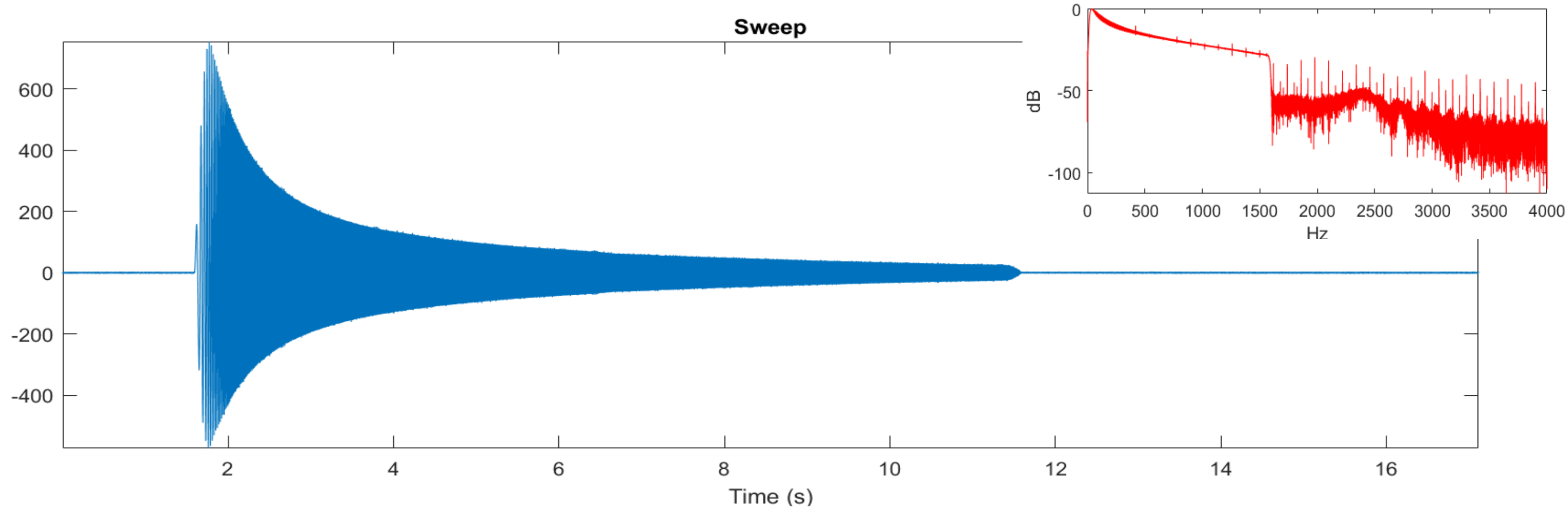
S-wave Spectra of Impulsive and Vibratory Sources

	Impulse Source 50 kg impact at 100g	**Vibratory Source** 10 sec Sweep 10 – 410 Hz
10 Hz V Geophone		
FOSVS Vertical		

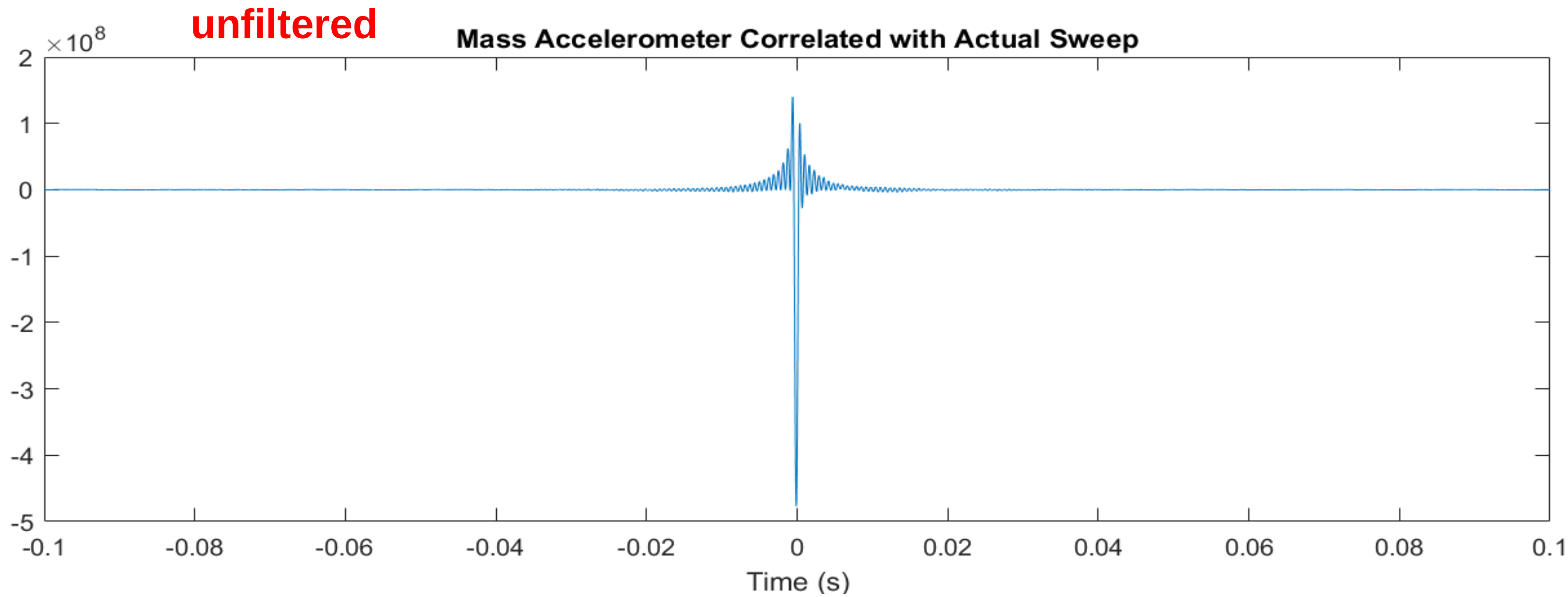
Uncorrelated Data: 10-1610 Hz, 10 sec sweep, 5 Vpp drive

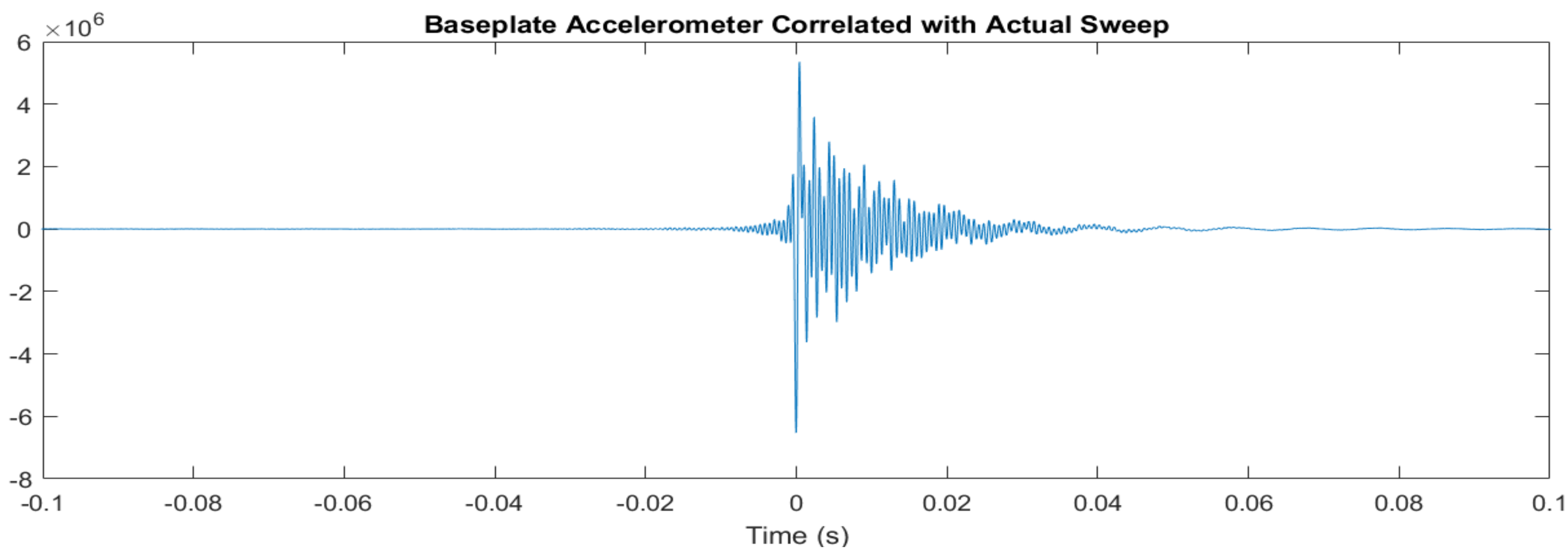
unfiltered



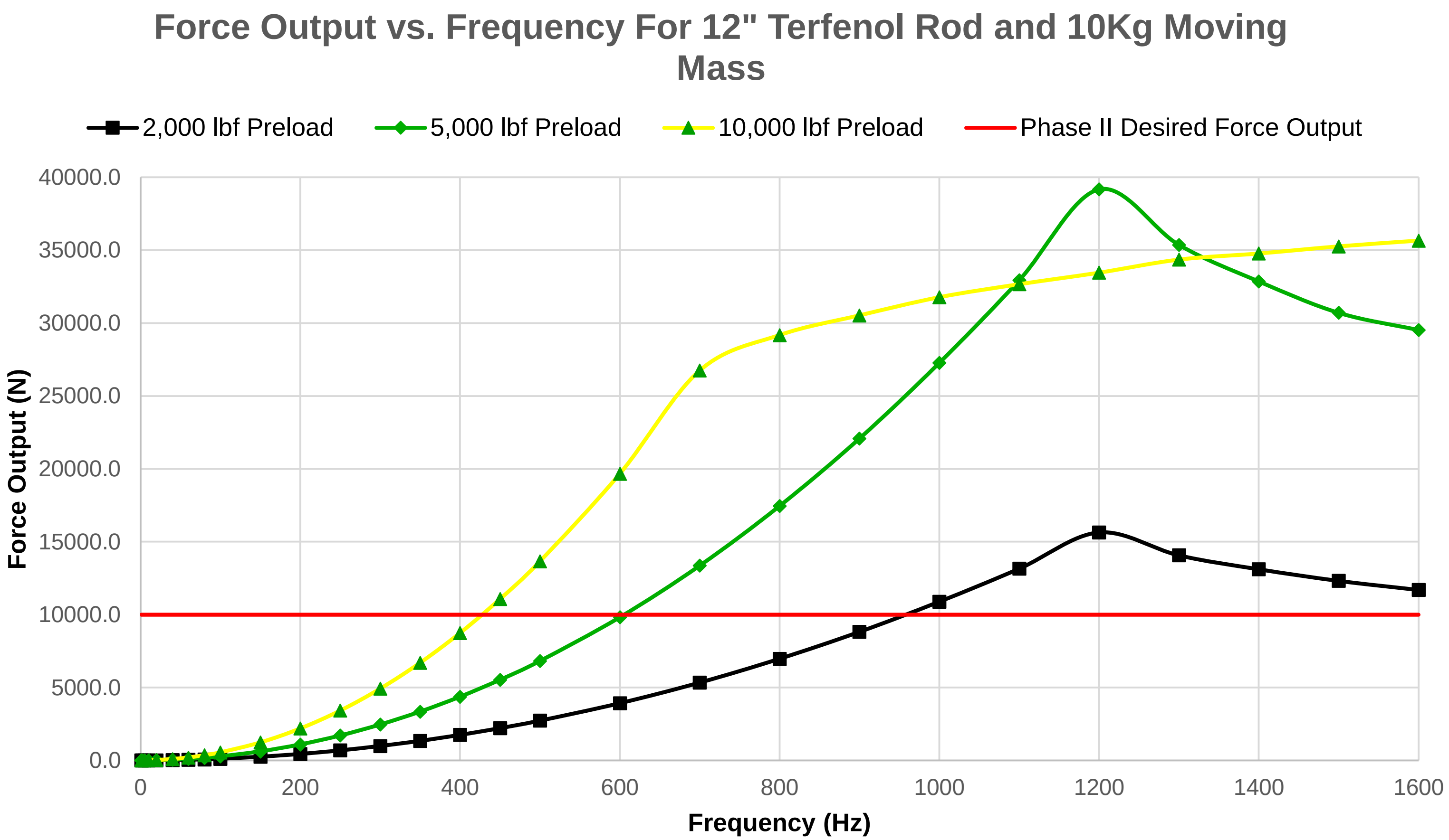


Correlated Data: 10-1610 Hz, 10 sec sweep, 5 Vpp drive





SBIR Phase II: Preliminary Model Results



Preload has a big effect on force output. Generally, higher preload = higher force output.

In Summary – Single Well Seismic Technology

- Borehole Vibratory Source Under Development:
    1. Magneto Strictive Actuator
    2. 3C Source Technology
    3. >250°C (>482°F) capable
    4. Operate in Vertical and Horizontal Boreholes

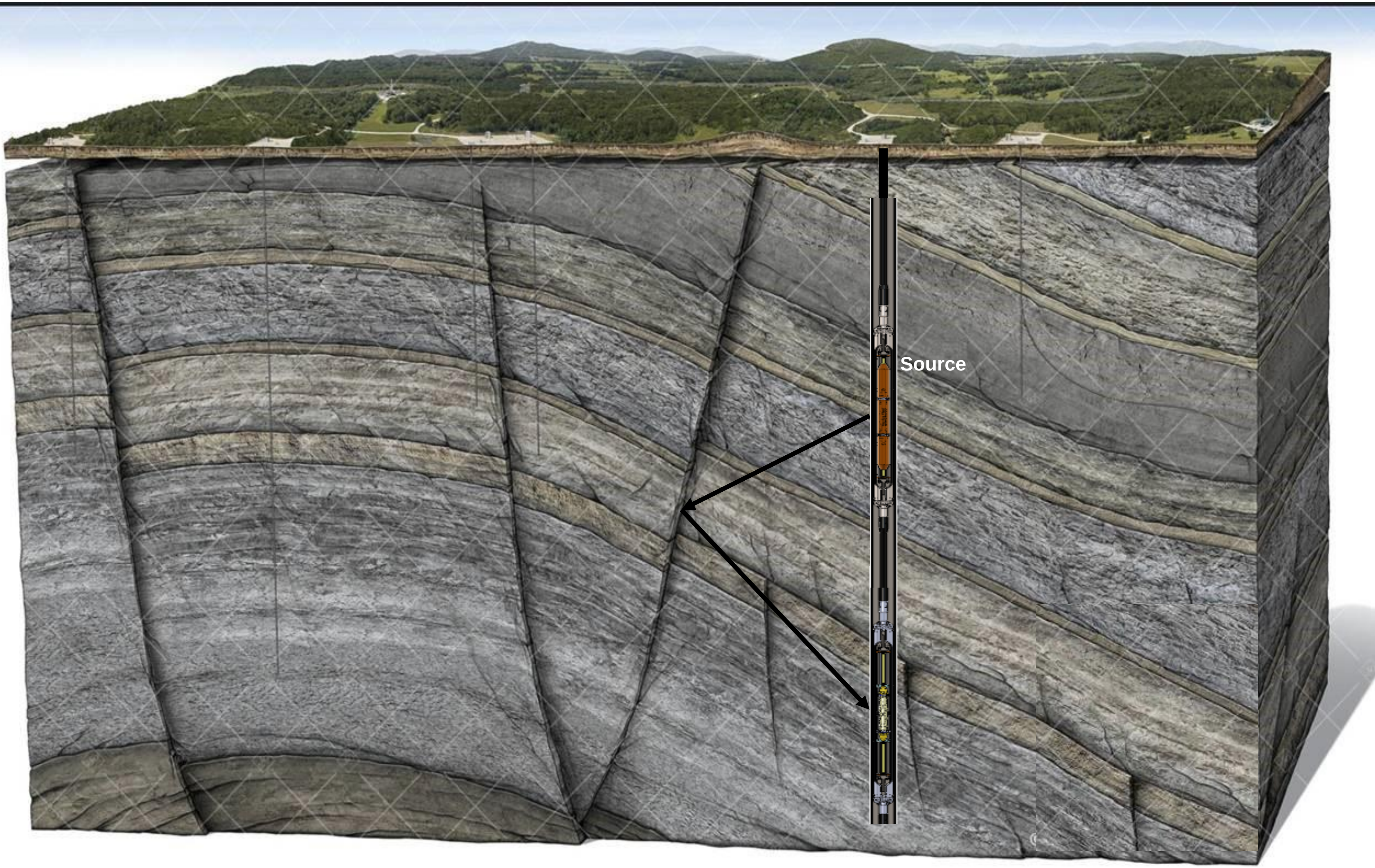
- Borehole Seismic Receivers Developed and Field Tested
    1. All Optical Vector Sensors
    2. 3C Clamped Receivers
    3. Tested to 320°C (608°F)
    4. Operate in Vertical and Horizontal Boreholes

First Set of Single Well Seismic Modeling

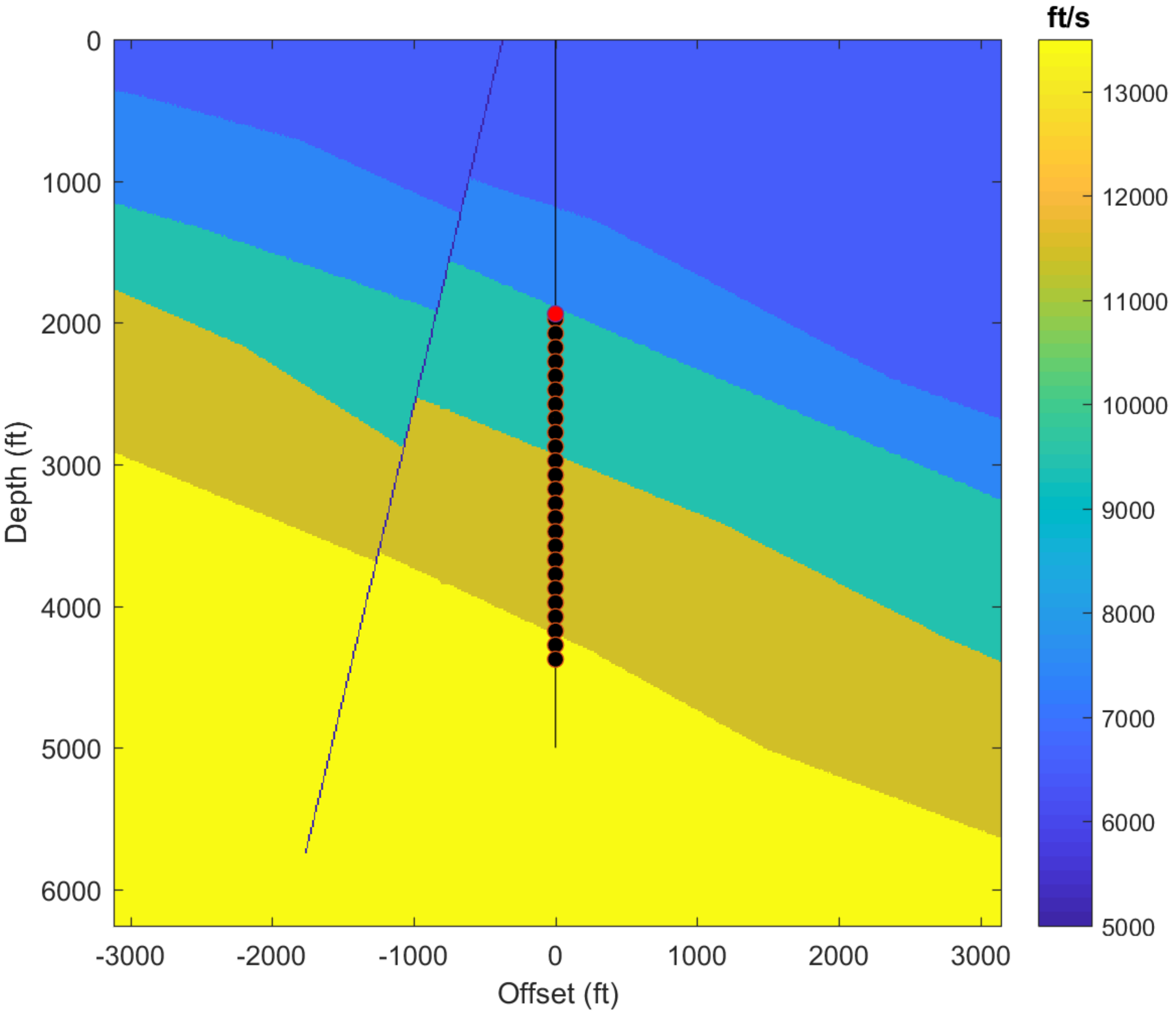
- 2D elastic modeling scheme:
  - 100 level receiver array at 25 ft spacing below the source
  - 60 sources @ 100 ft interval starting from depth 125 ft
  - dx = 12.5 ft
  - dt = 0.25 ms
  - Wavelet: Ricker wavelet 50 Hz peak frequency, 120 Hz @ -30 dB (For real data acquisition we will be able to record data with a minimum of 500 Hz dominant frequency)

- Radiation Pattern
  - Axial Source (modeled in this presentation)
  - Torsional Source
  - Radial Source

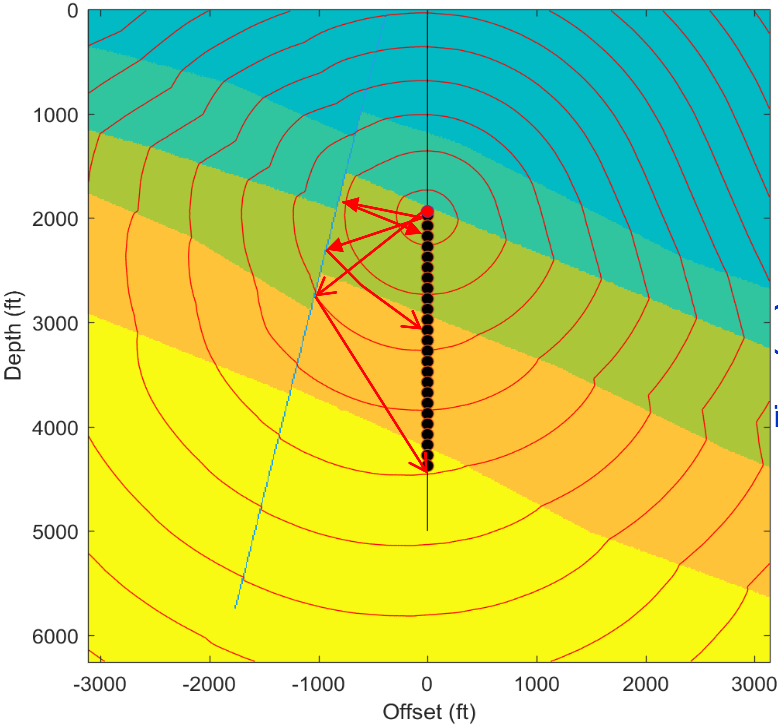
Single Well Seismic Imaging of a Fault

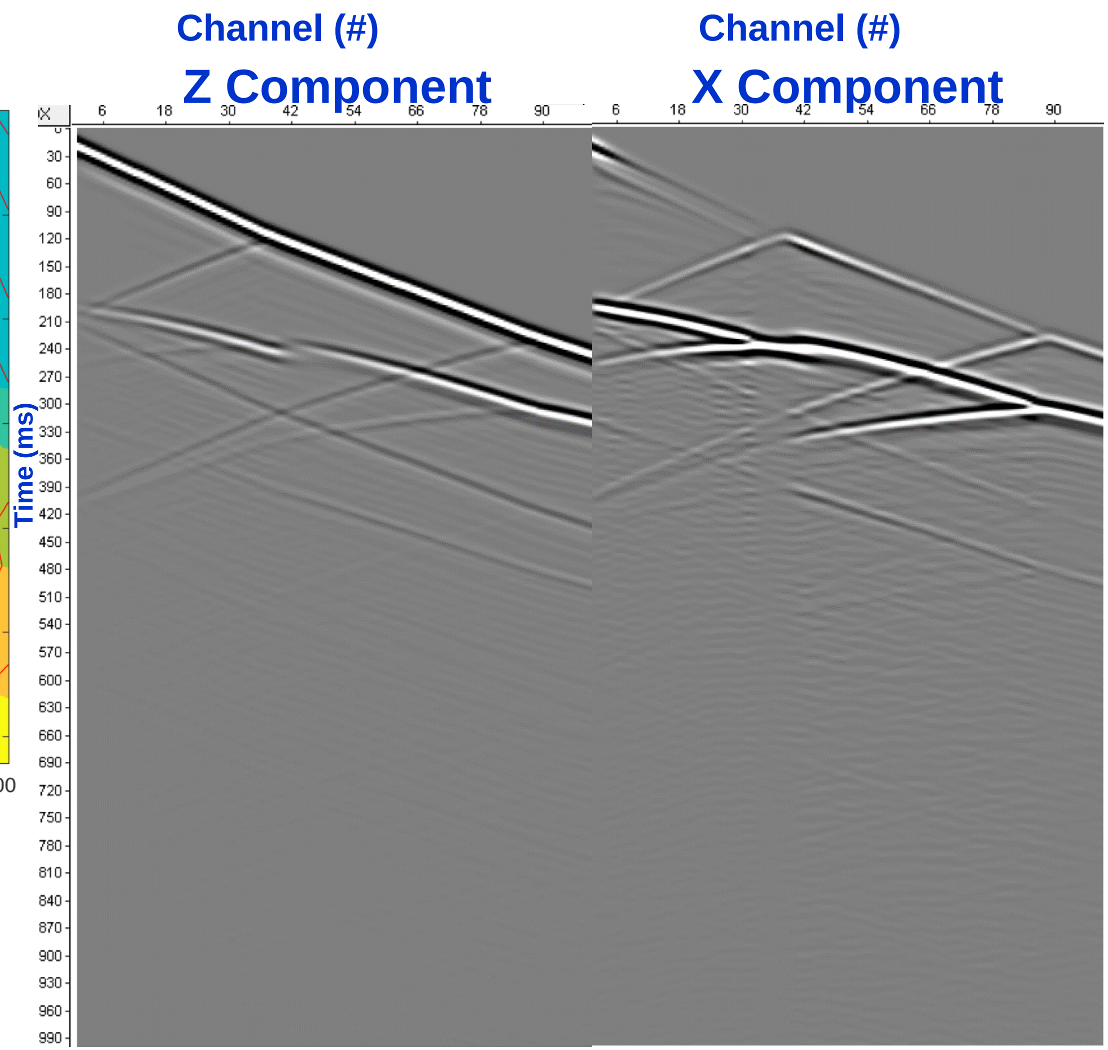


A Numerical Fault Velocity Model



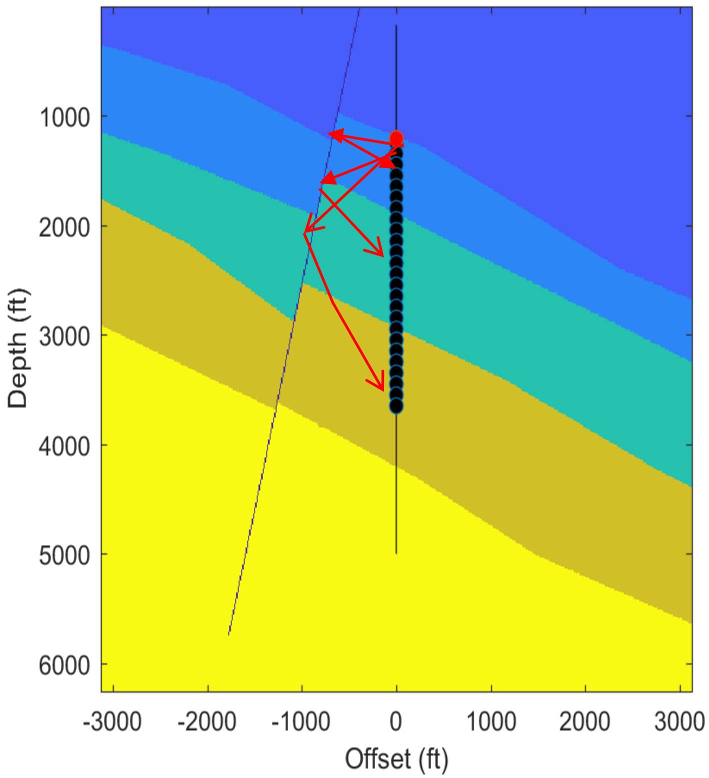
Model Single Well Seismic Data with an Axial Source



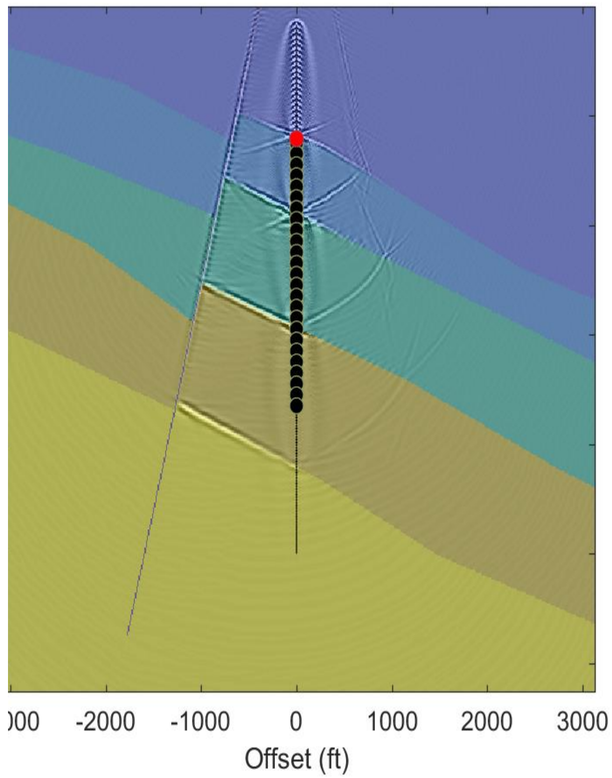


Reverse Time Migration Results

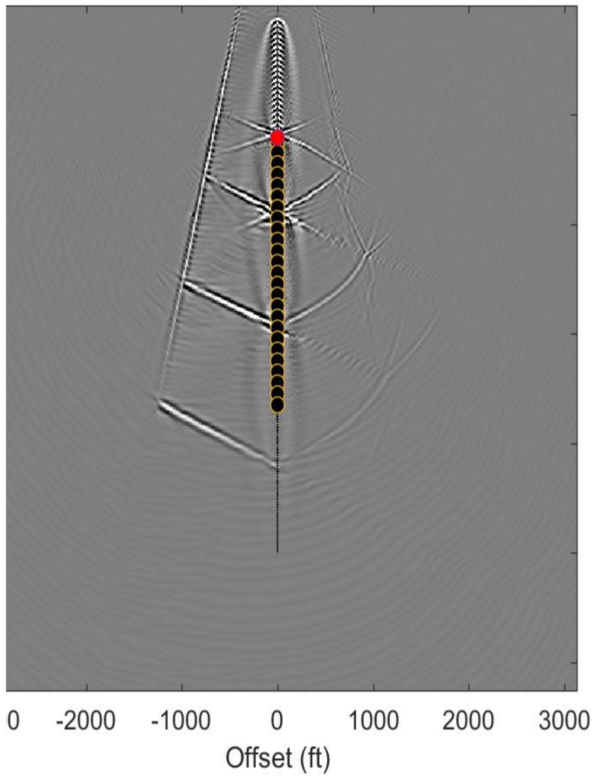
Geology & Velocity



Geology & Image



Seismic Image

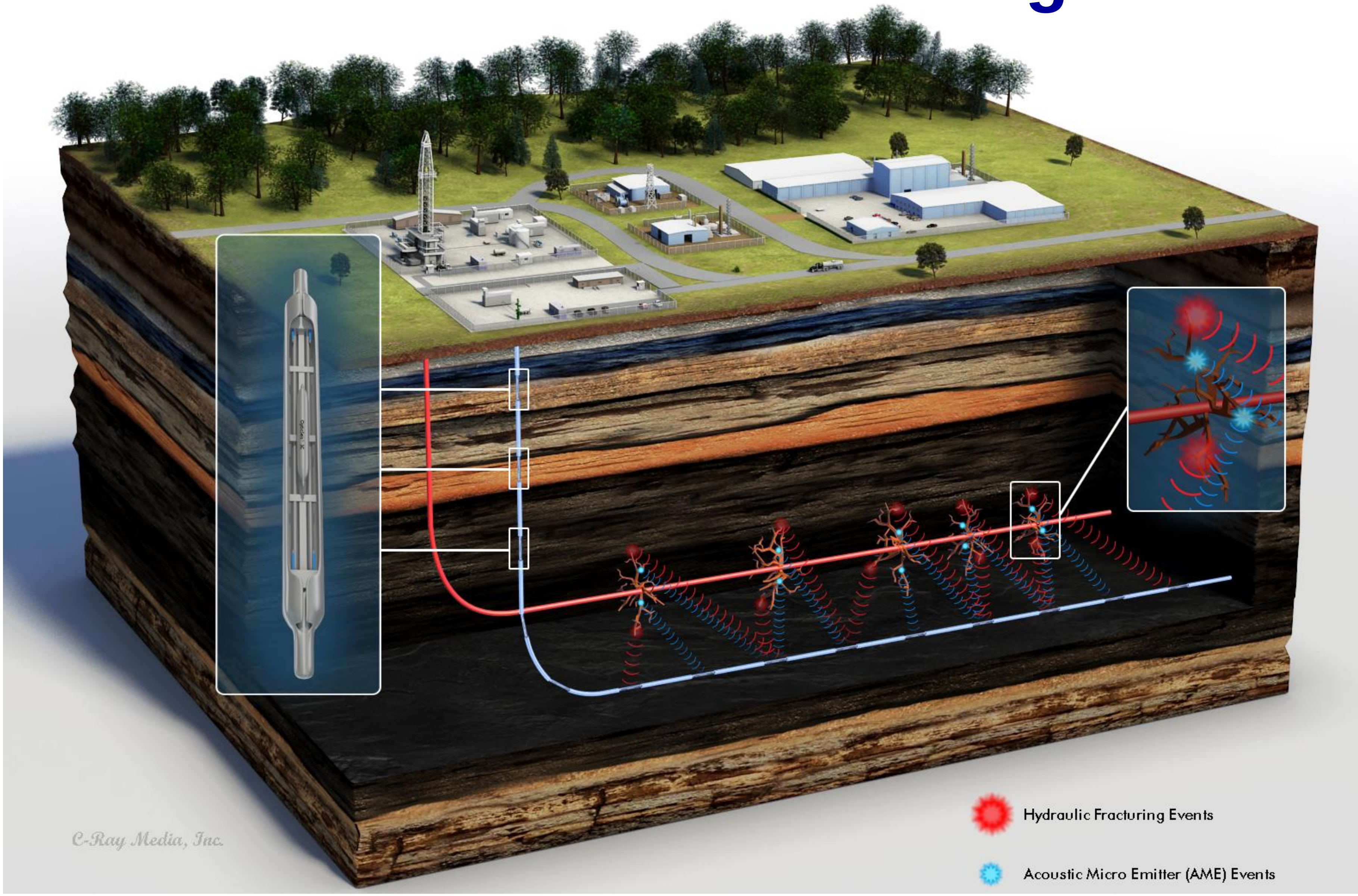


Second Set Single Well Seismic Modeling

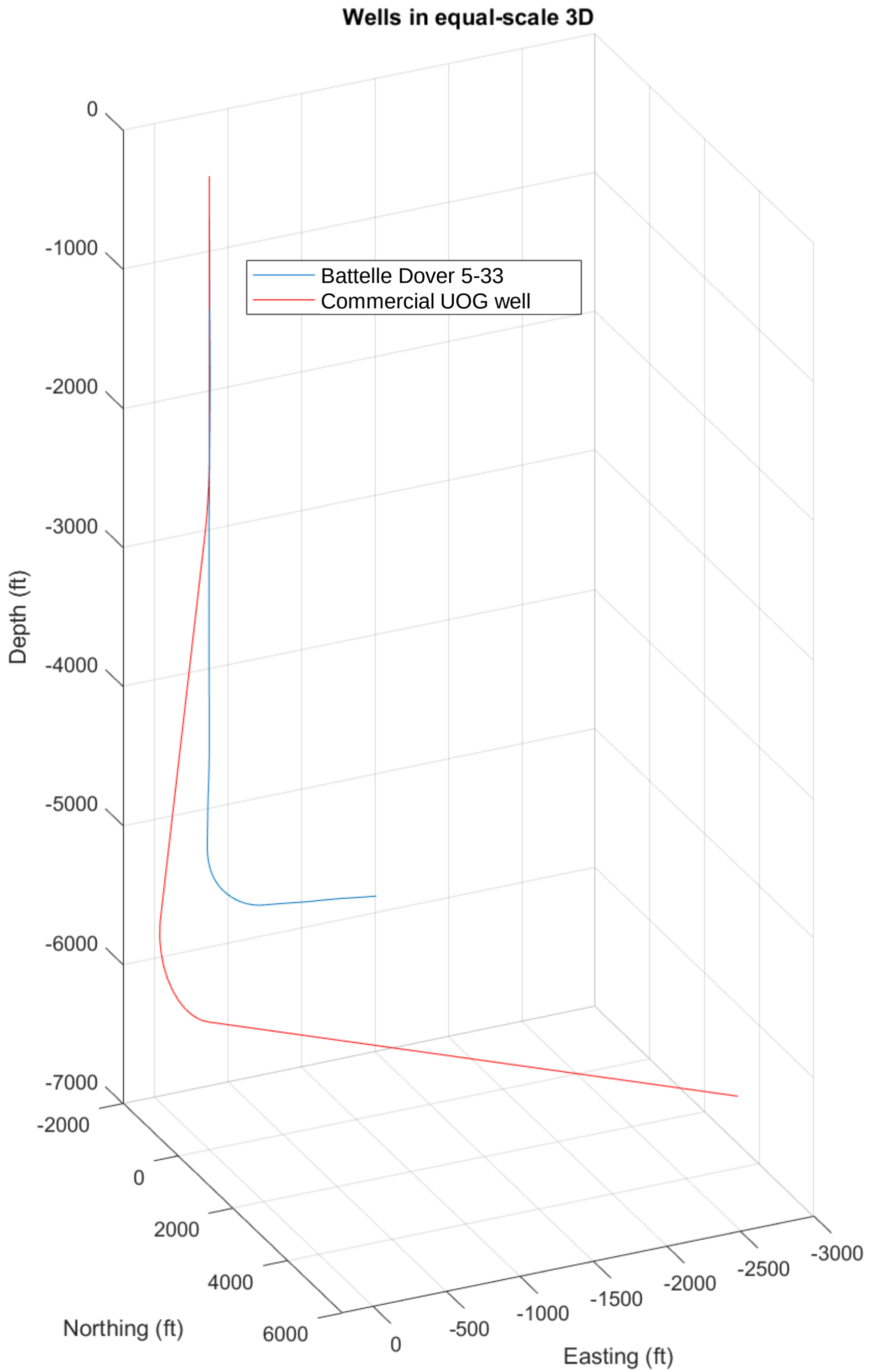
- 2D elastic modeling scheme:
  - 480 receivers @ 16 ft in the vertical well section
  - 60 sources @ 64 ft in the vertical well section
  - 250 receivers @ 16 ft in the horizontal well section
  - 200 sources @ 64 ft in the horizontal well section
  - dx = 16 ft
  - dt = 0.5 ms
  - Wavelet: Ricker wavelet 50 Hz peak frequency, 120 Hz @ -30 dB

- Radiation Pattern
  - Axial Source (modeled in this presentation)
  - Torsional Source
  - Radial Source

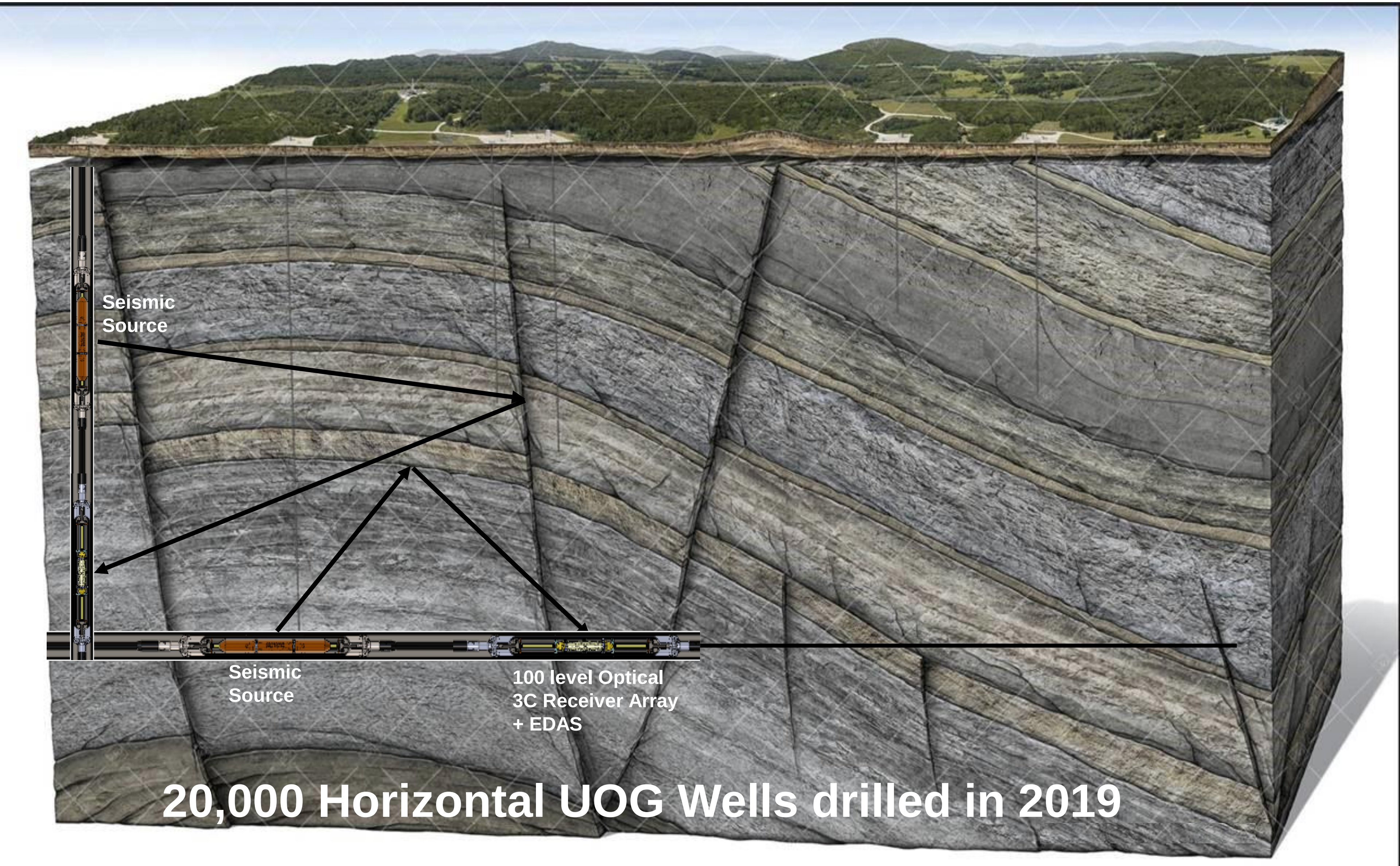
Effective & Accurate Monitoring of UOG



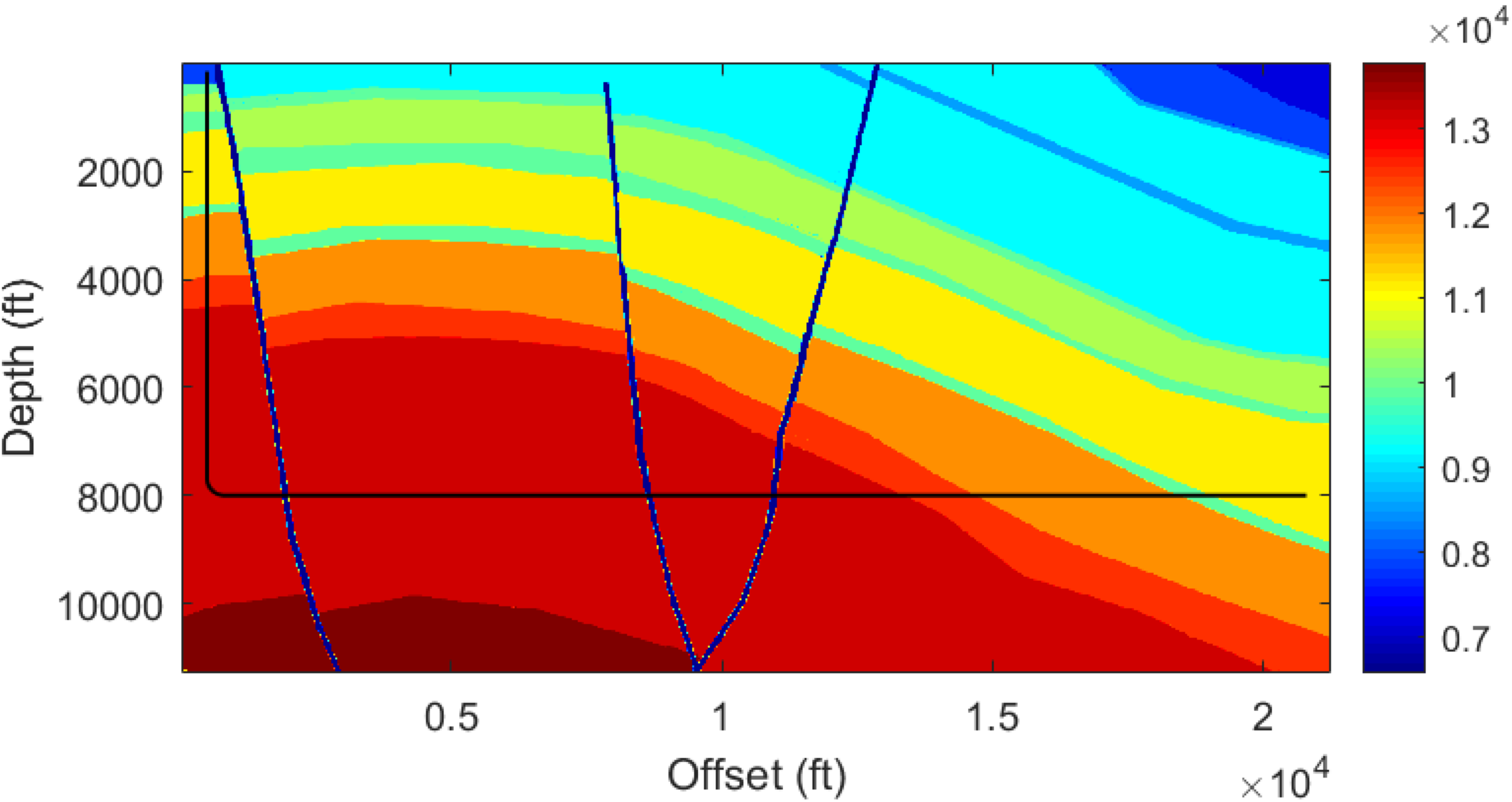
Deployment of the FOSVS System into Horizontal Wells



Subsurface UOG Imaging

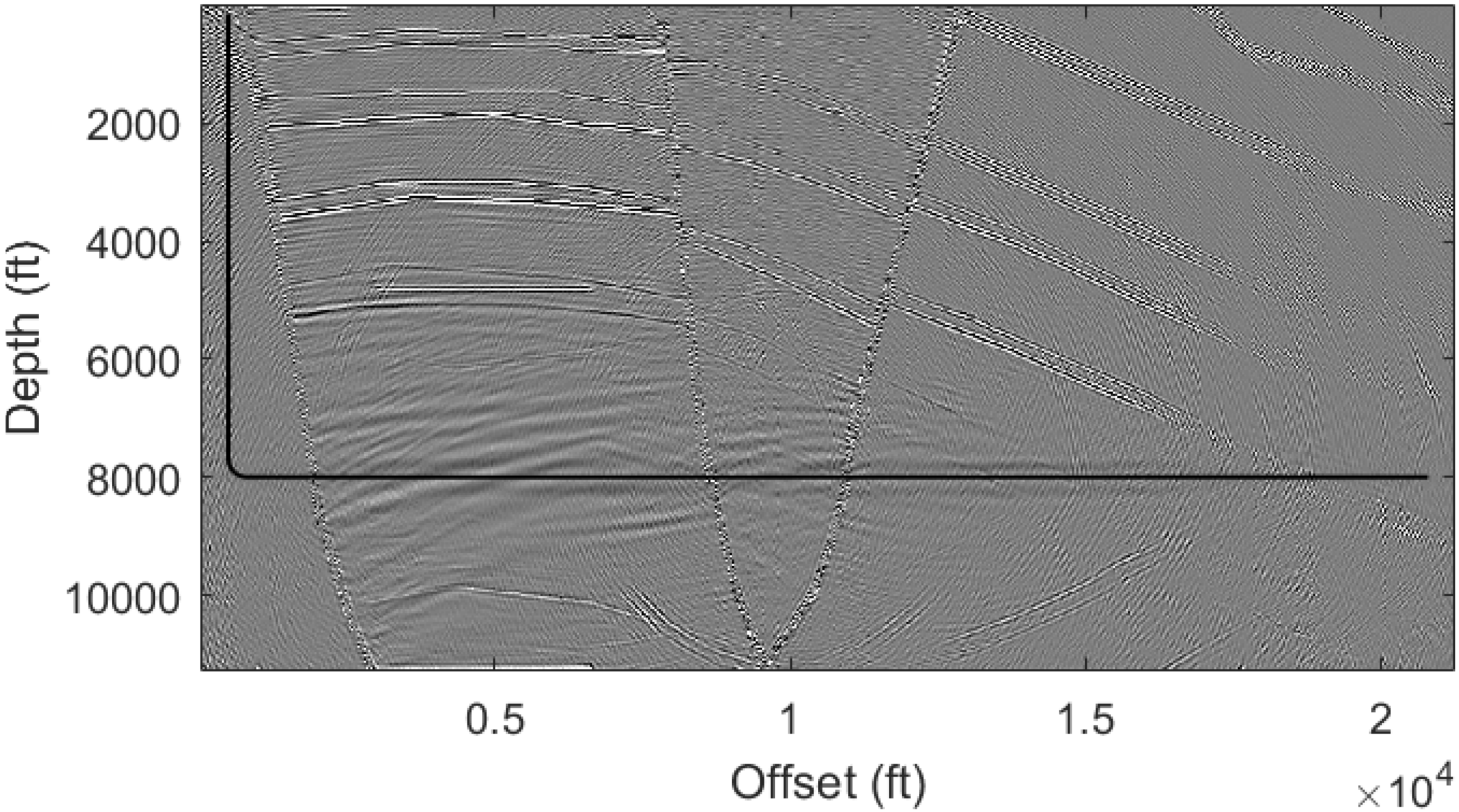


Another Synthetic Velocity Model



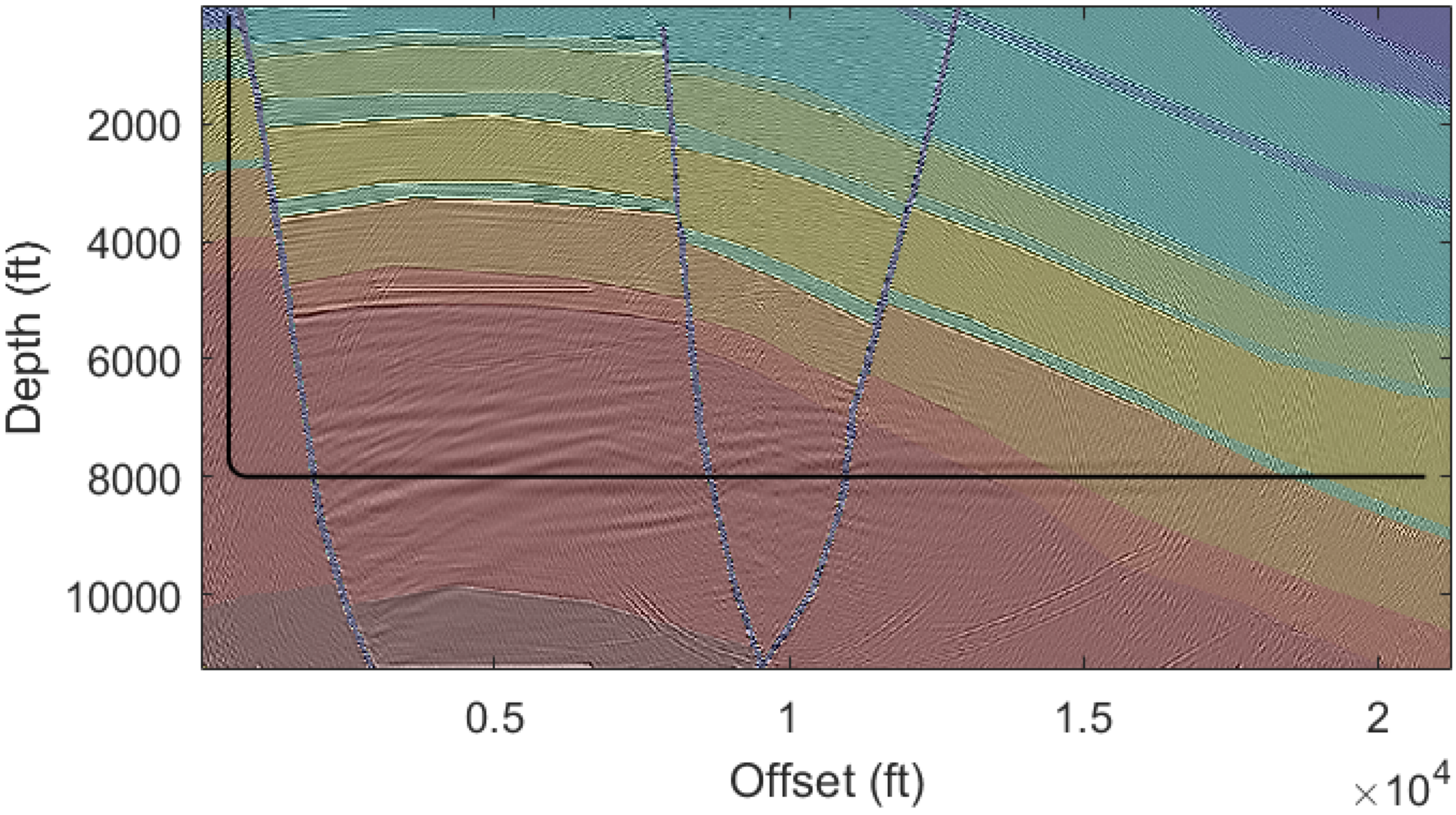
Horizontal-Well RTM Result

200 sources @ 64 ft interval
at the center of an array with
250 receivers @ 16 ft interval



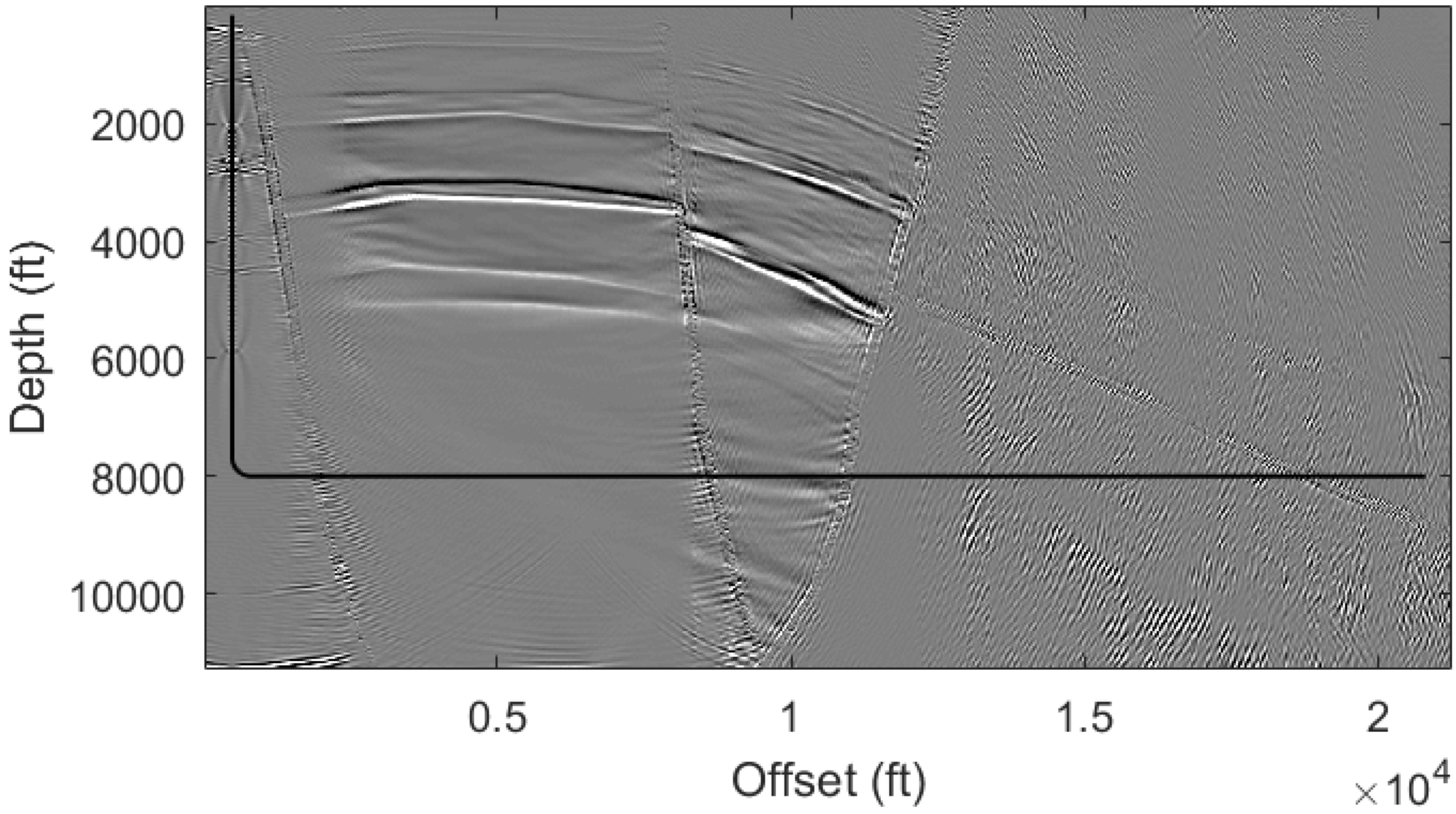
Horizontal-Well RTM Overlaid Velocity

200 sources @ 64 ft interval
at the center of an array with
250 receivers @ 16 ft interval



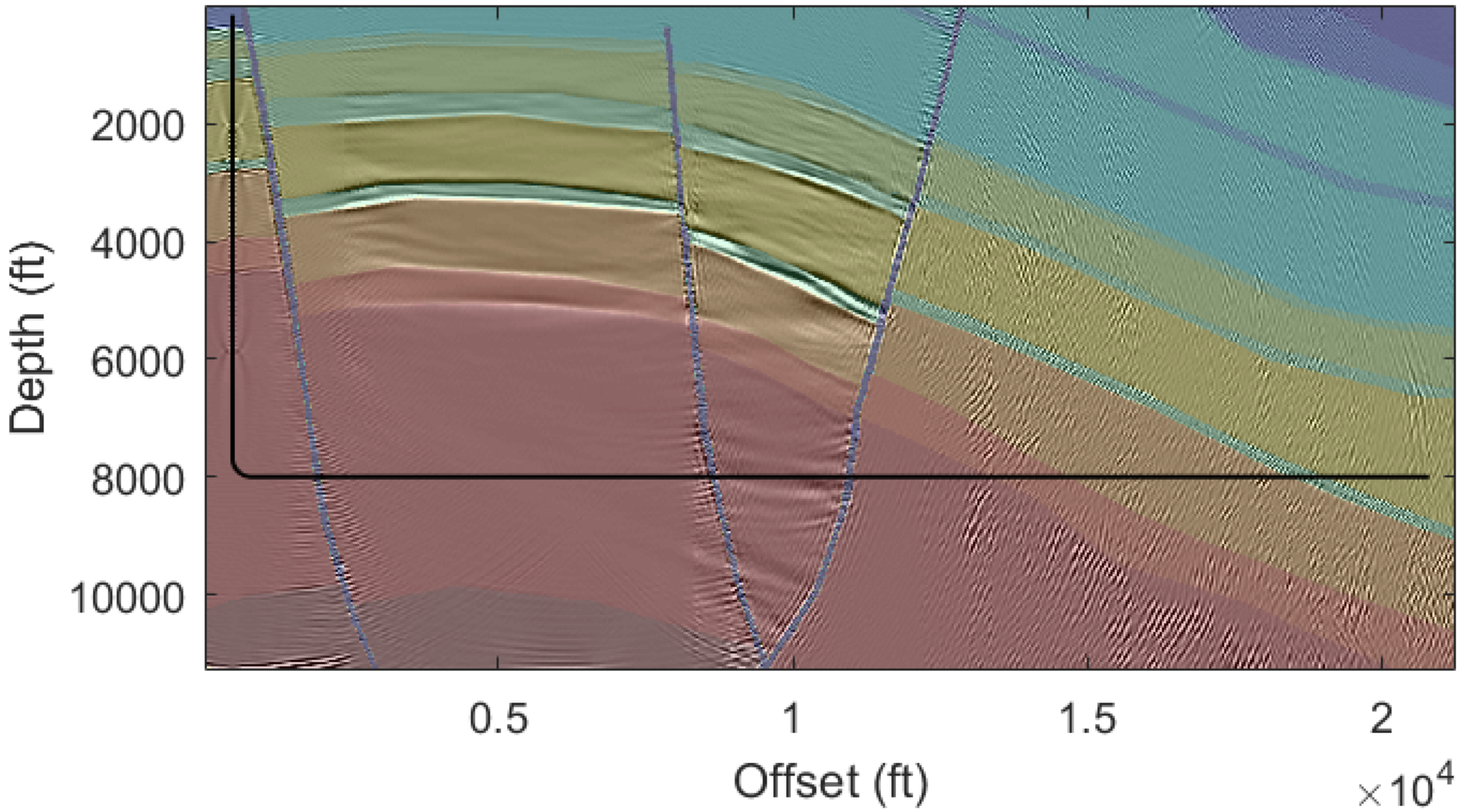
Vertical-Well RTM Result

**60 sources @ 64 ft interval
at the center of an array with
250 receivers @ 16 ft interval**



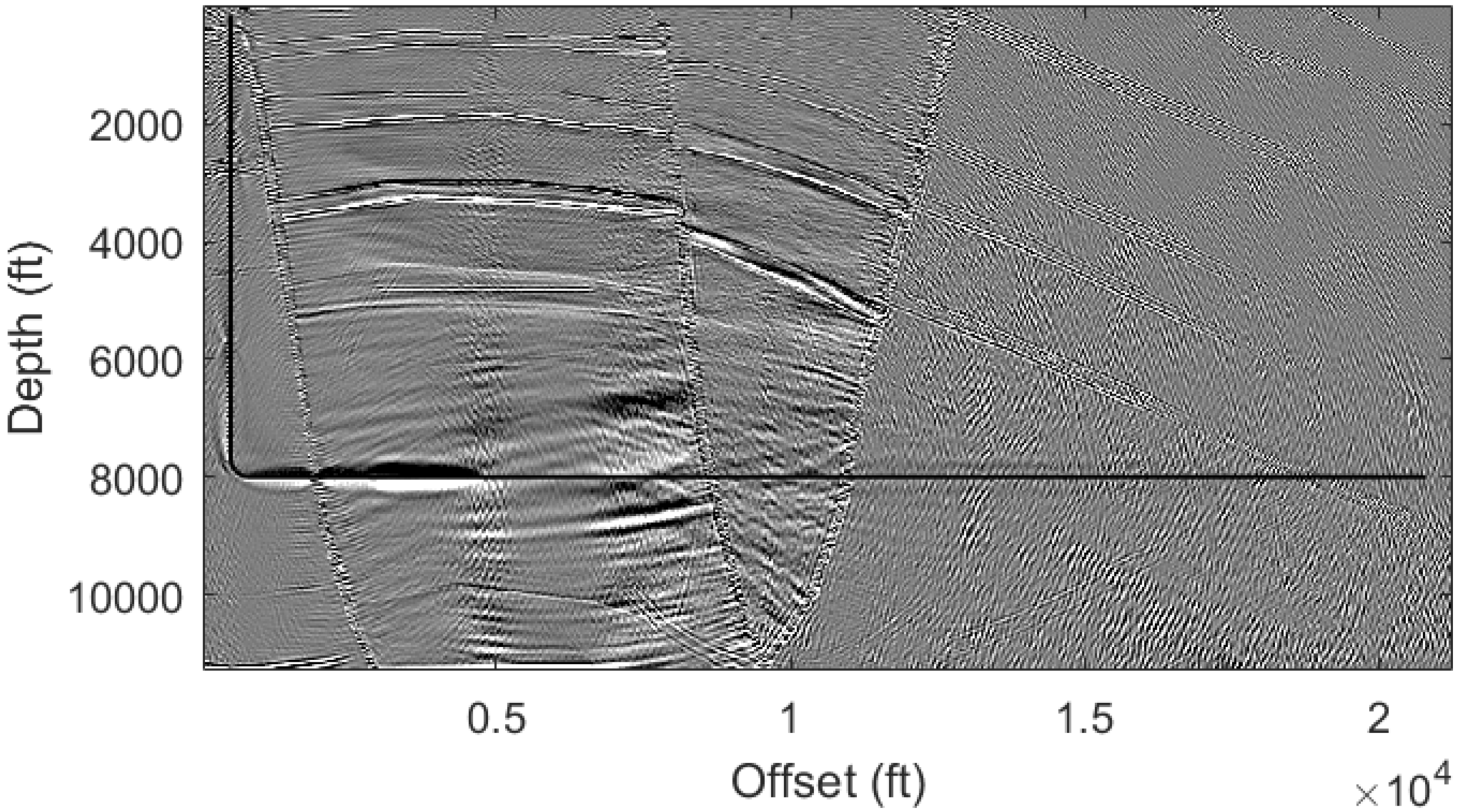
Vertical-Well RTM Overlaid Velocity

60 sources @ 64 ft interval
at the center of an array with
250 receivers @ 16 ft interval



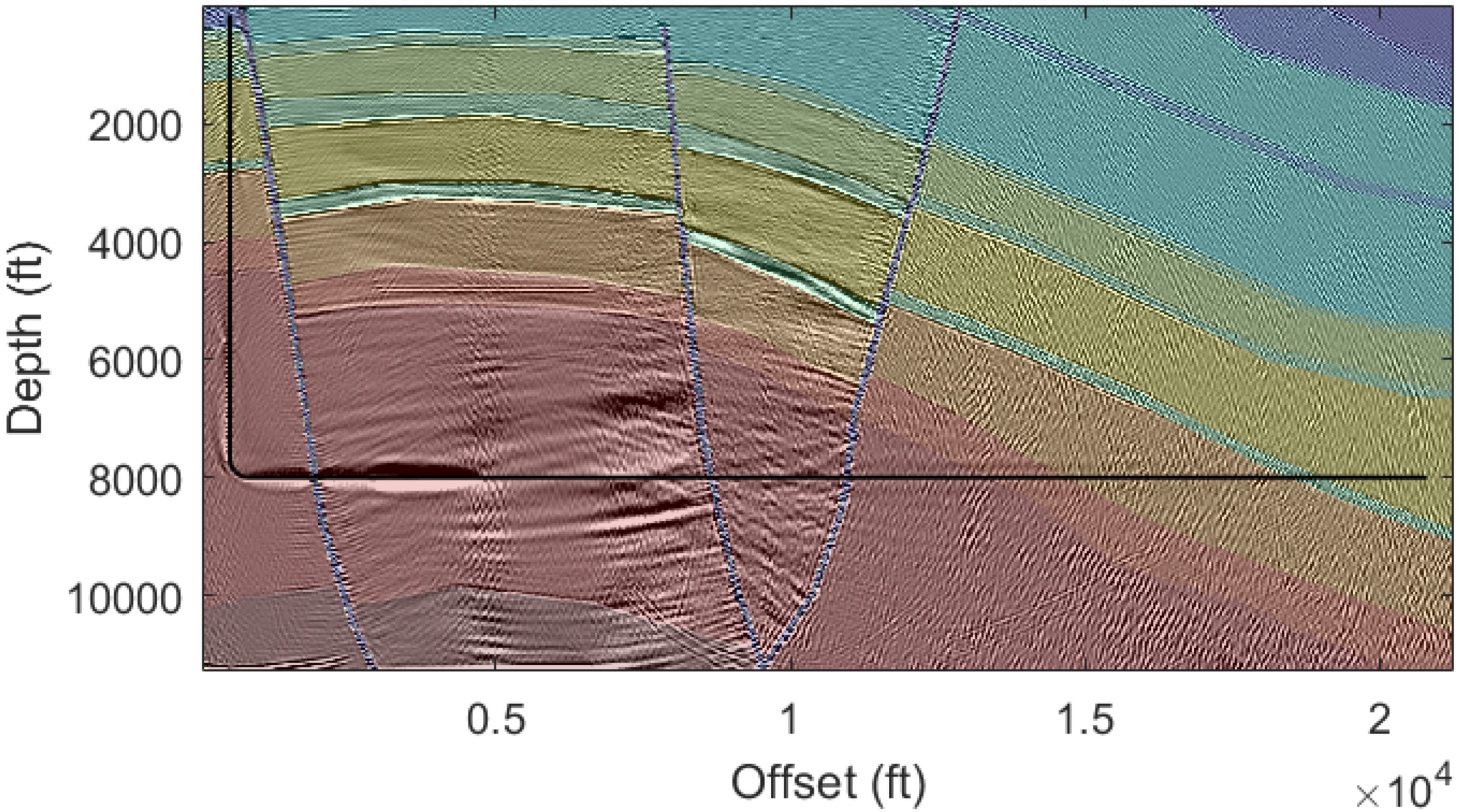
Whole-Well RTM Result

328 sources @ 64 ft interval
at the center of an array with
250 receivers @ 16 ft interval

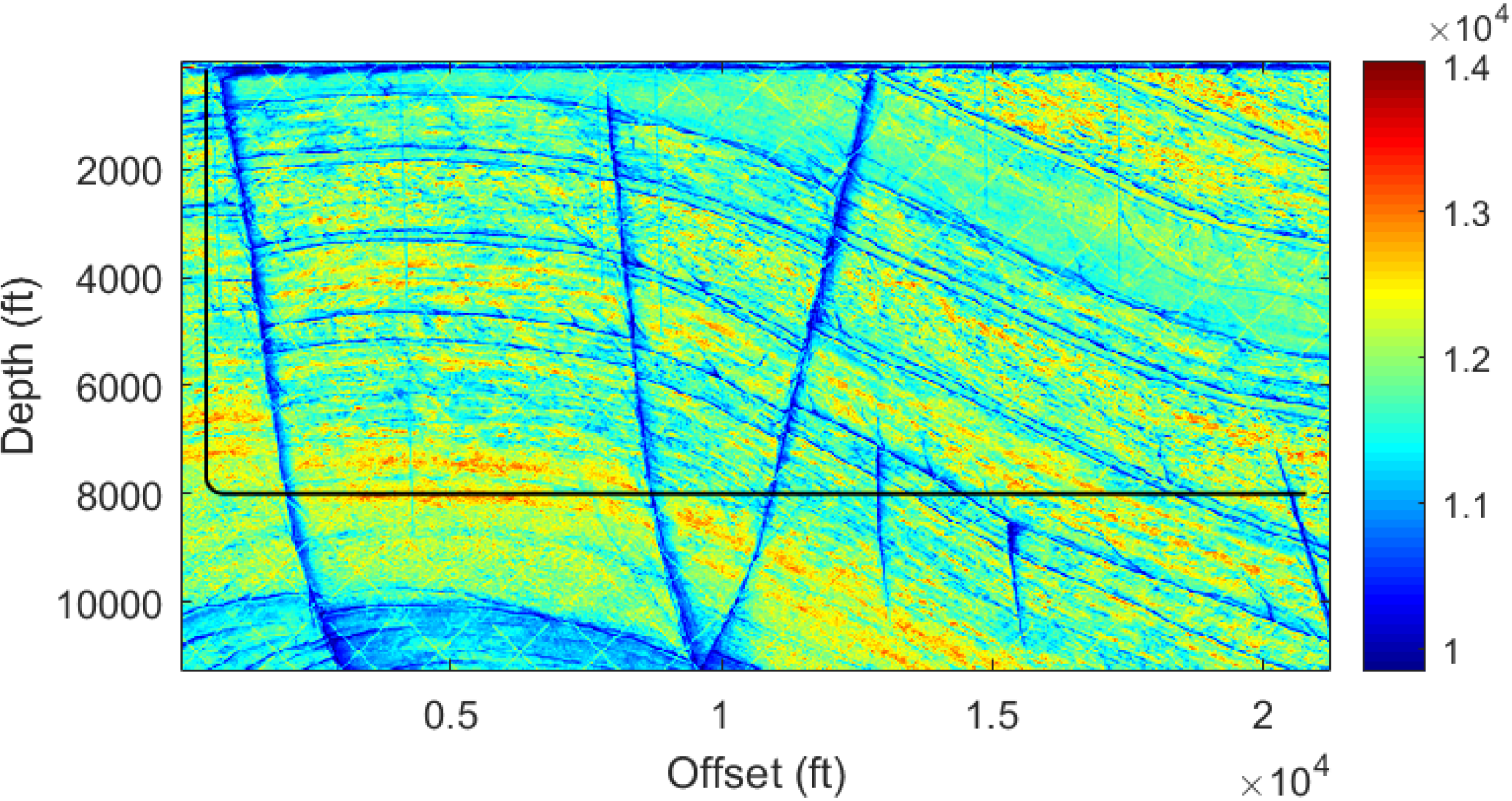


Whole-Well RTM Overlaid Velocity

328 sources @ 64 ft interval
at the center of an array with
250 receivers @ 16 ft interval

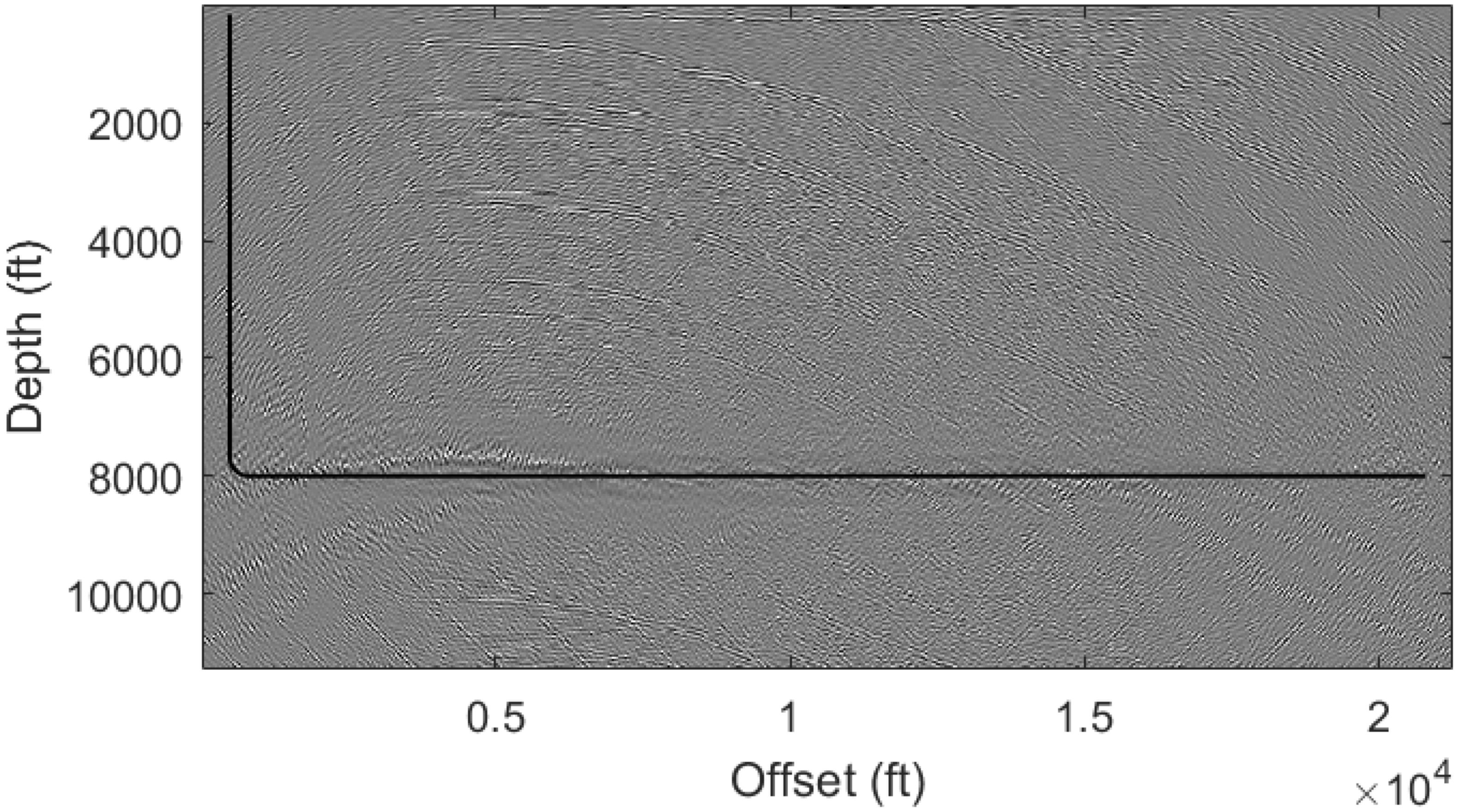


A Synthetic Velocity Model



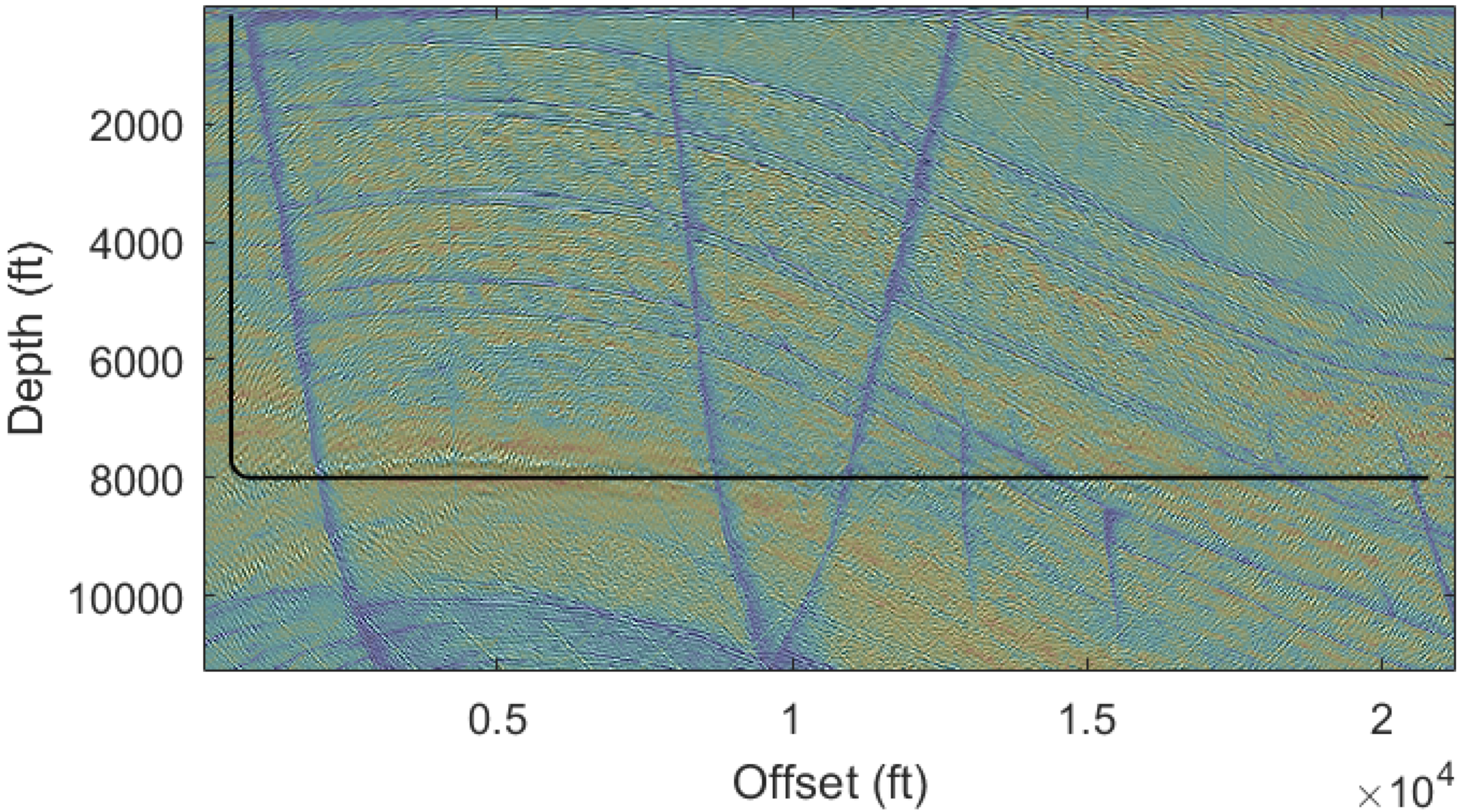
Horizontal-Well RTM Result

200 sources @ 64 ft interval
at the center of an array with
250 receivers @ 16 ft interval



Horizontal-Well RTM Overlaid Velocity

200 sources @ 64 ft interval at the center of an array with 250 receivers @ 16 ft interval



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)
  - DOE SBIR II Grants DE-SC0017222 & DE-SC0017729 (2018)
  - DOE SBIR II Grant DE-SC0018613 (2018) Downhole Source

The support and assistance from these grants made it possible to develop the fiber optic sensor and deployment technologies 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 and SBIR Grants DE-SC0017222/17729/18613 is gratefully acknowledged.