Paulsson, Inc. (PI)

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Optical Multi-Sensor Technologies (OMST)™

Presentation to DOE

August 7, 2022

Topics Today:
Borehole Optical Sensors, Seismic Sources and Their Applications

- Fiber Optic Seismic Vector Sensors (FOSVS)
- Optical Pressure Sensor ARray (OPSAR)(new)
- 3C BOrehole Seismic Source (3CBOSS)(new)
- Instrument Applications

- Distributed Acoustic Sensors (DAS)
- Distributed Temperature Sensors (DTS)

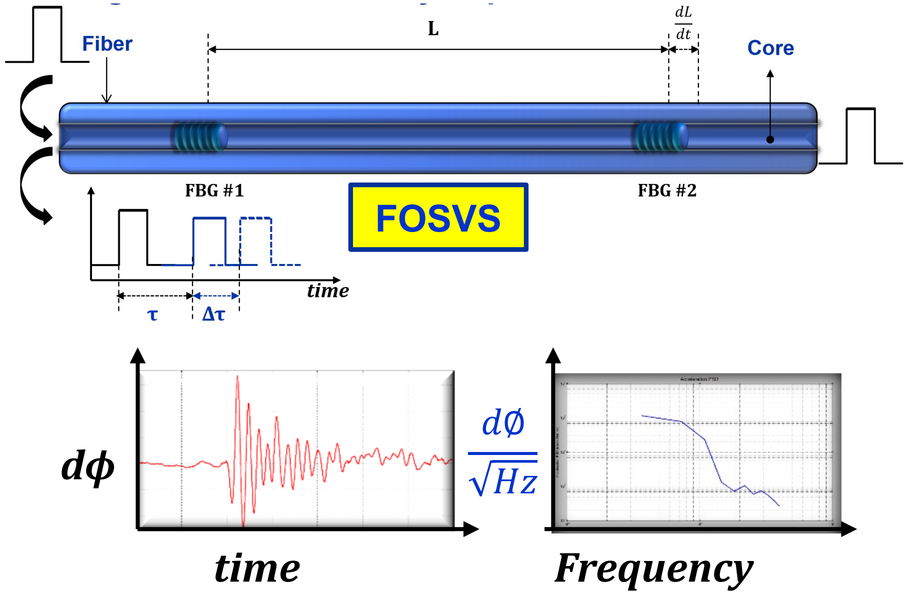
Presentation Outline

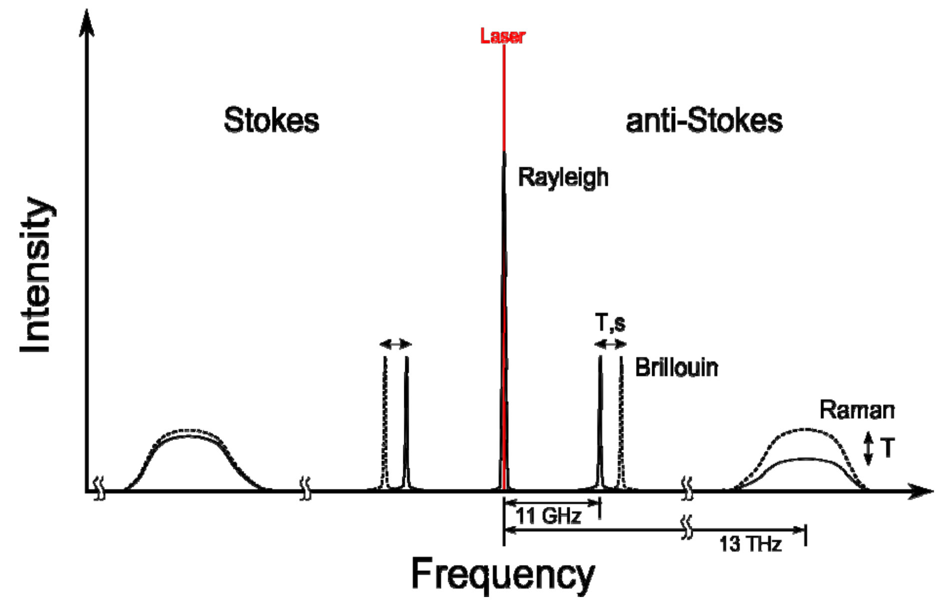
- Optical Sensors
  - Optical Accelerometers: DE-FE0024360
  - Optical Pressure Sensors
- Borehole Vibratory Seismic Sources
- Applications & Examples
- Paulsson Staff and Facility

Several All-Optical Sensors are Part of Our Borehole System

DOE supported Paulsson Point Sensors include: Accelerometers, Hydrophones & Pressure Sensors.

Distributed Fiber Optic Sensor Technologies for Acoustic, Strain & Temperature measurements.





Interferometric Sensing

- Two FBGs: Measure phase changes/time between two laser reflections from the two FBG's

Rayleigh (DAS)

- Rayleigh Scattering
- **Acoustic**

Raman (DTS)

- Intensity ratio of Stokes and anti-Stokes
- **Temperature**

Brillouin (DSS)

- Frequency of Brillouin peak
- **Strain** and temperature

Strengths of Fiber Optic Seismic Vector Sensors (FOSVS)

- **Long term stability:** 30-year MTBF by the Navy
- **Very large bandwidth:** 5 Hz - 14,000 Hz
- **Extremely sensitive:** 100X a geophone > 300 Hz
- **Outstanding Vector Fidelity:** (80 dB)
- **Very High Temperature Tolerant:** >320°C (700°C)
- **Intrinsically Safe and Very Robust**

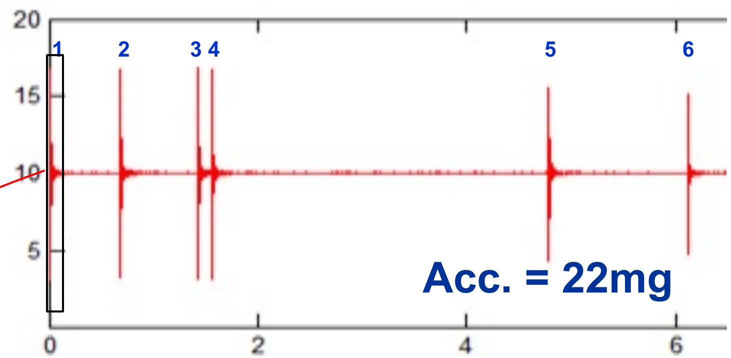
Survey and Monitoring Applications of Fiber Optic Seismic Vector Sensors (FOSVS)

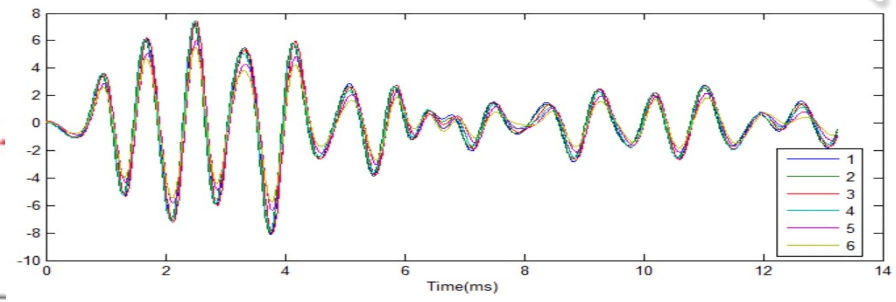
- Carbon Capture Usage and Storage sites (CCUS)
- Enhanced Geothermal Sites (EGS)
- Underground Gas Storage (UGS: NG, NG+H_2, H_2)
- Cleaner Enhanced Oil & Gas Recovery (CEOR)
- Nuclear Waste Sites (NWS)
- Wind Energy Installations (WEI – OWC)

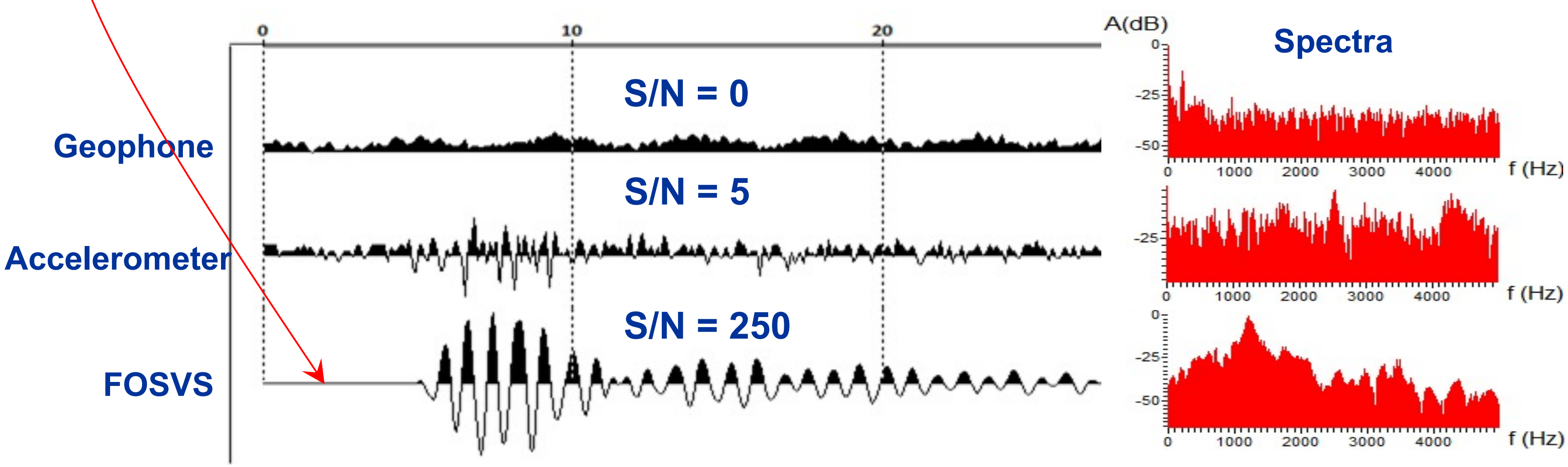
Test of Fiber Optic Seismic Vector Sensors (FOSVS) & IAME

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 IAMEs

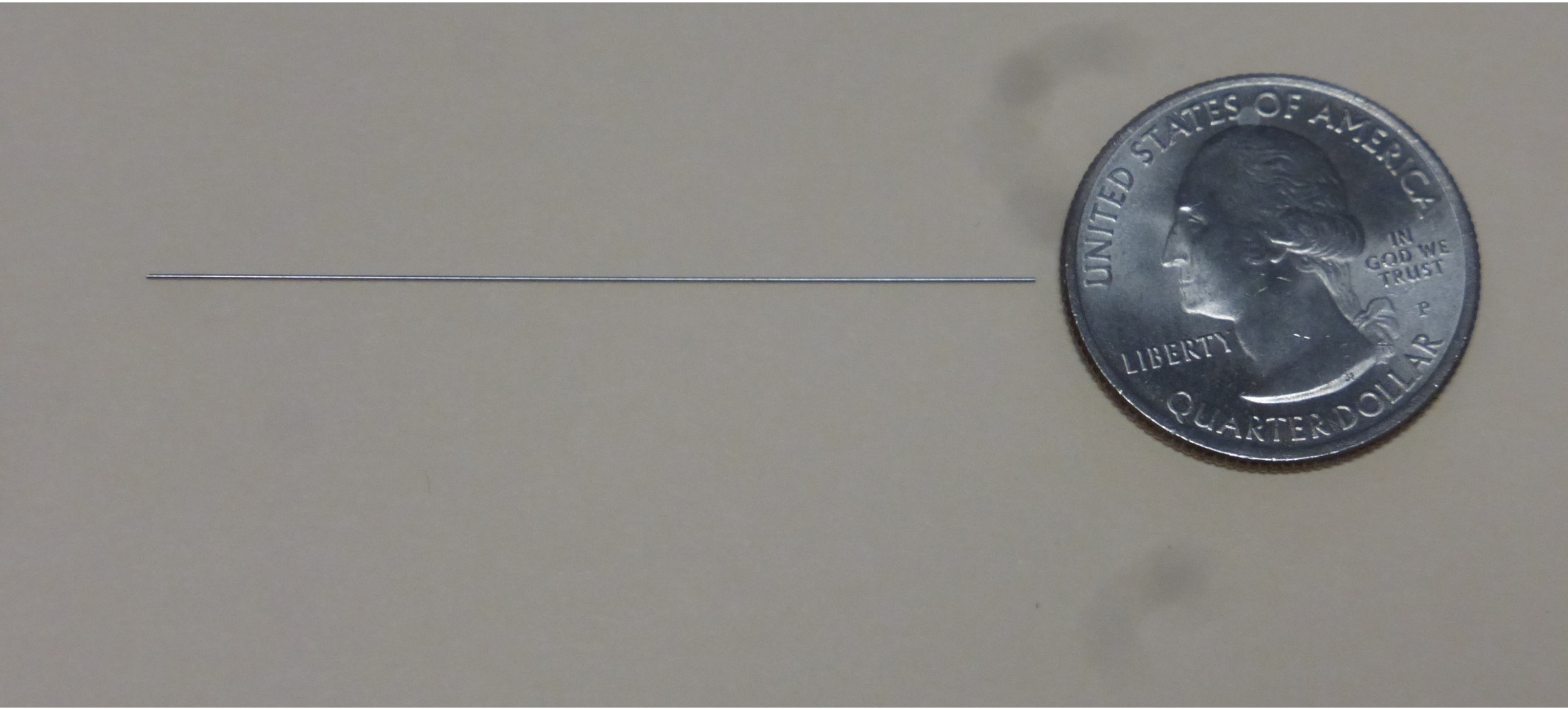
Repeatability Test: 6 IAME's recorded on FOSVS: Outstanding Repeatability.
Allow extraction of arrivals in high noise environment. IAME Energy Released: ~0.1 J = M-3.5





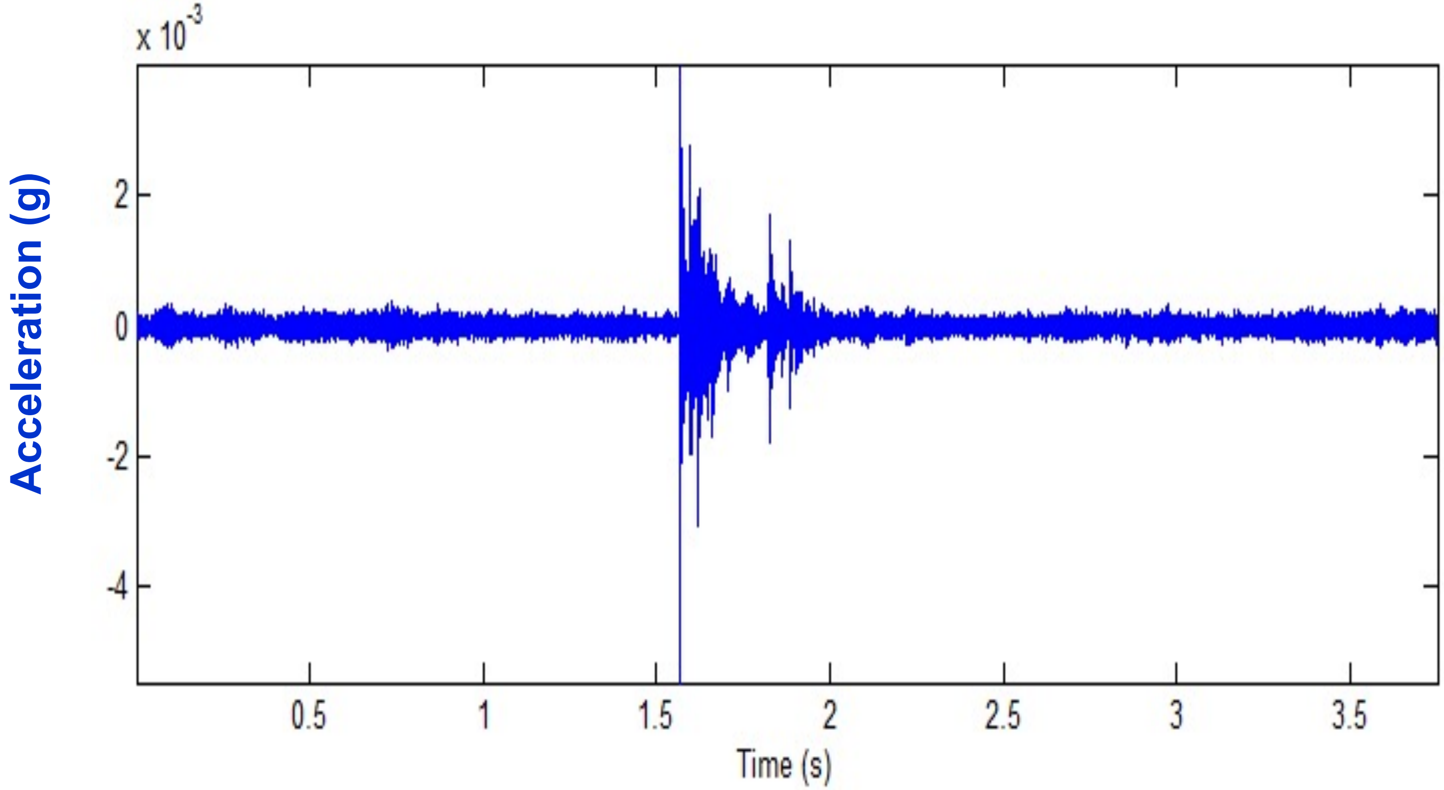


Can You Hear a Pin Drop?
Test Object: OD: 0.011”, 2” long, 24.8 mg



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

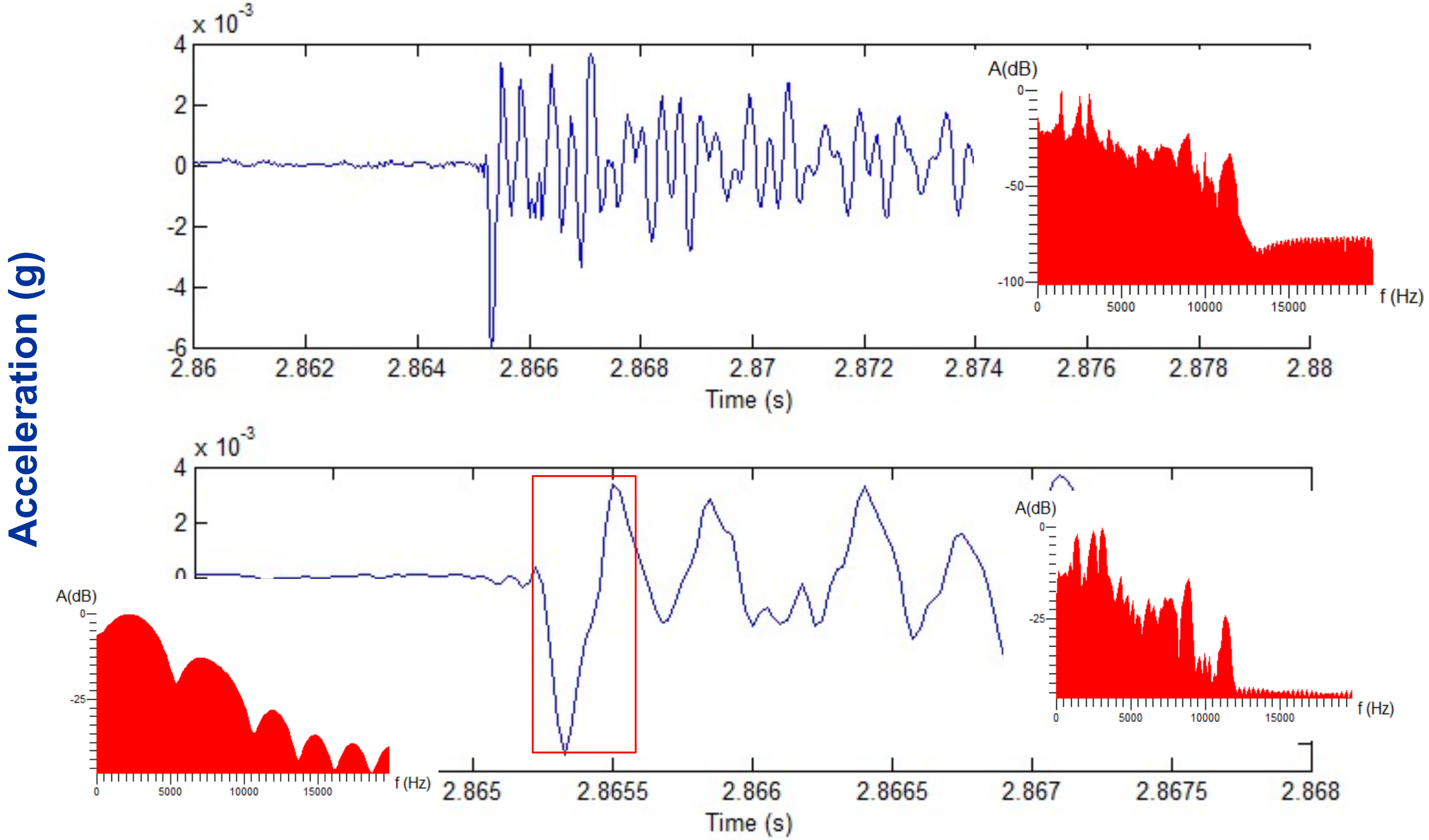
2.5 µJ kinetic energy (M-7) for 1st of 8 hits of Pin



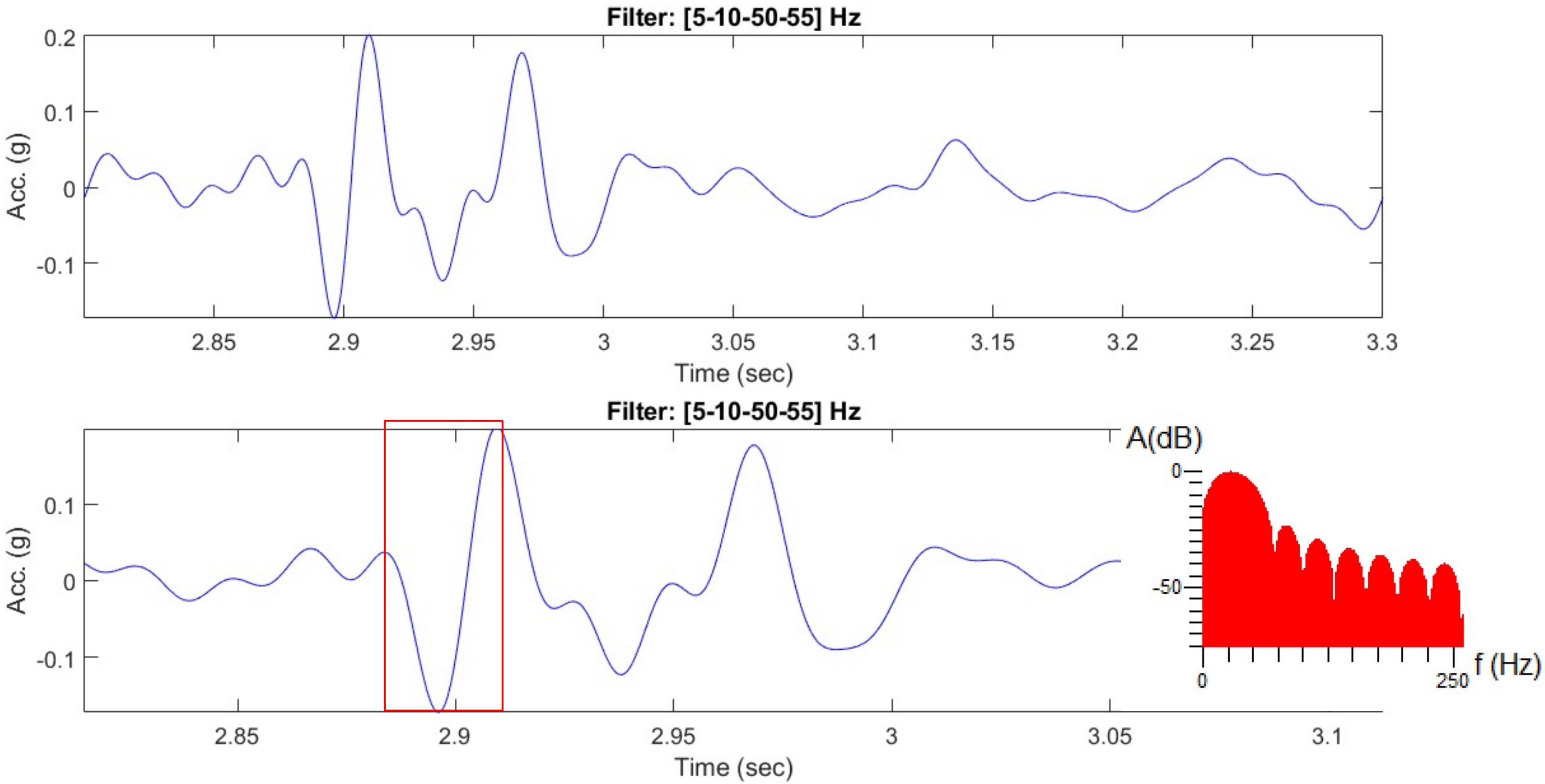
The FOSVS recorded ~17 bounces of the pin = <<M-7

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

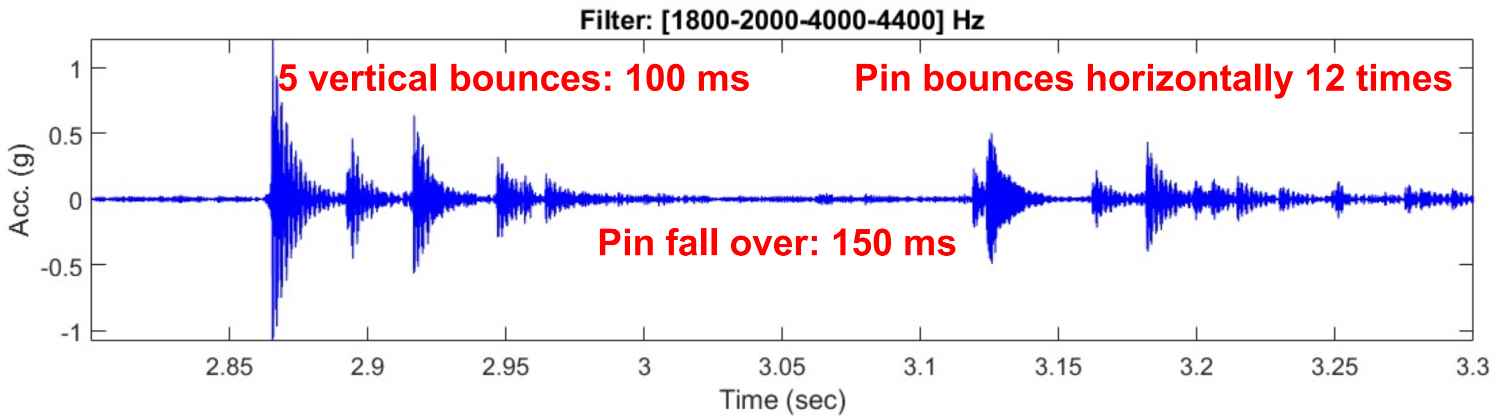
2.5 μJ kinetic energy (M-7) for 1st of 8 hits of Pin

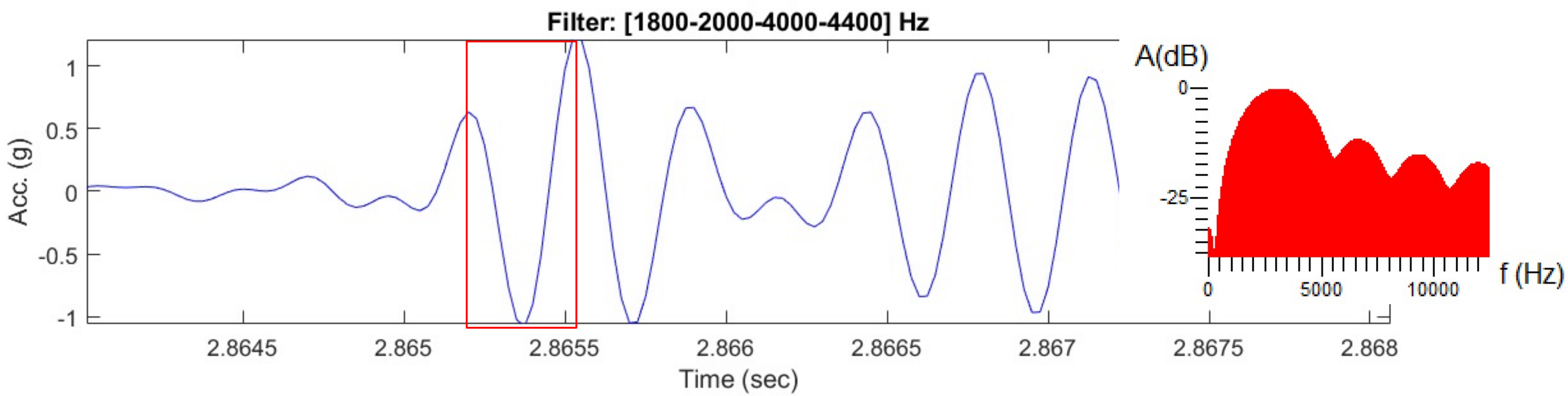


FOSVS Test: OD: 0.011”, 24.8 mg Pin Drop 1 cm: 2.5 µJ kinetic energy (M-7) on primary drop Ormsby Filter: 5-10-50-55 Hz

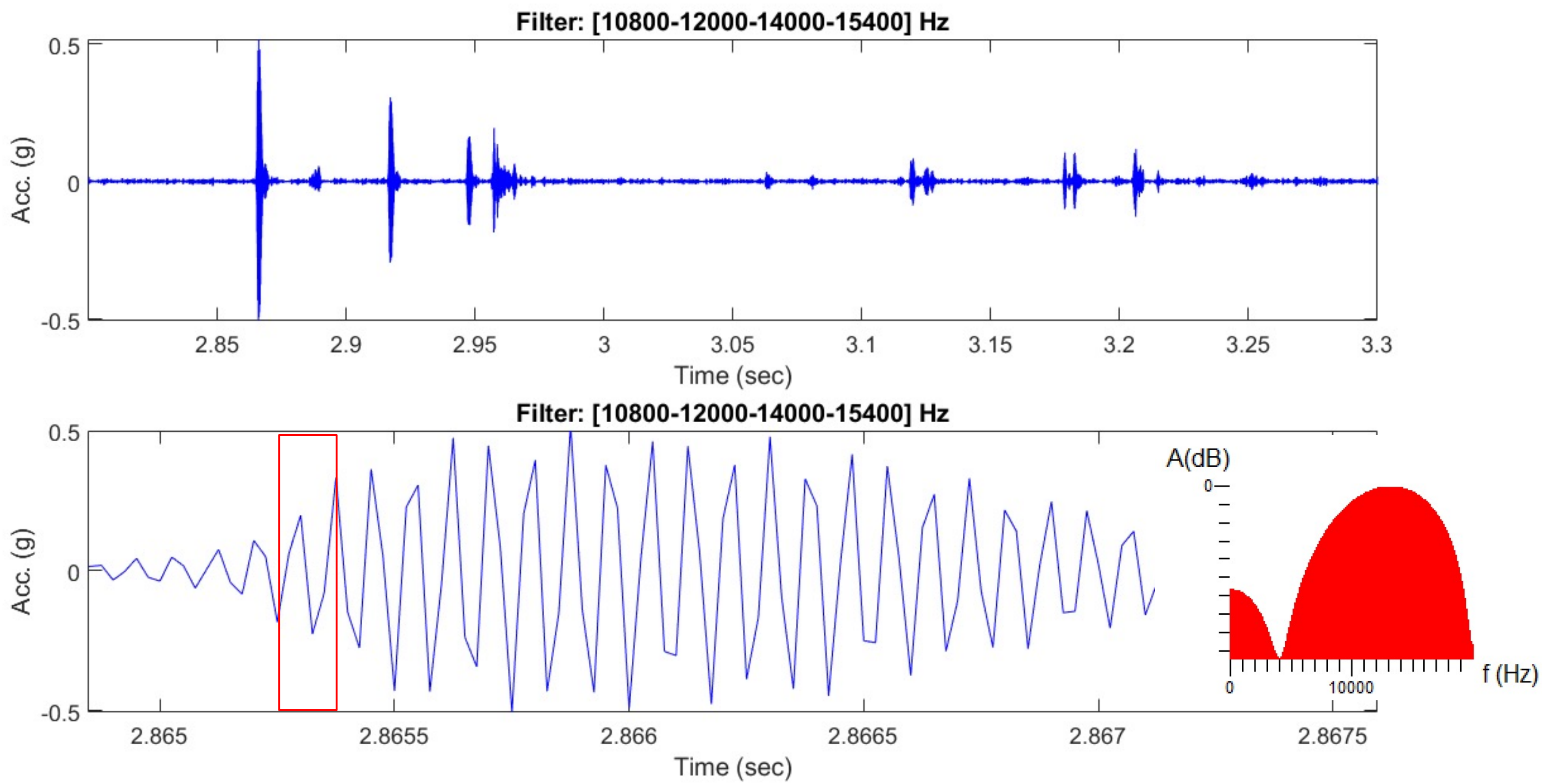


FOSVS Test: OD: 0.011”, 24.8 mg Pin Drop 1 cm: 2.5 µJ kinetic energy (Primary: M-7, Bounces: M-8) Ormsby Filter: 1,800-2,000-4,000-4,400 Hz





FOSVS Test: OD: 0.011", 24.8 mg Pin Drop 1 cm: 2.5 µJ kinetic energy (Primary: M-7, Bounces: M-8) Ormsby Filter: 10,800-12,000-14,000-15,400 Hz



Presentation Outline

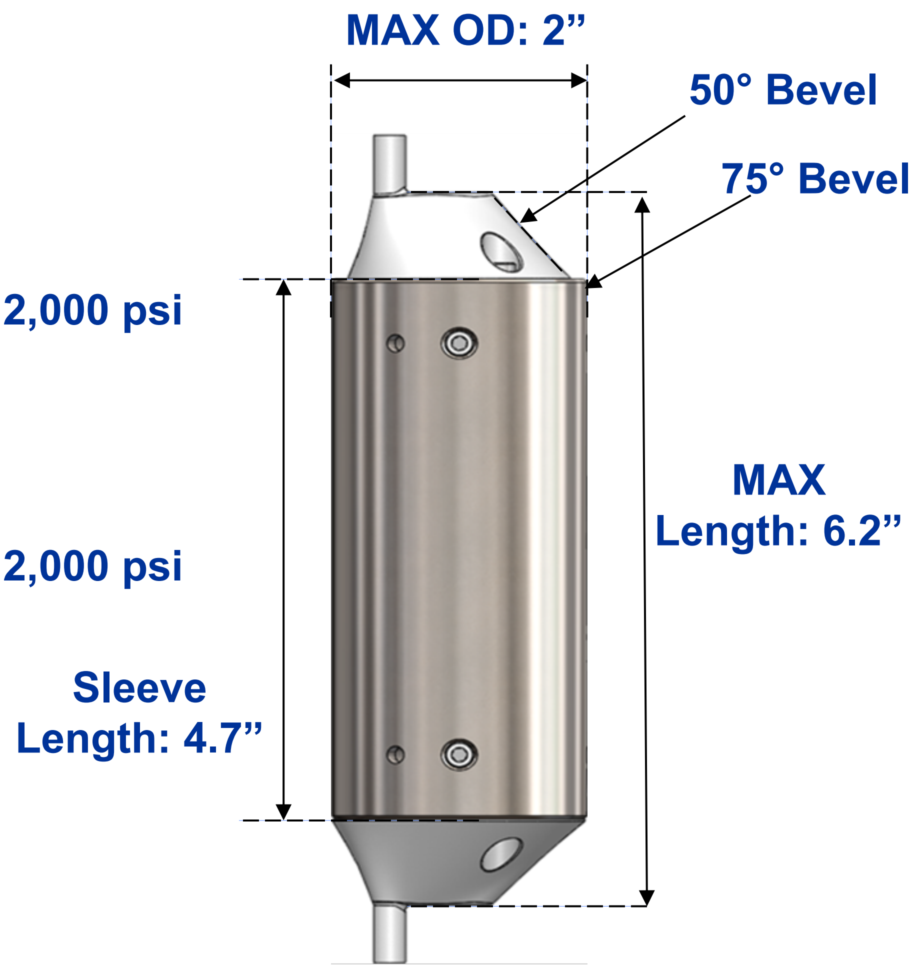
- Optical Sensors
  - Accelerometers
  - Pressure Sensors: DE-SC0020876
- Borehole Vibratory Seismic Sources
- Applications & Examples
- Paulsson Staff and Facility

All-Optical Pressure Sensor – The 2" Tool Mandrel Design of Great Interest to Production, Reservoir, Facilities & Industrial Engineers Working with CCUS, EGS, CEOR, Refineries & Pipelines

Specifications:
- Application: Oil and Gas
- Temperature Range: 0°C – 300°C
- Max Temperature: 324°C

Specifications at 200°C:
- Operational Pressure Range: 1 psi - 12,000 psi
- Survival Pressure: 15,000 psi
- Burst Pressure: 18,000 psi

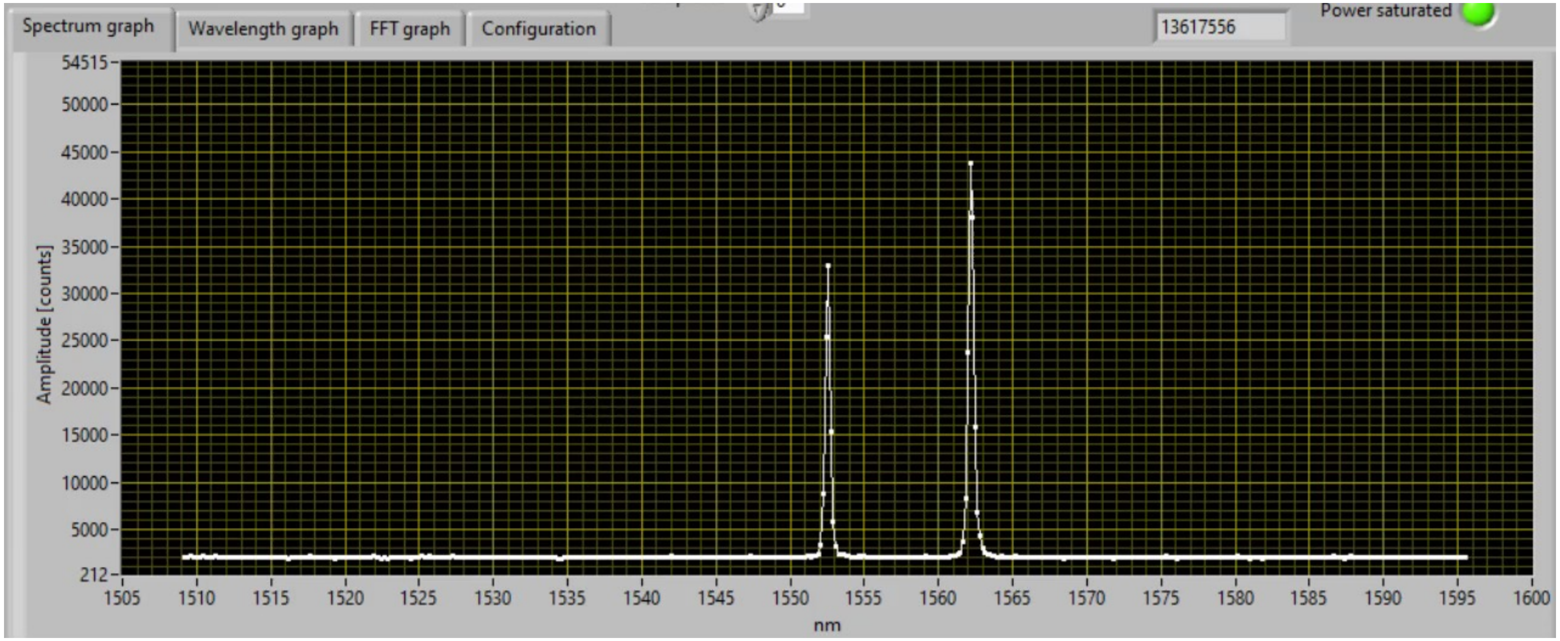
Specifications at 300°C:
- Operational Pressure Range: 1 psi - 12,000 psi
- Survival Pressure: 15,000 psi
- Burst Pressure: 17,000 psi



Pat. Pending

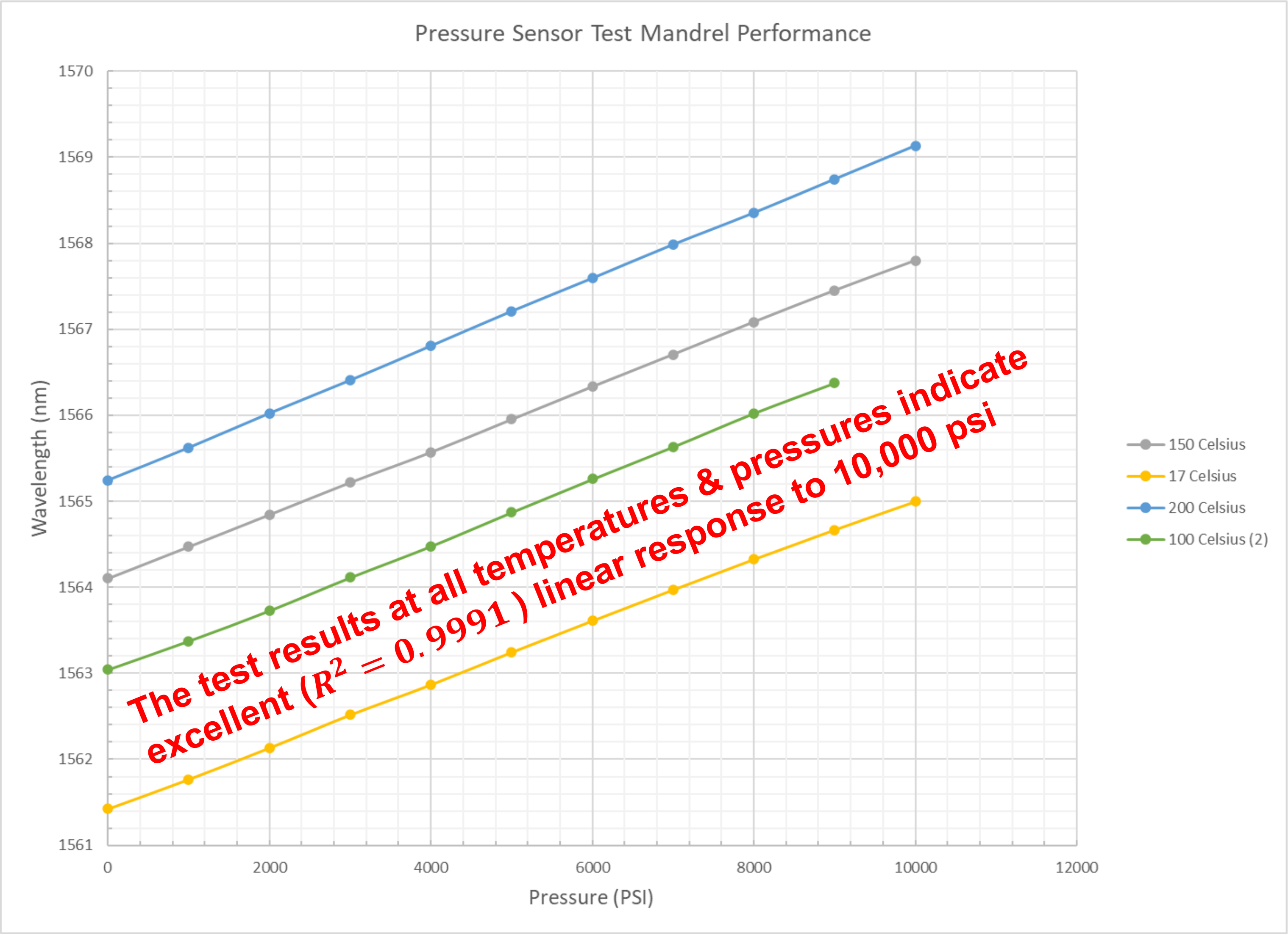
Pressurization Demo of 2” Mandrel

- Pressurize from 0 psi to 10,000 psi, then release pressure
- First response is temperature only
- Second response is pressure on the mandrel



Press play!

Linear Strain=Pressure at Four Different Temperatures

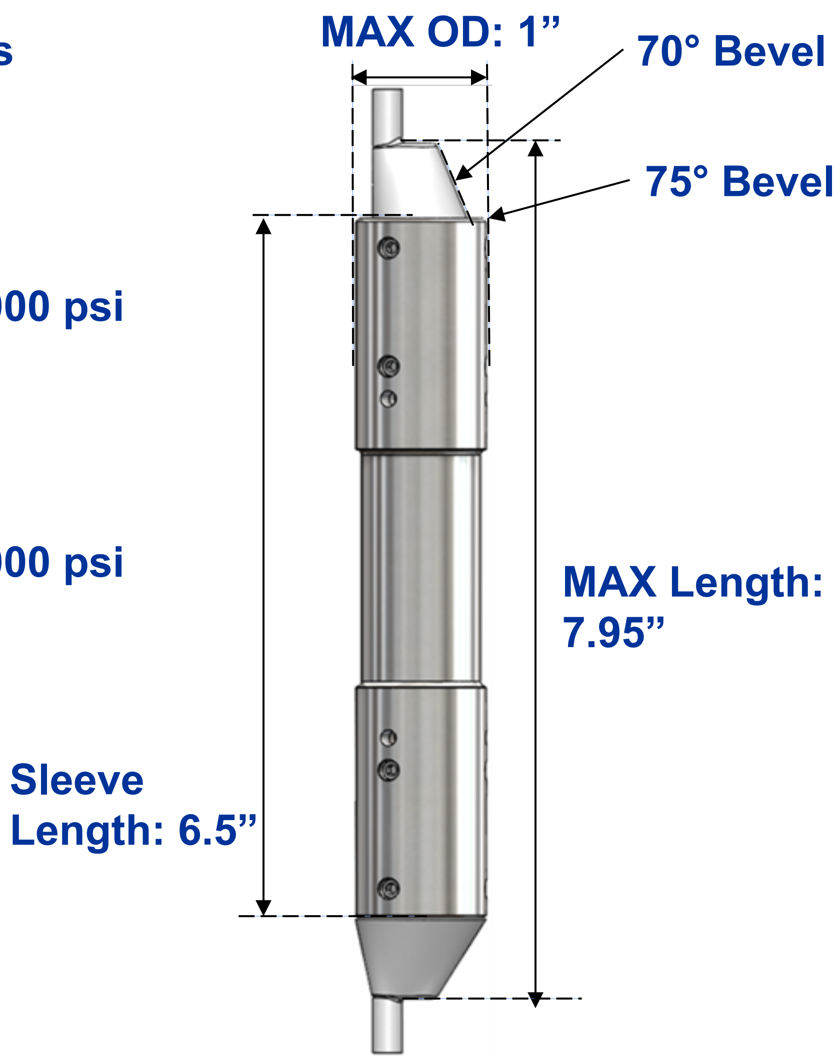


Pressure Sensor – The 1 Inch Tool Mandrel

Overall Specifications:
- Application: Geothermal, UGS, Oil & Gas
- Temperature Range: 0°C – 324°C
- Current Max Temperature: 324°C

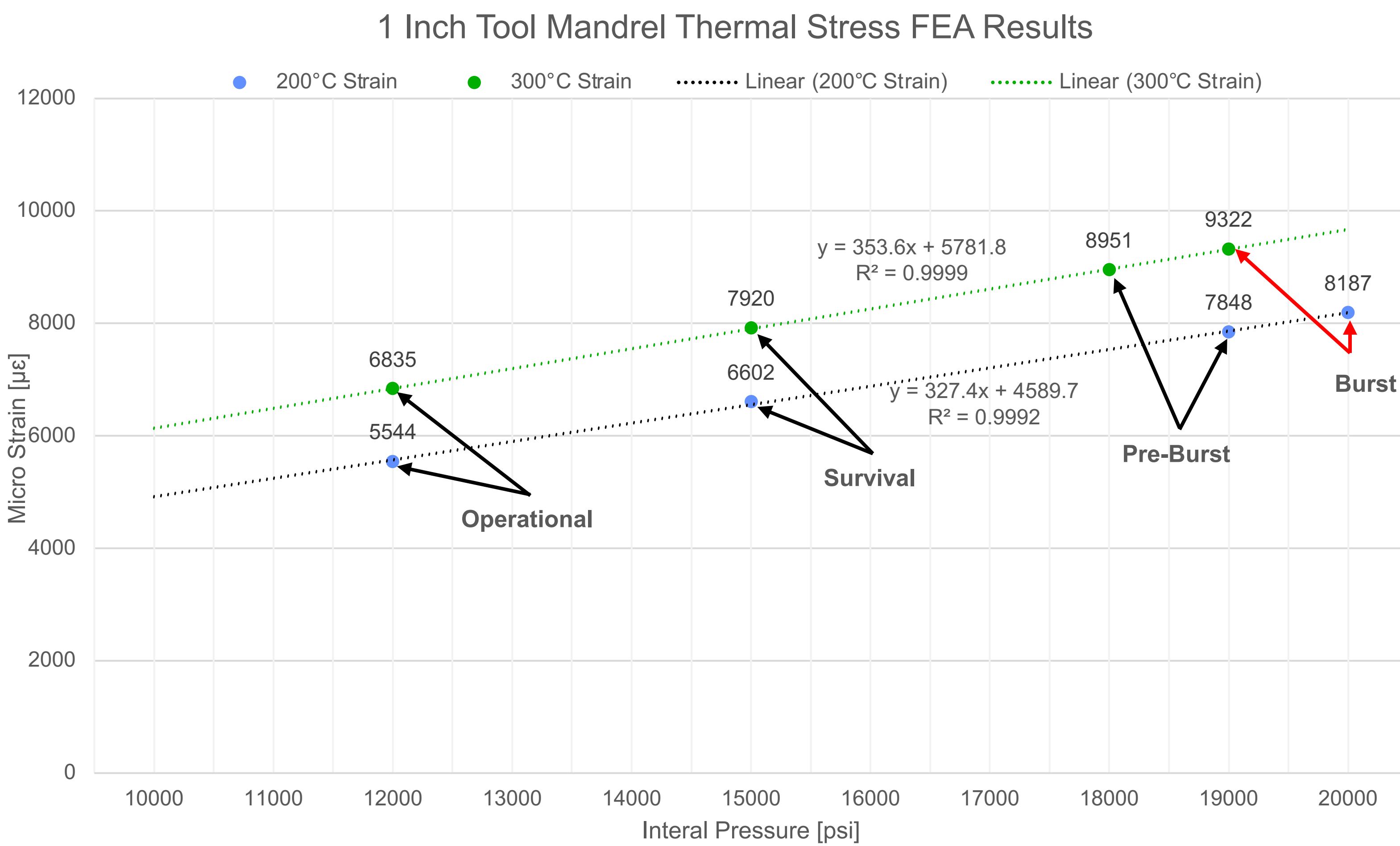
Low Temp Unit: Specifications at 200°C:
- Operational Pressure Range: 1 psi - 12,000 psi
- Survival Pressure: 15,000 psi
- Burst Pressure: 20,000 psi

High Temp Unit: Specifications at 300°C:
- Operational Pressure Range: 1 psi - 12,000 psi
- Survival Pressure: 15,000 psi
- Burst Pressure: 19,000 psi



Pat. Pending

Thermal Stress FEA Results of 1 Inch Tool Mandrel at 200°C



- The strain values resulted in a $R^2 = 0.9992$ to $.9999$, indicating an excellent linear fit!

Pressure Sensor – 1/2 Inch OD – 300°C

Temp Specifications: 300°C - 350°C
- Operational Pressure: 0 - 15,000 psi
- Failure Pressure: 20,000 psi

Major Dimension:
- Max OD: 0.5 Inch
- Main Body Length: 5.6 Inch

Fiber Upgrades:
- Aluminum Coated to increase the temperate range to 400°C
- Gold Coated Fiber Optics to increase the temperate range to 700°C

Pat. Pending

All Optical Pressure Sensor Models by Paulsson, Inc. (PI)

2 Inch OD, All-Inconel, 0-15,000 psi, 300°C Borehole Pressure Sensor

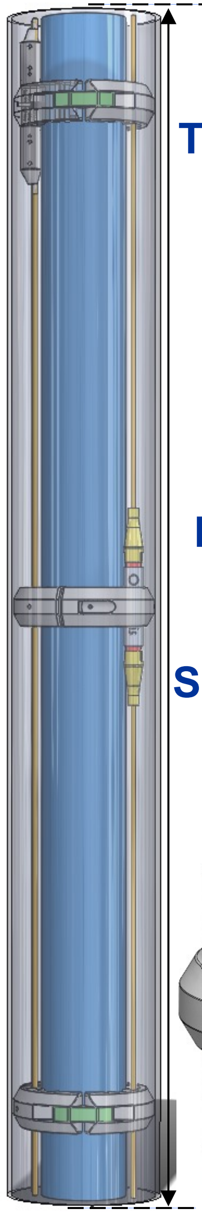
Pat. Pending

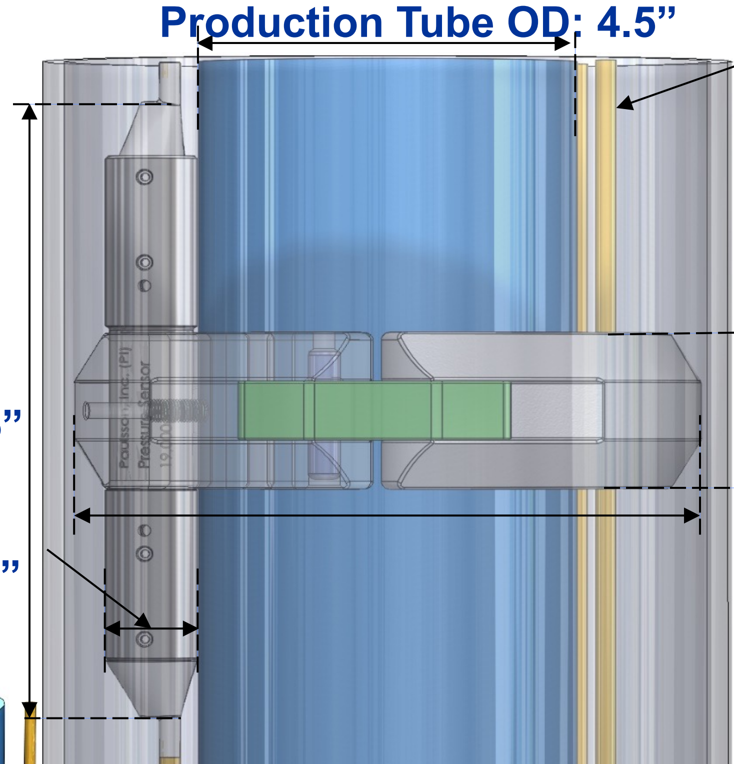
1 Inch OD, All-Inconel, 0-15,000 psi, 300°C Borehole Pressure Sensor

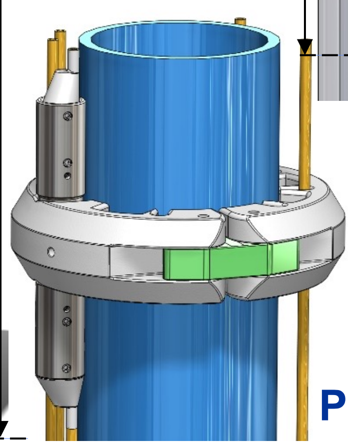
1/2 Inch OD, All-Inconel, 0-15,000 psi, 300°C Borehole Pressure Sensor

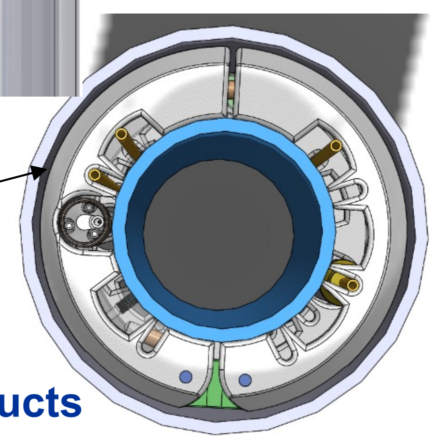
Paulsson, Inc. Exclusive Products

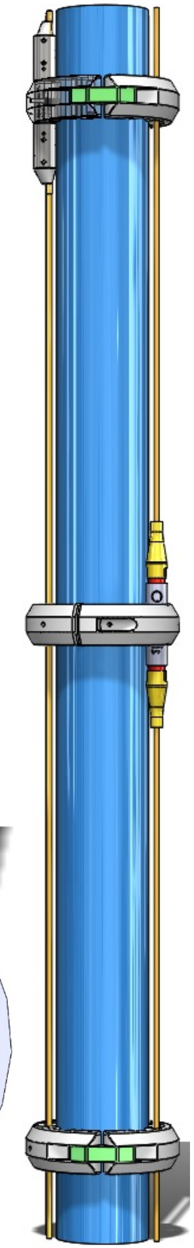
Paulsson, Inc. 1" Pressure Well Sensor with Centralizers and OpticSeis Sensor











Paulsson, Inc. Exclusive Products

Presentation Outline

- Optical Seismic Sensors
- Borehole Seismic Vibrator: DE-SC0018613
  - Controllable & Non-Destructive!
  - High Frequencies: up to 3,200 Hz
  - Better Coupling: 100x an impulsive source
- Applications & Examples
- Paulsson Staff and Facility

Seismic & Sonic Techniques

Frequency Bands and $\lambda/4$ P-wave Resolutions at 10,000 ft/sec:

- **Surface Seismic: 2 – 80 Hz, $\lambda/4$ = 31 ft**
- **3D Vertical Seismic Profiling: 2 – 240 Hz, $\lambda/4$ = 10 ft**
- **Single Well Seismic: 5 Hz – 3,200 Hz, $\lambda/4$ = 0.78 ft (40x)**
- **Sonic Logging: 2,000 Hz – 10,000 Hz, $\lambda/4$ = 0.25 ft**

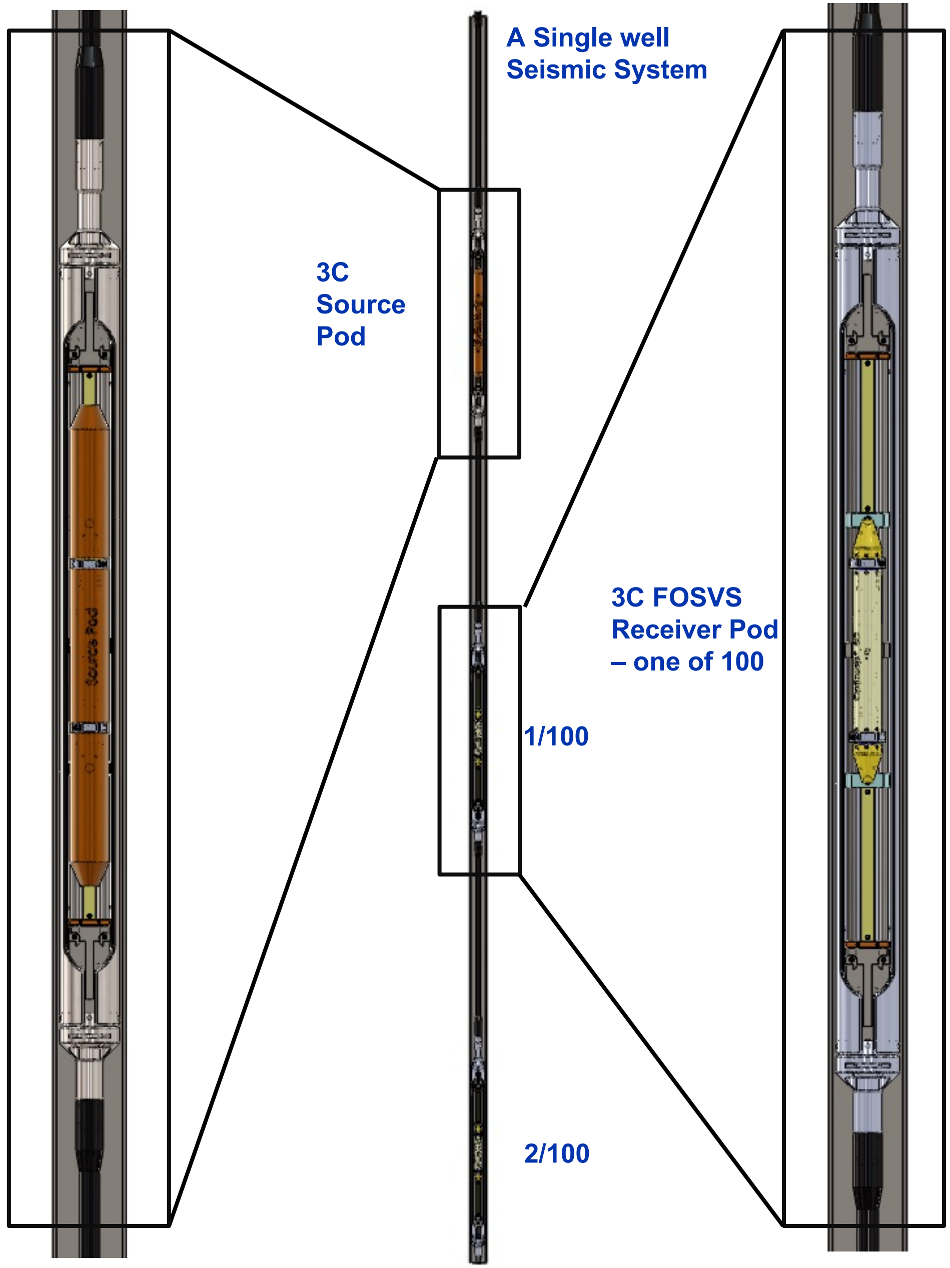
Resolution depends on the wavelength (λ) which is a function of velocity (v) and frequency (f): $v = f * \lambda$; $\lambda = \frac{v}{f}$.

A subsurface layer can be resolved at $\lambda/4$ and detected at $\lambda/20$. With sensors in boreholes, in addition to higher frequencies, we also record S waves, reducing the smallest imaged target by a factor of ~2.

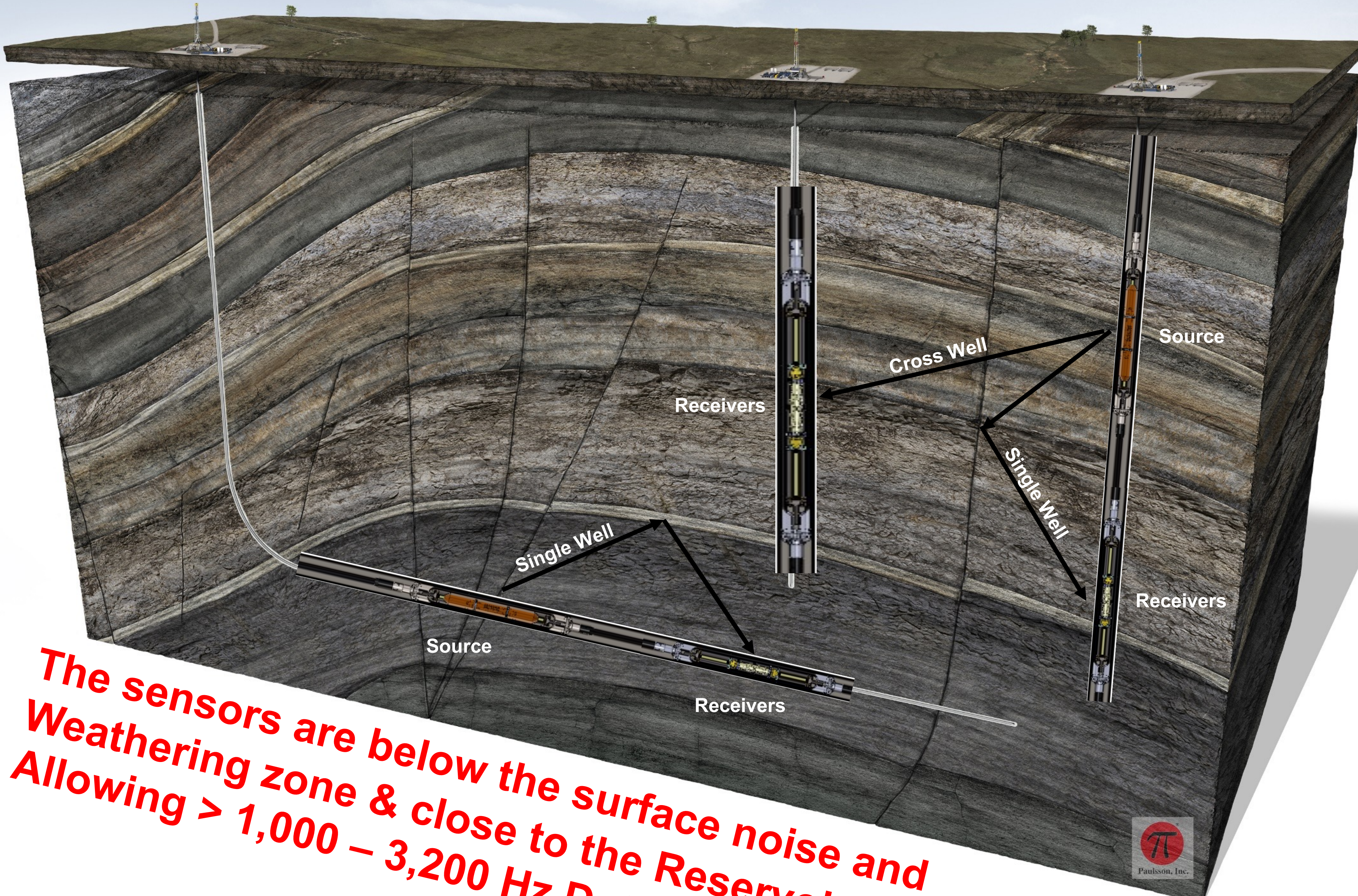
A Single Well Seismic System: Deploying the Source and the Receivers in the same well.

This is NOT a well Logging System – this is a Seismic System with a 10 – 3,200 Hz Operating Frequency.

This system will be able to image to a radius of 1 – 3 km (3,000 – 9,000 ft).

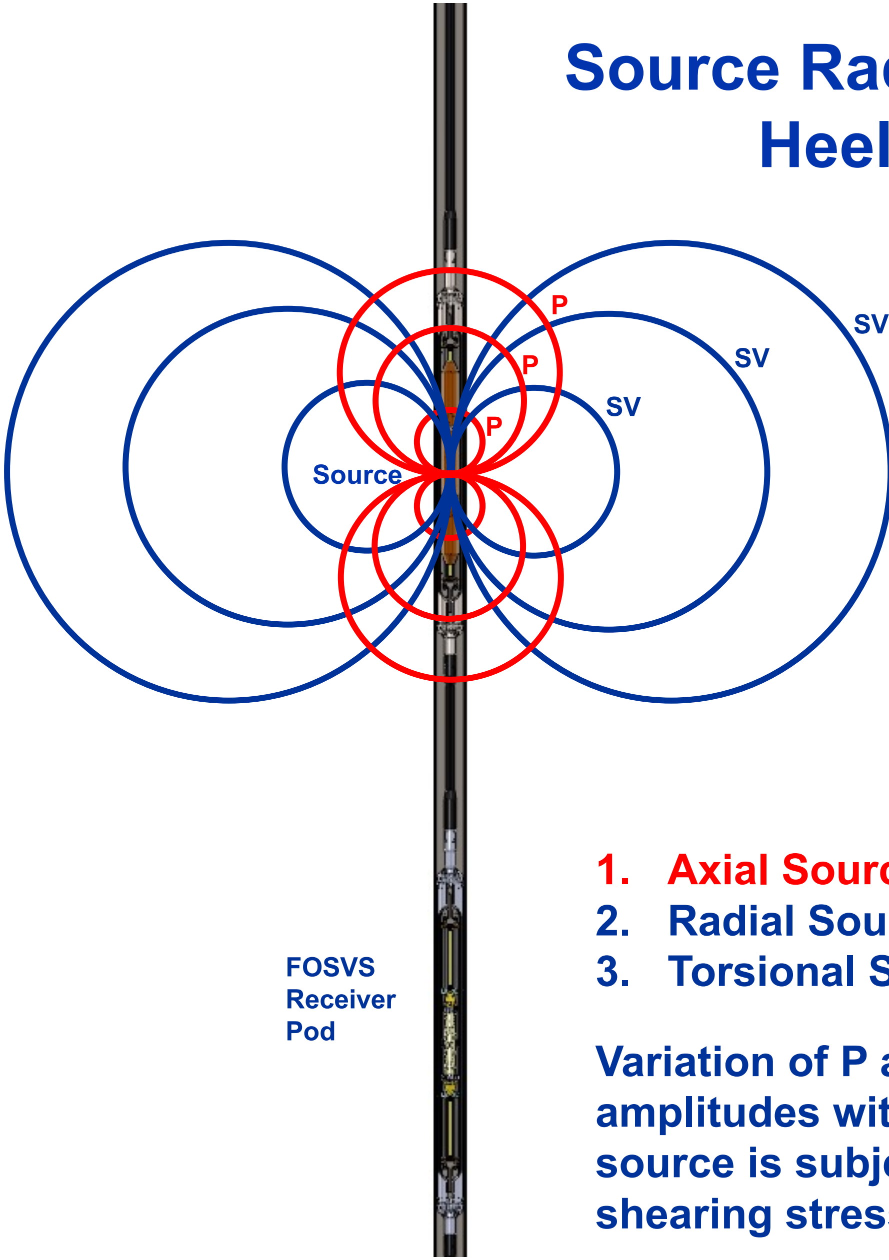


Well Seismic Imaging of Faults and Geology



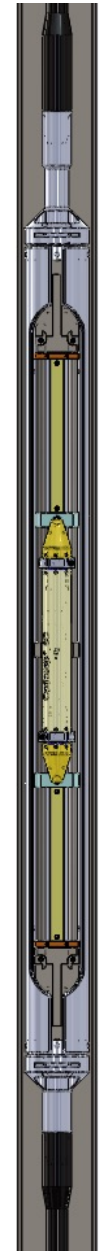
The sensors are below the surface noise and Weathering zone & close to the Reservoirs Allowing > 1,000 – 3,200 Hz Data

Source Radiation Patterns
Heelan (1953)

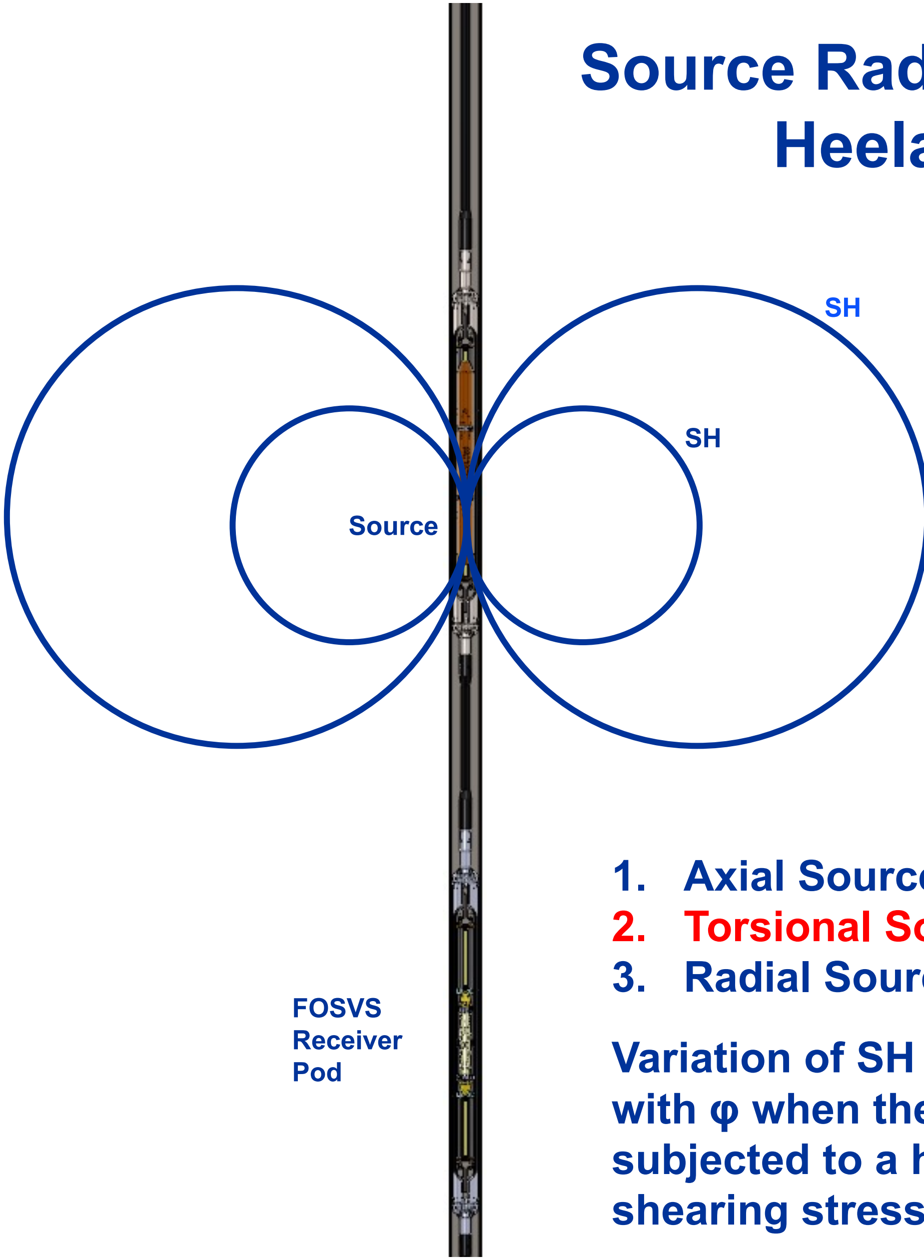


1. **Axial Source**
2. **Radial Source**
3. **Torsional Source**

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

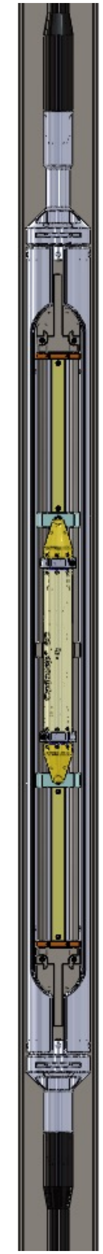


Source Radiation Patterns Heelan (1953)



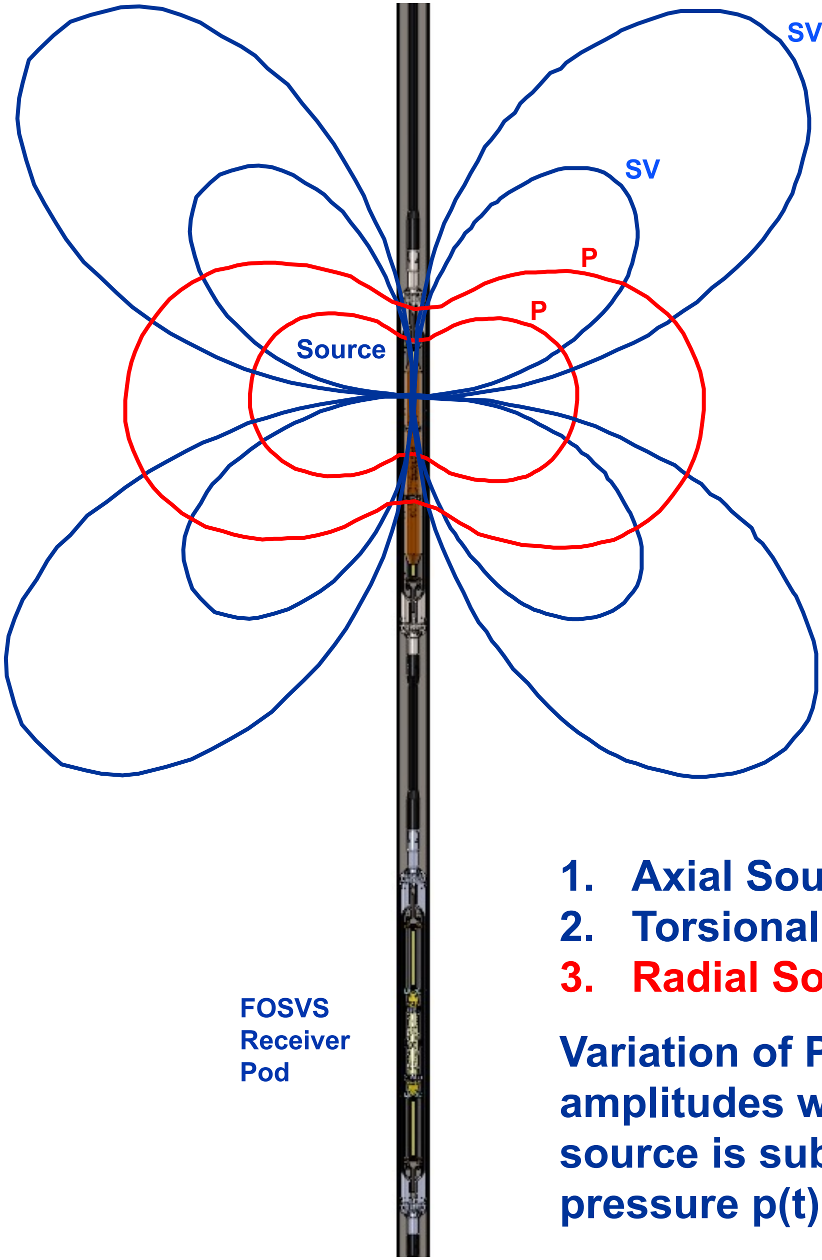
1. Axial Source
2. Torsional Source
3. Radial Source

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



FOSVS
Receiver
Pod

Source Radiation Patterns Heelan (1953)



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

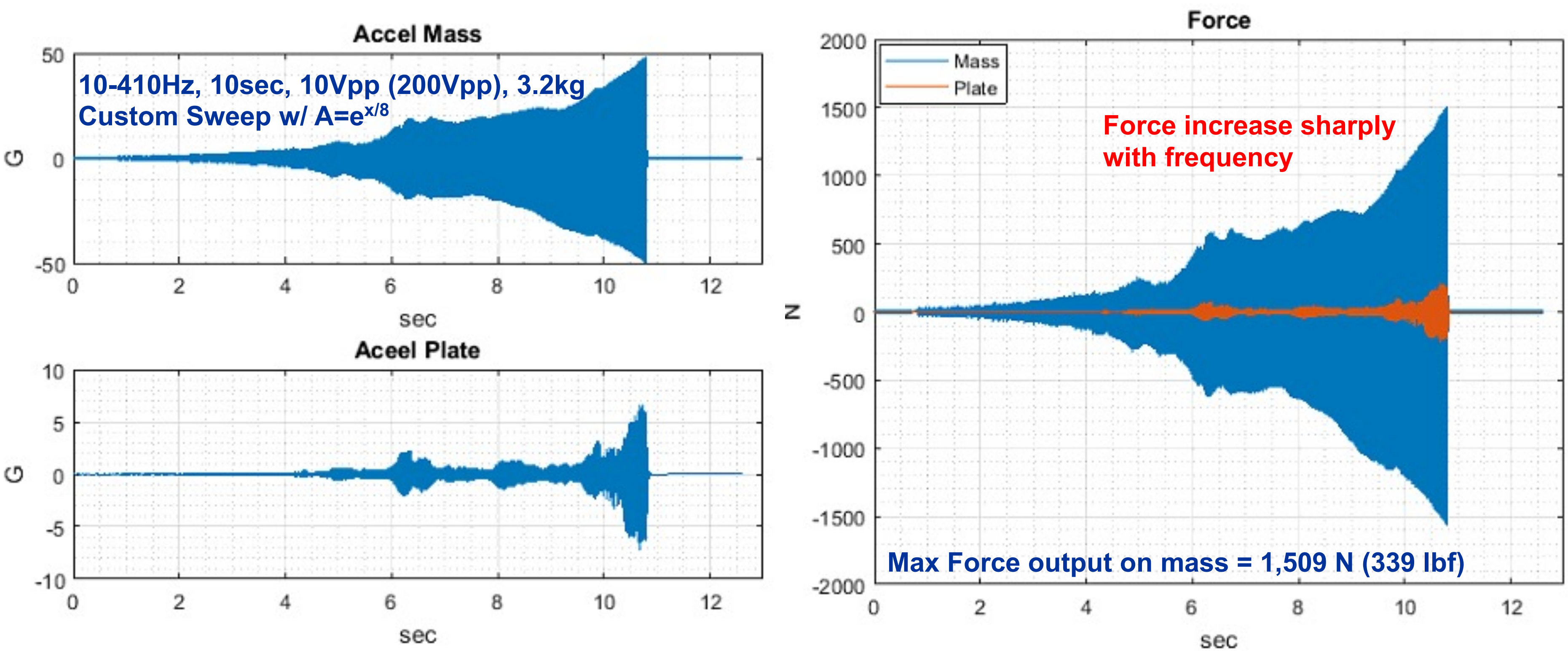
Variation of P and SV amplitudes with φ when the source is subjected to a pressure p(t) only

FOSVS Receiver Pod

Laboratory test of a Downhole Seismic Vibrator

First Laboratory test of a Downhole Seismic Vibrator

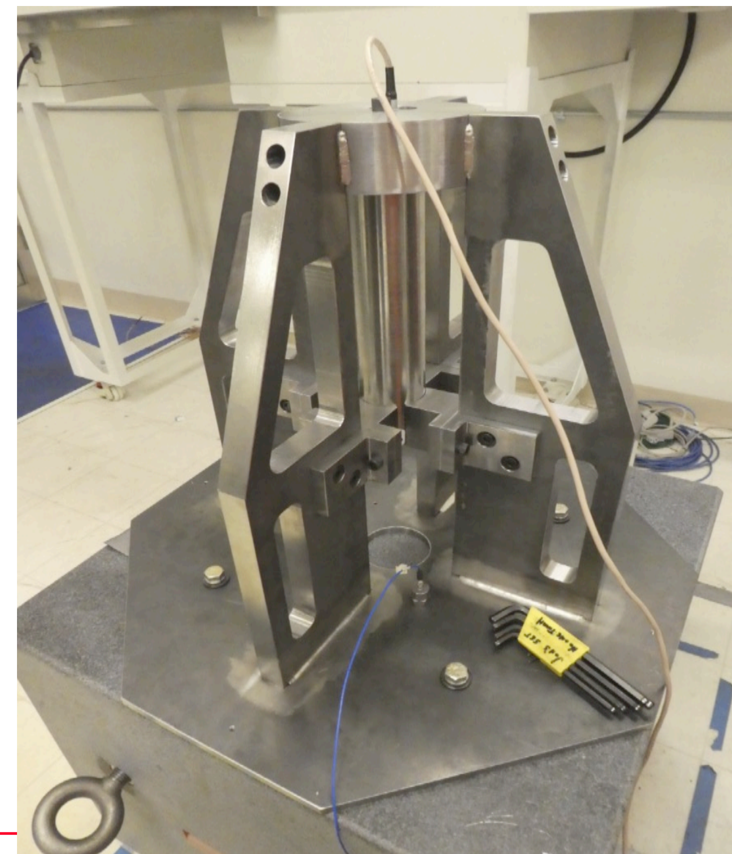
10 – 410 Hz; 10 second sweep



Test Fixture for a Downhole Seismic Vibrator

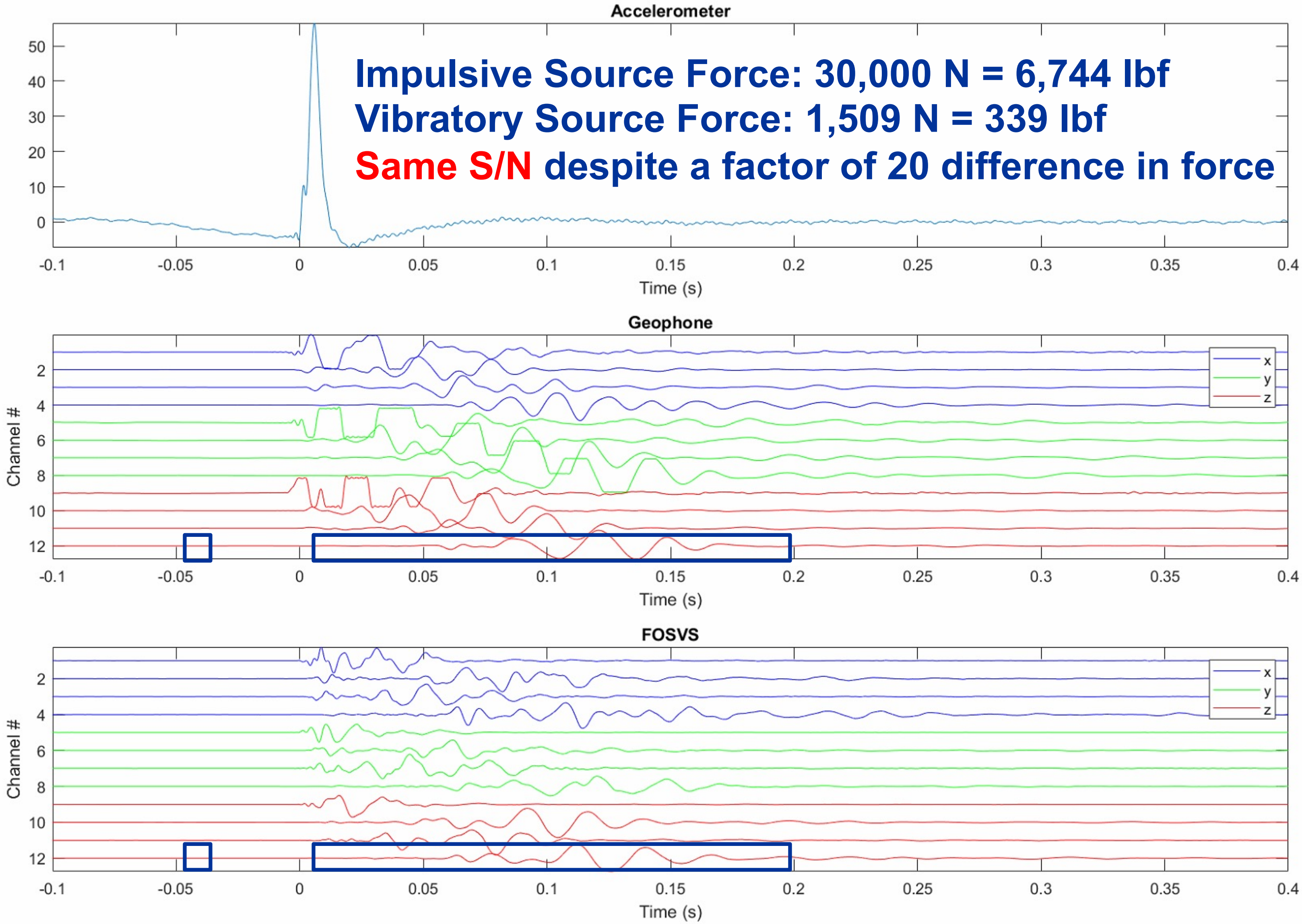
10 – 410 Hz, 10 sec, 10Vpp, 3.2kg

Custom Sweep w/ $A=e^{x/8}$

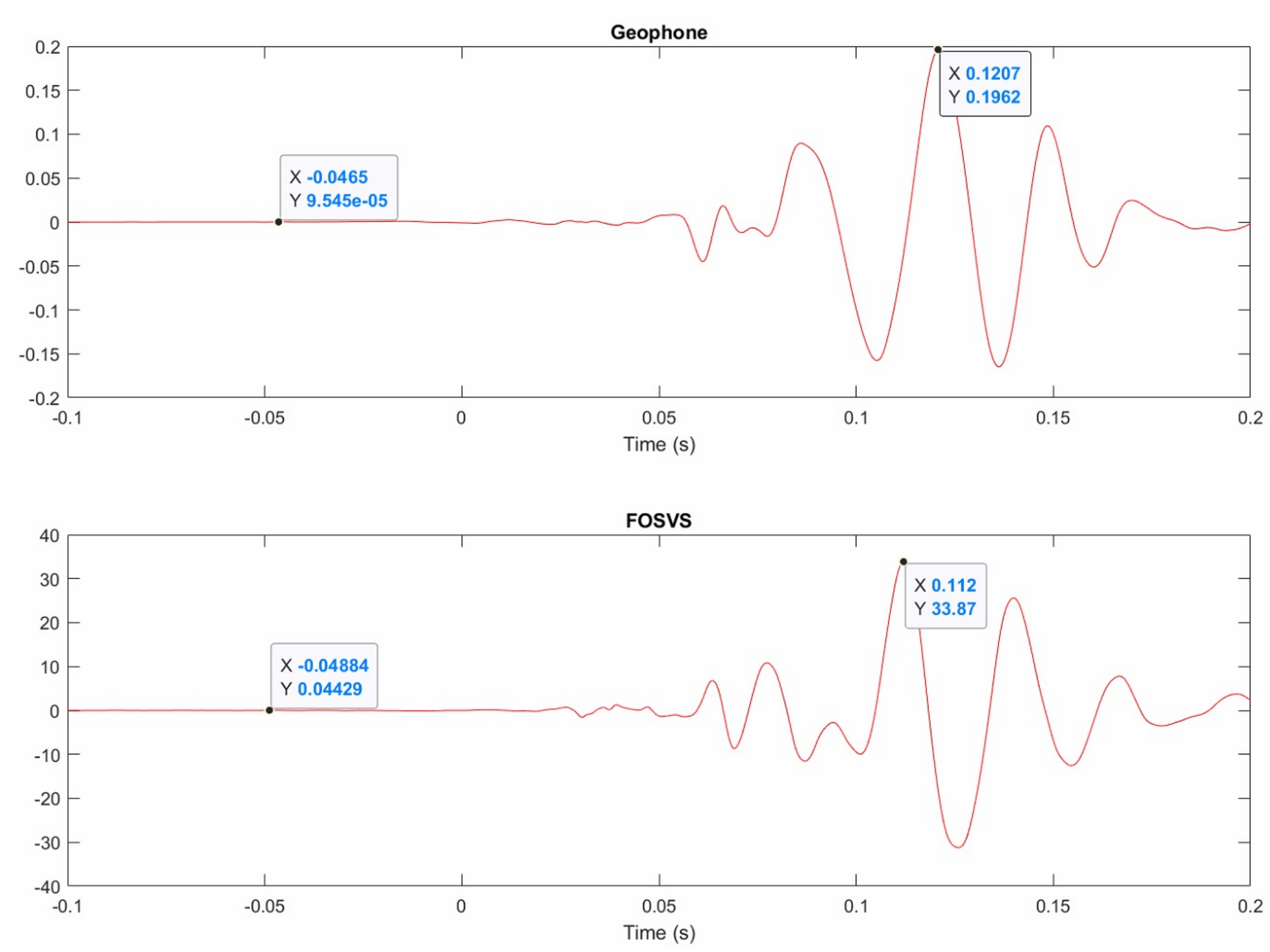


Impulsive Source: 50 kg (110 lbs) @ 60g. Hit Data – Zoomed In

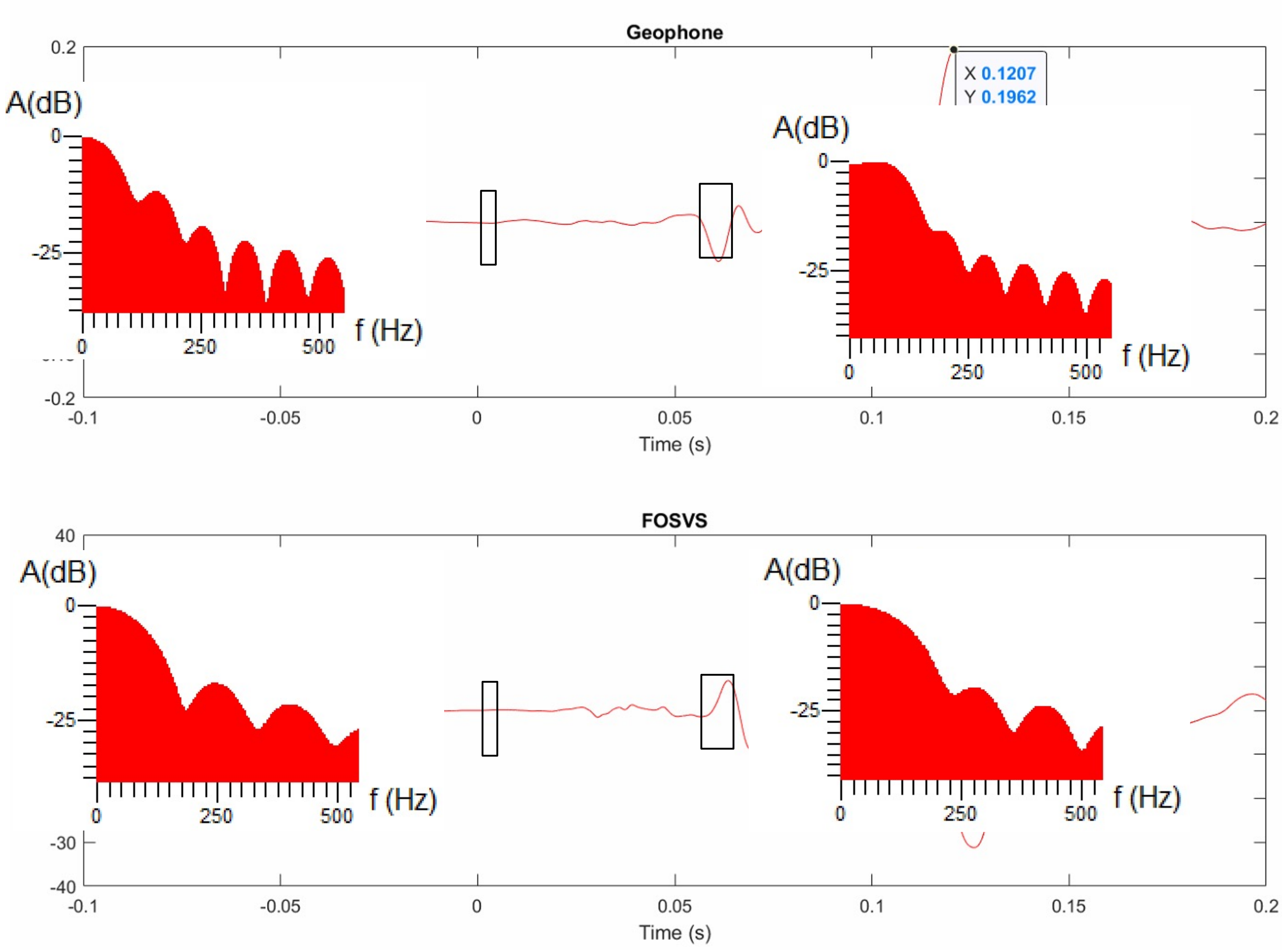
Impulsive Source Force: 30,000 N = 6,744 lbf
Vibratory Source Force: 1,509 N = 339 lbf
Same S/N despite a factor of 20 difference in force



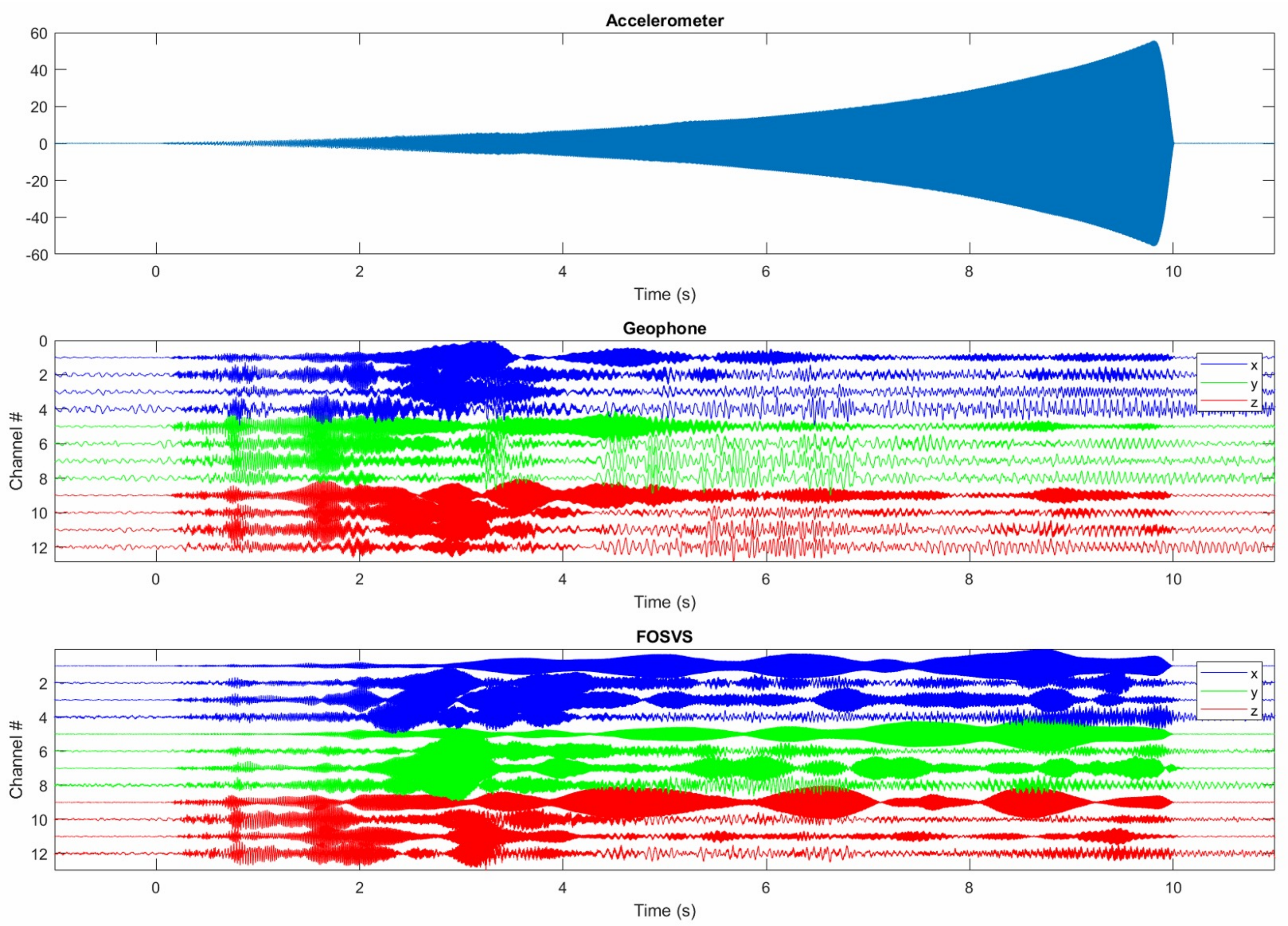
Impulsive Source: 50 kg (110 lbs) @ 60g. Hit Data – Zoomed In



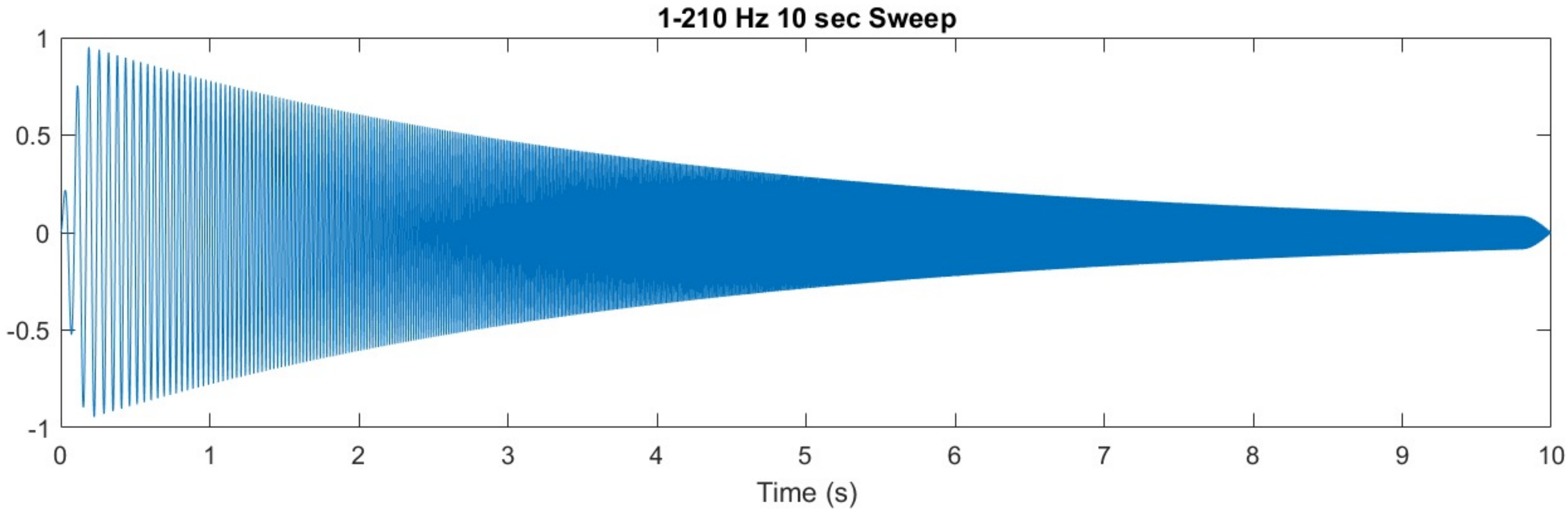
Impulsive Source: 50 kg (110 lbs) @ 60g. Hit Data – Zoomed

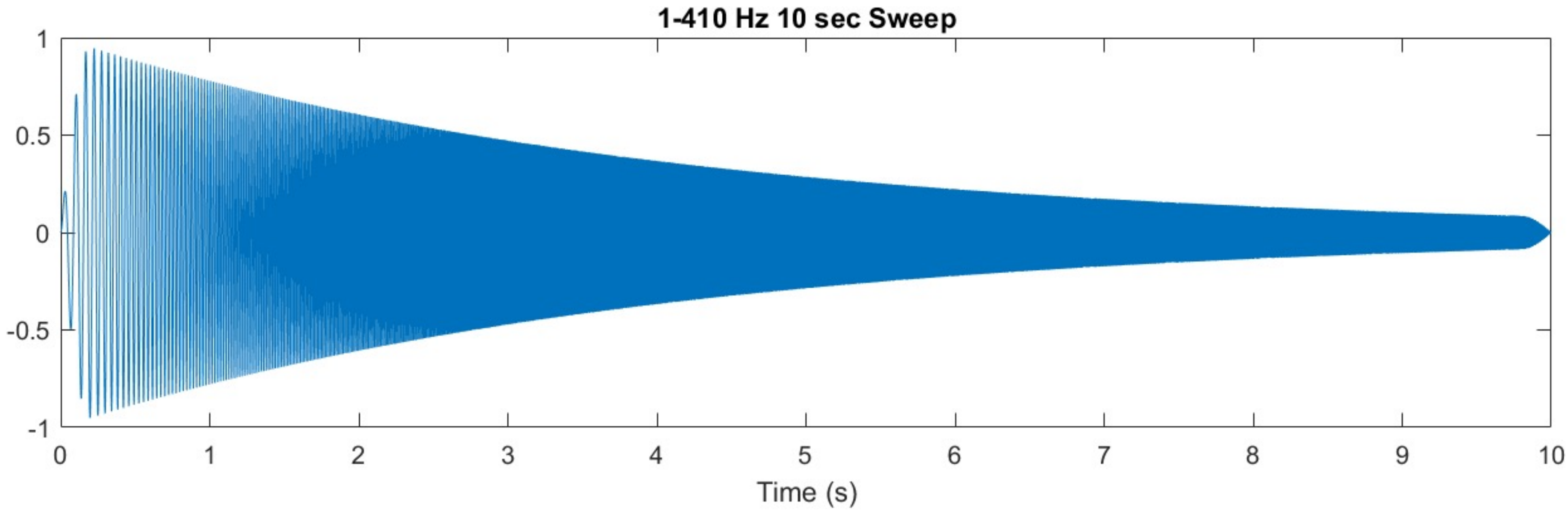


Vibrator Uncorrelated Data: 10-410 Hz, 10 sec sweep, 13.6 Vpp drive

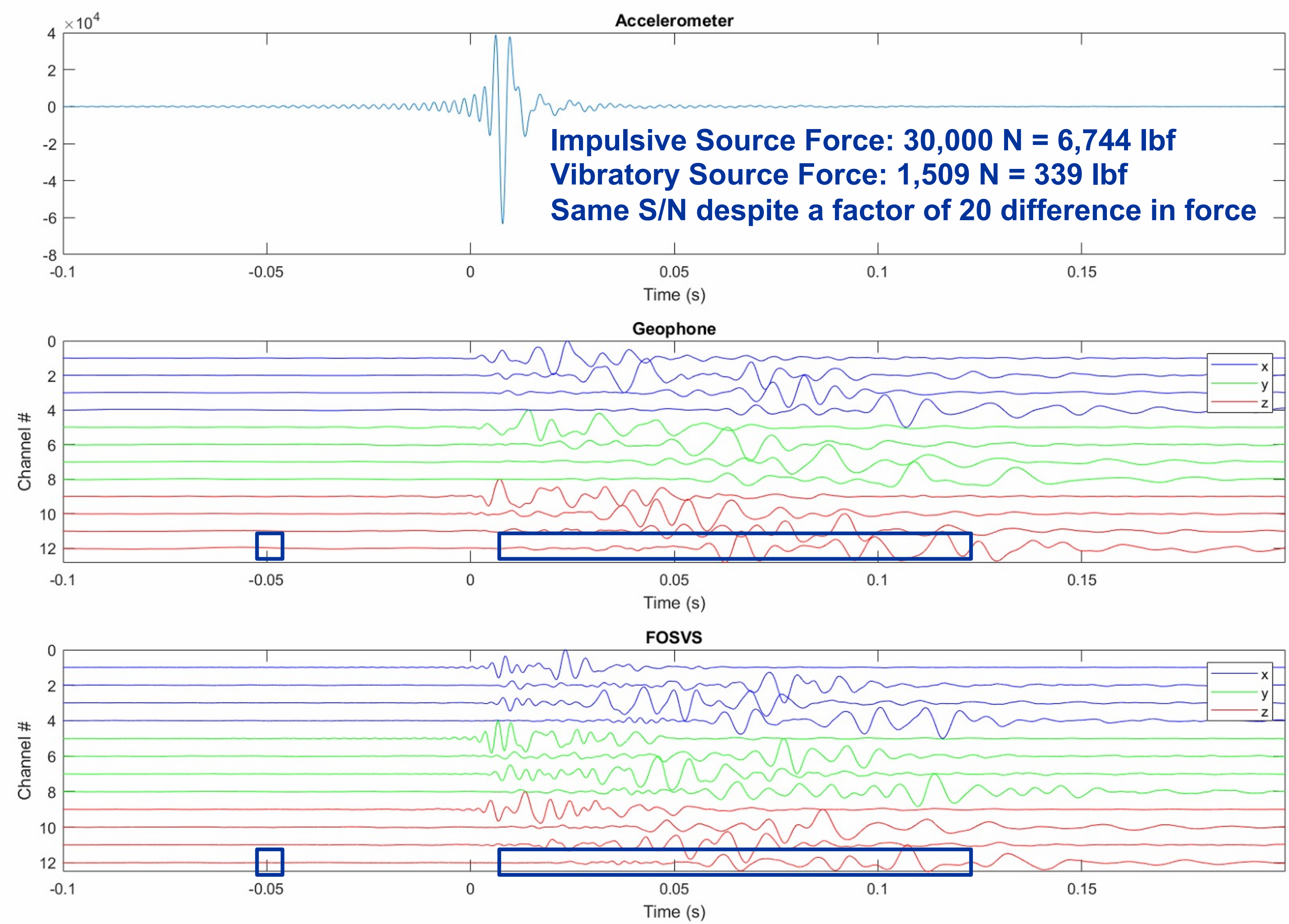


Theoretical 10 Second Sweeps used for Correlation - Case 4

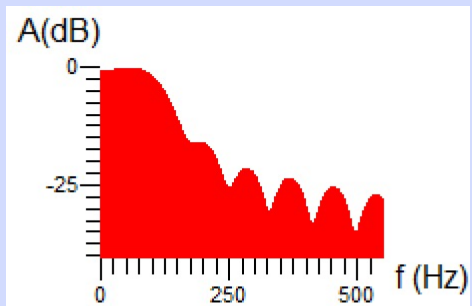
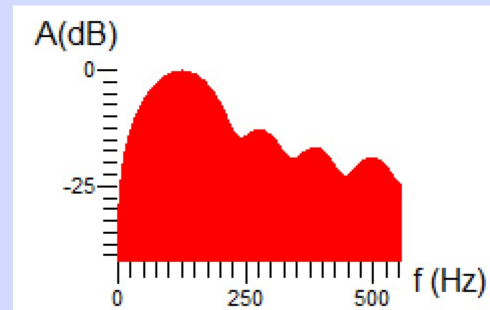
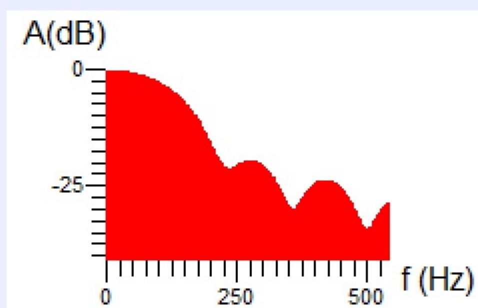
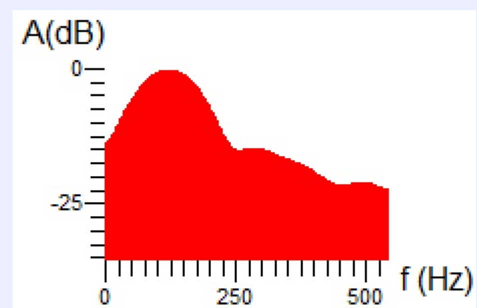




Vibrator Correlated Data: 10-410 Hz, 10 sec, 13.6 Vpp - Case 4

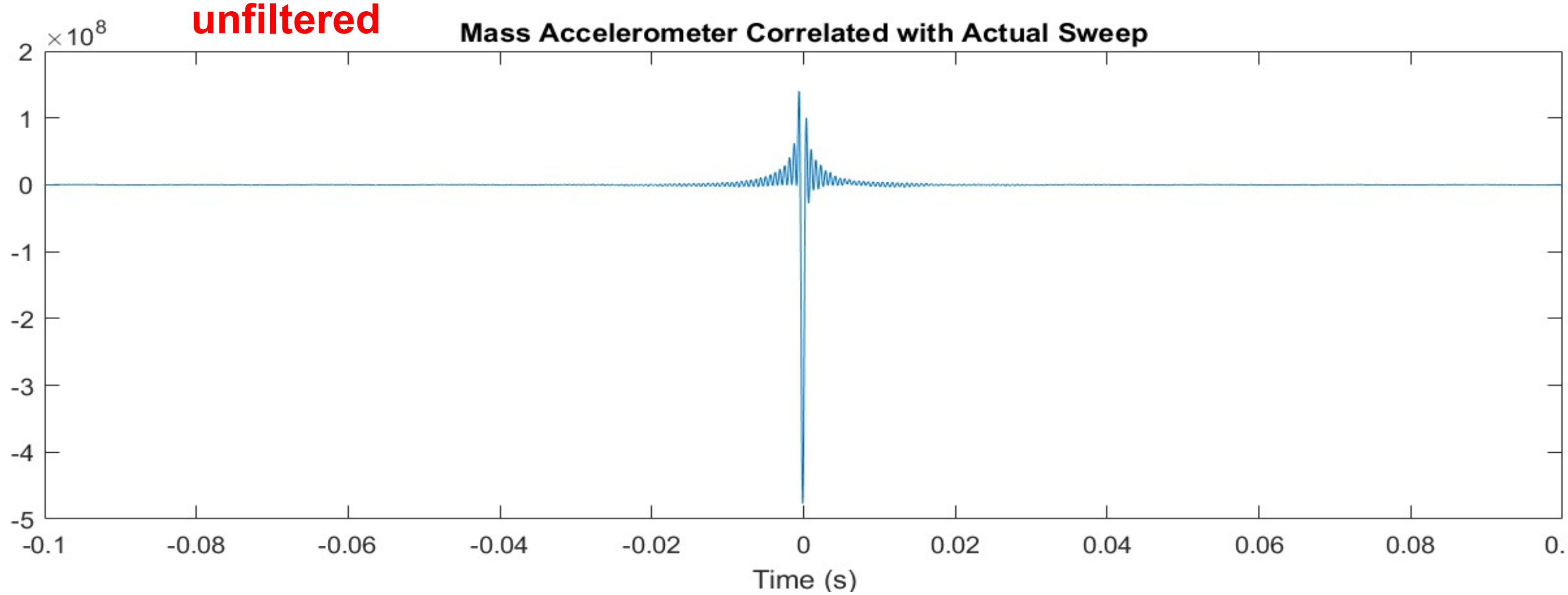


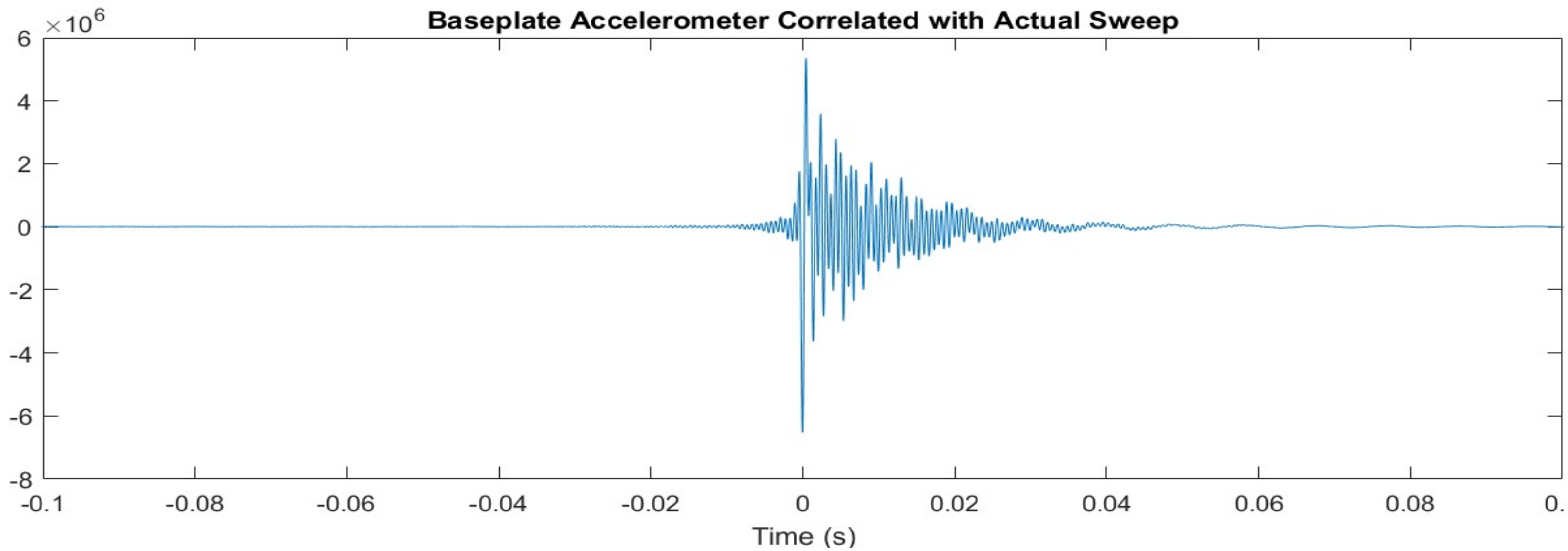
S-wave Spectra of Impulsive and Vibratory Sources

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

Correlated Data: 10-1,610 Hz, 10 sec sweep, 5 Vpp drive

unfiltered





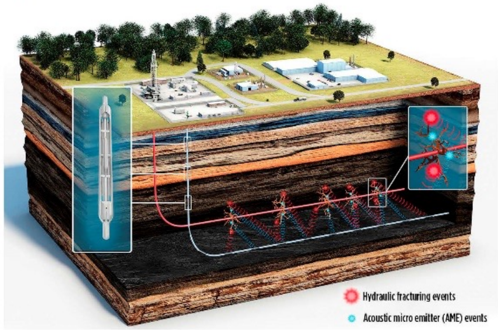
Article in World Oil, March 2021

Improving fracture performance through information collection and evaluation

The U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL) is actively pursuing, through funding and in-house research, a number of research and development projects that would contribute to enhanced fracture characterization through digital information gathering and processing. The aim of these projects is to better understand both natural and produced fractures, and to evaluate their ability to enhance production and ultimate recovery. The dialogue below discusses one of these projects that is funded by NETL.

■ JARED CIFERNO, NETL and BJÖRN PAULSSON, Paulsson, Inc.

Fig. 1. Effective and accurate monitoring of unconventional oil and gas.



DEVELOPMENT OF AN OPTICAL-BASED SINGLE-WELL SEISMIC SYSTEM (OSWS)

In the U.S., very large unconventional oil and gas (UOG) resources are found in shale deposits. According to a 2018 estimate in the *Annual Energy Outlook 2020* by the Energy Information Administration (EIA), the volume of technically recoverable gas from gas shale is 2,829 Tcf—enough for 92 years of consumption at the 2018 level of 31 Tcf. EIA also estimates that in 2018, the U.S. possessed 44 Bbbl of technically recoverable shale oil.

However, production of these shale gas and oil resources is often very inefficient, with UOG oil recovery rates reported as being as low as 5% to 8%. Thus, a tremendous additional resource is available at known locations, if an improved recovery can be designed and implemented. The first step in this process is to generate better images that will lead to an improved understanding of these complex reservoirs.

The lack of a detailed understanding of the reservoir and production processes is currently creating a significant environmental impact that can be lessened while improving the economics of gas resource extraction. This can be accomplished by mapping the natural fractures in greater detail than what is possible today. It also can by accomplished by monitoring—at much greater resolution than is possible with today's surface-based imaging technologies—the induced hydraulic fracturing and proppant distribution in the fractures, as well as the subsequent production.

It has been shown that seismology, using surface seismic sources and receivers, is technically able to image geology in 3D, albeit in low resolution, and monitor the production process using seismic data from surface seismic vibratory sources (VibroSeis). Thus, it is the resolution that is currently lacking.

It is well-established that if large volumes of high-quality borehole seismic vector data are recorded in vertical and horizontal boreholes, drilled to and into shale gas and oil reservoirs, the data can be used to image and monitor the reservoirs in 3D/4D, in higher resolution. Using borehole seismic receivers to record the data will improve the resolution by 2 to 4 times over the resolution provided by the surface seismic sources and receivers, since the seismic data only need to penetrate the near-surface attenuating formation once.

If the surface layer is avoided altogether by placing both the sources and the receivers in boreholes, then further improvement in the resolution, by a factor of 10–20X, is possible. This will lead to a step change in producers' understanding of the oil and gas extraction process that is only possible by applying large arrays of advanced seismic mapping and monitoring technologies recording a full suite of high-quality seismic data.

Propriet

TARGETED IMPACT

The project's approach, under the direction of William Fincham at NETL, to improve the UOG production process is to design, develop, and laboratory- and field-test, a more sensitive and more effective high- temperature seismic imaging and monitoring system, Fig. 1. Paulsson designs and builds fully operational prototype vector borehole seismic sources, which are engineered for deployment with seismic vector receivers in the same well.

Their single-well seismic system will detect very small changes in fracture properties and orientation; volumetric stress; pore pressure; fluid conductivity and types; proppant distribution; fluids; and saturation. The system also will be able to monitor and map passive seismic data from fracturing or fluid flow, as well as data from surface seismic sources. Vibratory seismic sources are preferred, since they couple non-destructive high-frequency signals much more effectively into the survey formation than impulsive sources.

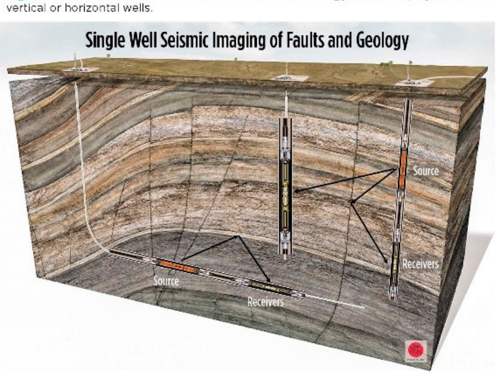
The new borehole seismic system will allow deployment in both vertical and horizontal wells, Fig. 2. This is not possible with commercial systems today without using expensive and fragile well tractors for the deployment.

The new single-well seismic source-receiver system will have a bandwidth from 5 to 3,200 Hz, using active vibratory seismic vector sources, which will provide for much broader bandwidth data than available from any existing commercial or research seismic system. The receivers also will record microseismic data, extending the useful bandwidth to at least 8,000 Hz. The new all optical-based vector sensor system will be about 100 times more sensitive than geophone-based seismic systems.

The new system will deploy sensors with an 80-dB rejection of out-of-plane seismic energy, allowing for a precise location of reflections and microseismic events. The Fiber Optic Seismic Vector Sensor (FOSVS) system also will allow for source and receiver deployment in deeper wells, at higher pressures and temperatures than what is possible today. In combination, the new fiber optic-based seismic sensor and downhole seismic sources will record far-superior multi-component high-fidelity data, allowing for superior imaging, detection and location of all seismic events.

The downhole source and receiver system will also integrate Injectable Acoustic Micro Emitters (IAME) by Terves LLC into the overall seismic system. The development of IAMEs, together with the means to record the high-frequency seismic data that the IAMEs generate, will, for the first time, provide operators of UOG resources with a proppant tracking technology that potentially allows operators to calibrate and tune the hydro-fracturing, proppant injection and oil production processes. In turn, this significantly increases the recovery of the hydrocarbon resources.

Fig. 2. Paulsson's new source and receiver seismic technology can be employed in either vertical or horizontal wells.



ACCOMPLISHMENTS

Under this project, the Principal Investigator (PI) is developing a broad-bandwidth downhole seismic vibratory source that will be combined with existing FOSVS. The new source is designed to be clamped to the inside of the borehole wall, and generate and couple non-destructive seismic energy in three modes—Axial, Torsional and Radial—into the geologic formation. The three source motions will generate complimentary seismic wavefields, enabling the combination of 3C seismic sources with 3C optical accelerometers, thereby generating 9C seismic data. Together, the source and the receivers will be able to image vertical faults and salt domes, and monitor reservoir changes that are invisible to surface seismic techniques.

- The PI and TdVib (a partner in the project) are currently designing the full-scale, fully operational prototype of the downhole axial seismic vibrator. They expect that this prototype will be completed in Mid 2021 and undergo significant laboratory testing in Mid to late 2021.
- The PI and TdVib performed extensive modeling of several options for the downhole vibrator, leading to an understanding of the optimal size of the reaction mass and Terfenol actuator pre-load. The following parameters will be used going forward:
  - o Force Output: 10,000 N (2,500 lbf)
  - o Frequency band: (5 -3,200 Hz)
  - o Terfenol-D Rod diameter: 1.25 in.
  - o Terfenol-D Rod length: 6 in.
  - o Accelerated mass: 20 kg
- The PI performed a small field test, using the prototype Terfenol vibrator source and a small array of both 3C geophones and 3C FOSVS. The data recorded demonstrated that the energy from the Terfenol vibratory source with a force output of 1,509 N (339 lbf) can be coupled into the ground efficiently. The correlated signal-to-noise ratio from the vibratory 1,509 N (339 lbf) Terfenol seismic source matched the signal-to-noise ratio of a 50,000-N (11,240 lbf) impact source.
- The PI and TdVib successfully completed a laboratory bench-scale

test of the Downhole Vibratory Seismic Source (DVSS) prototype in conjunction with the FOSVS and

generating a controllable, peak non-destructive force in excess of 10,000 N (2,500 lbf).

number of projects either conducted internally by, or funded by, NETL. For more details on this, and related, projects, visit the ...te at www.netl.doe.gov. WO

...r: *"This project was funded by ...ent of Energy, National Energy ...Laboratory an agency of the ... Government, through a sup-... Neither the United States Gov-... any agency thereof, nor any of ... nor the support contractor, nor ...mployees, makes any warranty, ...plied, or assumes any legal li-...onsibility for the accuracy, com-... usefulness of any information, ...roduct, or process disclosed, or ...t its use would not infringe pri-... rights. Reference herein to any ...ercial product, process, or ser-...name, trademark, manufactur-...e does not necessarily constitute ...ndorsement, recommendation, ...y the United States Govern-...agency thereof. The views and ...uthors expressed herein do not ...te or reflect those of the United ...ment or any agency thereof."*

...NO is technology manager for ...ergy Technology Laboratory ...J.S. DOE, with oversight for ... gas, hydrates and midstream ...perience encompasses a broad ...chnology areas, including fossil ...wer generation; advanced gas ...esses; coal conversion processes; ...del simulation and techno-...ems analysis. Prior to joining ...no served as a research engineer ...on Corporation in Pittsburgh, Pa., ...esponsible for developing new ...rocesses related to advanced ... environmental technologies ...r, including activated carbon, ...y, oxidation technologies (UV and ...l) and ion exchange. Mr. Ciferno ... and MS degrees in chemical ...m the University of Pittsburgh.

...SON is CEO and President at ...d Paulsson, Inc (PI), having ... in 2009. He has worked with ...ology since 1977. Mr. Paulsson has ...50 papers in the field of borehole ... has invented and designed ...nt borehole seismic instruments ...00-level downhole tubing ...ray (1997) and the downhole ...34). Mr. Paulsson formed ... 2009 to continue his work in ...hole seismology. PI specializes ...smology for reservoir and site ... and monitoring. Mr. Paulsson ... seismology and rock mechanics ... of California, Berkeley, in ...orked at Chevron Oil Field ...pany 1984 to 1997, culminating ...or research geophysicist. He ...n Geophysical Services in 1997, ...ident and CEO to 2008.

Presentation Outline

- Optical Sensors
- Borehole Vibratory Seismic Sources
- Applications & Examples
  - CCUS: Carbon Capture Utilization & Storage
  - EGS: Enhanced Geothermal Systems
  - UGS of NG+H2: Underground Gas Storage
  - CEOG: Cleaner Enhanced Oil & Gas Recovery
  - Pipeline Monitoring: NG, NG+H2 (Hythane), CO2
  - WEI: Wind Energy Installations
- Paulsson Staff and Facility

Paulsson Commercial Experience

- Enabled by DOE Funding -

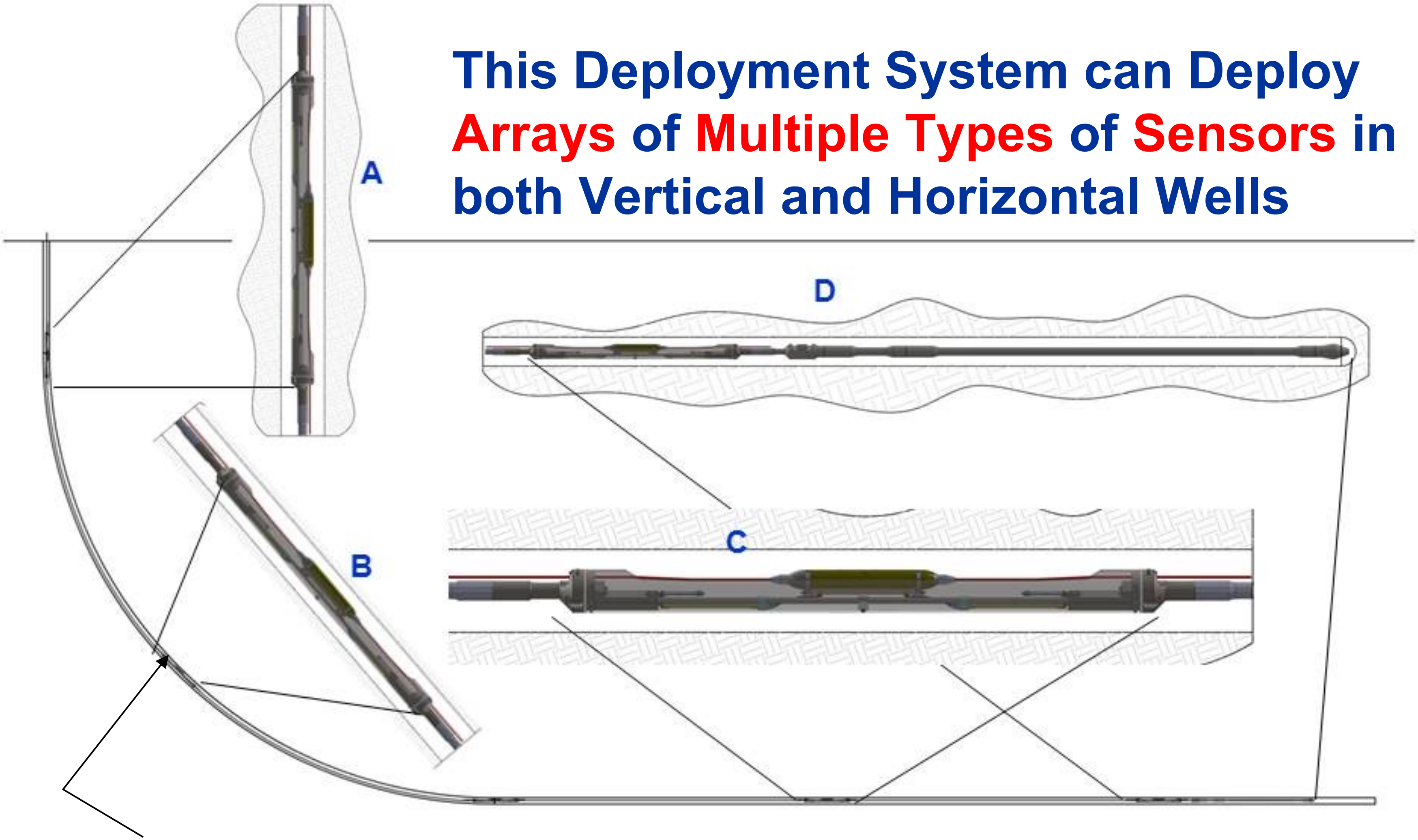
Recorded:

- Over 65 3D-VSPs around the world
- Largest 3D-VSP in the world using a 960-channel system (4 wells x 80 x 3C)
- VSP's with the largest number of 3C clamped stations: 160 3C levels & 8,000 ft long
- First multi-well (8 wells) 3D VSP
- 3D-VSP surveys in the USA, Canada, China, UAE and Oman
- Sinkhole Monitoring
- Pipeline monitoring across faults.

Published ~50 papers

Drill Pipe Deployed System – Housing and Clamping

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



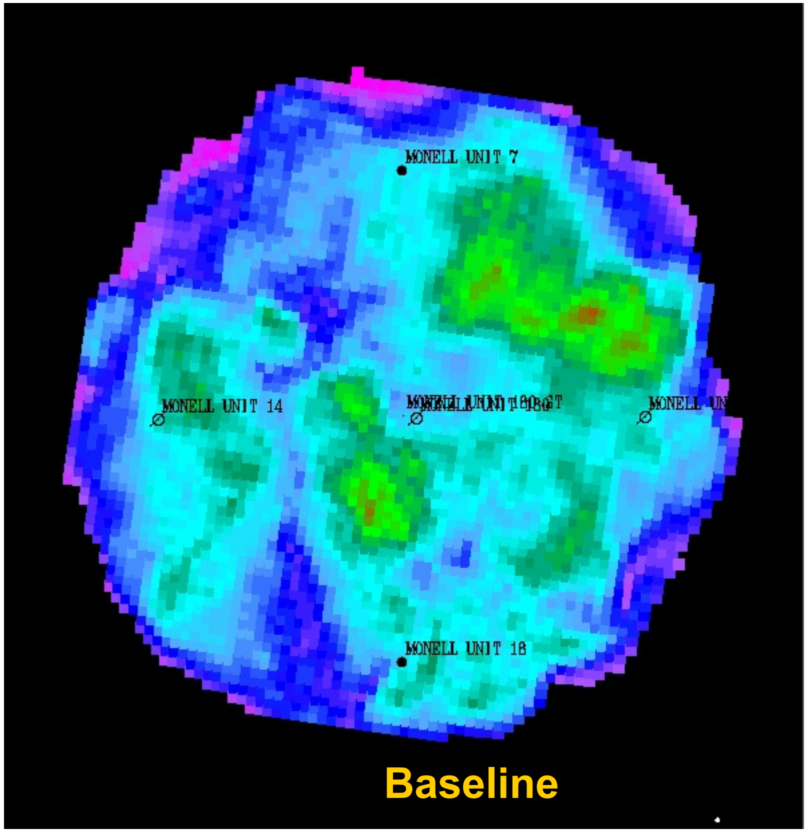
Clamping system operates by increasing the pressure inside the drill pipe and manifolds using the borehole fluid as the pressurized medium

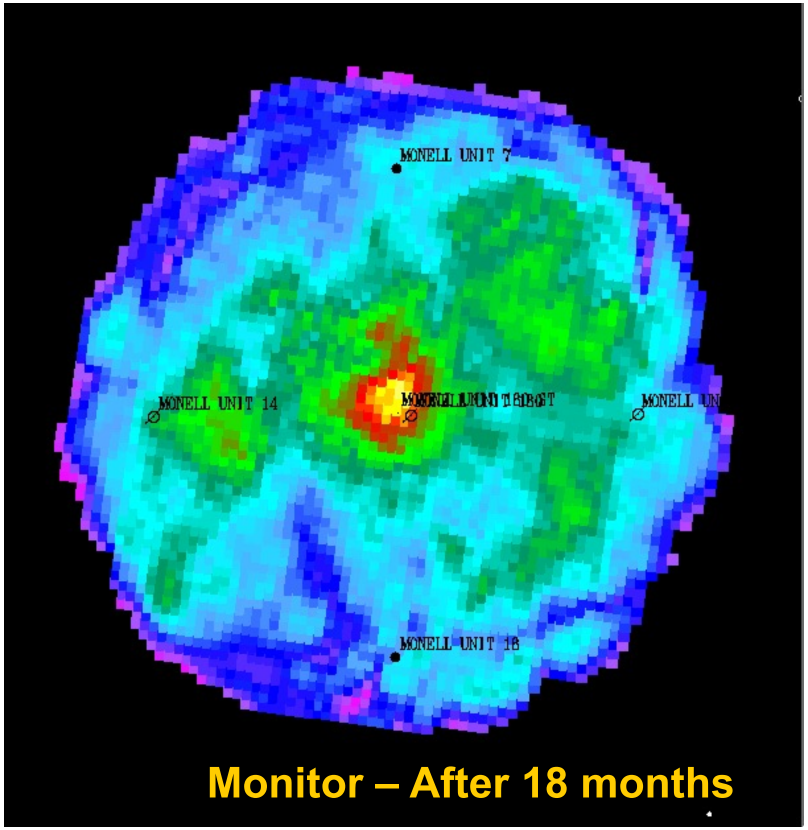
Applications & Examples

- CCUS
  - Anadarko – Wyoming
  - Battelle & Core Energy – Michigan Reef
  - LBL – Texas and Alabama
- EGS
- UGS
- CEOG
- Pipeline Surveying and Monitoring (PSM)
- Wind Energy Installations

Borehole Seismic Time lapse surveys to monitor CO_2 Depth Amplitude Maps at 4,800 ft showing the CO_2 Plume

Simultaneous imaging and monitoring possible using long borehole seismic arrays using FOSVS and Acoustic Micro Emitters in combination.





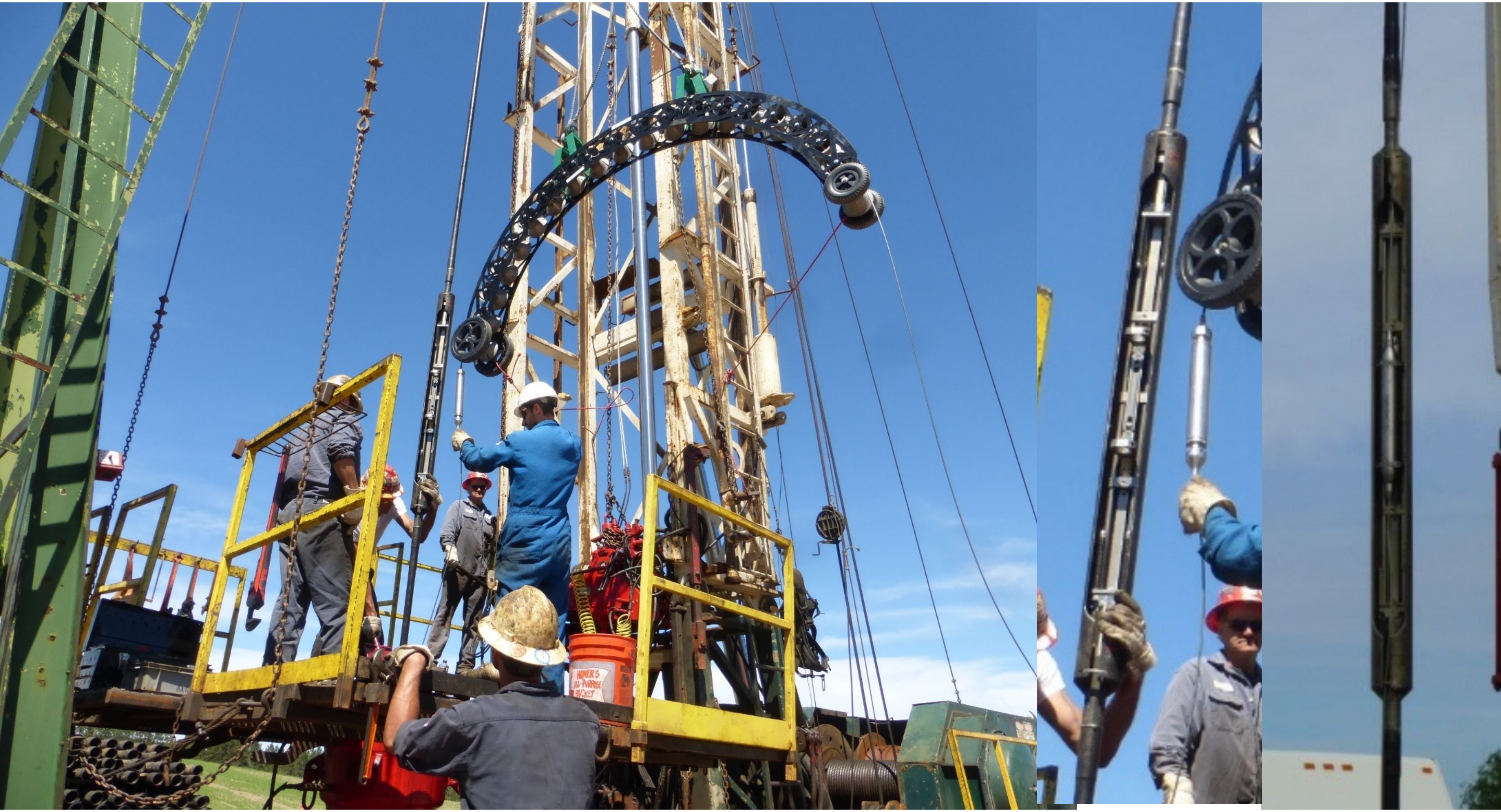
Increased reflectivity in the Monitor Survey at a depth of 4,800 ft at the well is due to the injected CO_2. Also seen is the increased reflectivity around the water injector wells.

Applications & Examples

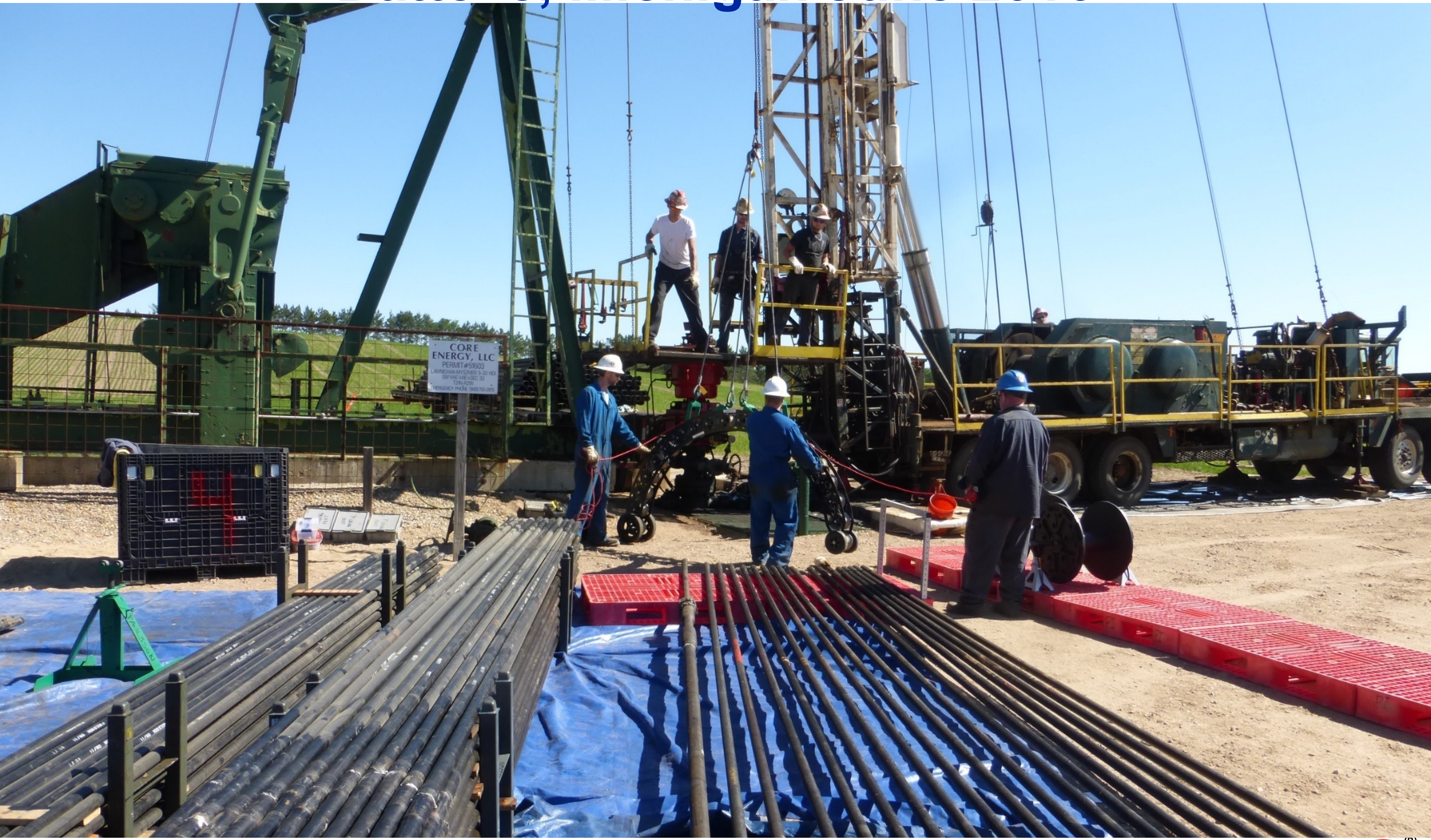
- CCUS
  - Anadarko – Wyoming
  - Battelle & Core Energy – Michigan Reef
  - LBL – Frio, Texas and Alabama
- EGS
- UGS
- CEOG
- Pipeline Surveying and Monitoring (PSM)
- Wind Energy Installations

The Battelle 2016 Survey to Monitor CO2 Injection:
Fiber Optic Seismic Sensor System: Two 20 ft containers for Cable Spool & Equipment & Drill Pipe Joints: 19 ft +/- ¼”

Fiber Optic Seismic Sensor System Deployment
Battelle, Michigan June 2016

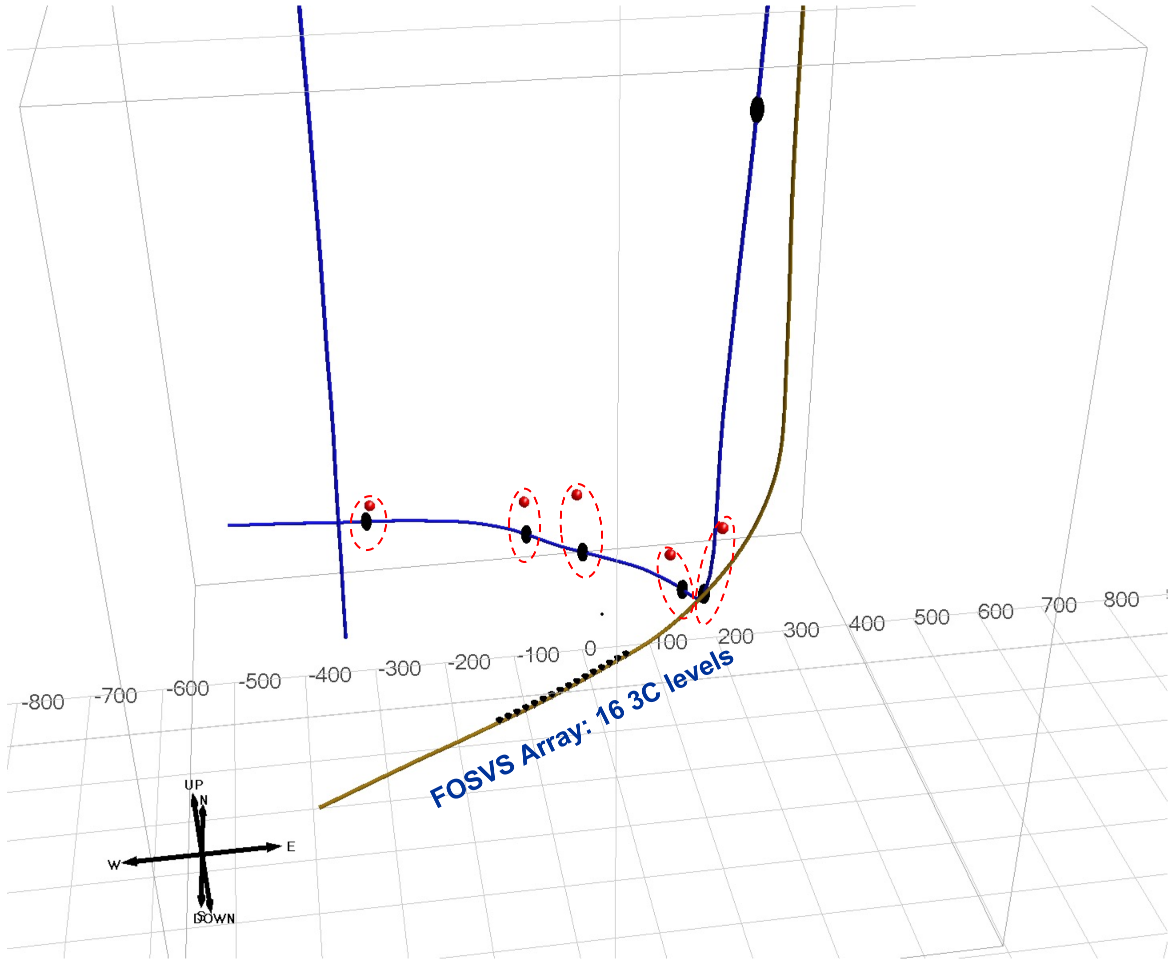


Fiber Optic Seismic Sensor System Deployment
Battelle, Michigan June 2016



Fiber Optic Seismic Sensor System Deployment for Battelle in Michigan June 2016

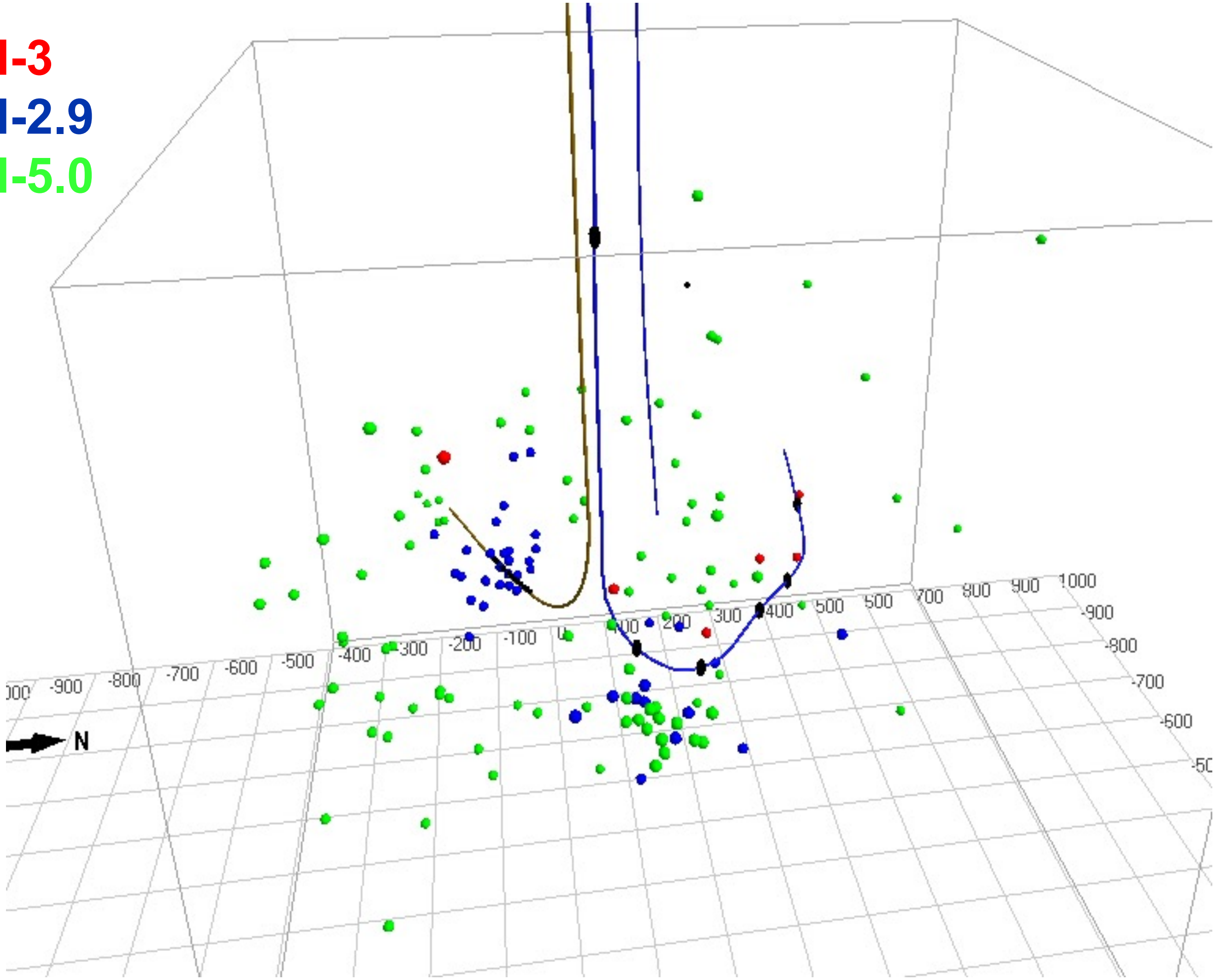
Results from Locating ½ gram String Shots @ z = 6,000 ft & x = 800 ft, During a Survey for Battelle & DOE in June 2016



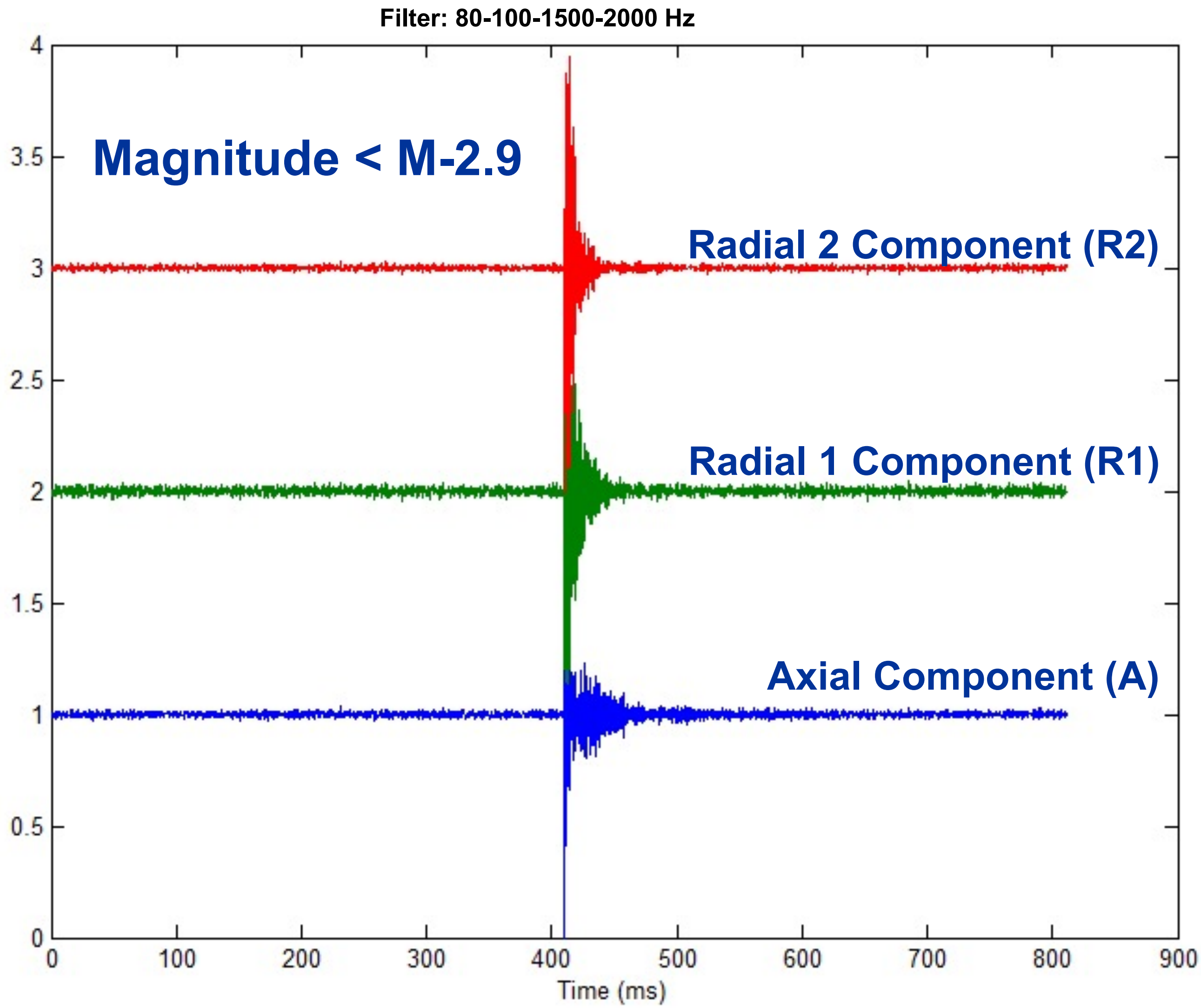
Survey for Battelle - Locating String Shots and Micro Seismic Events
Recorded >100,000 events in four weeks. Displayed here are 130 events.

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

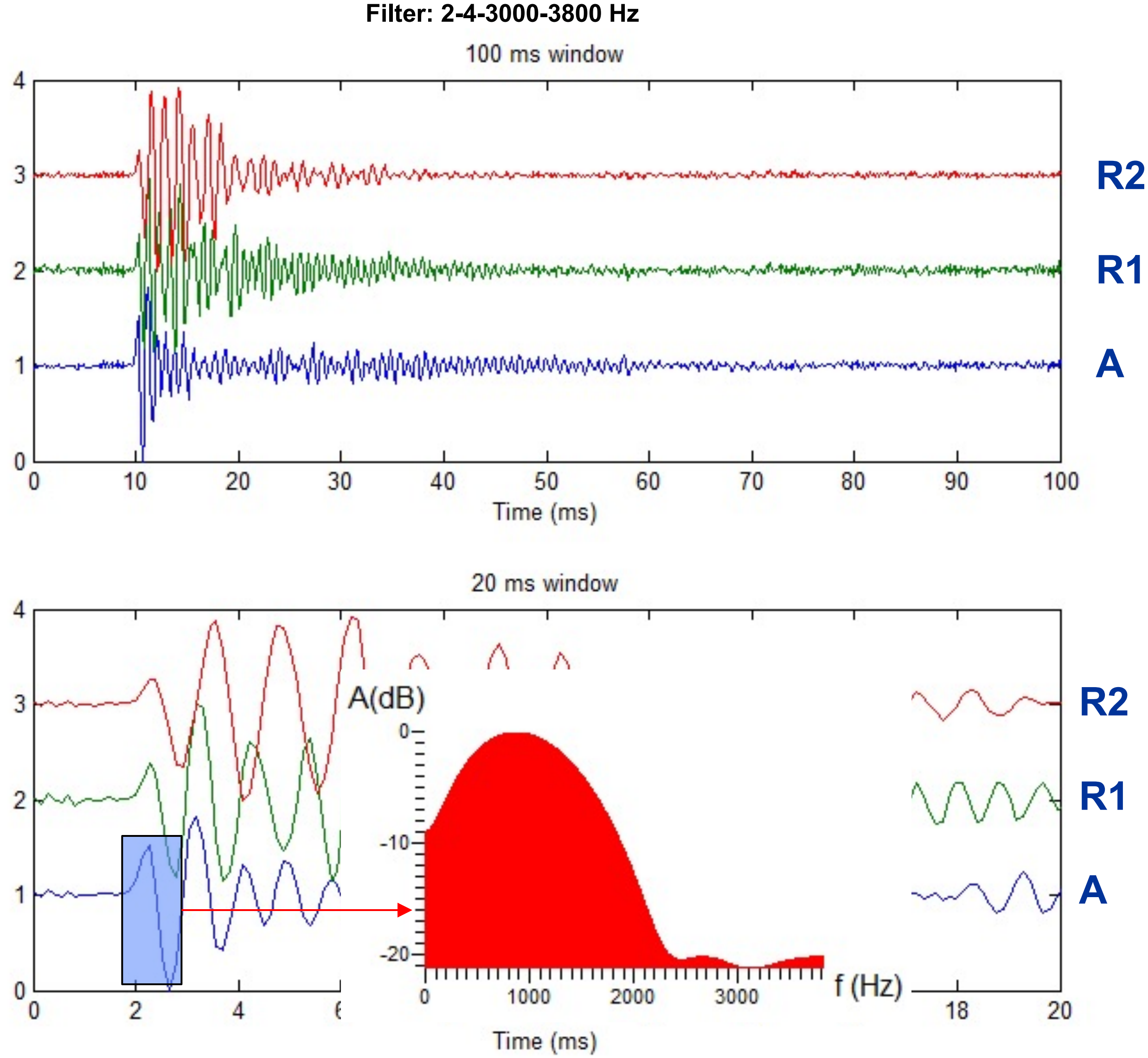
Magnitude < M-3
Magnitude < M-2.9
Magnitude < M-5.0



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

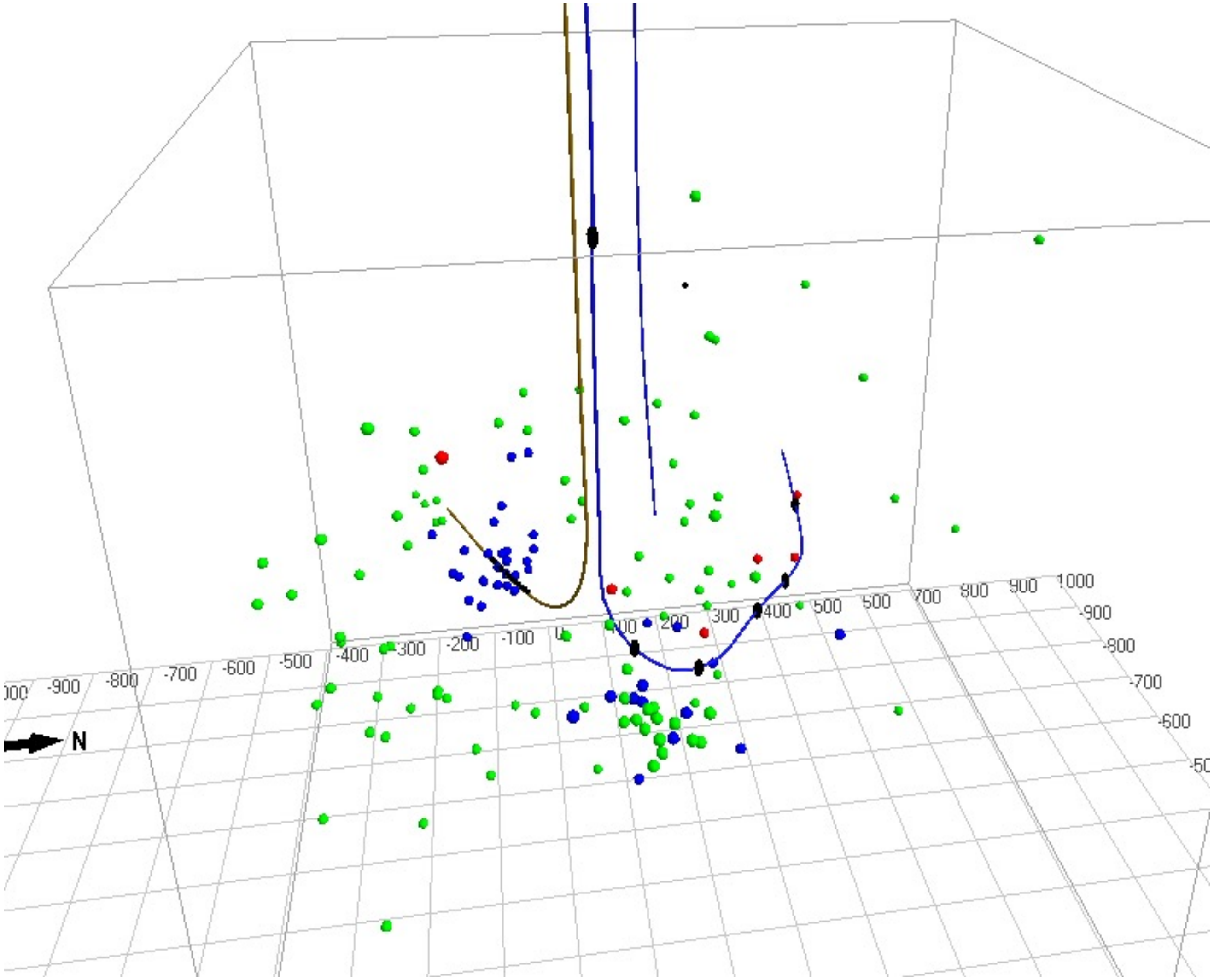


Zoomed-In Focused MS in 3C- Filter: 2-4-3,000-3,800 Hz

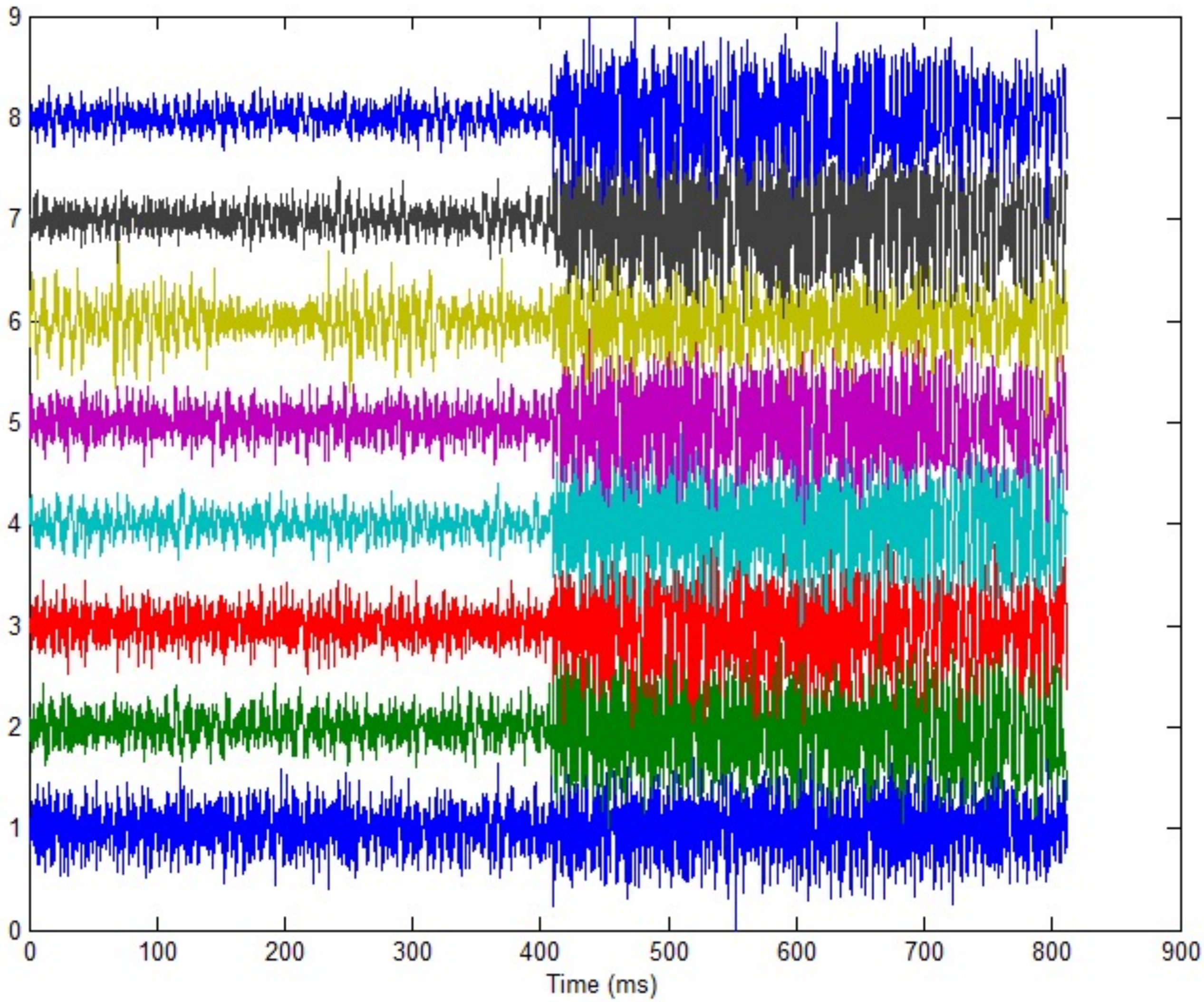


Locating String Shots and Micro Seismic Events – Work in Progress
Recorded 11,000 events in four weeks. Displayed here are 130 events.

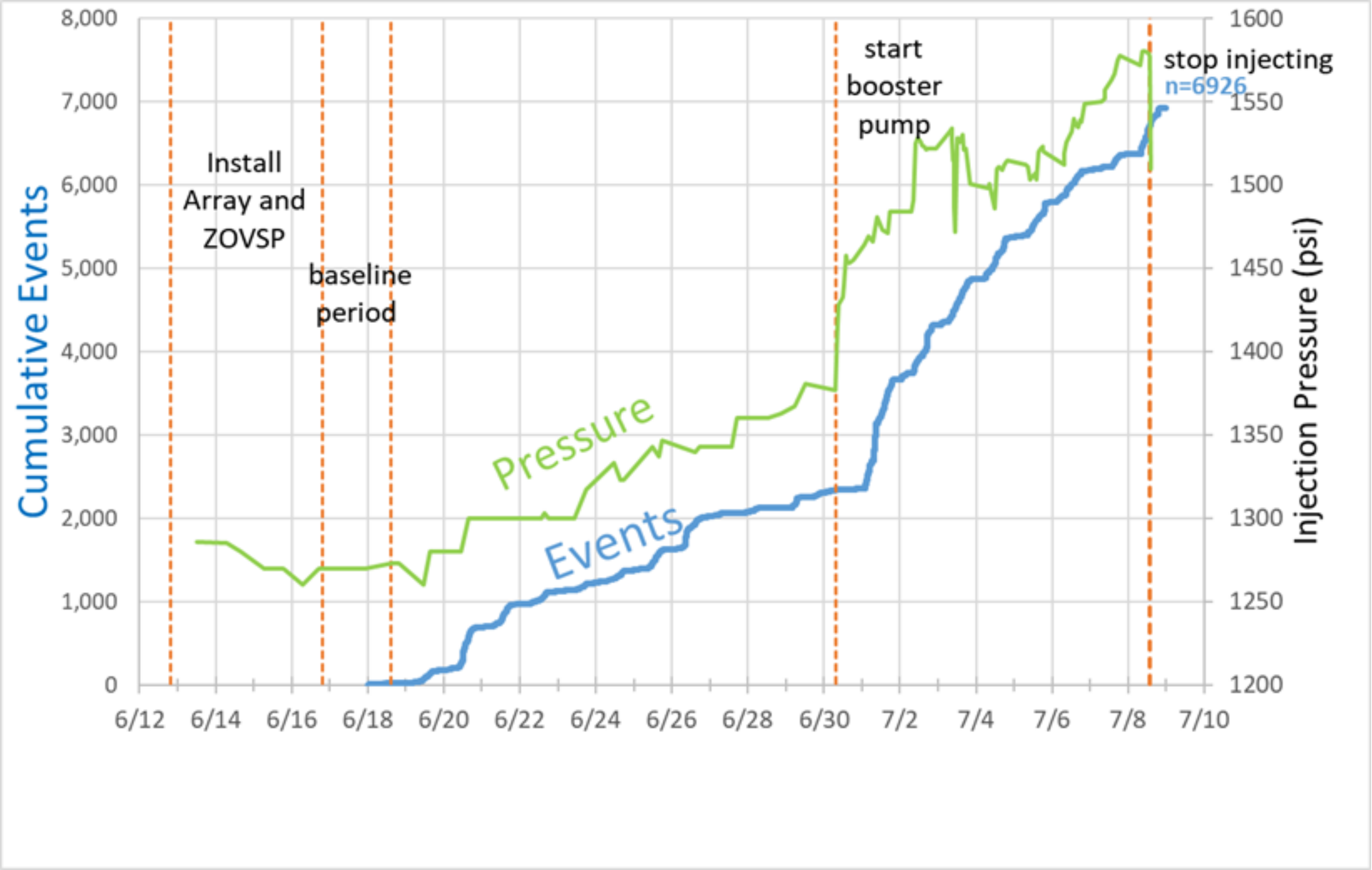
Red: String Shots; Blue: Focused Micro Seismic; Green: "Distributed" Events



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



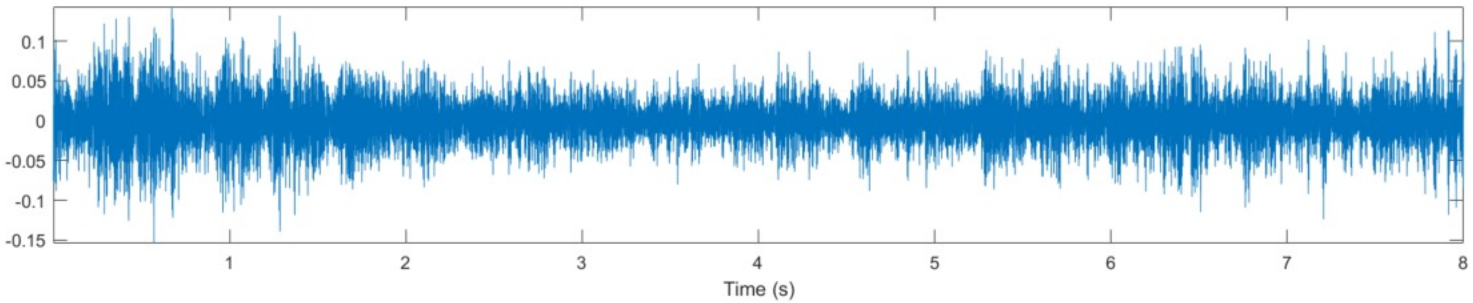
Micro Seismic Events as Function of Injected CO2 Pressure



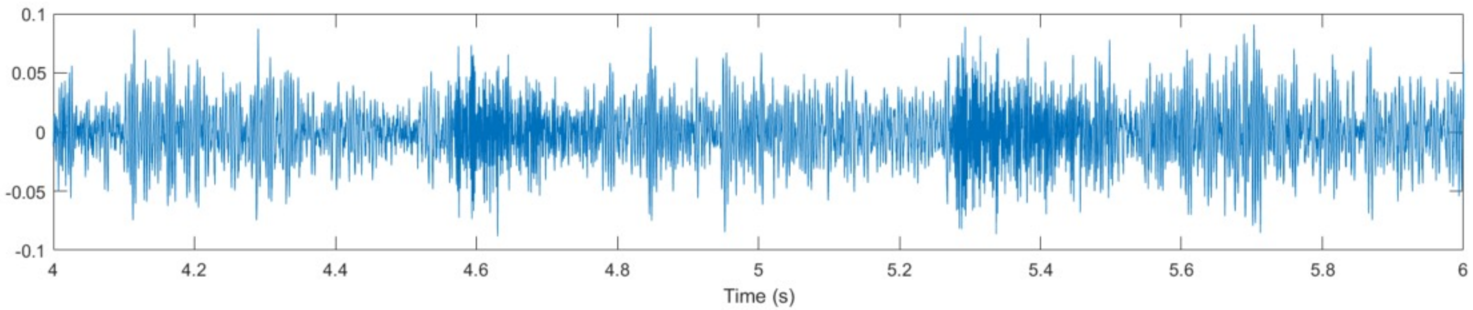
Micro Seismic Data from Paulsson, Inc., Injection Pressure Data Courtesy Mark Kelley, Battelle, 2019

We looked for Analogs: Cardiac Blood Flow

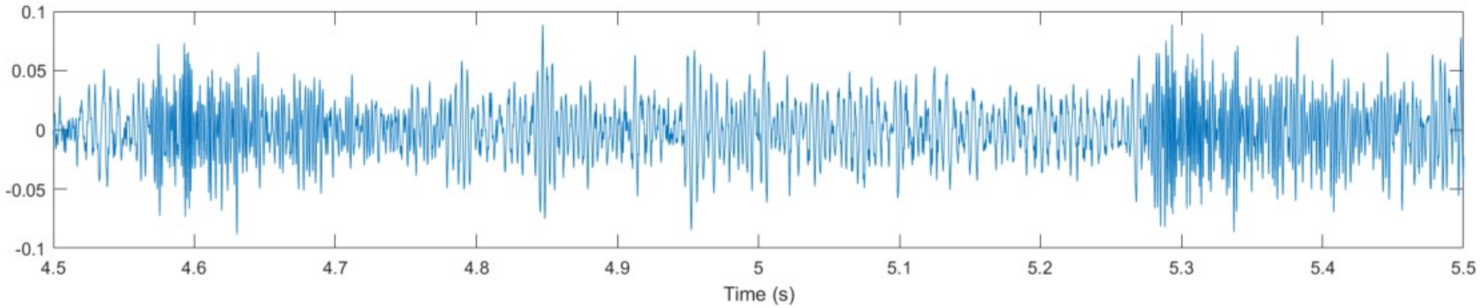
8 seconds



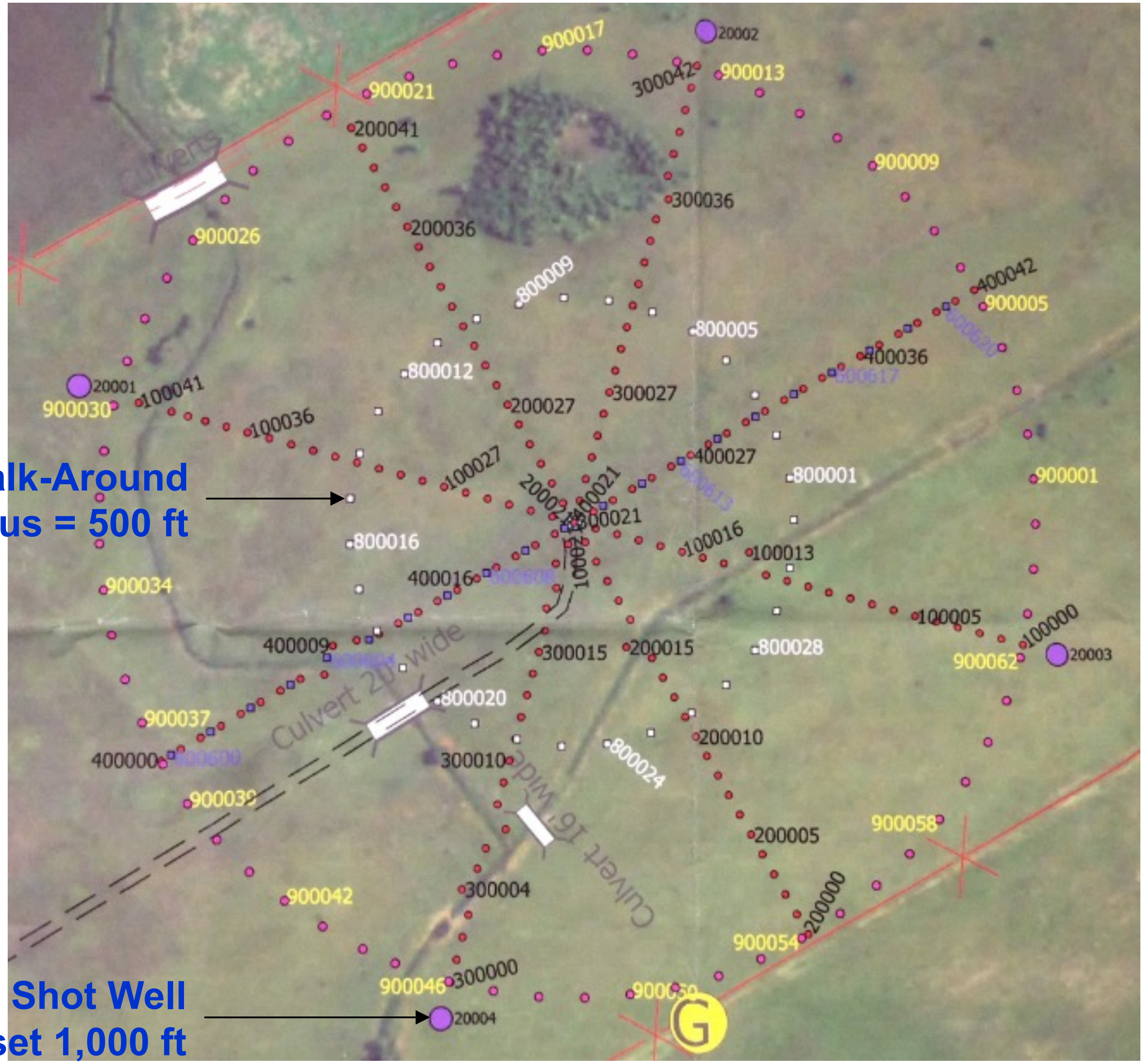
Zoomed in
2 seconds



Zoomed in
1 second



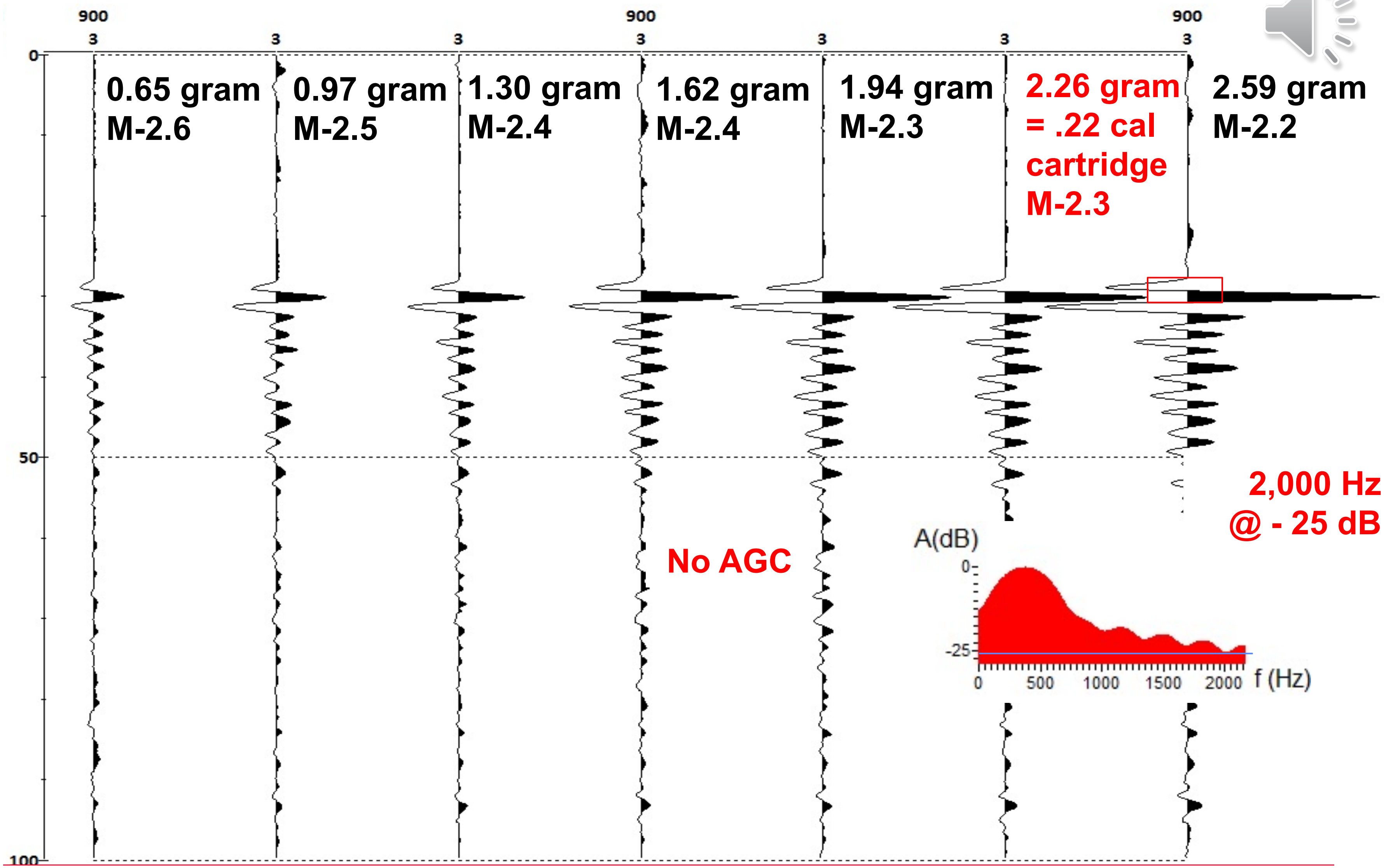
ConocoPhillips Downhole Seismic Sensor Test Site Map



Vibrator Walk-Around Radius = 500 ft

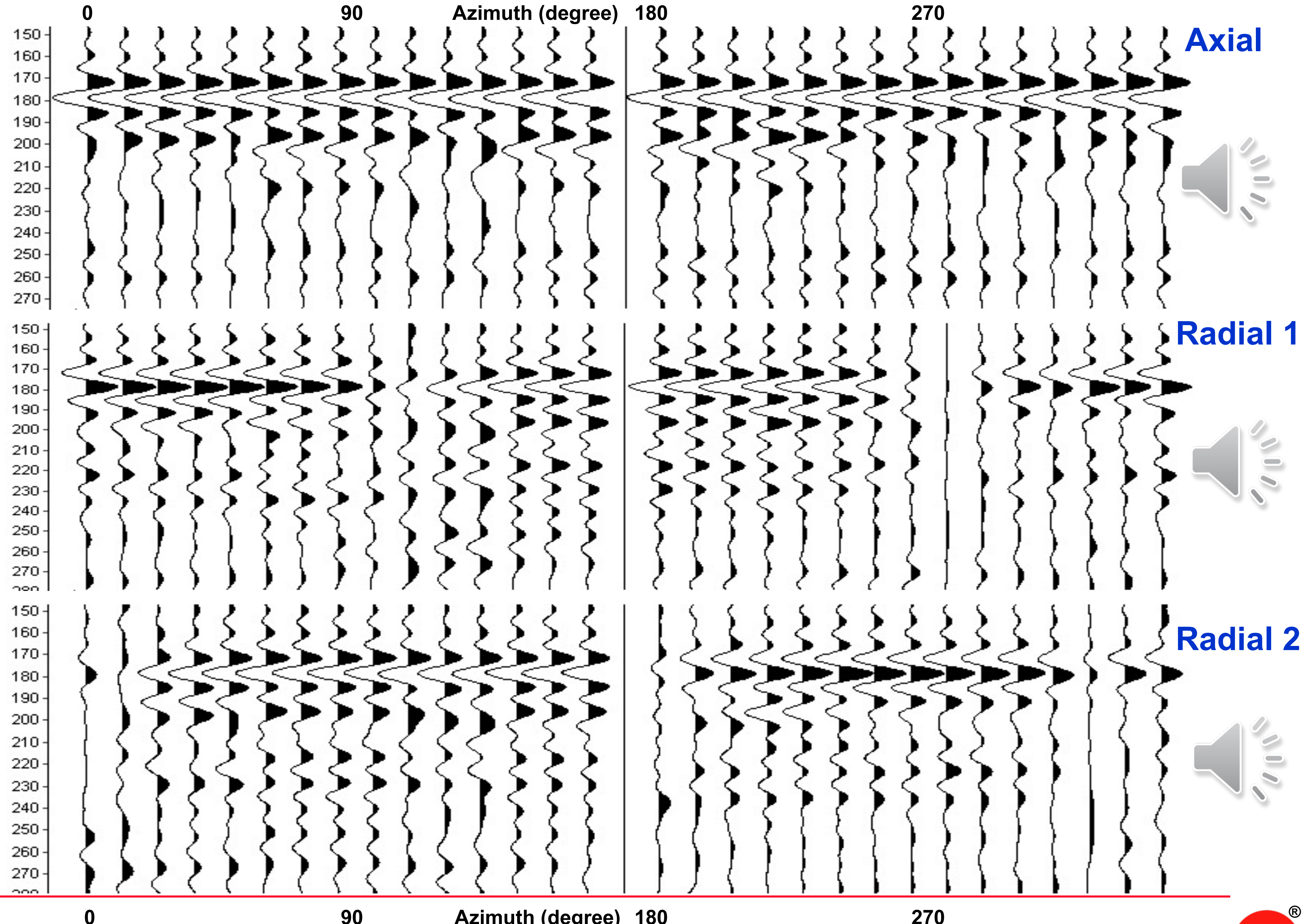
String Shot Well Offset 1,000 ft

Small Shots Recorded on FOSVS Principal Component @ distance of 1,200 ft (400 m) (Filter: 80-100-1500-2000 Hz)



Vibrator walking around the receiver well @ R=500 ft

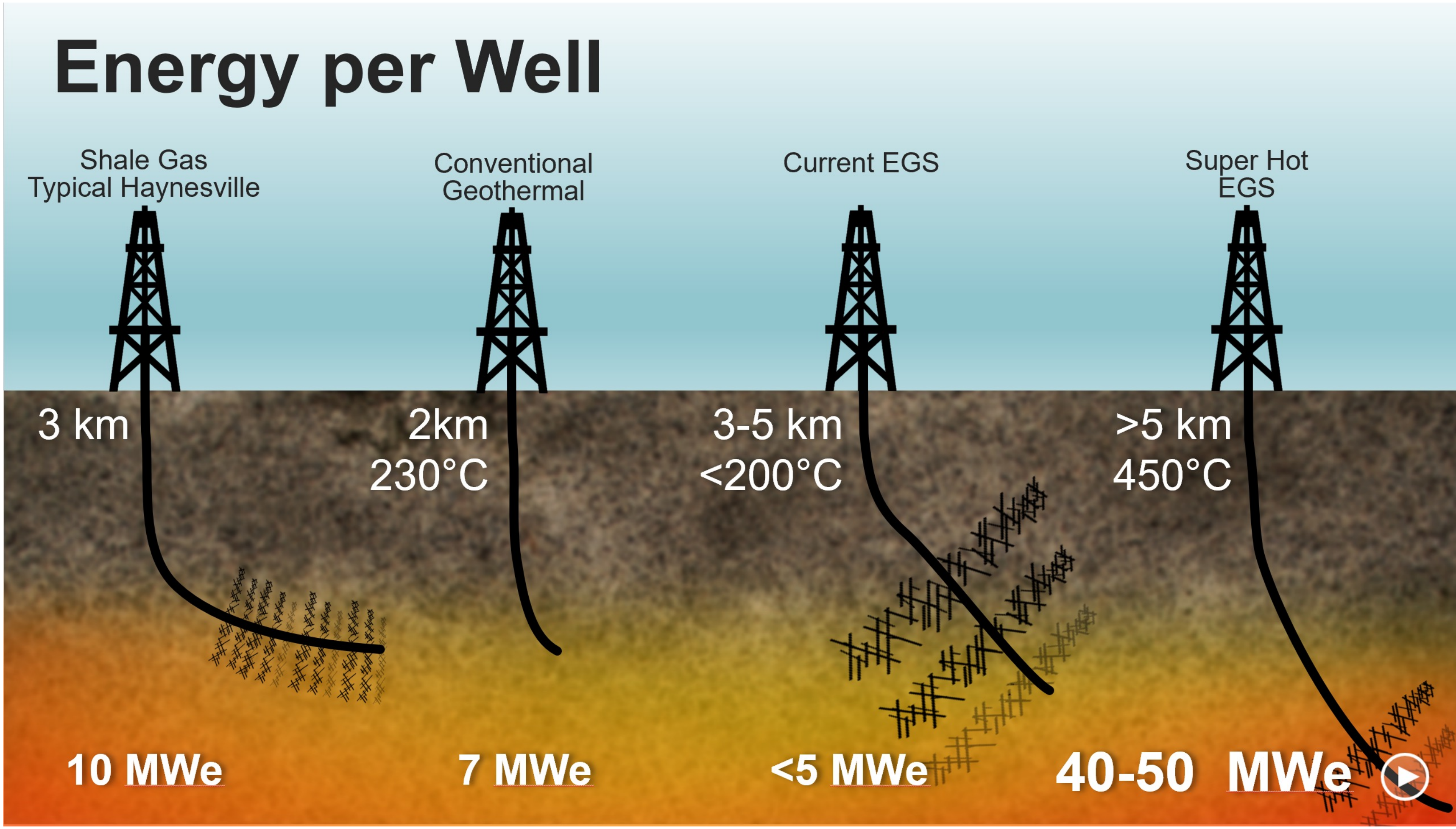
(Data aligned for waveform and phase analysis, Filter: 4-6-96-120 Hz)



Applications & Examples

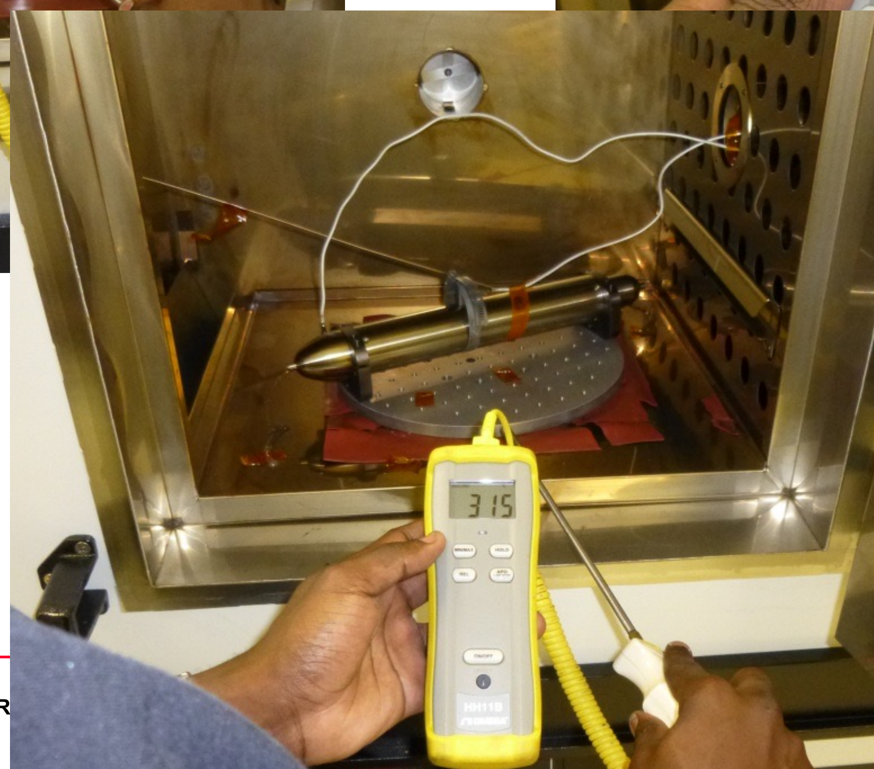
- Carbon Capture Utilization and Storage (CCUS)
- Enhanced Geothermal Systems (EGS)
  - Coso Geothermal Field (Funded by CEC)
- Underground Gas Storage including H_2 (UGS)
- Cleaner Enhanced Oil & Gas (CEOG)
- Pipeline Surveying and Monitoring (PSM)
- Monitor Wind Energy Stations

Geothermal Energy vs. Unconventional Oil & Gas
In 2019, 20,000 UOG wells drilled for $120 Billion

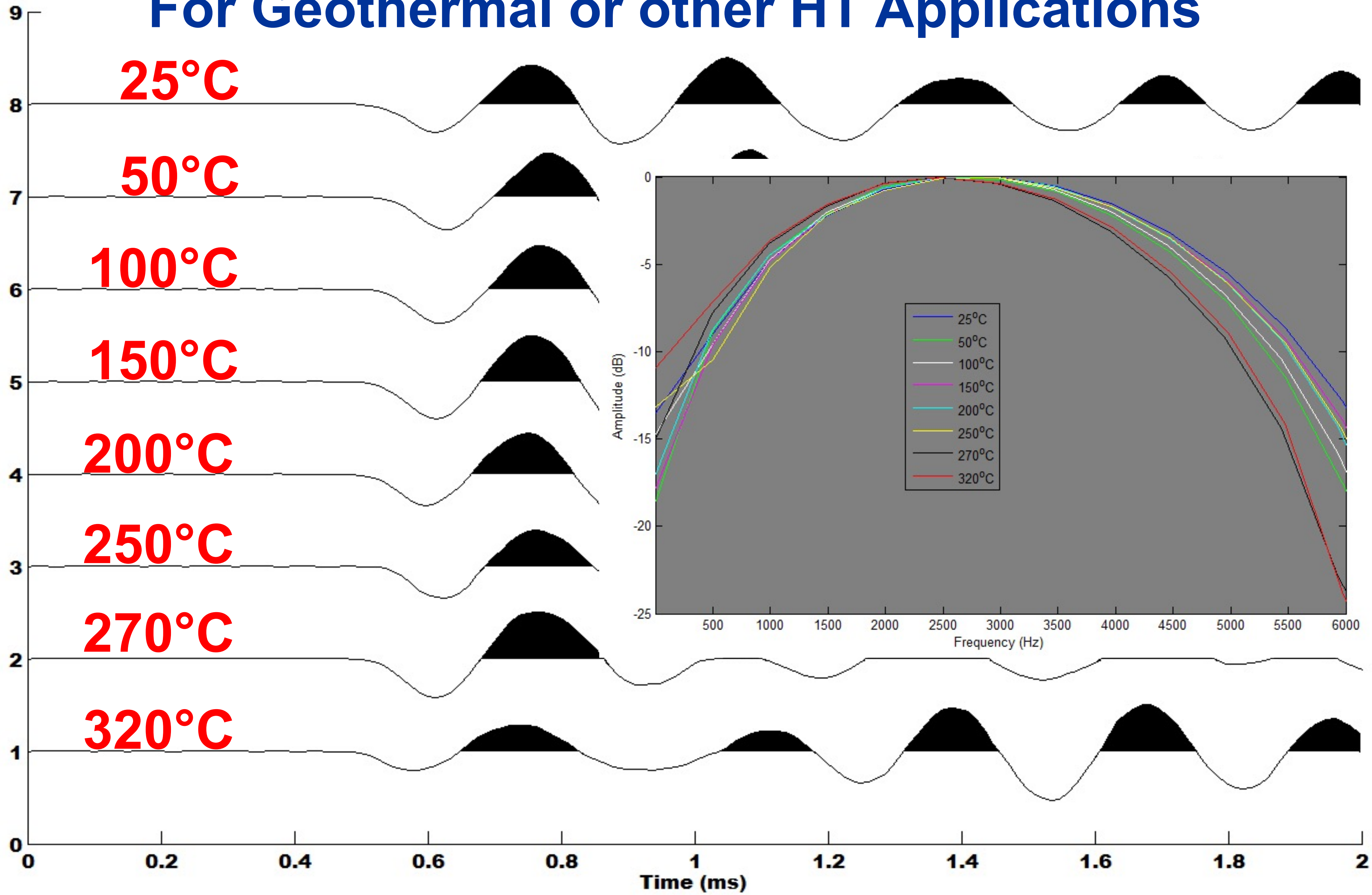


AltaRock Energy / National Renewable Energy Laboratory

High Temperature Tests of Fiber Optic Seismic Sensors (FOSS)



FOSVS: Optical Radial Component @ 25°C - 320°C
For Geothermal or other HT Applications

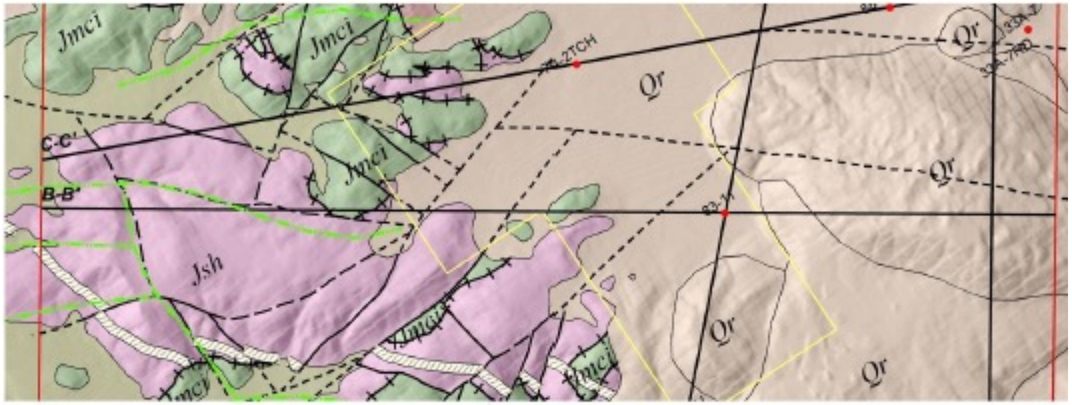


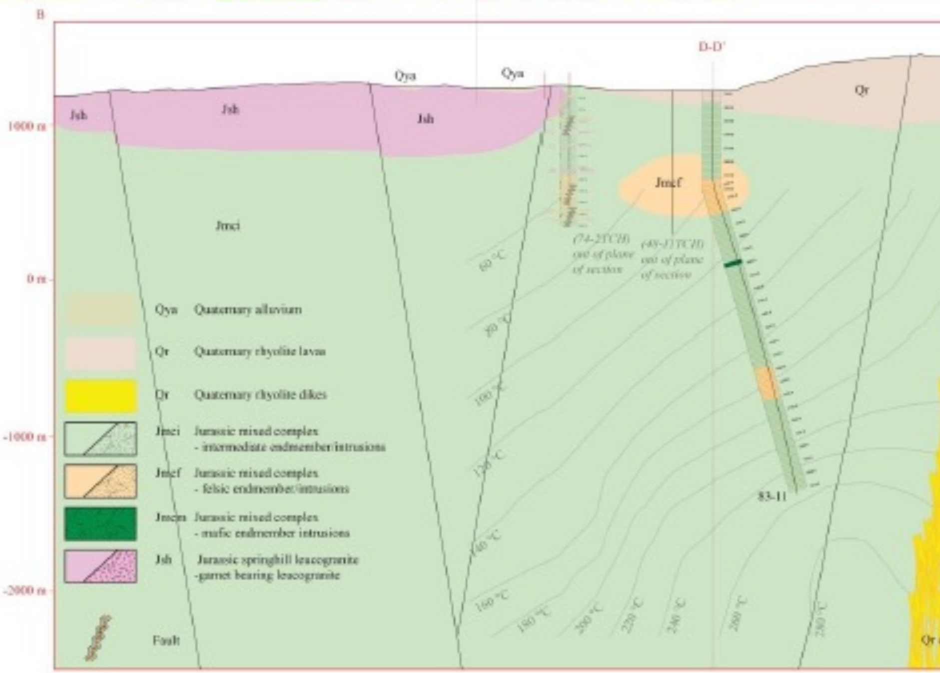
The Coso Microseismic Survey

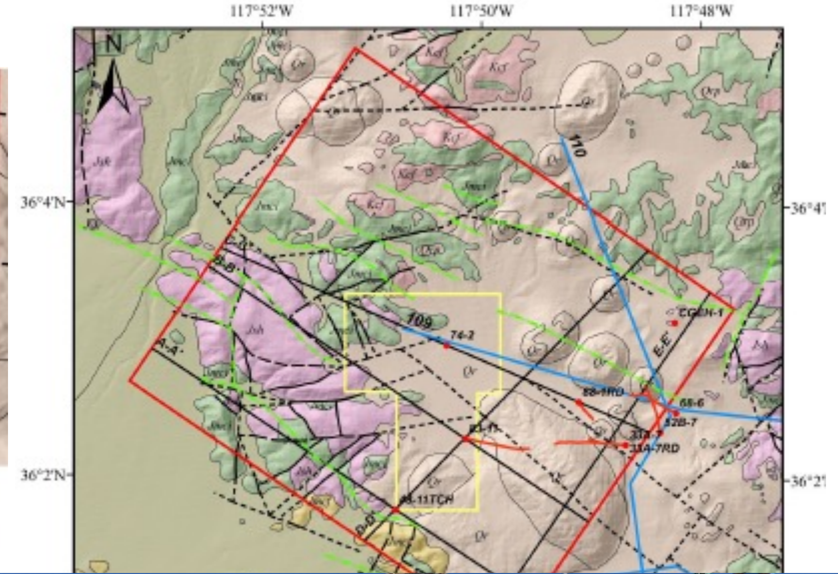
- Survey Date: March 13 – 21, 2017
- Data Recording: March 14 – 20, 2017
- VSP Well: 83-11
- Lease: Naval Air Weapons Station China Lake
- Seismic Sensors: 12-Level 3C FOSVS
- Recording System: TDI sampling @ 48,076.92 Hz
- Deployment Depth: MD 1,525 – 1,800 ft @ 25 ft interval

The West Flank FORGE Site Candidate

Maps from FORGE Phase 1 West Flank of Coso, CA

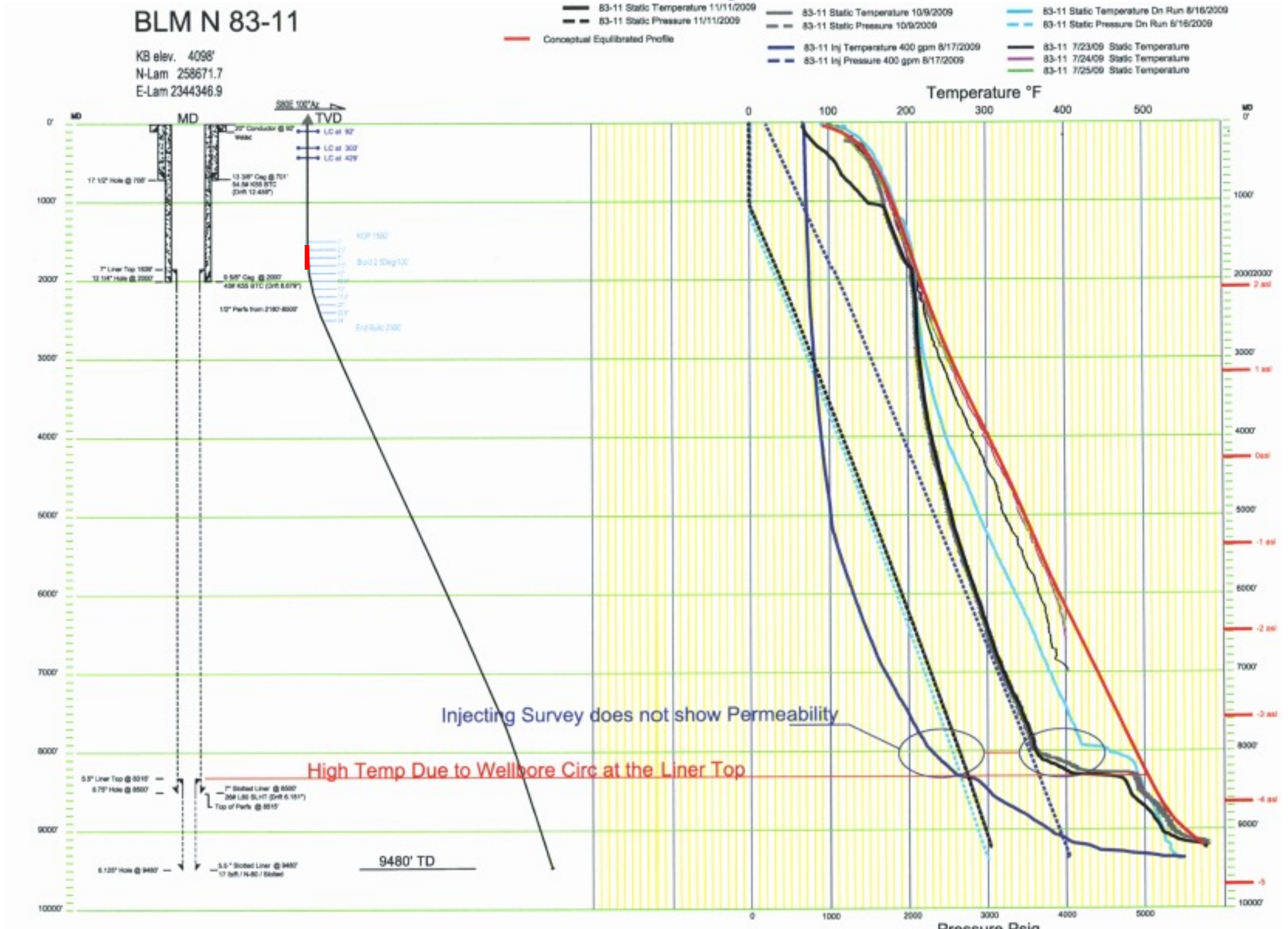




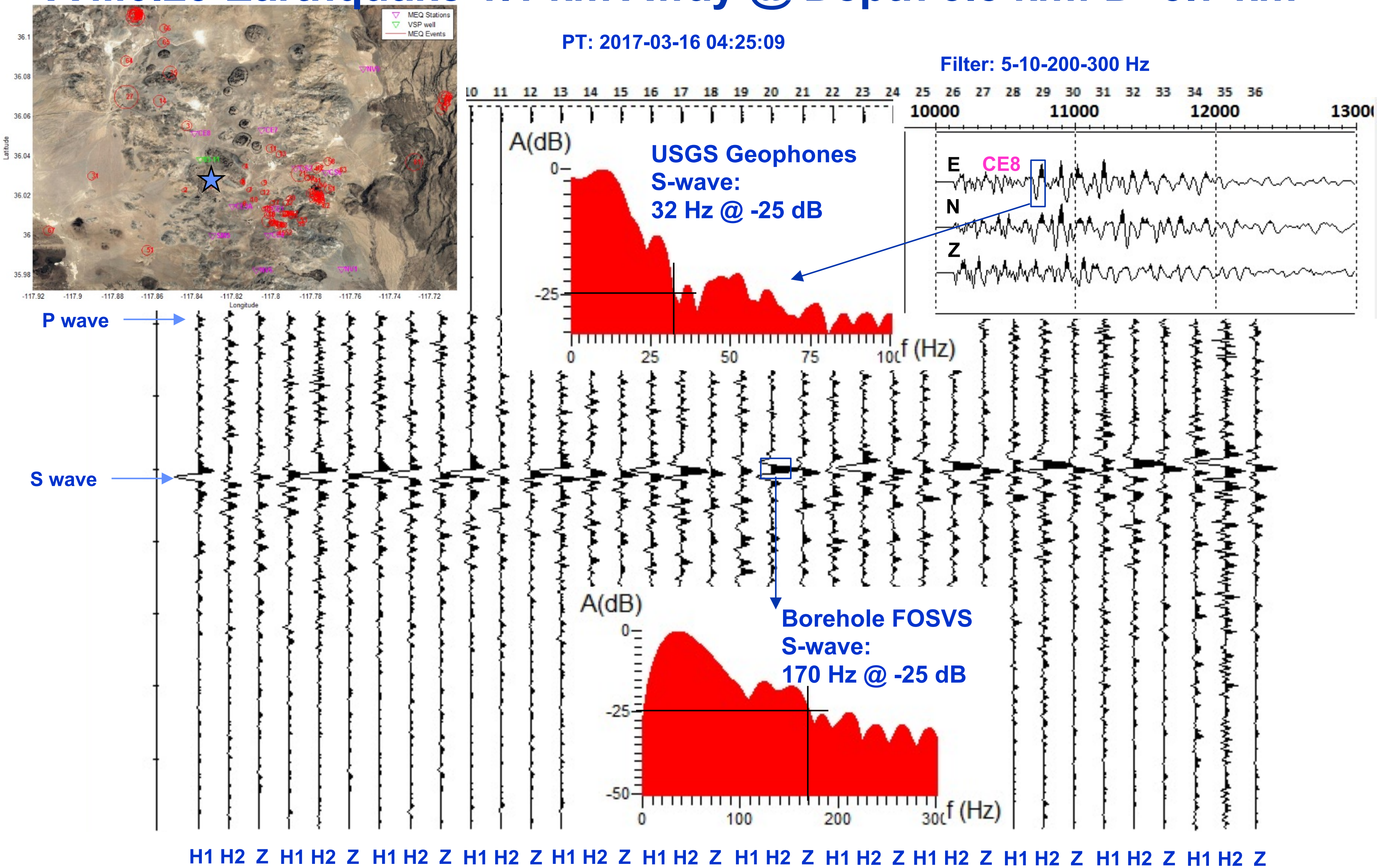


The Paulsson FOSVS system deployed into well 83-11 on March 13-21, 2017

Well 83-11 at COSO - Forge Site Candidate

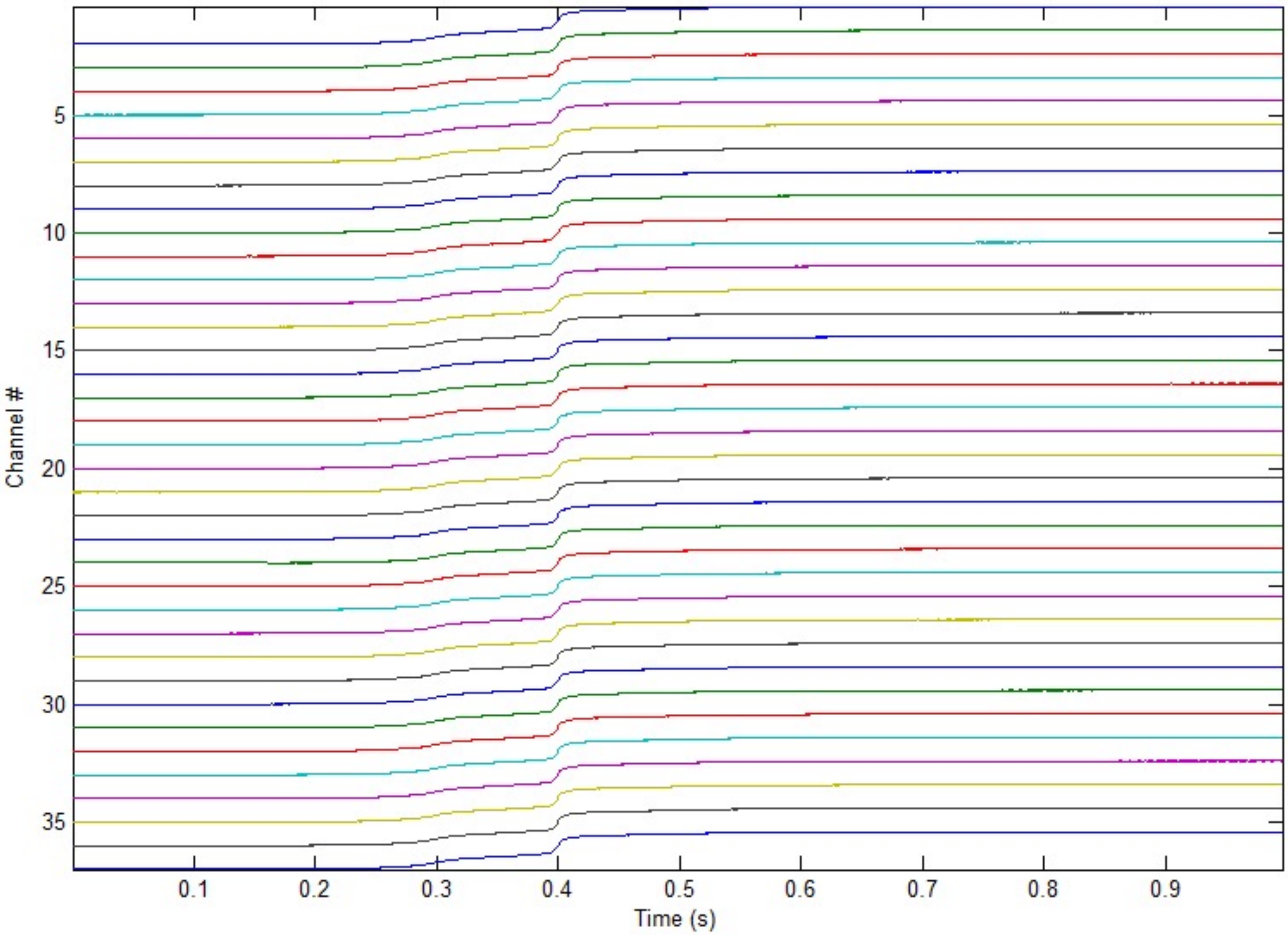


A M0.29 Earthquake 1.1 km Away @ Depth 3.5 km: D=3.7 km



Unusual Event Associated with Blowdown in well 6,000 ft away

PT: 2017-03-17 10:21:01



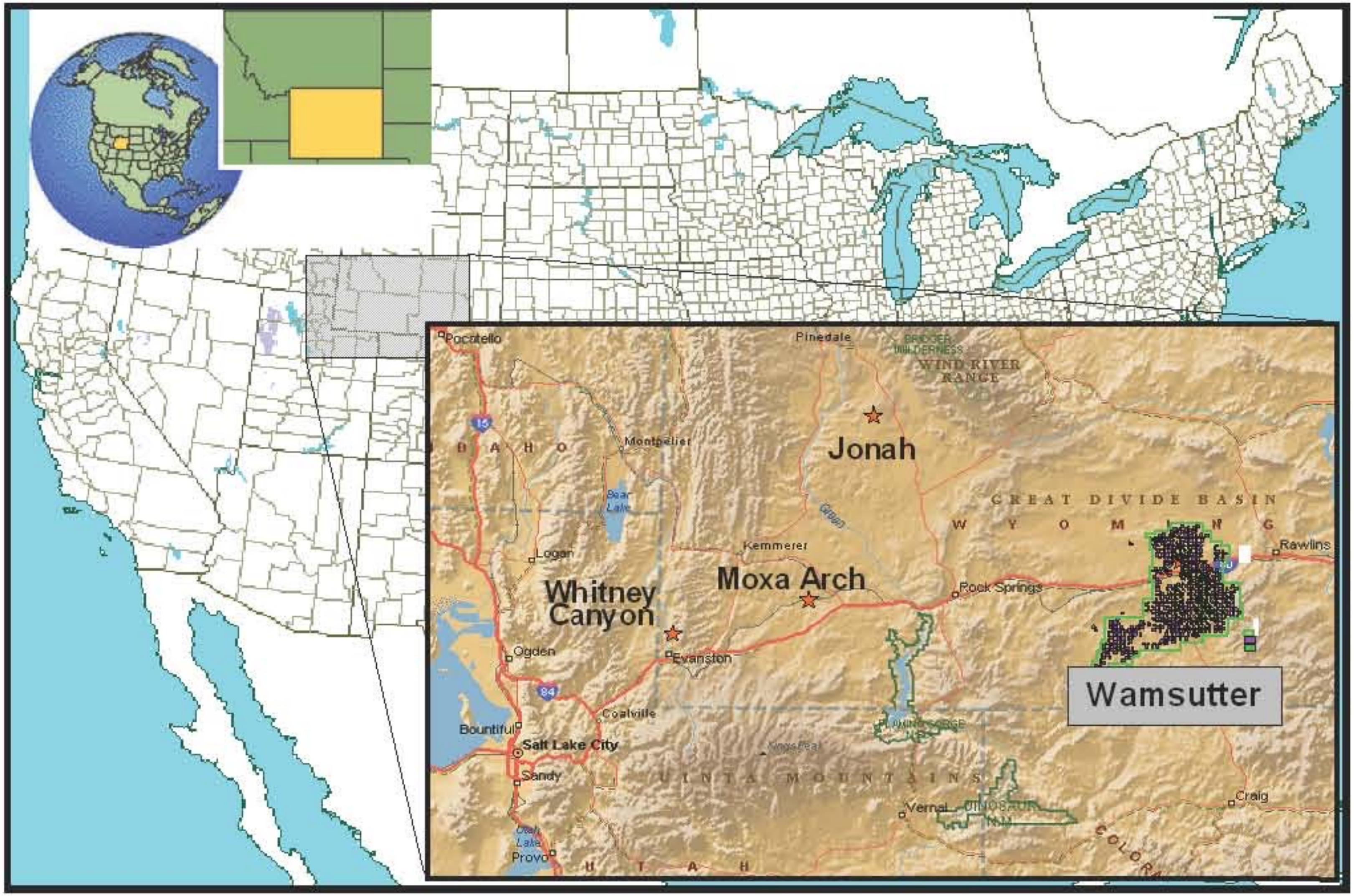
Applications & Examples

- Carbon Capture Utilization and Storage (CCUS)
- Enhanced Geothermal Systems (EGS)
- Underground Gas Storage including H_2 (UGS)
  - PG&E funded by CEC – July 2021
- Cleaner Enhanced Oil & Gas (CEOG)
- Pipeline Surveying and Monitoring (PSM)
- Monitor Wind Energy Stations

Applications & Examples

- Carbon Capture Utilization and Storage (CCUS)
- Enhanced Geothermal Systems (EGS)
- Underground Gas Storage including H2 (UGS)
- Cleaner Enhanced Oil & Gas (CEOG)
  - BP – Wamsutter, WY. Gas Field.
  - Anadarko – CO2 EOR
  - Anadarko – Methane Hydrate @ Hot Ice
- Pipeline Surveying and Monitoring (PSM)
- Wind Energy Installations

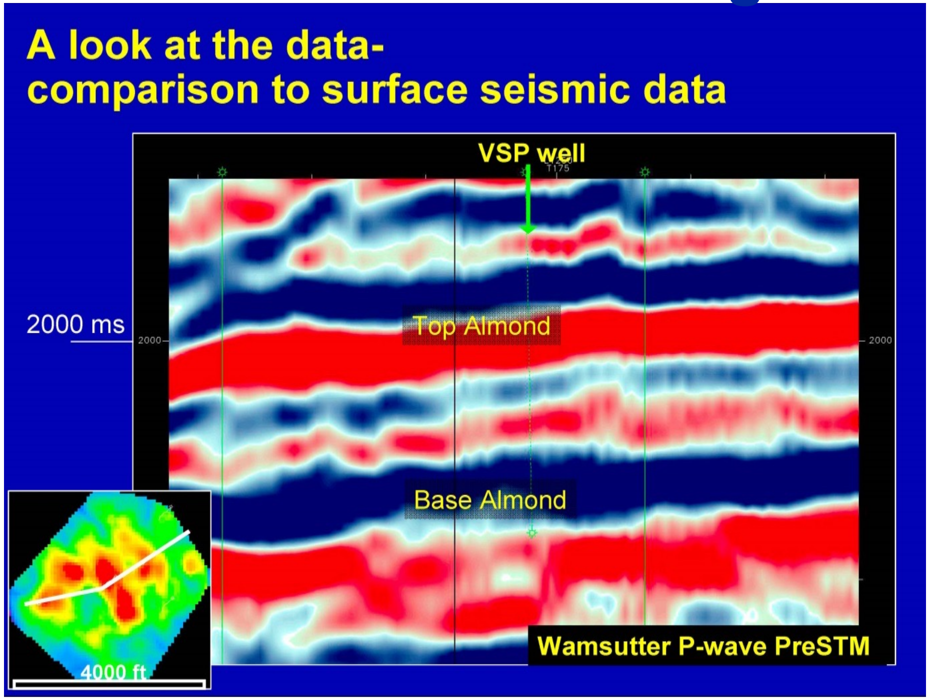
3D VSP w/ 160 Level 3C Array in the BP Wamsutter Gas Field
Compare Surface Seismic & 3D VSP Technologies



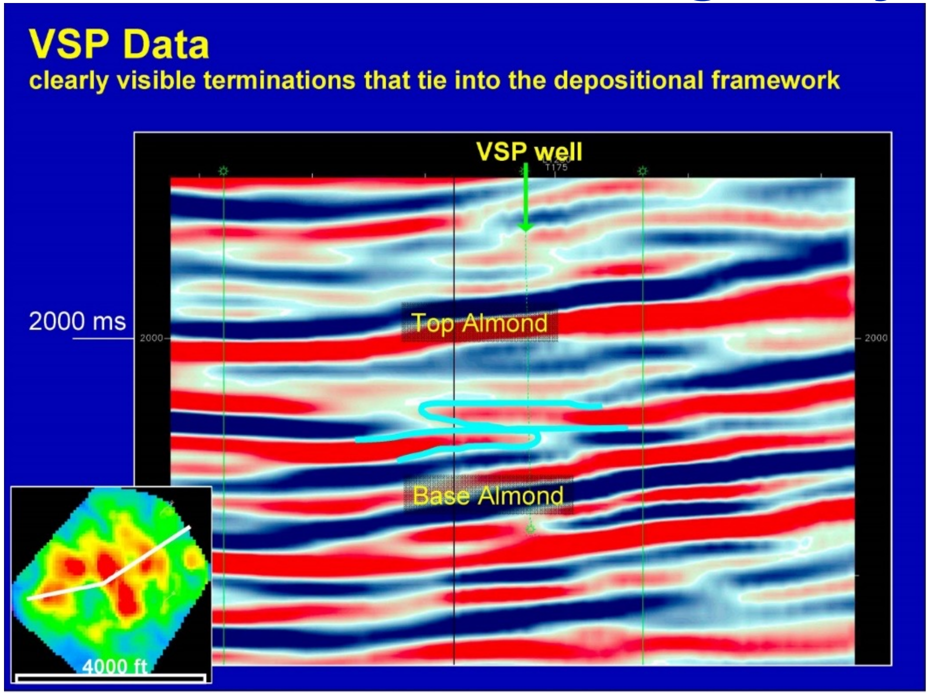
Ramkhelawan et al., 2008

Surface Seismic vs. 3D VSP Imaging
Terminations seen in 3D VSP tie depositional framework.

Surface Seismic Image



VSP Image using an 160-level, 8,000 ft Long Array

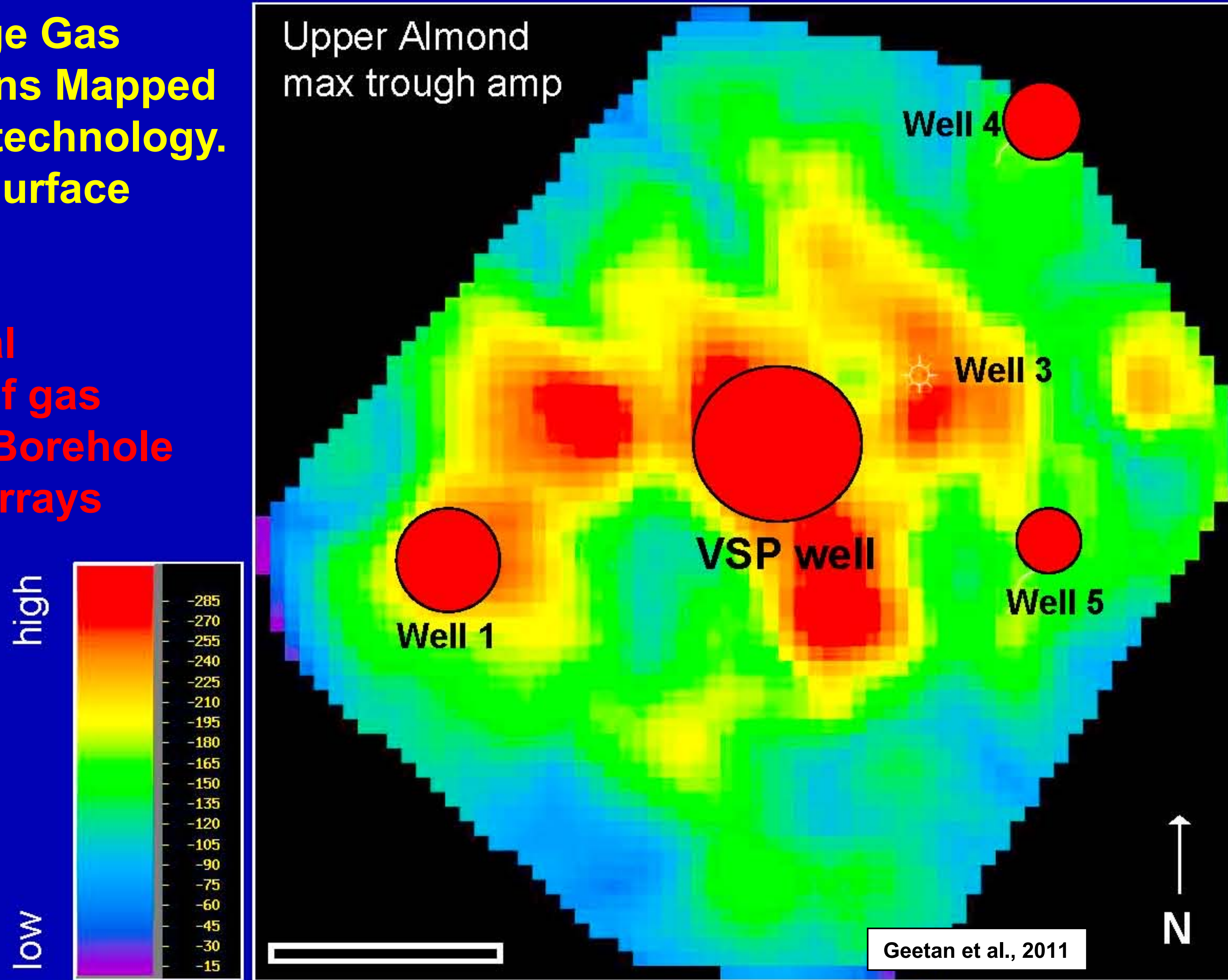


The 3D VSP has 4X better resolution than Surface Seismic

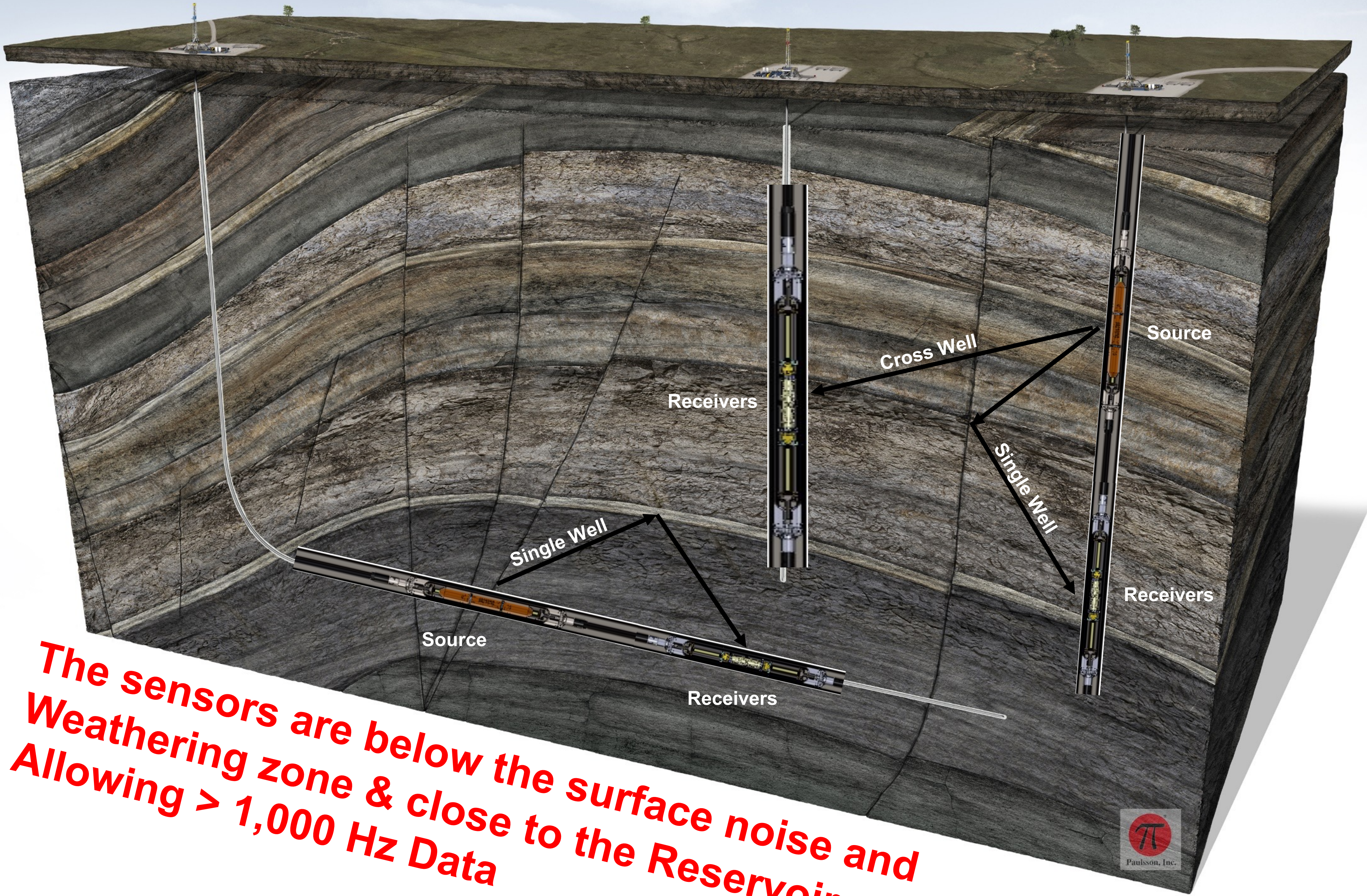
Almond reservoir 3D VSP and Production overlay

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

Mapping areal distribution of gas require long Borehole Seismic 3C Arrays

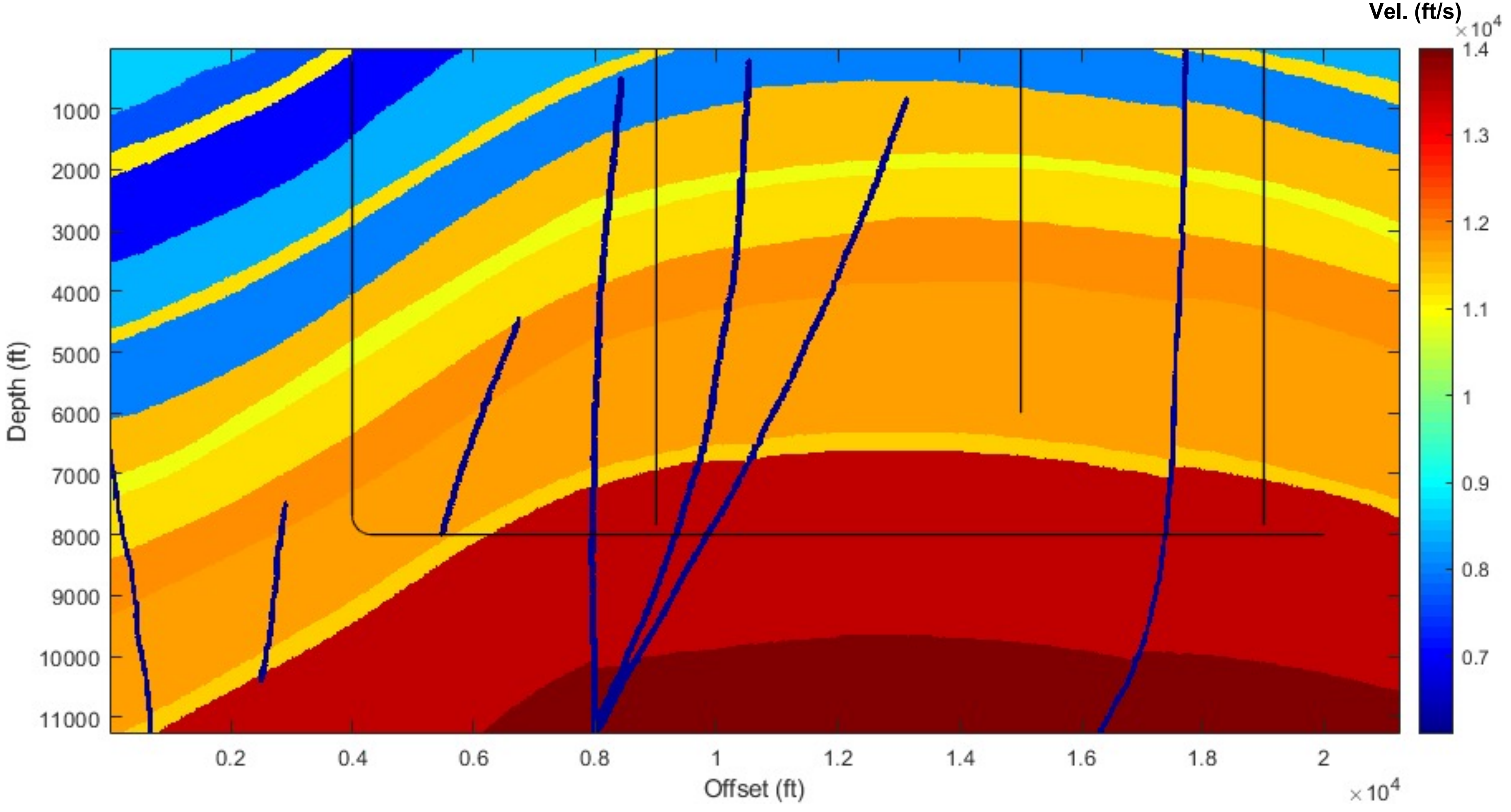


Well Seismic Imaging of Faults and Geology

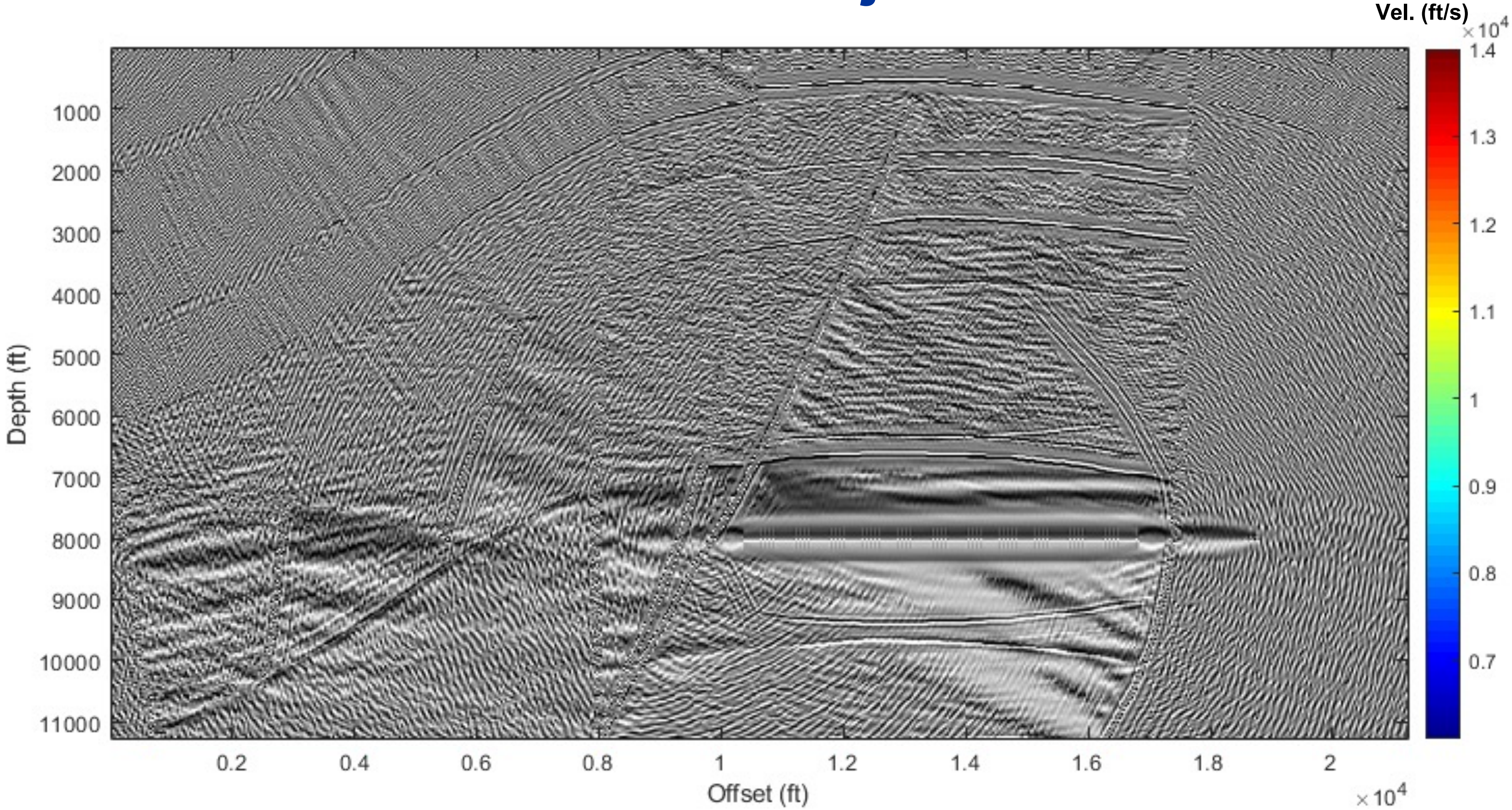


The sensors are below the surface noise and Weathering zone & close to the Reservoirs Allowing > 1,000 Hz Data

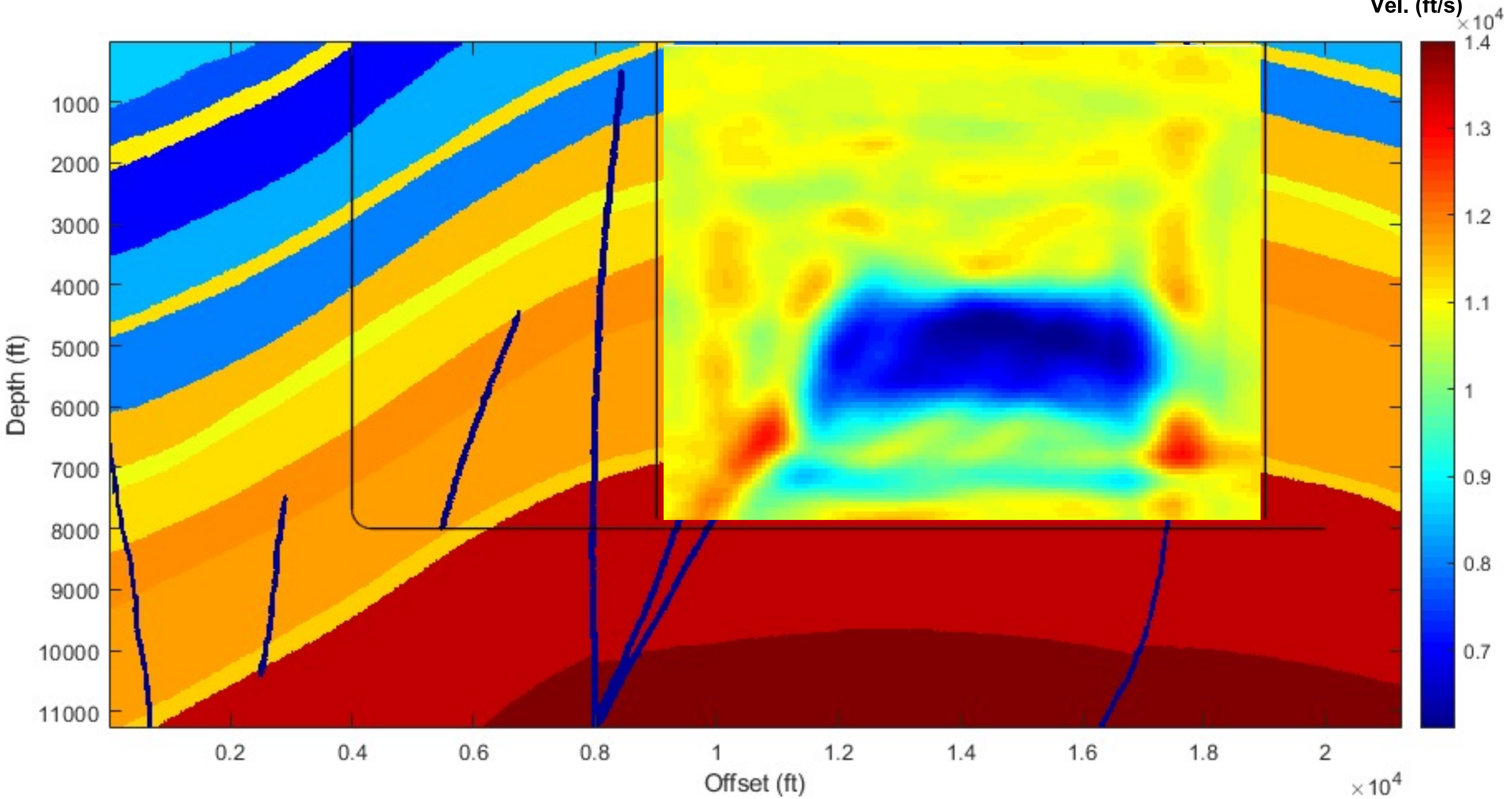
Initial Velocity Model before CO2 Injection



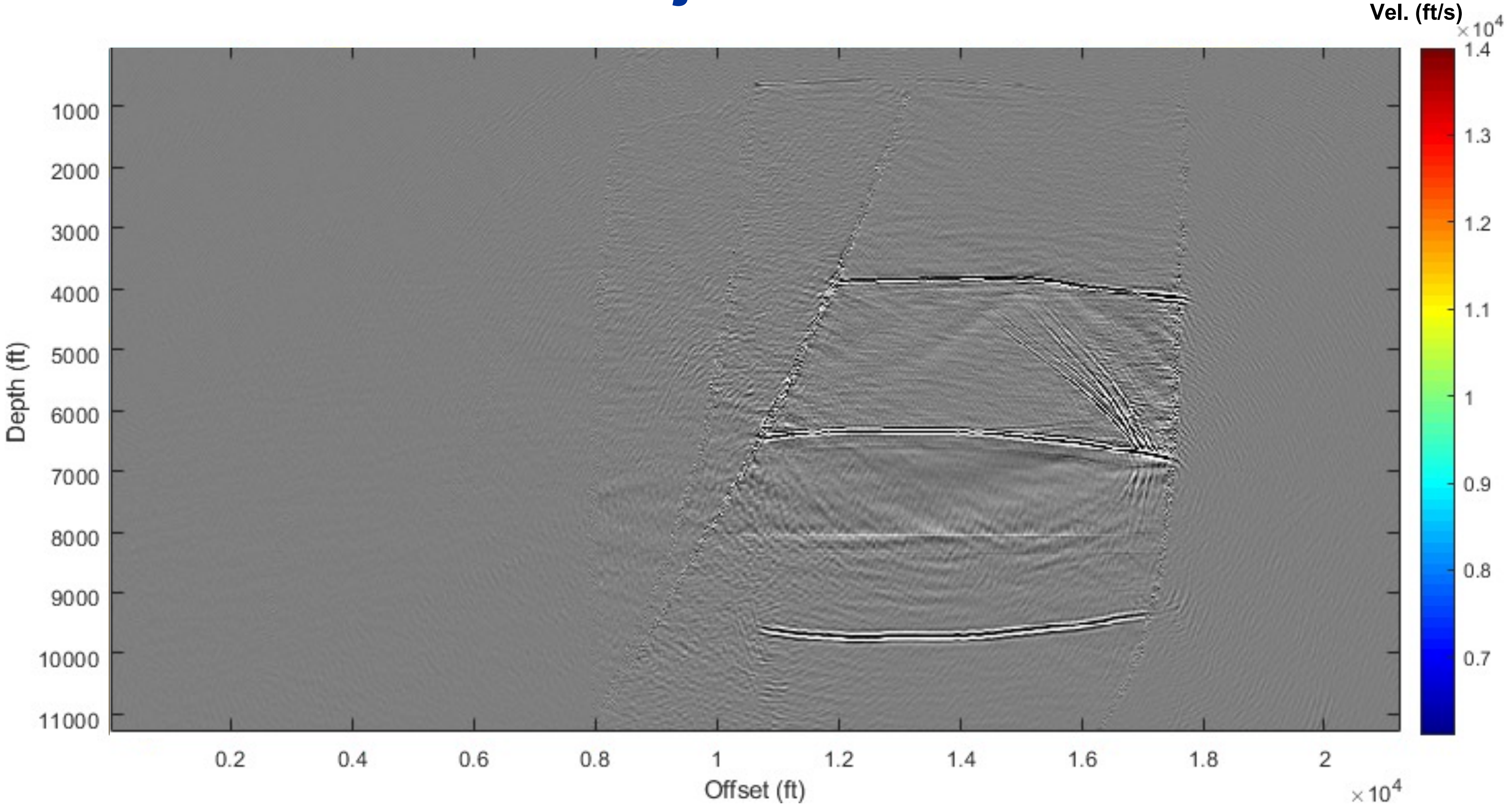
Initial Reverse Time Migration (RTM) Image before CO2 Injection



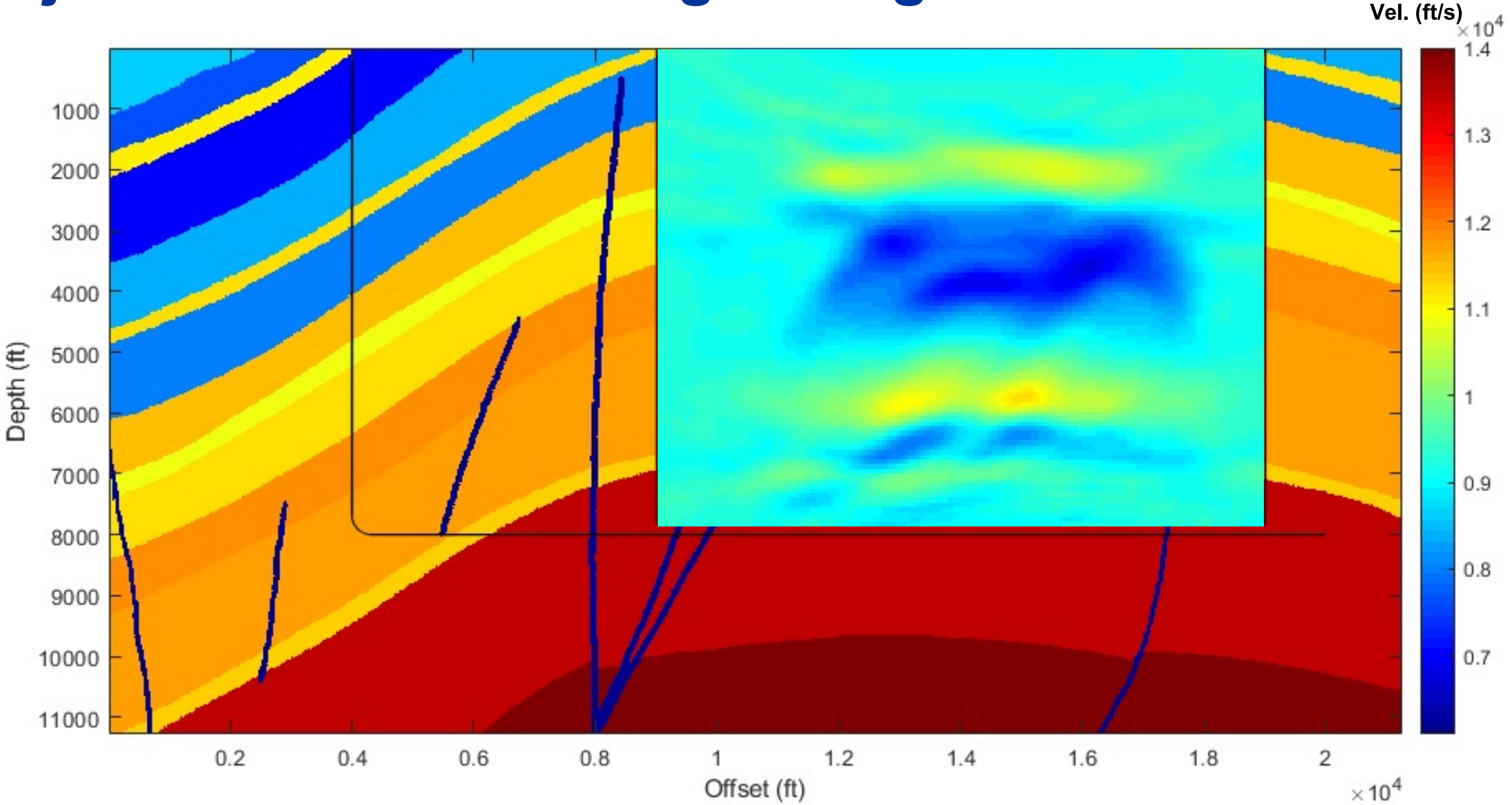
Velocity Tomogram Change from Initial Pre-Injection Condition to CO2 Injection into the Reservoir



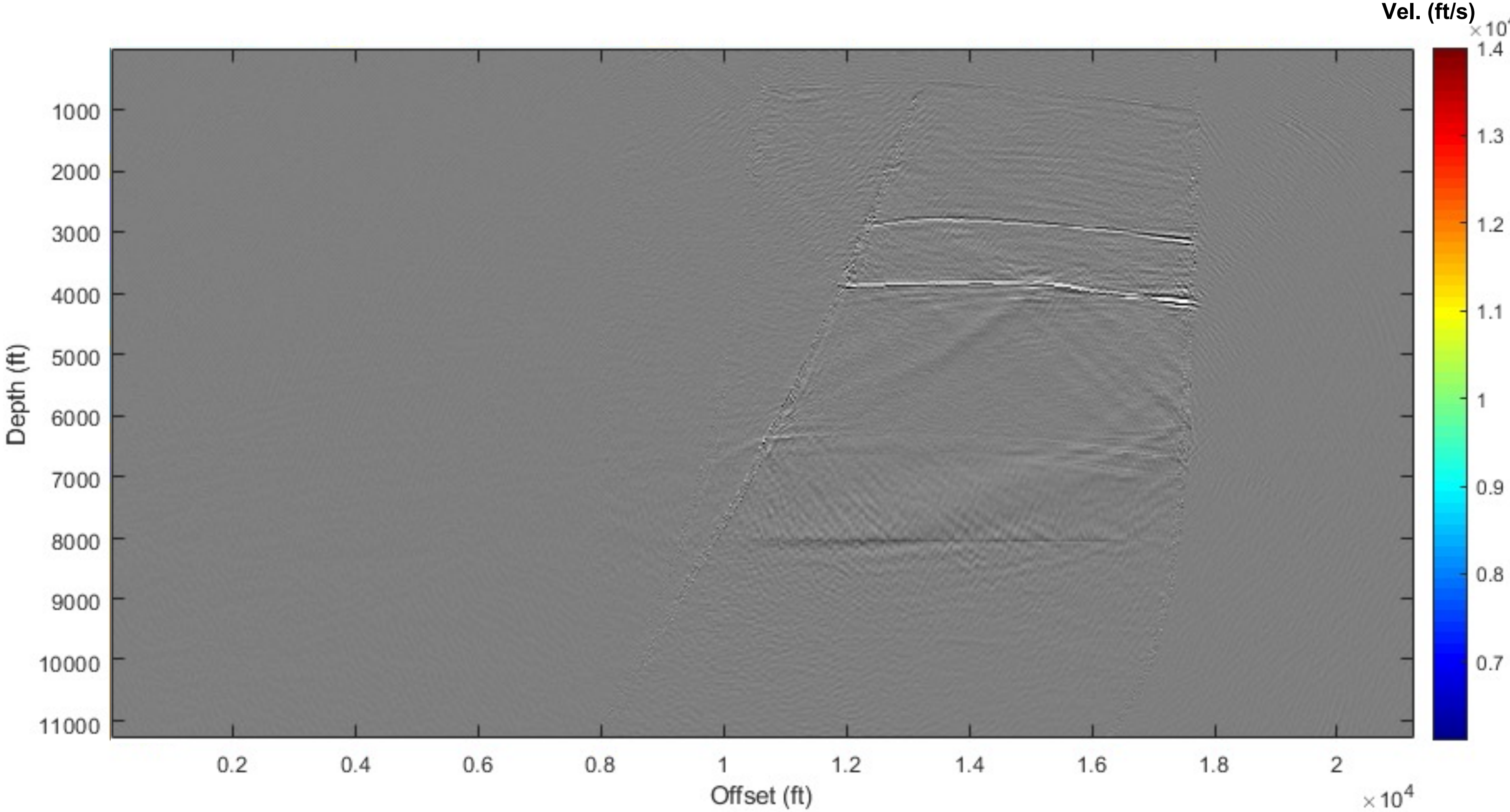
Time-Lapse RTM Change from Initial Pre-Injection Condition to CO2 Injection into the Reservoir



Time-Lapse Tomogram Change from CO2 Reservoir Injection to CO2 Leaking through the Reservoir Seal



Time-Lapse RTM Change from CO2 Reservoir Injection to CO2 Leaking through the Reservoir seal.

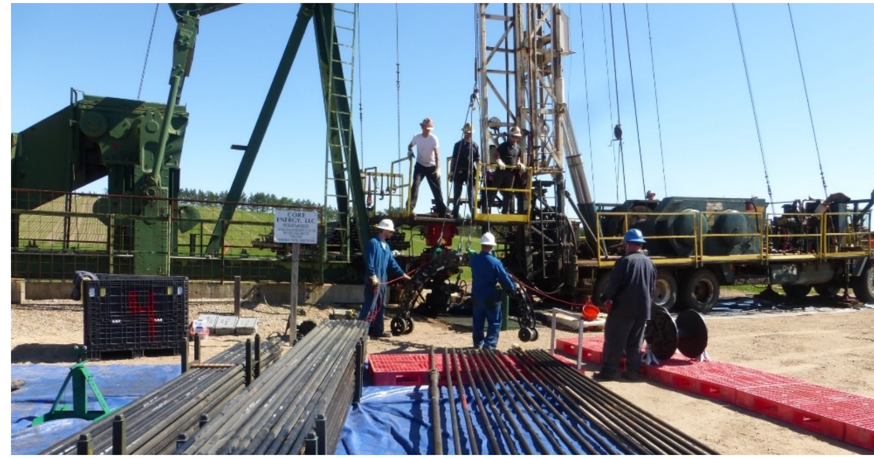


Applications & Examples

- Carbon Capture Utilization and Storage (CCUS)
- Enhanced Geothermal Systems (EGS)
- Underground Gas Storage including H_2 (UGS)
- Cleaner Enhanced Oil & Gas (CEOG)
- Pipeline Surveying and Monitoring (PSM)
  - Pipeline crossing Hayward Fault
- Monitor Wind Energy Installations

Paulsson, Inc. – Field Experience w/ Optical Sensors

GTI Pipeline Field Test at the PG&E Training Facility in Winters, CA



Battelle/Core Energy Monitoring CO_2 Injection for 30 days

Installation of a 2.7 km optical DSS, DTS & DAS Cable to a depth of 14 ft

Installation of Optical Cables on a Pipeline @ Hayward Fault

What can we learn from the "New Seismic Data"

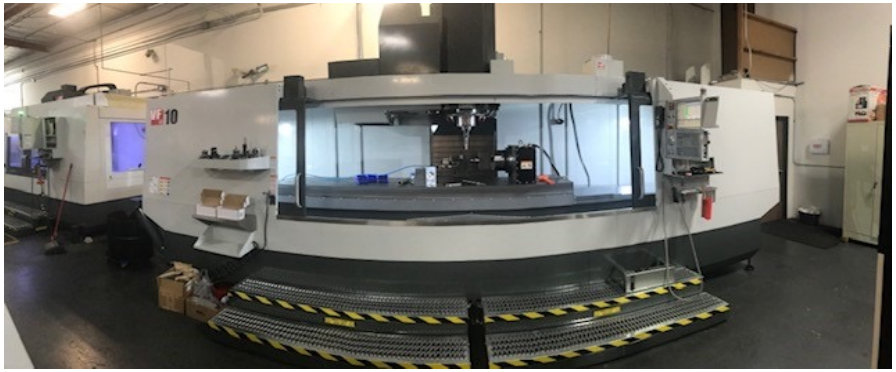
- High Resolution images – much better than surface seismic
- Large volume images – much larger volumes than well logs
- 3D Velocity model to be used for surface seismic processing
- Anisotropic velocity information to focus imaging
- Volumetric rock-mass stress distribution
- 3D Maps of Faults & Fractures - distribution and directions
- Map fluid flow and fluid boundaries
- Types of fluids in the reservoirs:
  - Gas vs Oil vs Water vs CO2 vs Steam
- Map permeability in reservoirs
- Map temperature distribution
- Monitor Hydro Fracturing Operations

- **Much better understanding of the dynamic processes of injecting and producing liquids and gases**

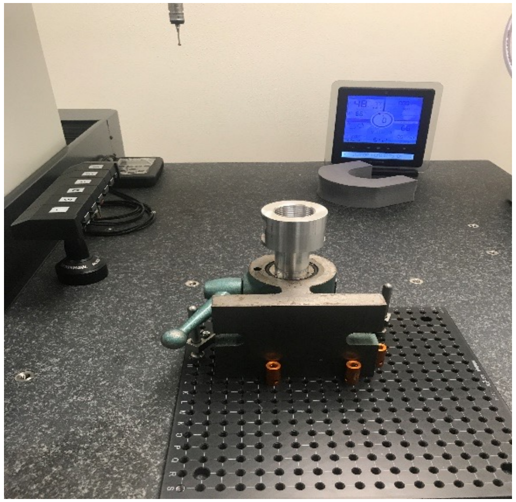
Presentation Outline

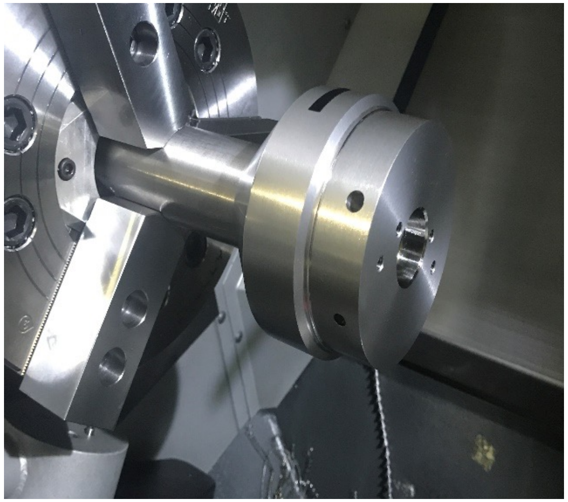
- Optical Seismic Sensors
- Borehole Vibratory Seismic Sources
- Applications & Examples
- Paulsson Staff and Facility

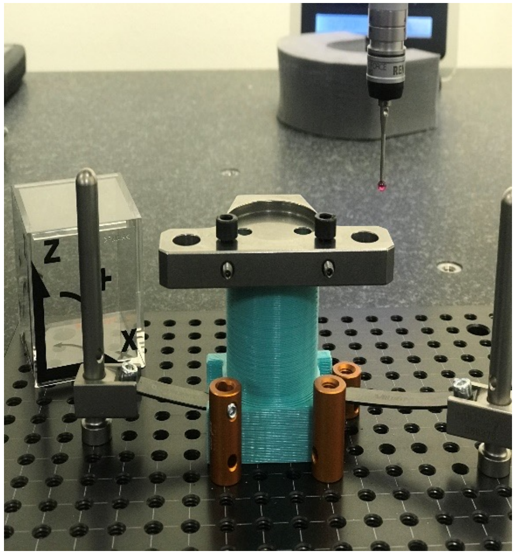
Paulsson Machine Shop 2021 – Seven CNC machines



Coordinate Measuring Machines (CMM)
Sample of In-process parts as of 2021.01.25







60 3D VSP Surveys Recorded with Our Pipe Deployed Seismic Arrays
About 50 papers & reports published on these surveys.

2018 – Large geotechnical survey in Florida to detect & map developing sinkholes.
2017 – MS survey in the COSO field. Large geotechnical survey in Florida to detect & map developing sinkholes.
2016 – VSP and MS survey for Battelle in a carbonate reef in Michigan to track CO2.
2015 – MS survey in the Geysers Geothermal Field. XSP test for S. Cal operator.
2014 – Extensive Operational and Performance Tests of Fiber Optic Seismic Vector Sensors (FOSVS)®
2013 – VSP & XSP Operational and Performance Tests of Fiber Optic Seismic Vector Sensors (FOSVS)® for ConocoPhillips in Pearland, TX
2012 – First Test of Fiber Optic Seismic Vector Sensors (FOSVS)®

4th Gen FOSVS Array introduced

2011 – 100 Level 3D VSP for Gold prospecting
2011 – 100 level 2D VSP for Gold prospecting
2008 – 80 level array survey for BGP in the Daqing Oil field, China.
2007 – 160 level array survey for BGP in the Daqing Oil field, China.
2007 – 80 level array survey for Gas Storage Reservoir characterization in Santa Barbara, CA.
2007 – 160 level array surveys for ADCO in two wells. In 2007 World Record: 9 million traces.
2007 – 80 level arrays in two wells time lapse survey for Shell Canada.
2007 – 80 level array in one well for ConocoPhillips to characterize a fractured reservoir.
2007 – 80 level array survey for ExxonMobil to characterize a fractured reservoir.
2006 – 160 level array survey for BP. Largest onshore survey in the US as of 2006: 3 million traces. World Record.
2006 – 80 level arrays in two wells time lapse survey for Shell Canada.
2005 – 80 level array: Passive Seismic Survey: 1,000 earthquakes/3TB/0.25 ms sampling rate for 2 weeks

3rd Generation Array introduced

2005 – 80 level arrays in two wells time lapse survey for Shell Canada.
2004 – 80 level array survey for CO2 monitoring for US Dep. of Energy.
2004 – 80 level array survey for CO2 monitoring for US Dep. of Energy.
2004 – 40 level tools - 1.8 million trace three well 3D VSP survey in Oman in the Middle East.
2004 – 80 level tool, 25’ spacing - 285,000 trace VSP in AK to map methane hydrate deposits.
2003 – 80 level tool - 400,000 trace 4D (Time lapse) VSP in WY.
2003 – 160 level tool - 800,000 trace 3D VSP in TX.
2002 - 80 level tool - a 9C 576,000 trace 3D VSP in NM.
2002 – 80 level tool - 3.0 million trace 4 well 3D VSP survey at the Milne Point field on the North Slope, AK. World Record # 3C sensors in four wells
2002 – 80 level tool - 7.5 million trace five well marine 3D VSP survey in Long Beach, CA. World Record
2002 – 80 level tool - 400,000 trace 4D (Time lapse) VSP in WY.
2001 – 80 level tool - 400,000 trace 3D VSP in the Weyburn Field SK, Canada.
2001 – 80 level tool - 400,000 trace 3D VSP in WY.
2001 – 80 level tool - 360,000 trace 3D VSP In TX.
2001 – 80 level tool - 372,000 trace 3D VSP in TX.
2000 – 80 level tool - 350,000 trace 3D VSP in the North Coyote Field AB, Canada.
2000 – 40 level tool - 1,040,000 trace eight Well 3D VSP in the Edison Field CA.
1999 – 80 level tool - 152,000 trace 3D VSP in the Weyburn field SK, Canada.
1998 – 40 level tool - 100,000 trace VSP the Lost Hills Oil field in CA.

2nd Generation Array introduced

1998 – 40 level tool - 600,000 trace VSP at the Vinton Dome in LA. World Record

DOE is a Long-Term Partner - Thank you!

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  - DOE Contract DE-EE0005509 (2012)
  - California Energy Commission Contract GEO-14-001 (2013)
  - DOE Contract DE-FE0024360 (2014)
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  - DOE SBIR II Grant DE-SC0018613 (2018) Downhole Source

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Thank You!
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