Paulsson, Inc. (PI)

Fiber Optic Seismic Vector Sensor Arrays
by Paulsson, Inc.
&
Injectable Micro Emitters
by Terves LLC
Support by Department of Energy (DOE)
June 25, 2020

Paulsson, Inc. – The Company

- **Paulsson, Inc. is located in Van Nuys, CA**
- **The Paulsson Team is 10 strong = Our Success Key!**
  - 3 Ph.D.'s, 3 M.S. Eng., 3 Machinists, 1 Administrator/Support
- **Three Ph.D. Scientists**
  - Dr. Björn Paulsson: >40 years borehole seismic acquisition
  - Dr. Ruiqing He: >15 years borehole seismic software dev.
  - Dr. Michael Wylie: >10 year optical sensing development
- **Three M.S. Electrical and Mechanical Engineers**
- **Three Machine Shop Staff. Two from a local college that trains machinists on the autistic spectrum.**
- **One Administrator/Support Staff**

Paulsson, Inc. – The Company

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

ISO 1,000 Clean Room to Build Sensors

Machine Shop: Five state-of-art CNC Machines

Fiber Optic Cable Deployment Spools

Applications
for
Borehole Seismic Technology (BST)

Paulsson Commercial Applications Made Possible by DOE Support

The Surveys Below where Recorded by Gen 1, 2 & 3 which Provided Data to Build the 4th Gen System

- 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, Oman and Abu Dhabi

3D VSP Surveys Recorded with Our Pipe Deployed Seismic Arrays

2018 – Large geotechnical survey in Florida to detect & map developing sinkholes.
2017 – MS survey in the COSO field.
2017 - 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. World Record. 1: Optical 3C sensors. 2: Mapped fluid flow.
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. Several World Records: M-3.5 @1,000 Hz.

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

A Large 3D VSP Survey for Anadarko/DOE using an 80 level 3C borehole seismic array on the North Slope, Alaska February 2004

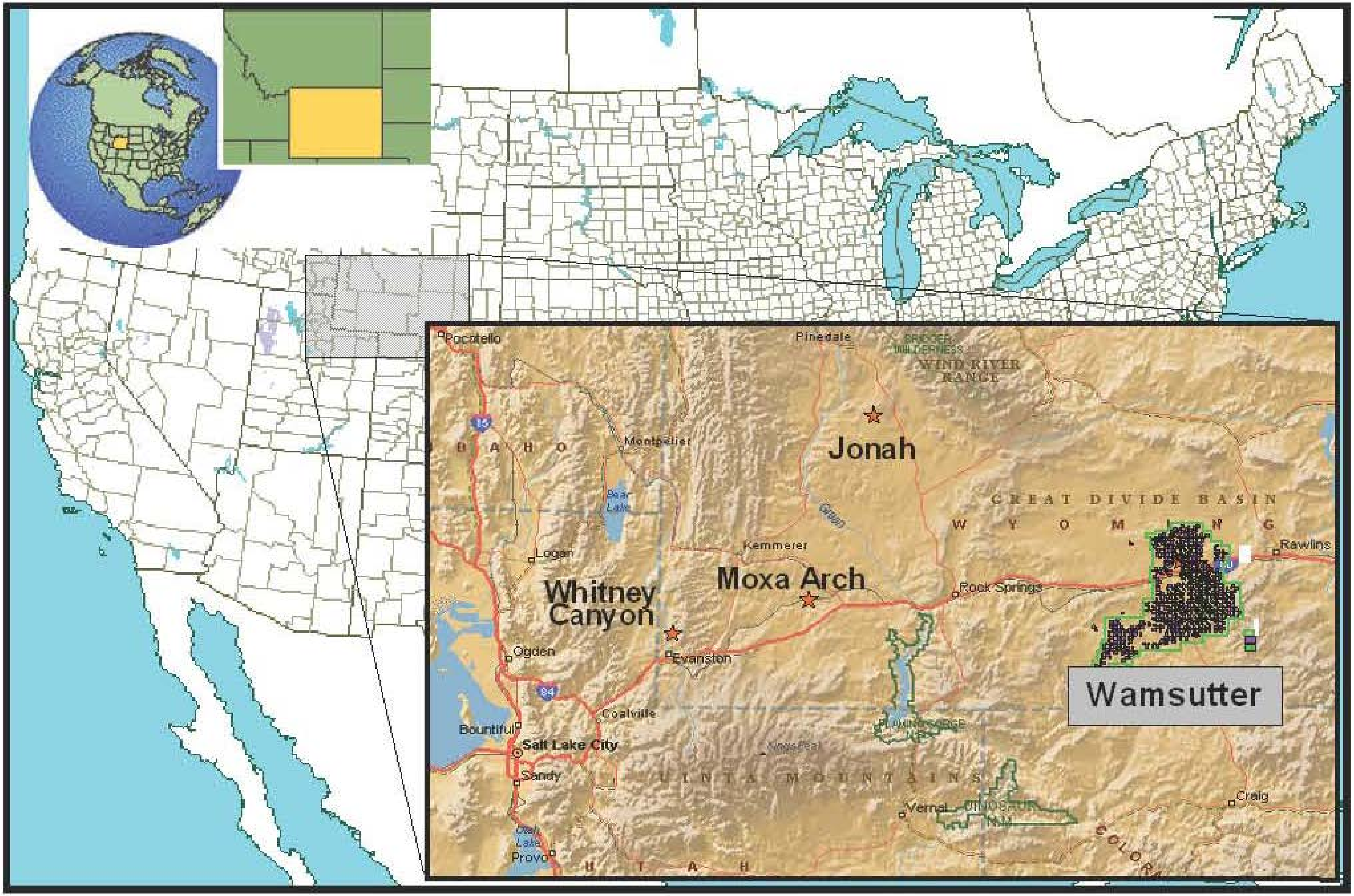
Successfully Mapped Methane Hydrate during the Hot Ice Project!

JPT Cover Feb 2005

A Large 125 level array 3D VSP Survey for ADCO in Abu Dhabi, February – April 2007

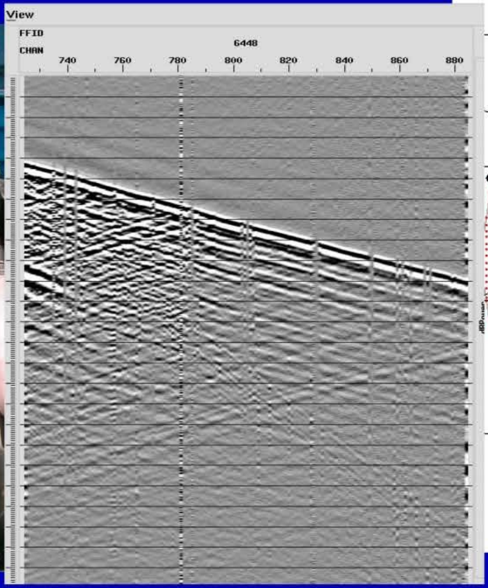
3D/4D Imaging Results Using a 160 level 3C array In the BP Wamsutter Field

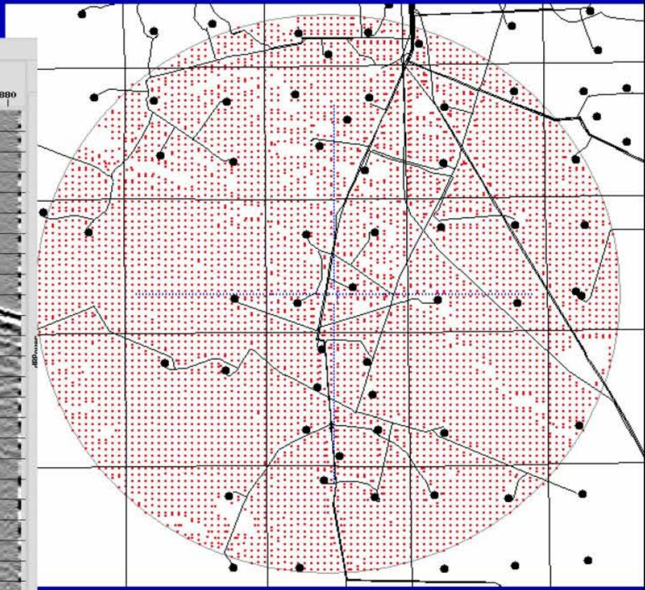
Location of the Wamsutter Field, WY, USA
Test of Surface Seismic & 3D VSP Technologies



Ramkhelawan et al., 2008

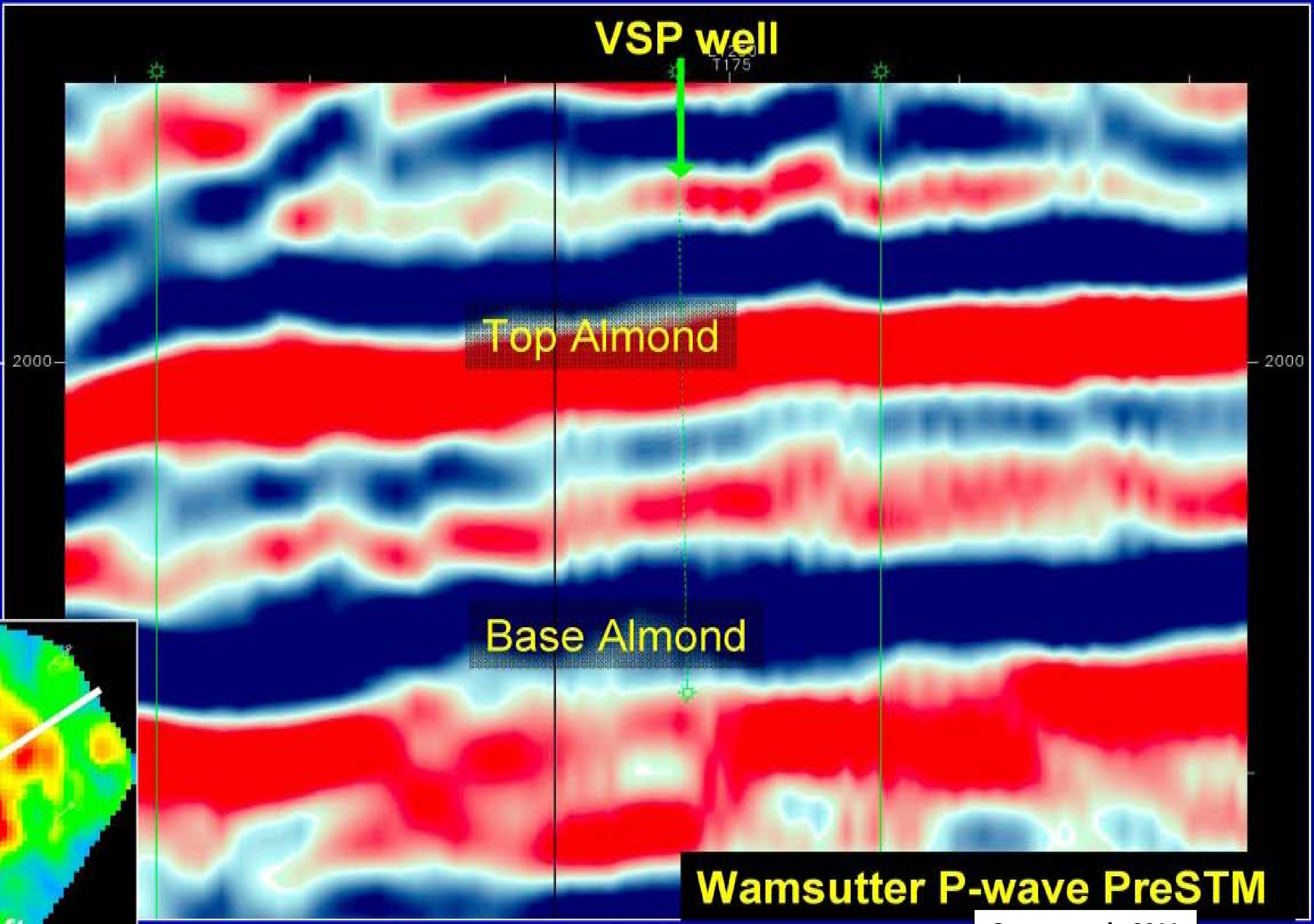
Massive 160 level 3D VSP Survey at Wamsutter, Wy

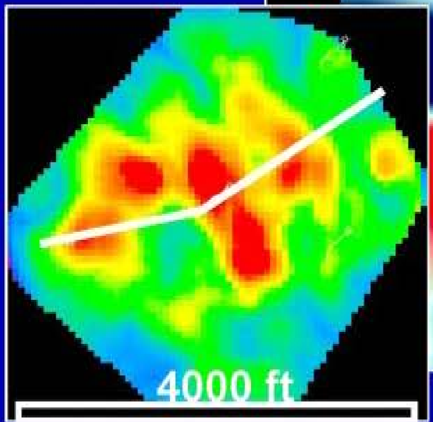




Geetan et al., 2011

A look at the data-comparison to surface seismic data

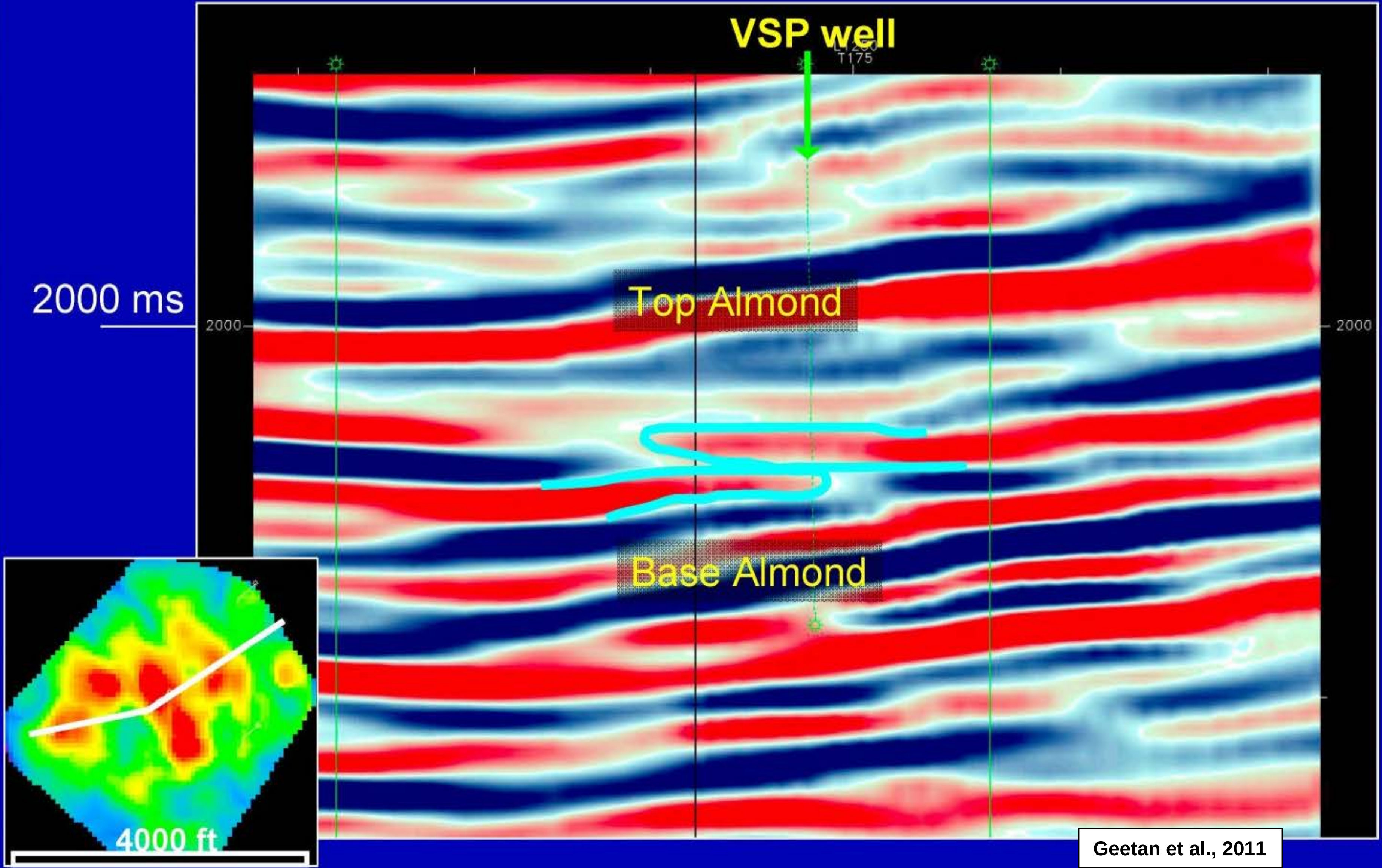




Geetan et al., 2011

VSP Data

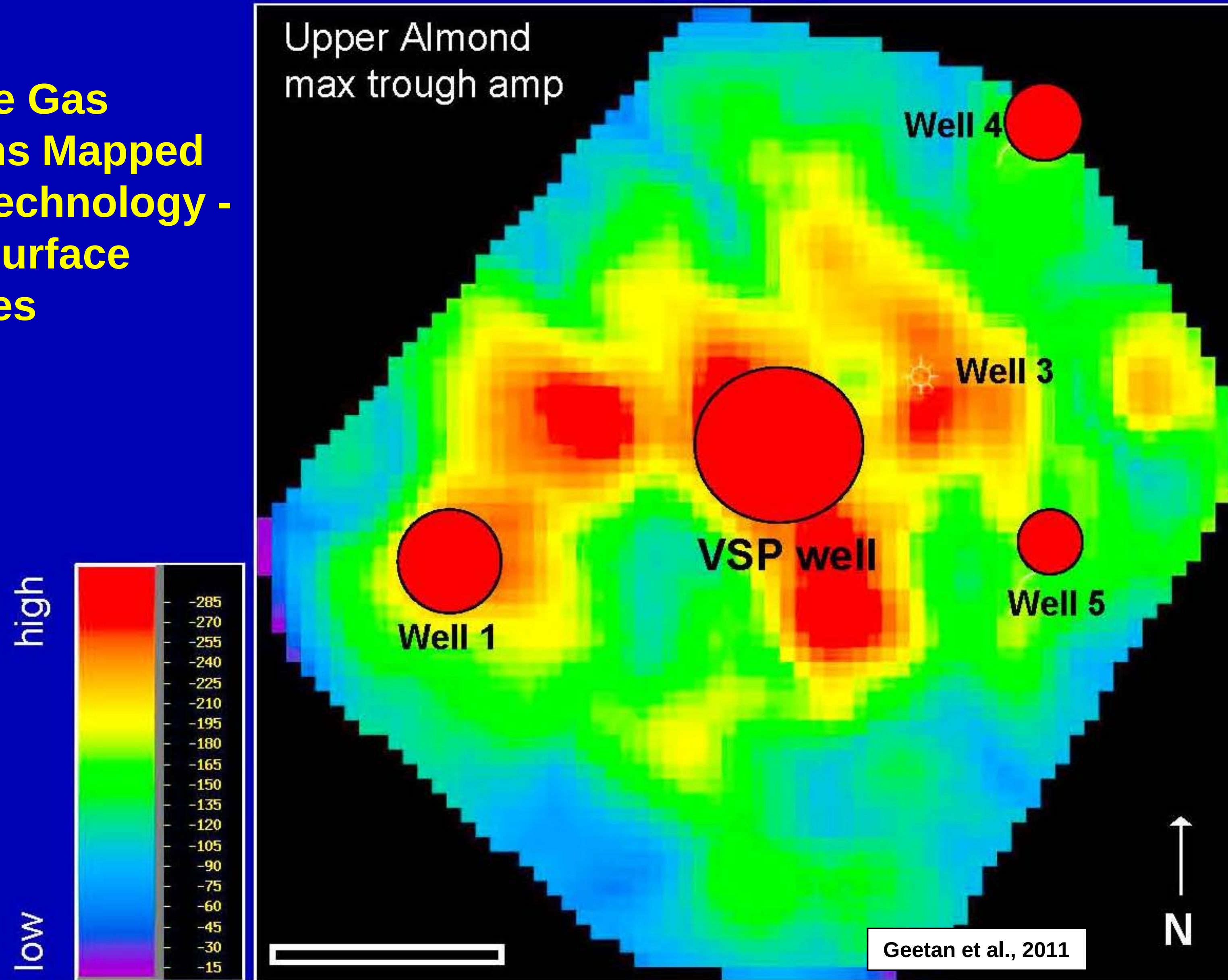
clearly visible terminations that tie into the depositional framework



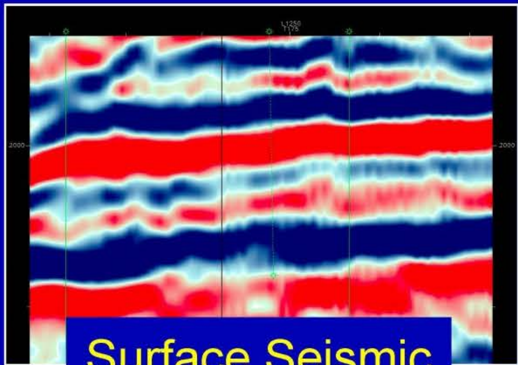
Geetan et al., 2011

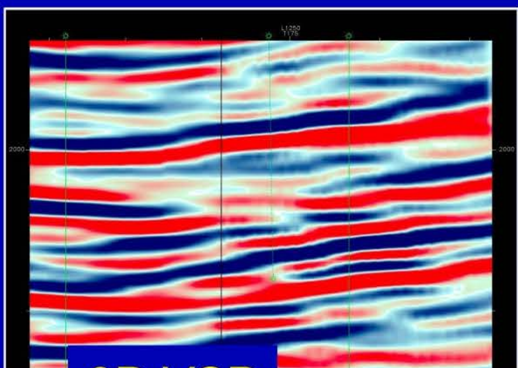
Almond reservoir 3D VSP and Production overlay

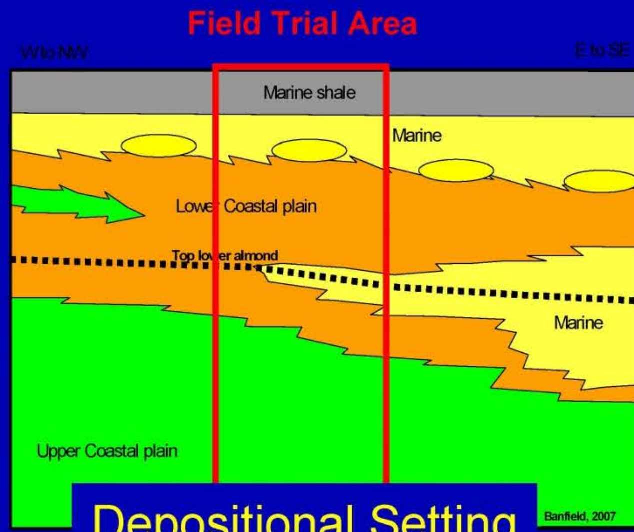
Areas of Large Gas Concentrations Mapped with 3D VSP technology - Not seen on Surface Seismic Images



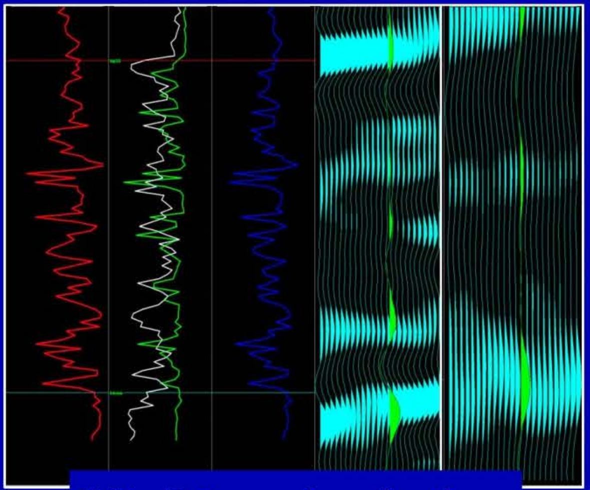
Integration


Surface Seismic

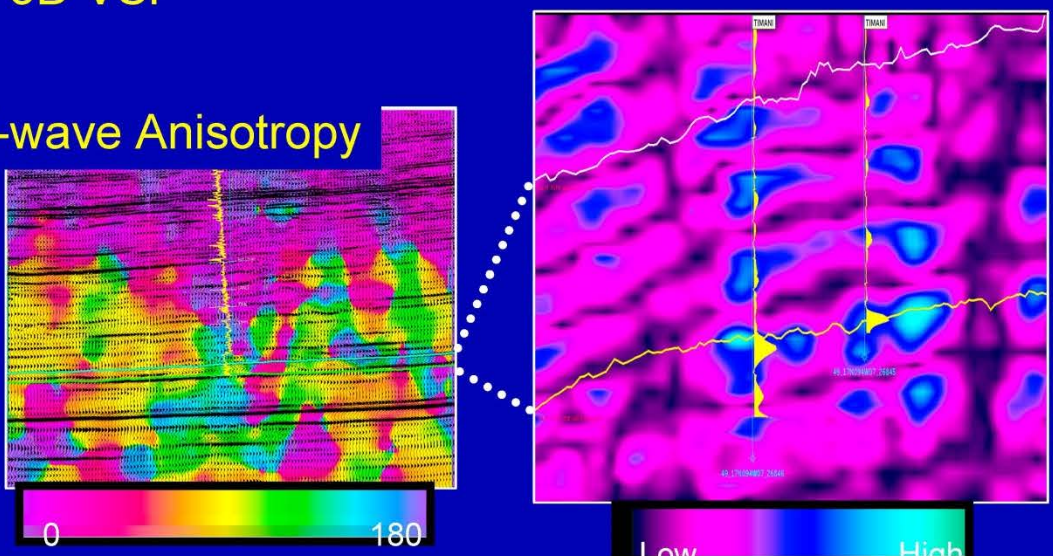

3D VSP

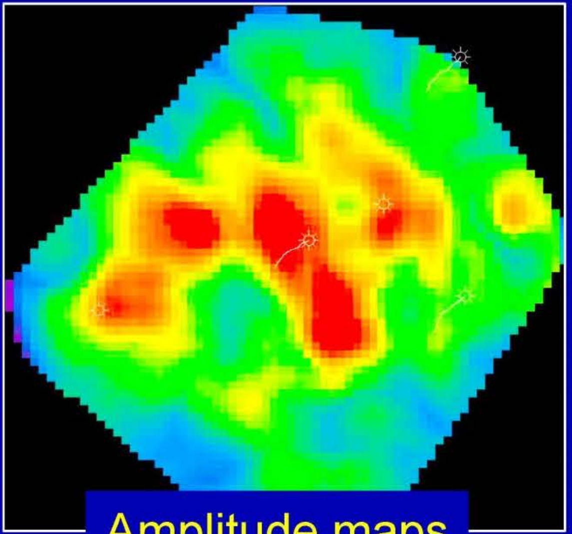


Depositional Setting


Well-to-seismic ties

P-wave Anisotropy

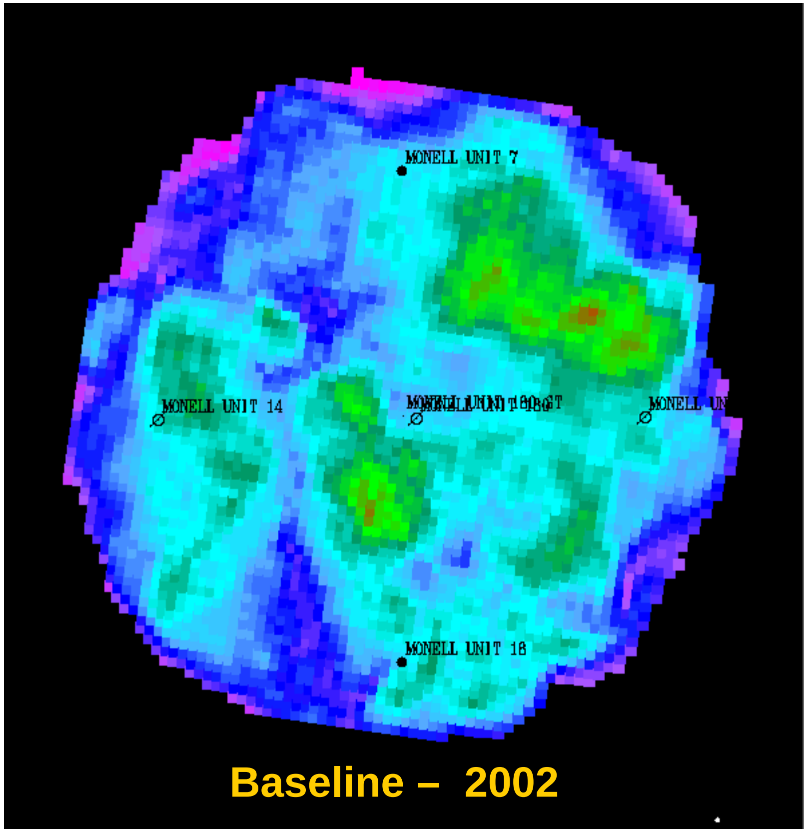


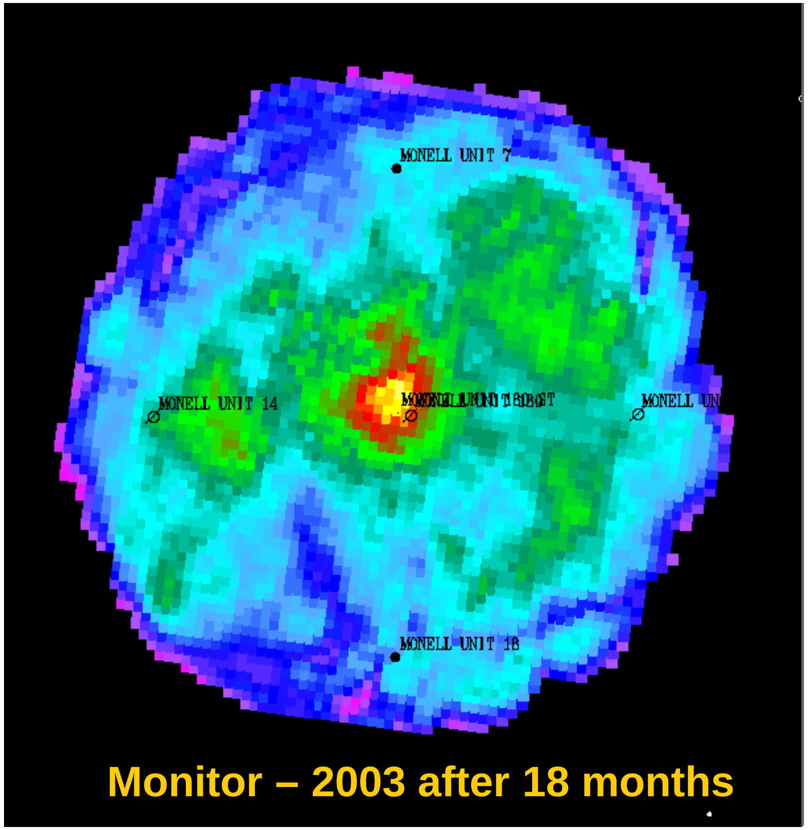

Amplitude maps

Geetan et al., 2011

Time lapse surveys to monitor CO_2 Injection for EOR Depth Amplitude Maps at 4,800 ft showing the CO_2 Plume

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





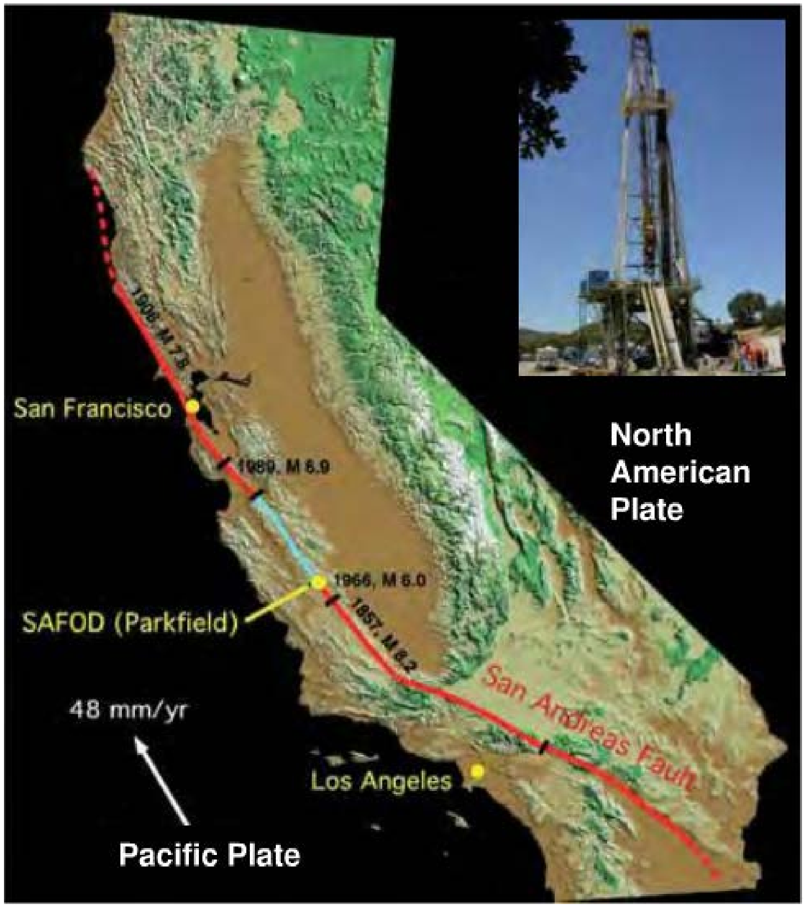
Increased reflectivity in the Monitor Survey 2003 at a depth of 4,800 ft at the well is due to the injected CO_2. Also seen is the increased reflectivity around the water injector wells.

O'Brien et al., 2004

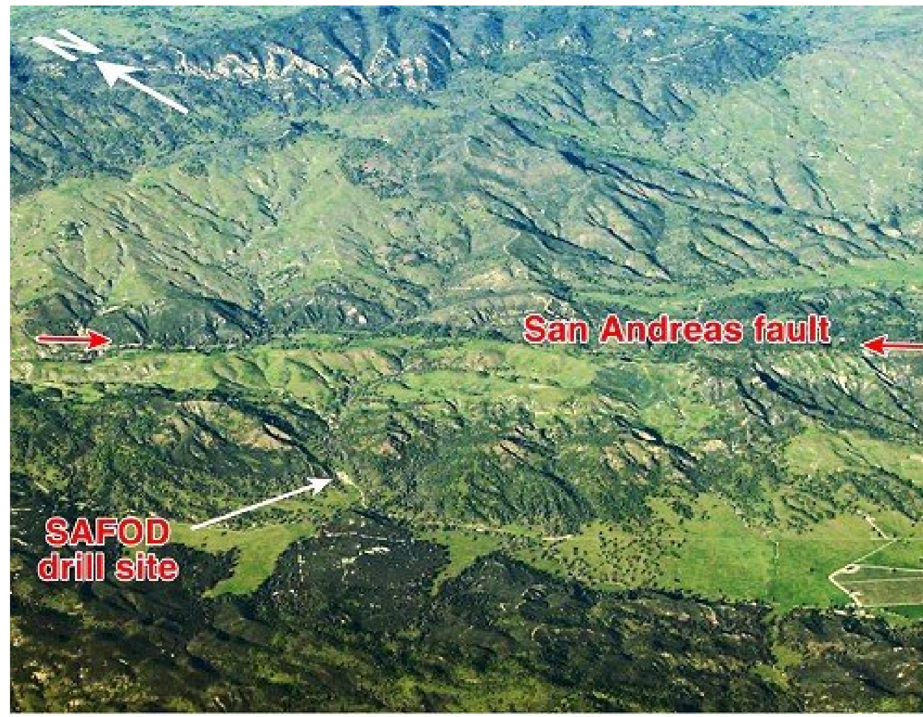
Earthquake Monitoring

SAFOD Survey Area

SAFOD: San Andreas Fault Observatory at Depth

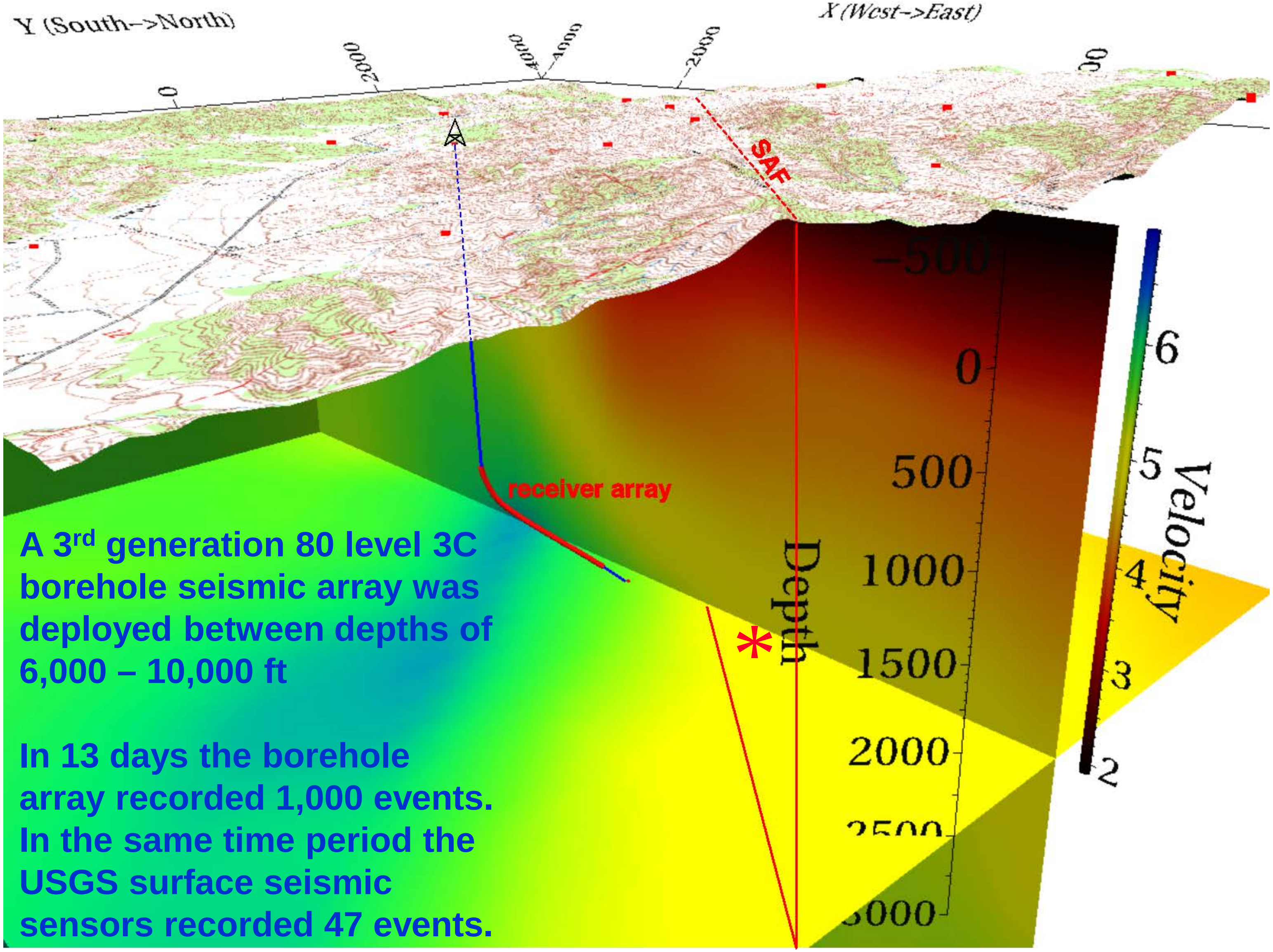


At this rate Los Angeles will be next to San Francisco in 11.3 million years (543 km @ 48 mm/year (LAX – SFO))



Zoback (2006)

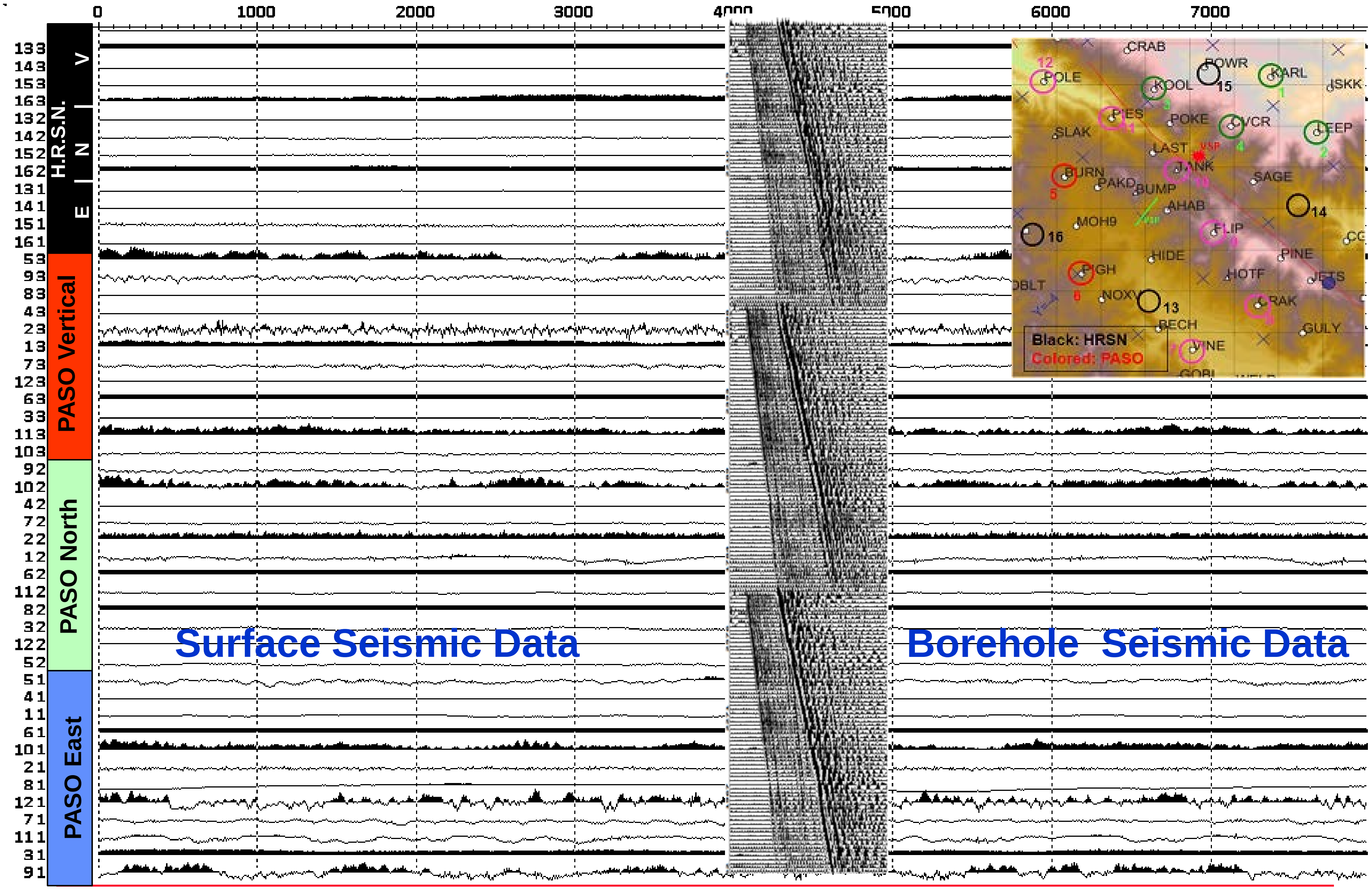
San Andreas Fault Survey Site – Parkfield, California



A 3rd generation 80 level 3C borehole seismic array was deployed between depths of 6,000 – 10,000 ft

In 13 days the borehole array recorded 1,000 events. In the same time period the USGS surface seismic sensors recorded 47 events.

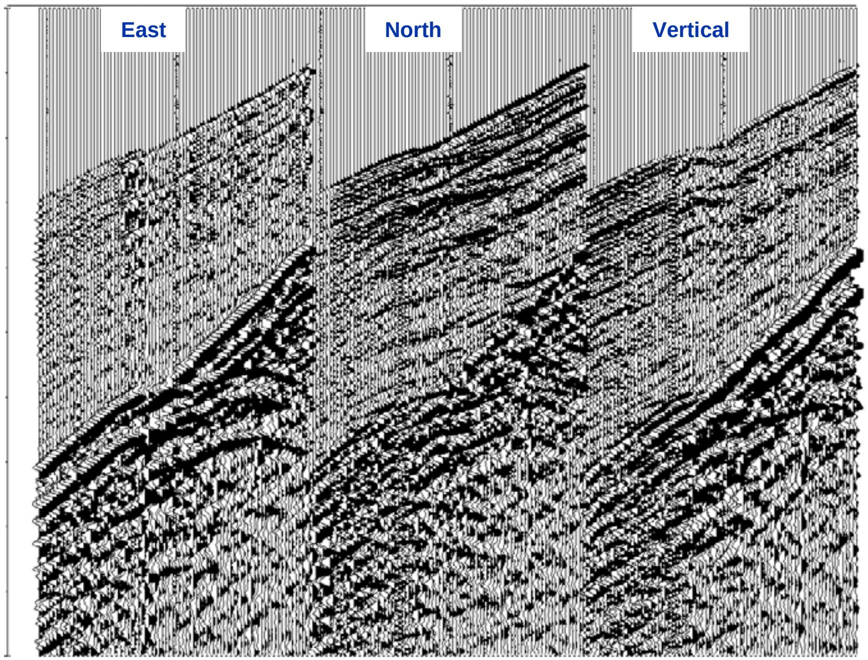
Micro-earthquake Event at SAFOD (4/30/2005 18:49:59)

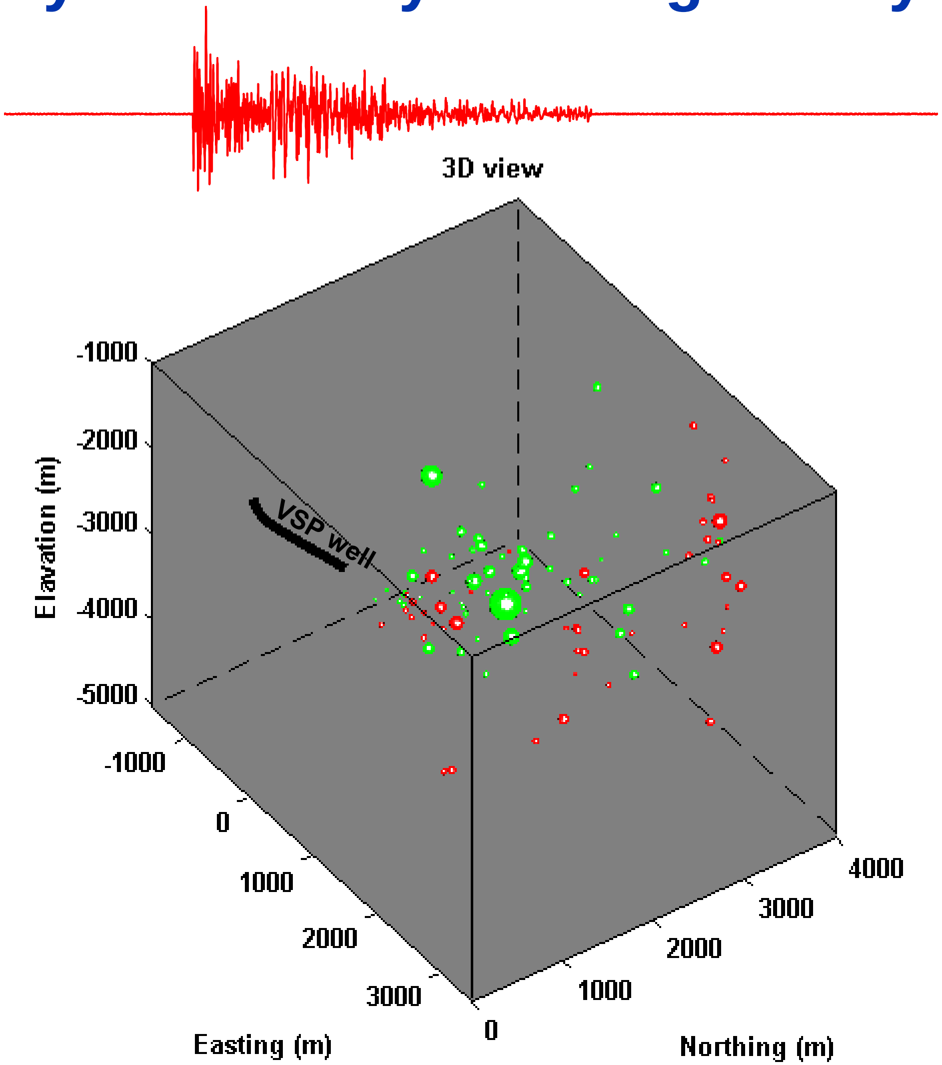


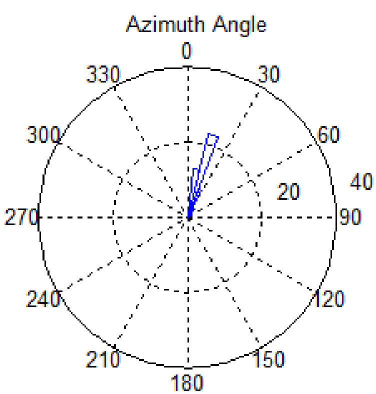
A Micro-Seismic Event Precisely Located by the Large Array

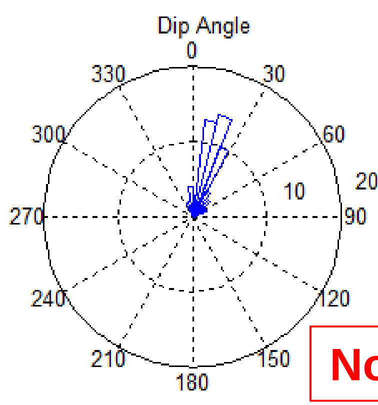
5/10/2005 8:10

USGS: M0.99



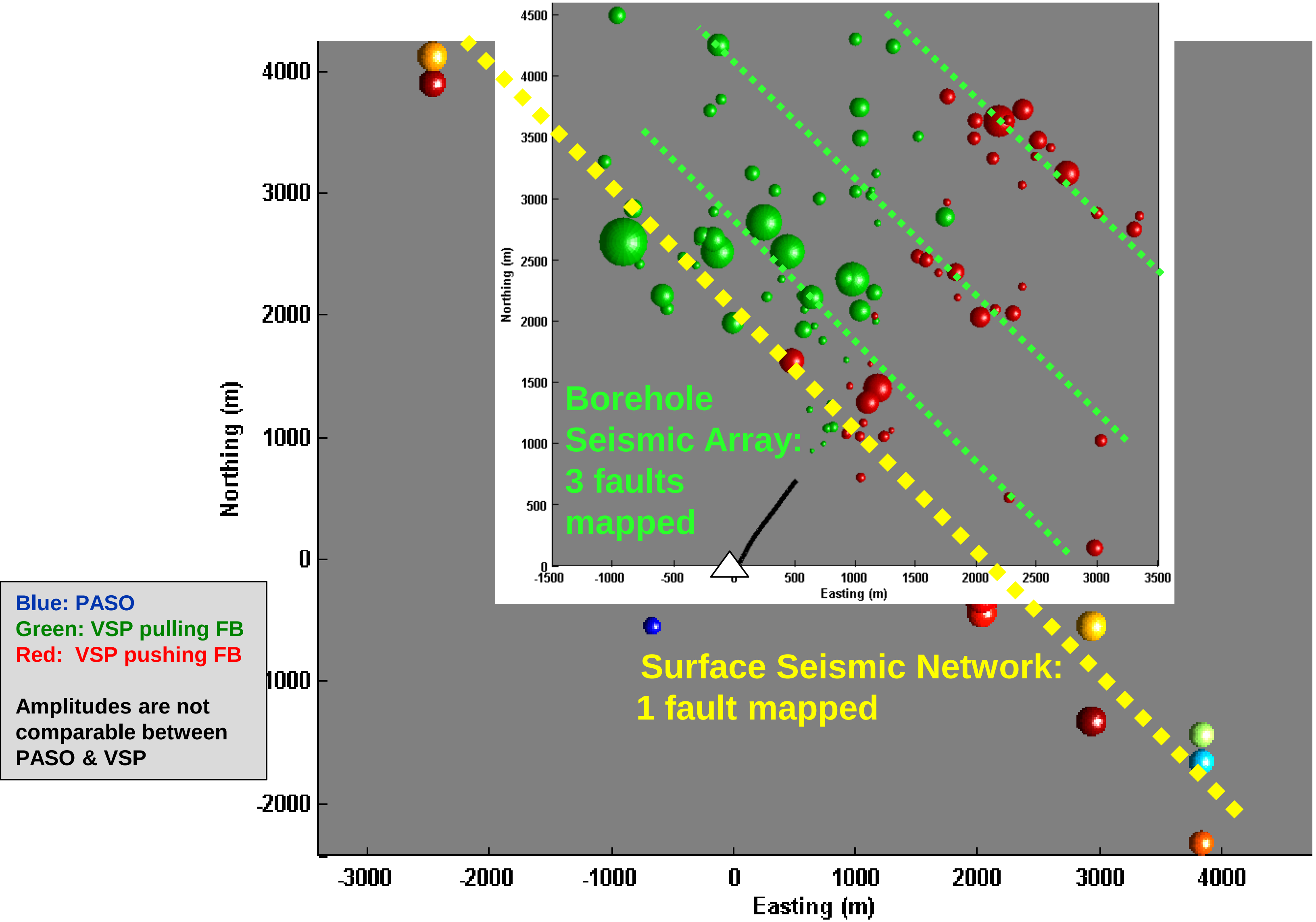






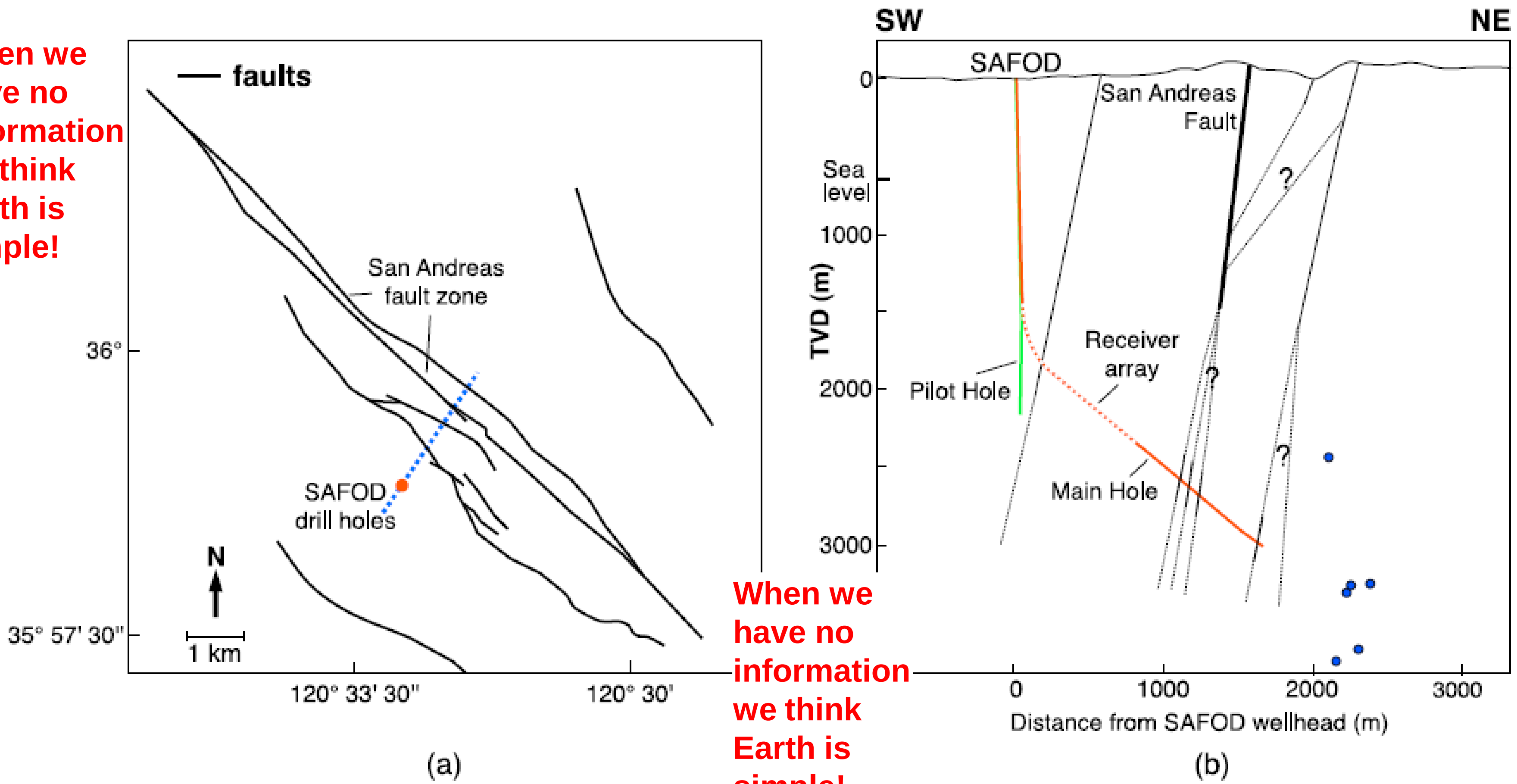
Note the Vector Fidelity of the 80 3C Sensors

Surface Monitoring vs Borehole Monitoring



The Multiple Faults Mapped in SAF Where Verified by Drilling

When we have no information we think Earth is simple!



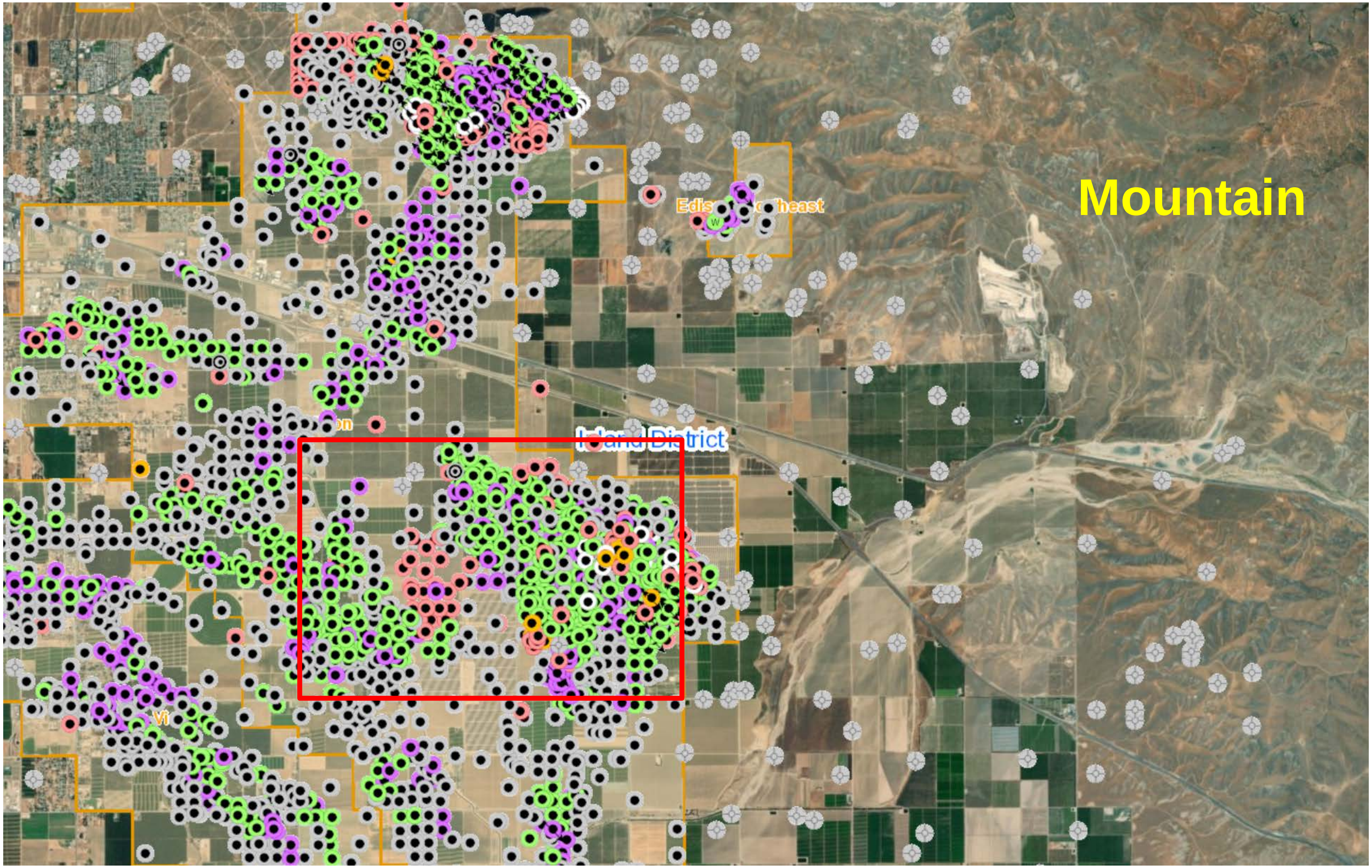
When we have no information we think Earth is simple!

Figure 1. (a) Faults map of the area in the vicinity of the SAFOD drill holes (the geometry of the faults is taken from *Bradbury et al.* [2007]); the blue dotted line represents the direction of the cross section. (b) Fault perpendicular cross section around SAFOD boreholes (geologic interpretation is taken from *Zoback et al.* [2010]) and location of the six earthquakes analyzed further.

A. Reshetnikov, et al., (2010)

Drilling a deviated well in the Edison Field, California Using a 3D image from a Massive 3D VSP

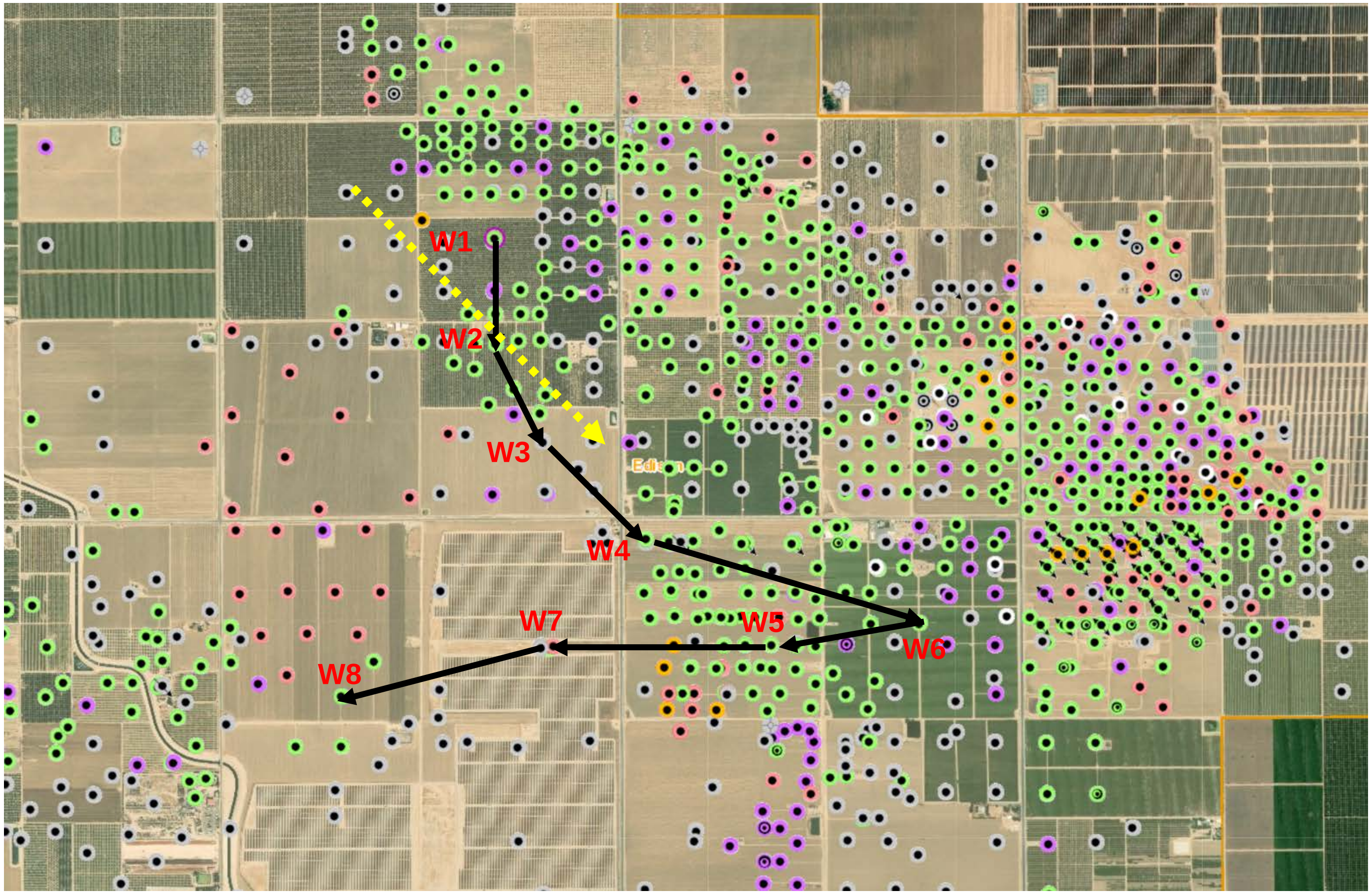
Edison Field. Discovered in 1927.



Edison Field. Discovered 1927. Wells in The Field

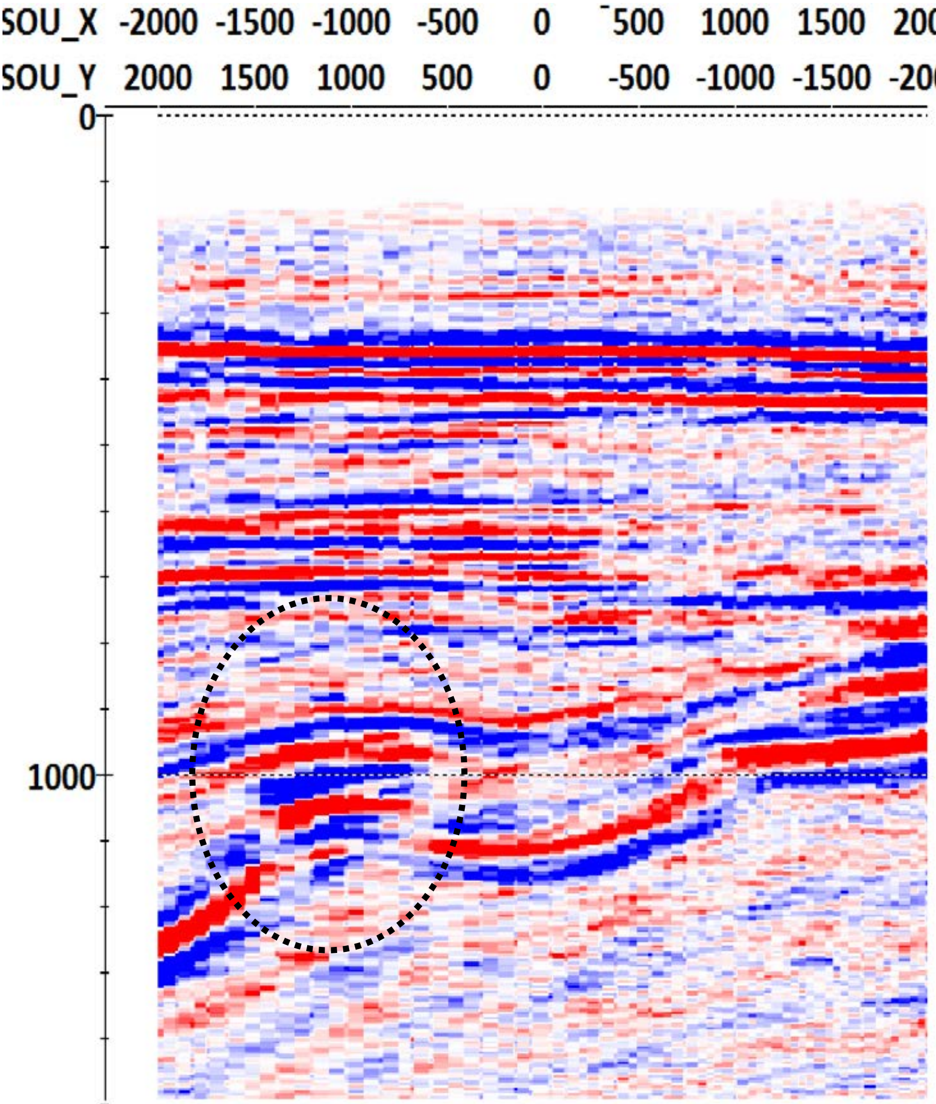
8 well 3D VSP (BST)

Green: active
Gray: plugged
Empty center: dry
Purple: idle
Gold: new
Red: cancelled
Arrow: steaming

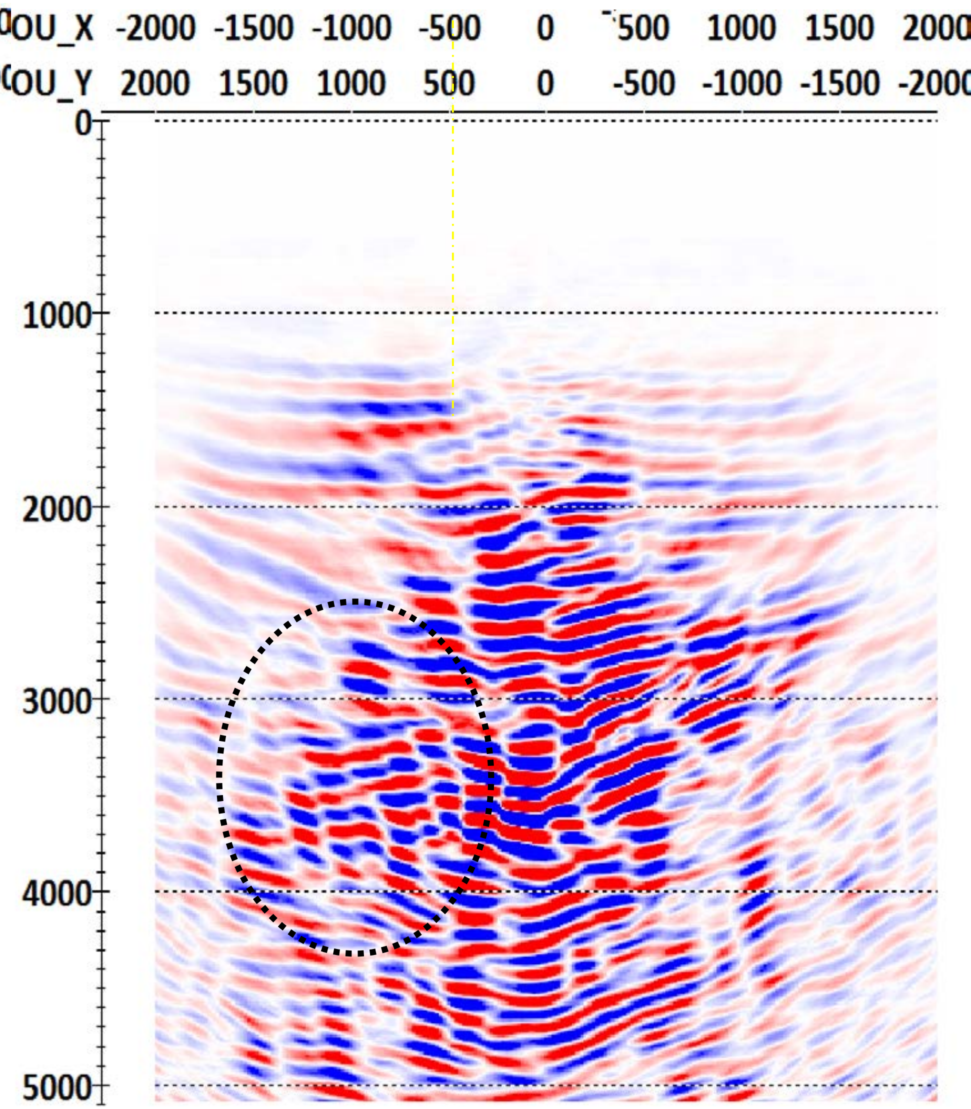


Well 2: NW-SE Section. The second of 8 wells used for the 3D VSP

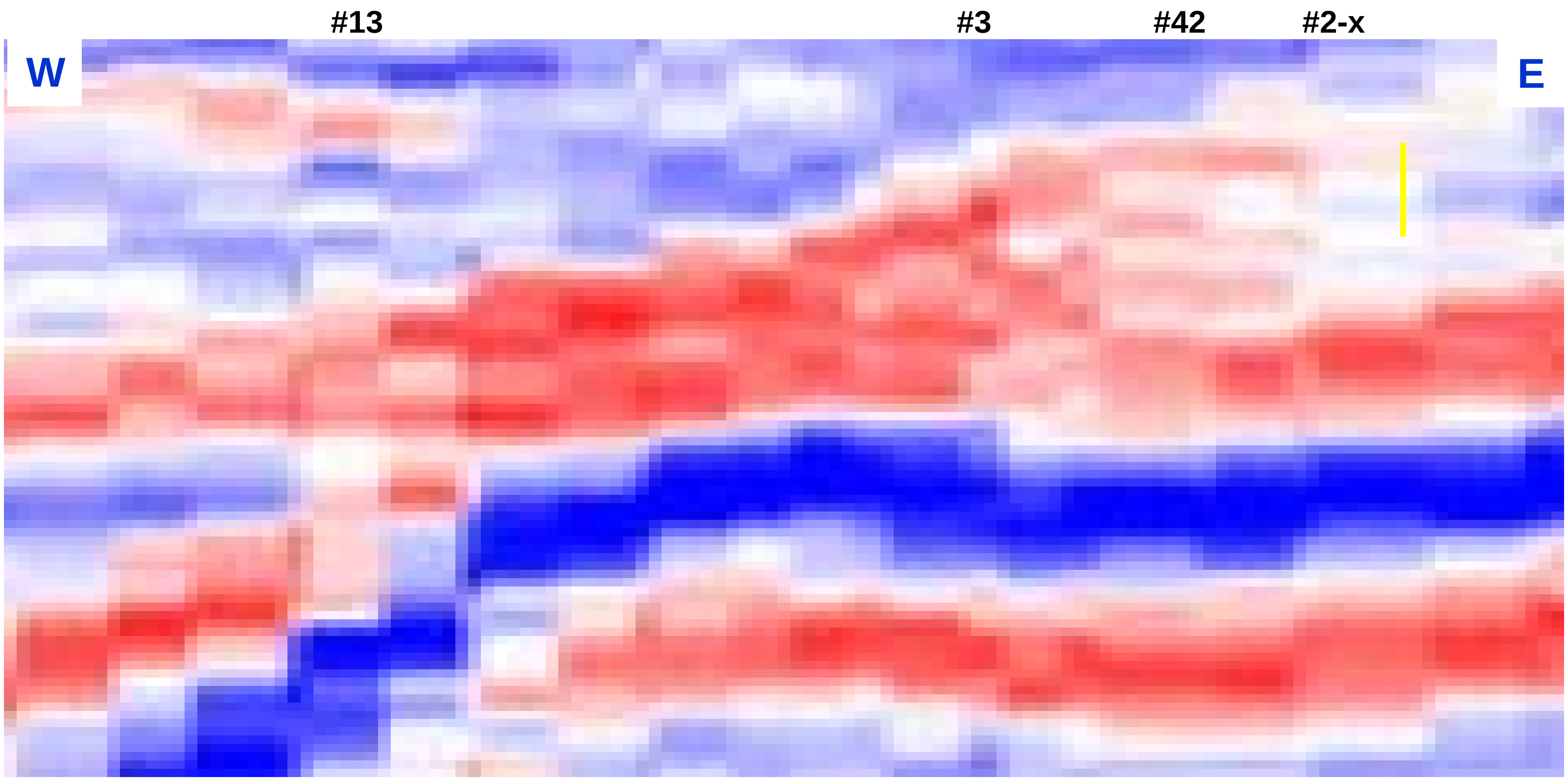
Surface Seismic (PSTM)



Paulsson 3D VSP

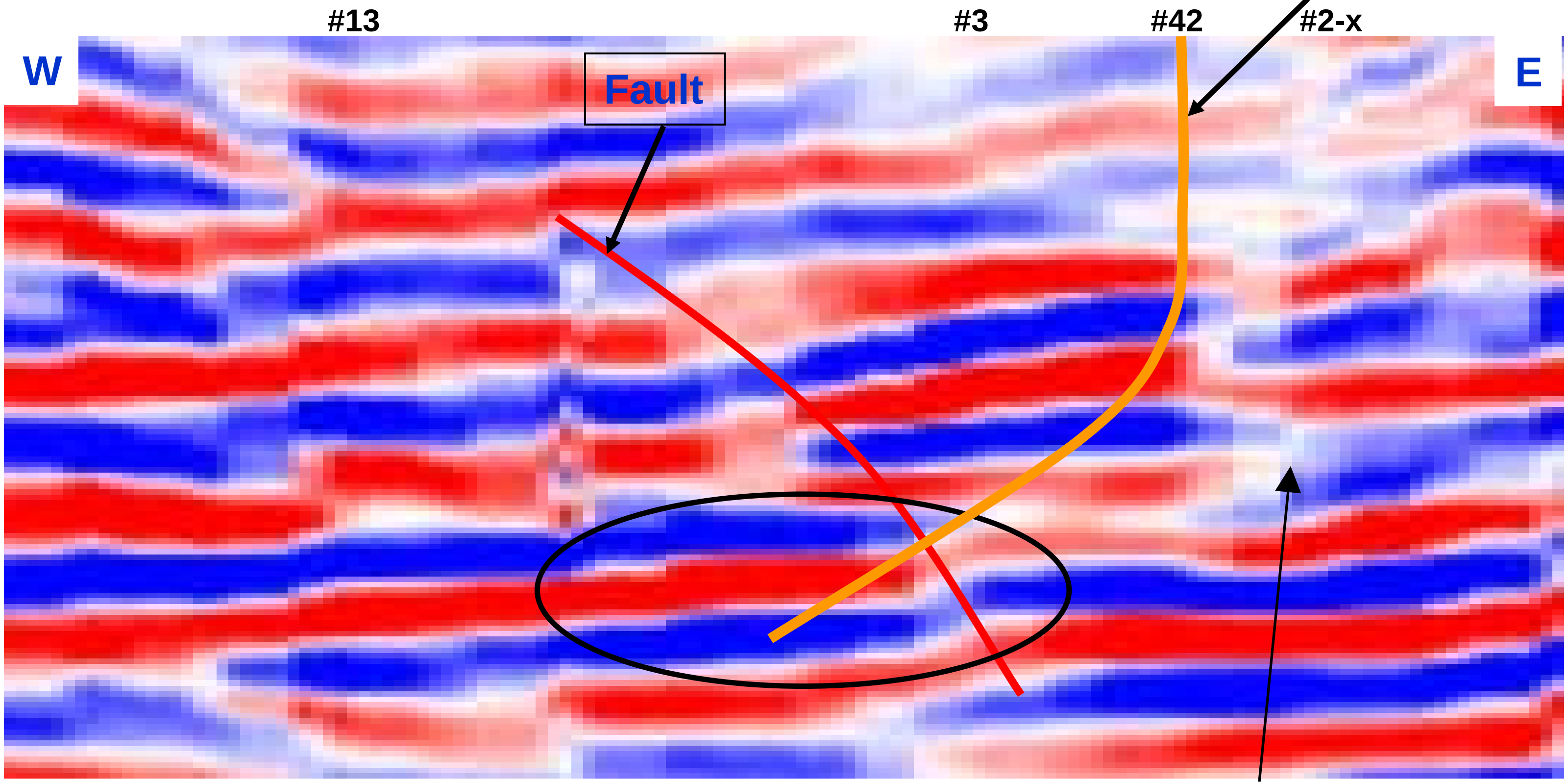


3D Surface Seismic Technology (SST)



3D Borehole Seismic Technology (BST)

New deviated well Drilled on a 3D Borehole Seismic Image

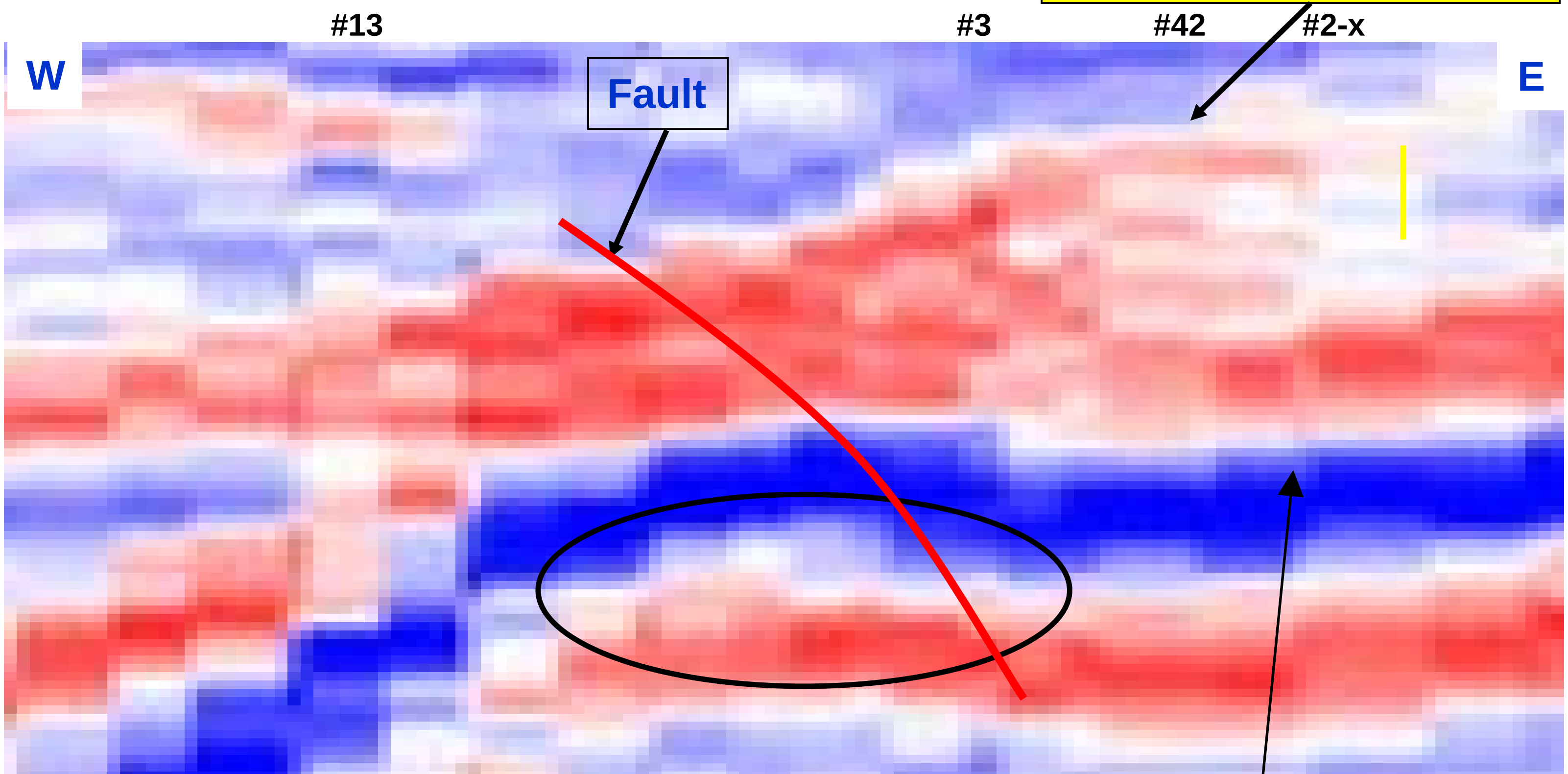


Drilling result: The new well encountered 300 ft of oil and became the biggest producer in the field

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

3D Surface Seismic Technology (SST)

New deviated well Drilled on a 3D Borehole Seismic Image



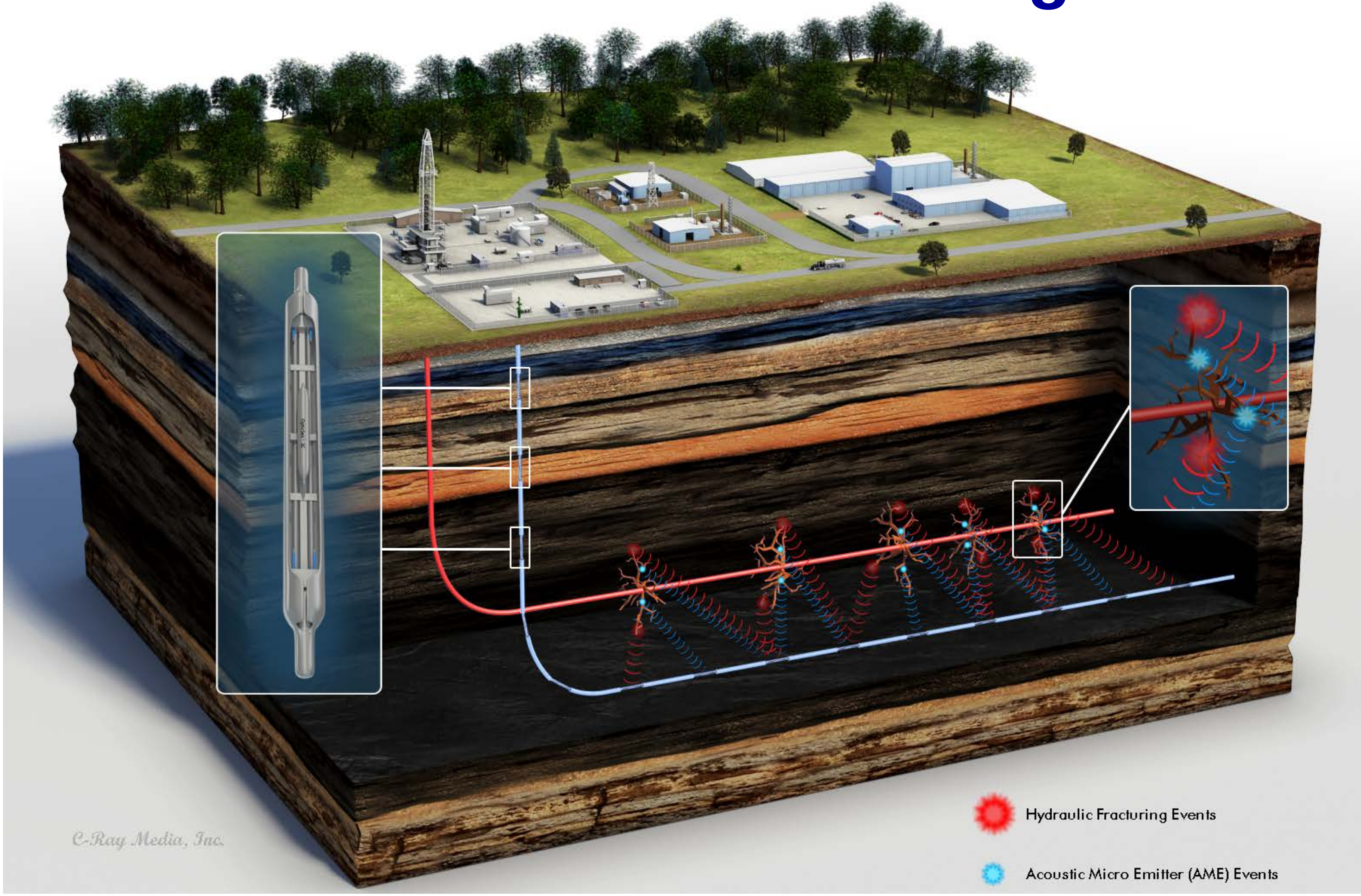
Drilling result: The new well encountered 300 ft of oil and became the biggest producer in the field

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

Technology

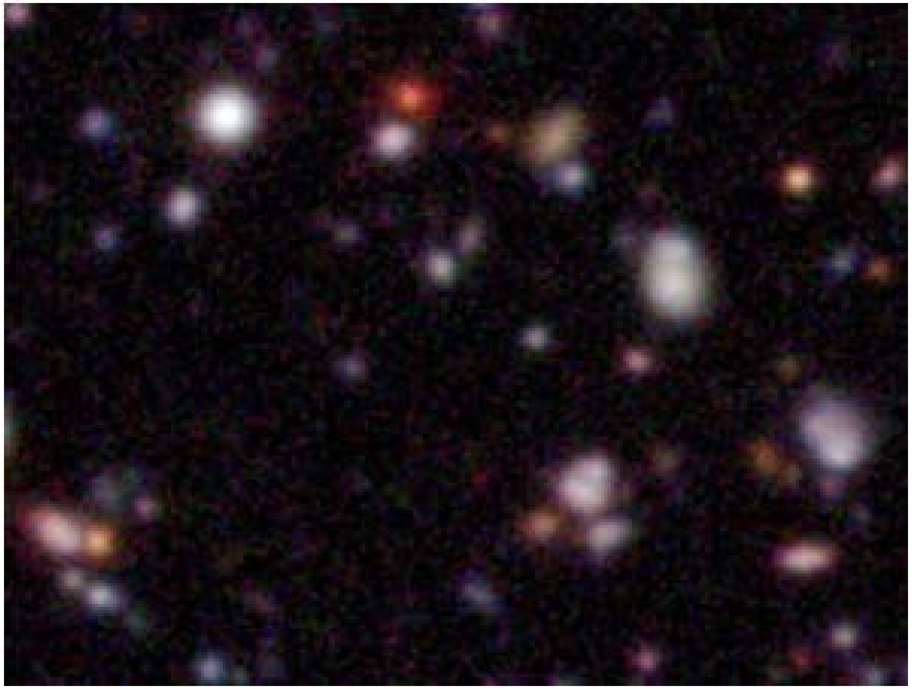
Fiber Optic Seismic Vector Sensor (FOSVS) Field System Funded under DE-FE00024360

Effective & Accurate Monitoring of UOG

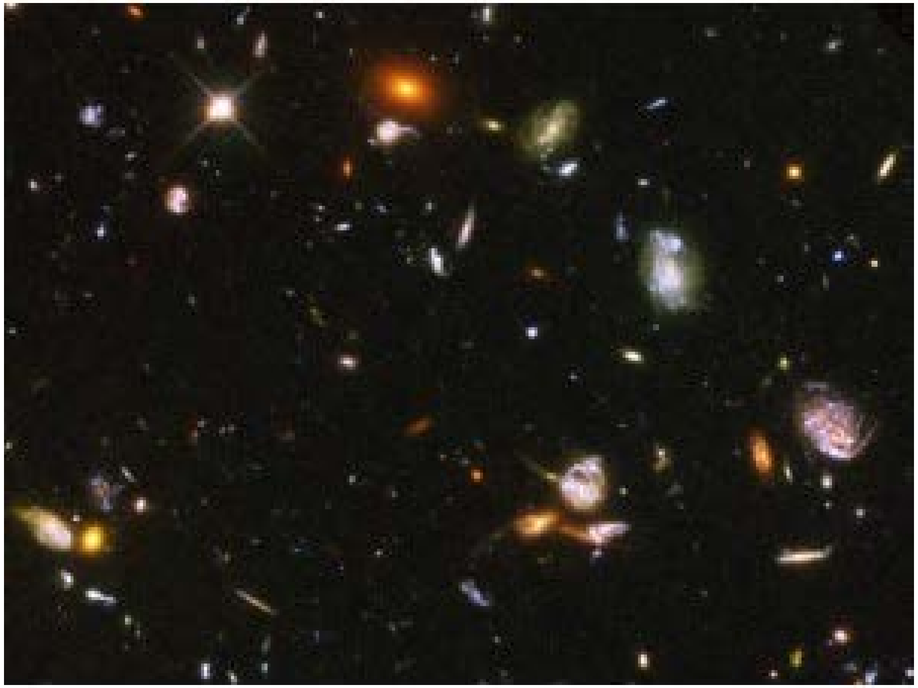


Example From Space Exploration:
Images From Same Region in Space
Technology Allow Us to See the Stars

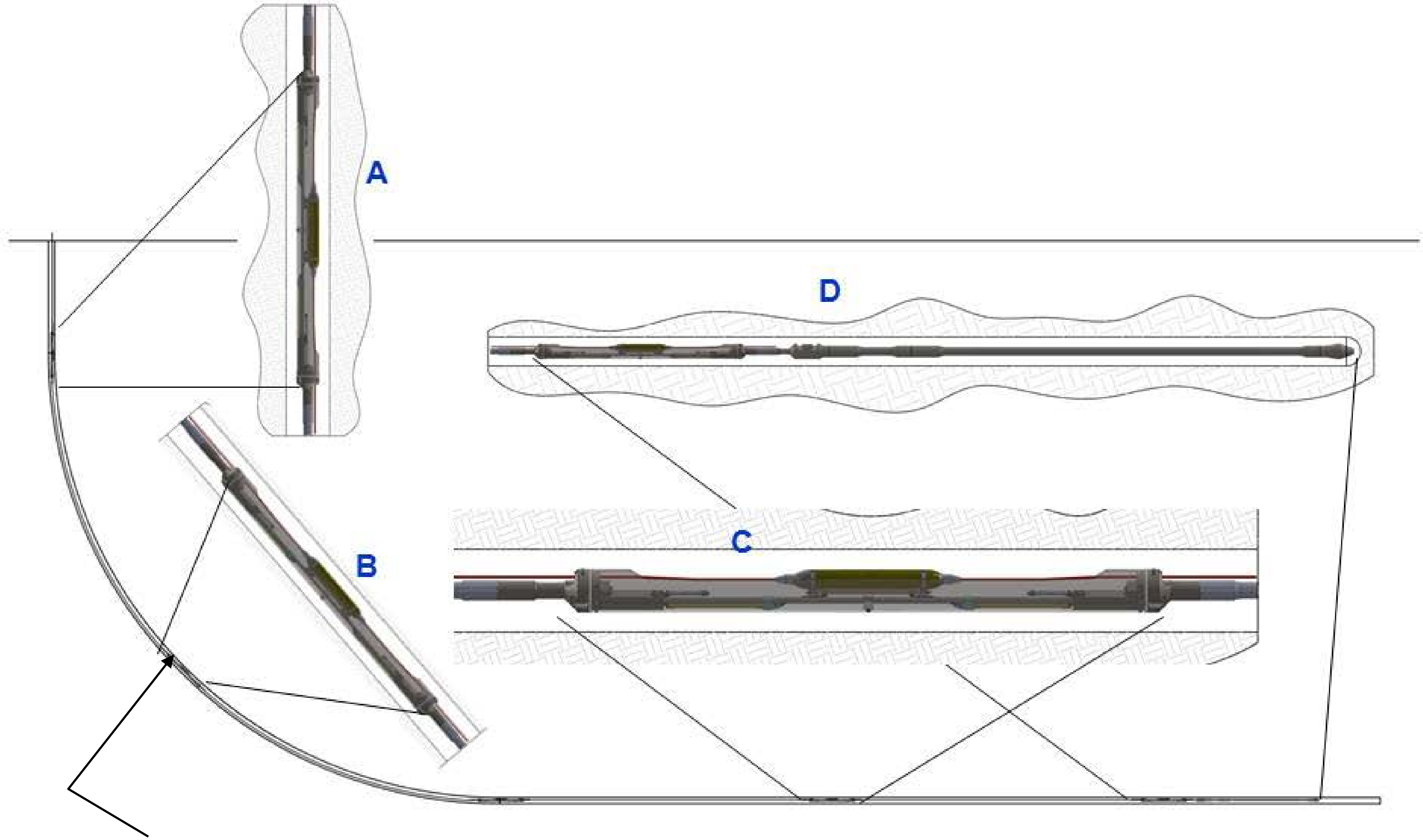
Earth Telescopes
Show Blurry Imprecise Images



The Hubble Space Telescope
Shows Sharp Precise Images

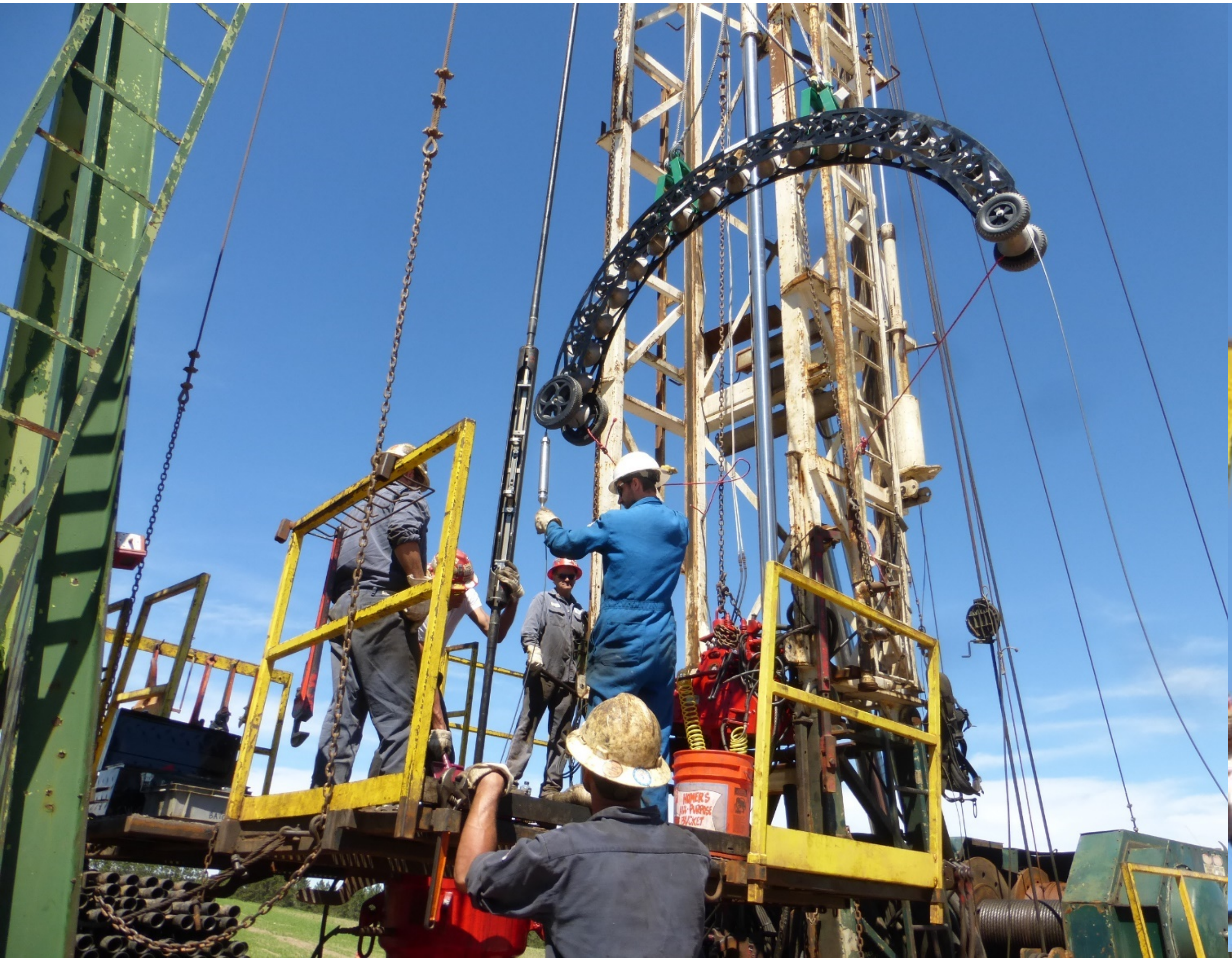


Drill Pipe Deployed System – Housing and Clamping

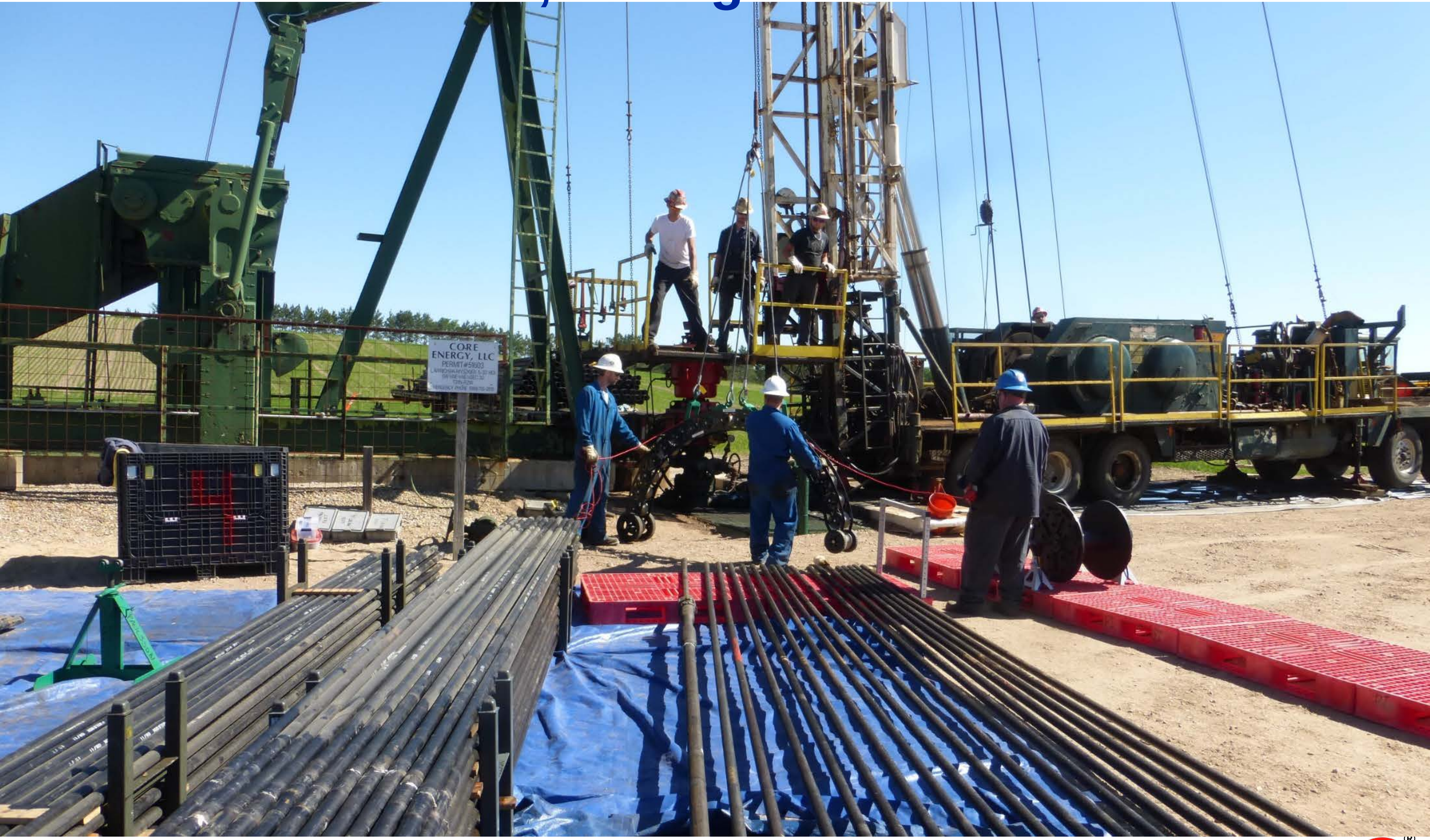


Clamping system operates by increasing the pressure inside the drill pipe and manifolds using the borehole fluid as the pressurized medium

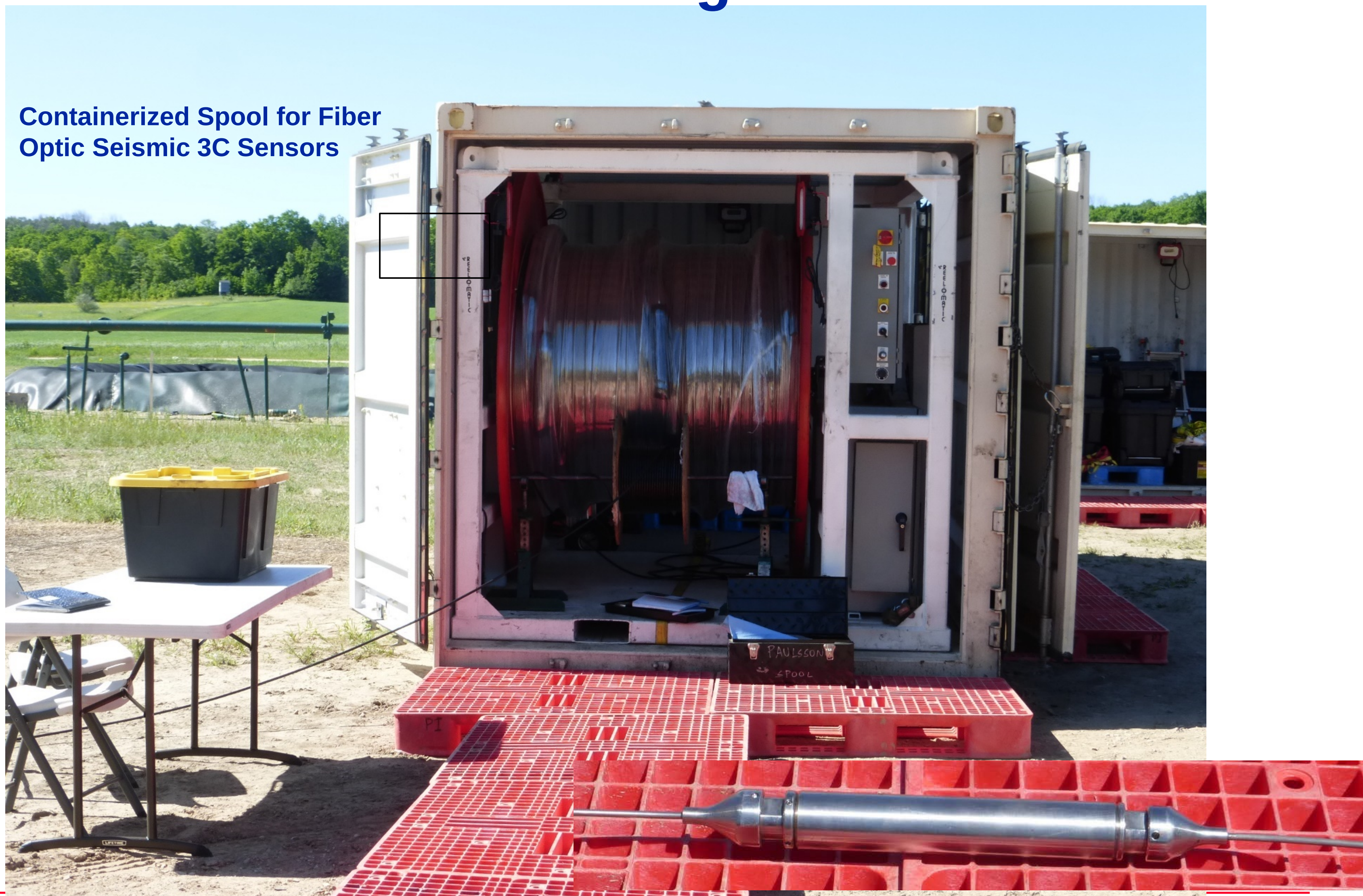
Fiber Optic Seismic Sensor System Deployment
Battelle, Michigan June 2016



Fiber Optic Seismic Sensor System Deployment
Battelle, Michigan June 2016



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



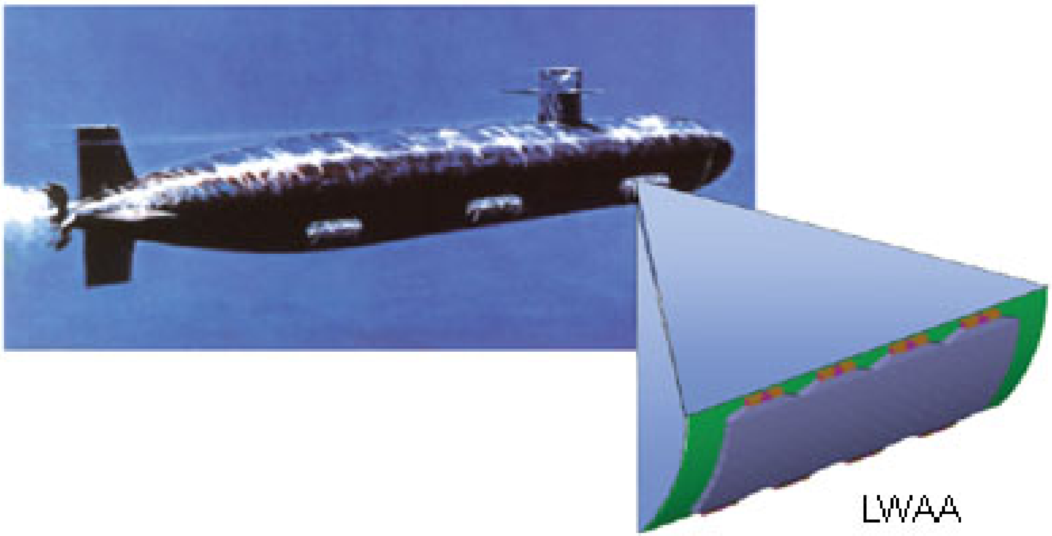
Fiber Optic Seismic 3C Sensor Pod

16 Level Micro Seismic in Coso Geothermal Field, CA, March 2018

Fiber Optic Seismic Vector Sensors

The Paulsson Fiber Optic Technology Started at the NAVY NRL

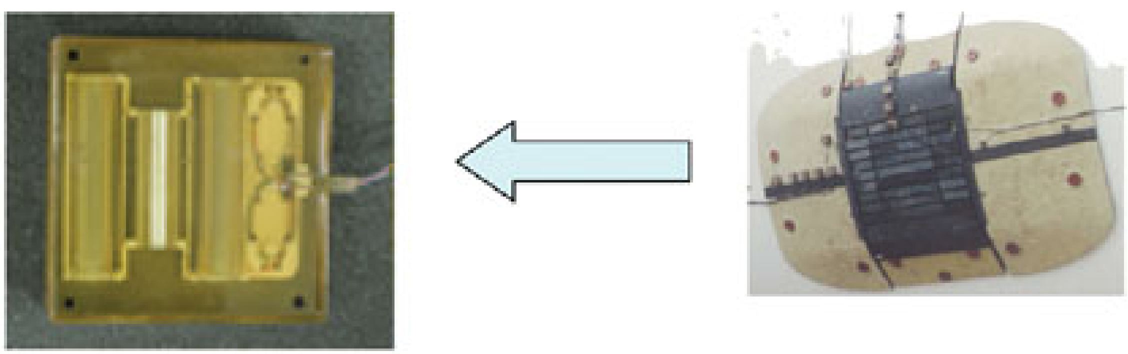
- NSSN (New Attach Submarine (nuclear Propulsion)) Virginia Class Attack submarine FOAS array
- Light Weight Wide Aperture Array (LWWAA) is a passive ASW sonar system which consists of three large array panels mounted on either side of the submarine's hull.
- NRL developed and demonstrated fiber optic methods based on the Michelson interferometry technique which measure the strain in fiber from dynamic signals (acoustic).



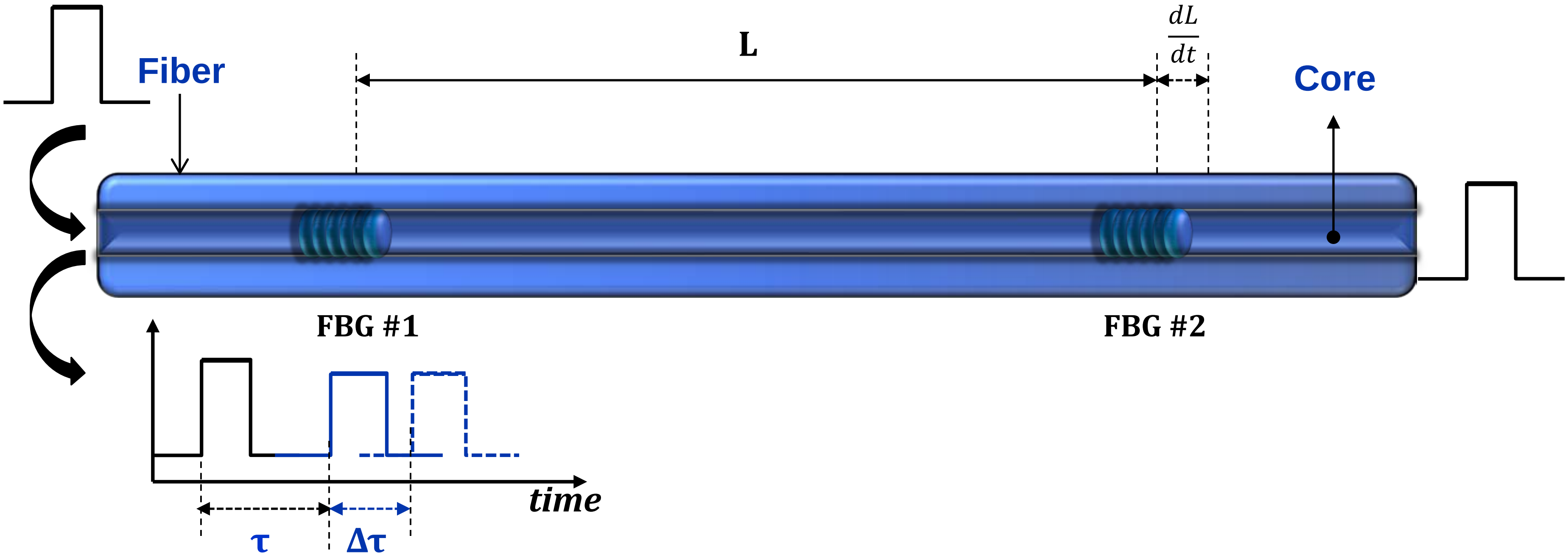
Fiber Optic LWAA

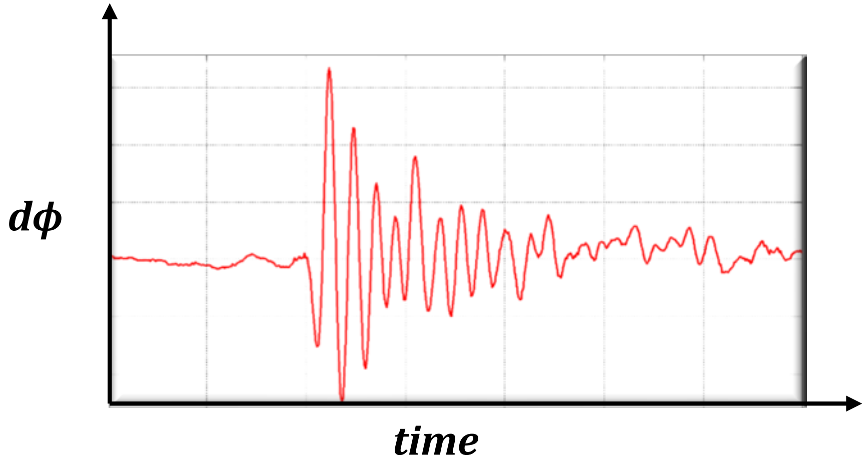
- 6 arrays (three per side)
- -450 hydrophones per array
- Provides ranging capability without maneuvers
- Passive acoustics

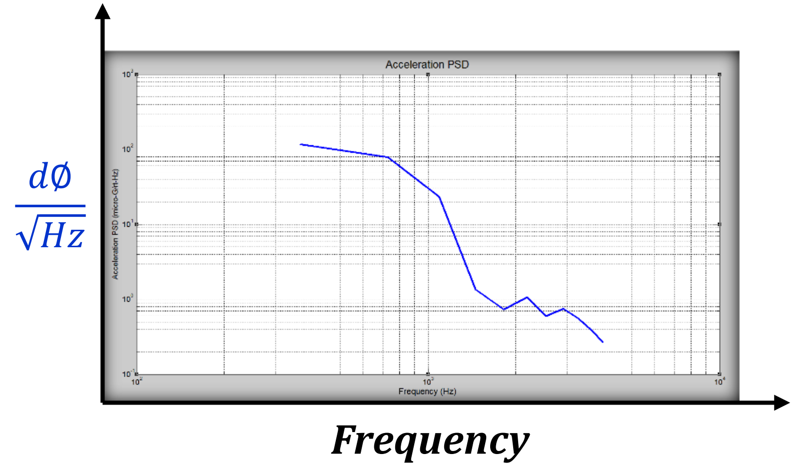
All-Optical Hydrophones



Fiber Bragg Grating: Theory







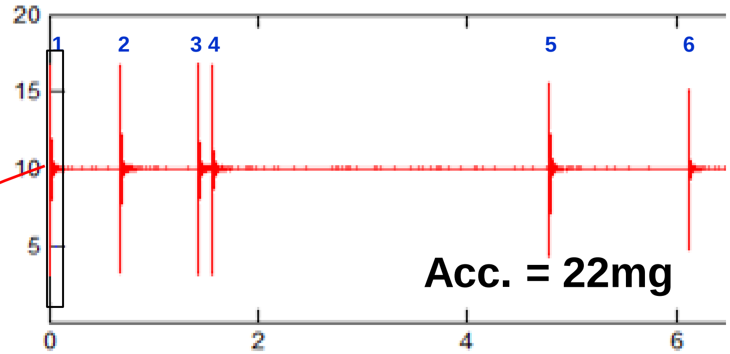
Laboratory Test of

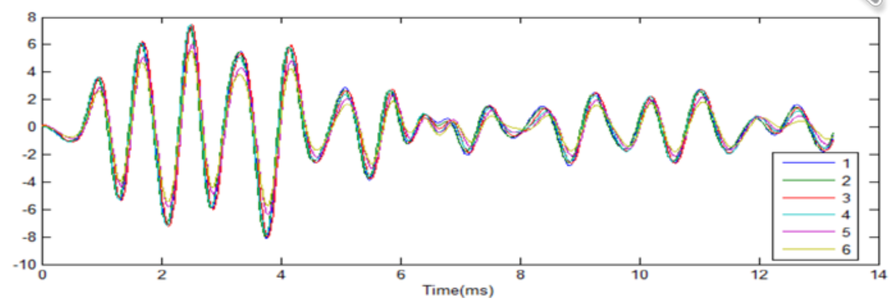
Fiber Optic Seismic Vector Sensors

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

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 environment. AME Energy Released: ~0.1 J = M-3.5

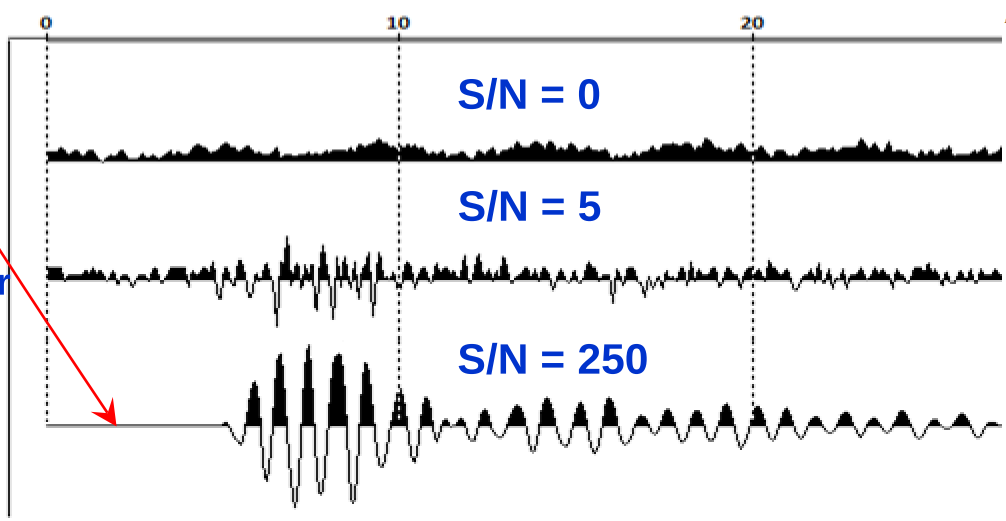


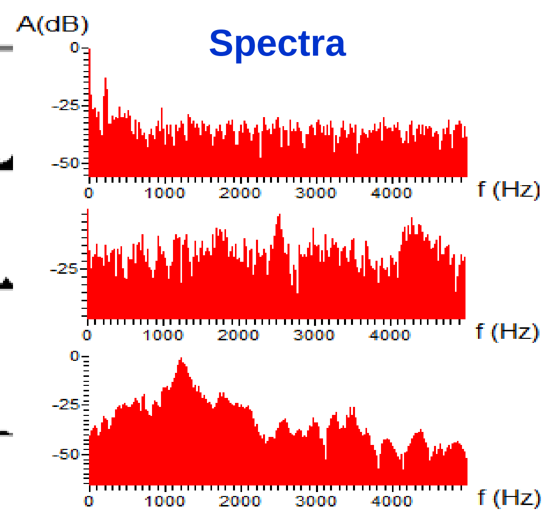


Geophone

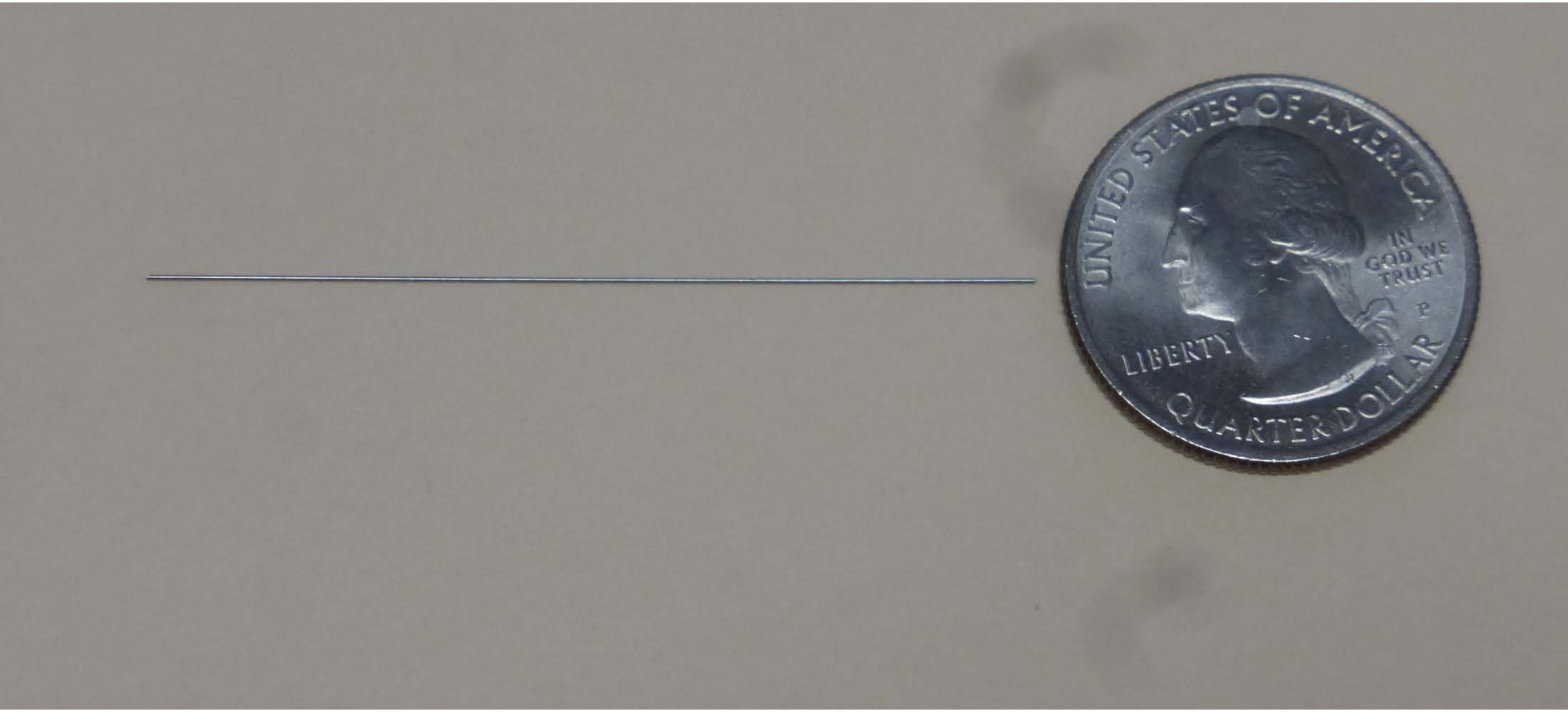
Accelerometer

FOSVS



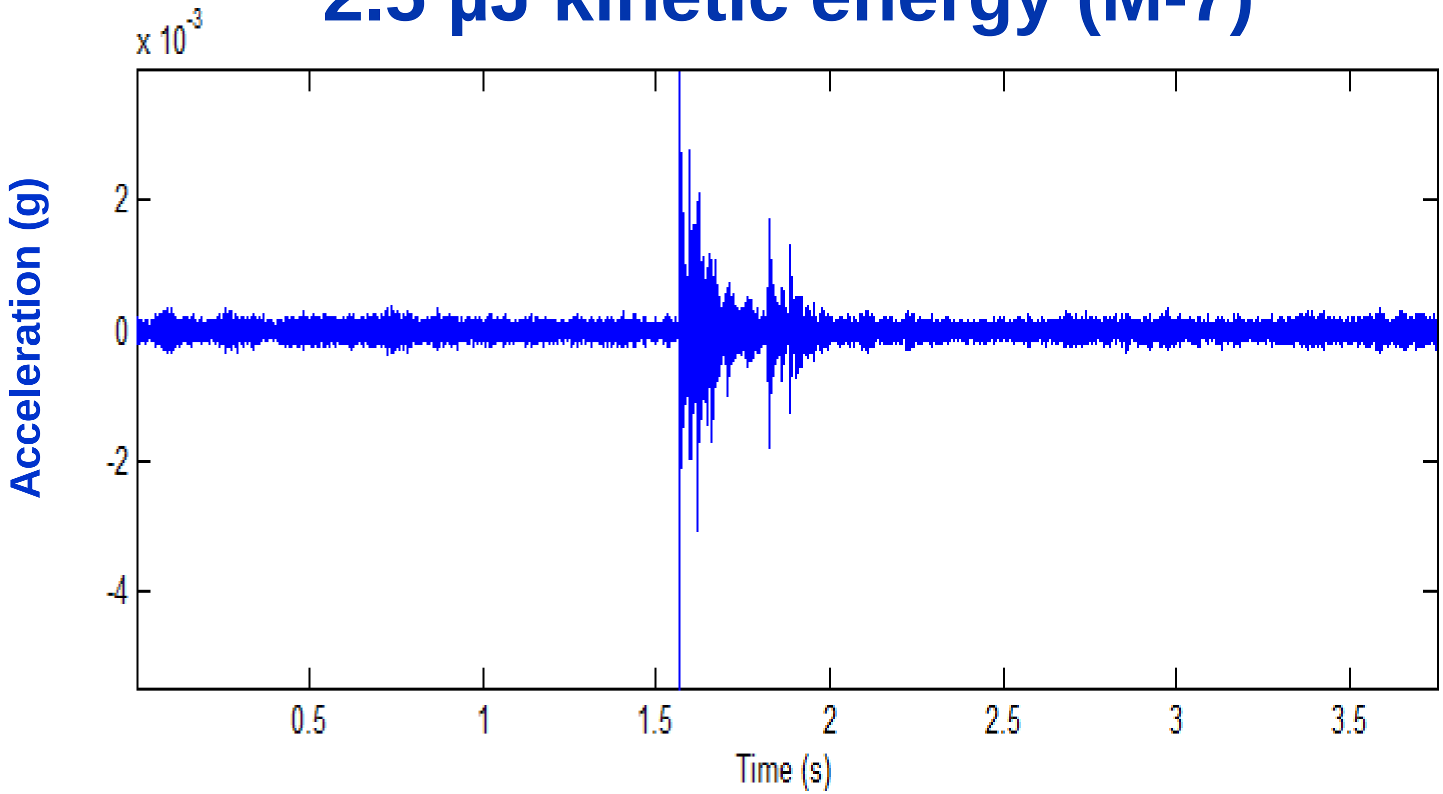


Can You Hear a Pin Drop?
Test Object: OD: 0.011”, 2” long, 24.8 mg



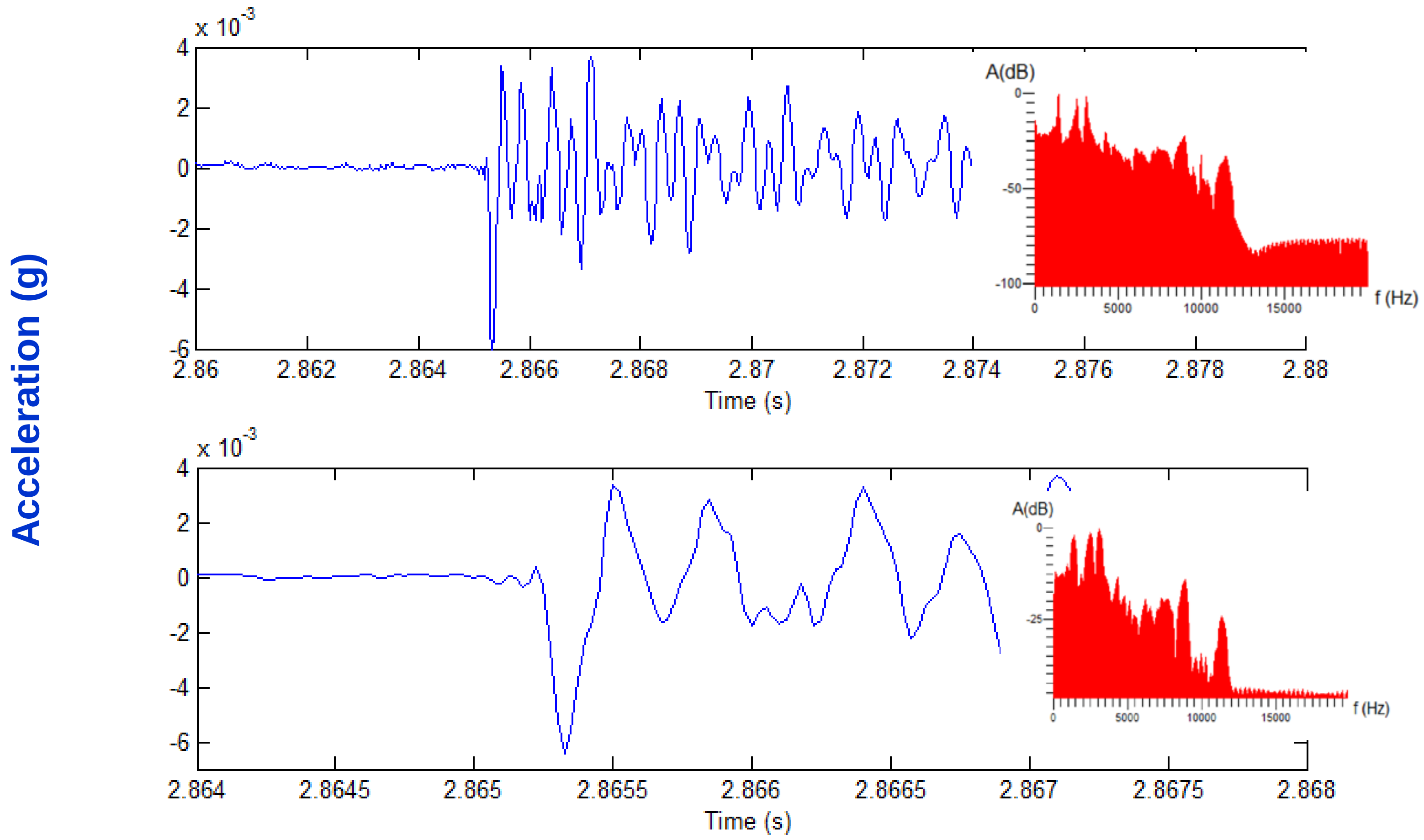
FOSVS Test: OD: 0.011", 24.8 mg Pin Drop 1 cm:

2.5 µJ kinetic energy (M-7)

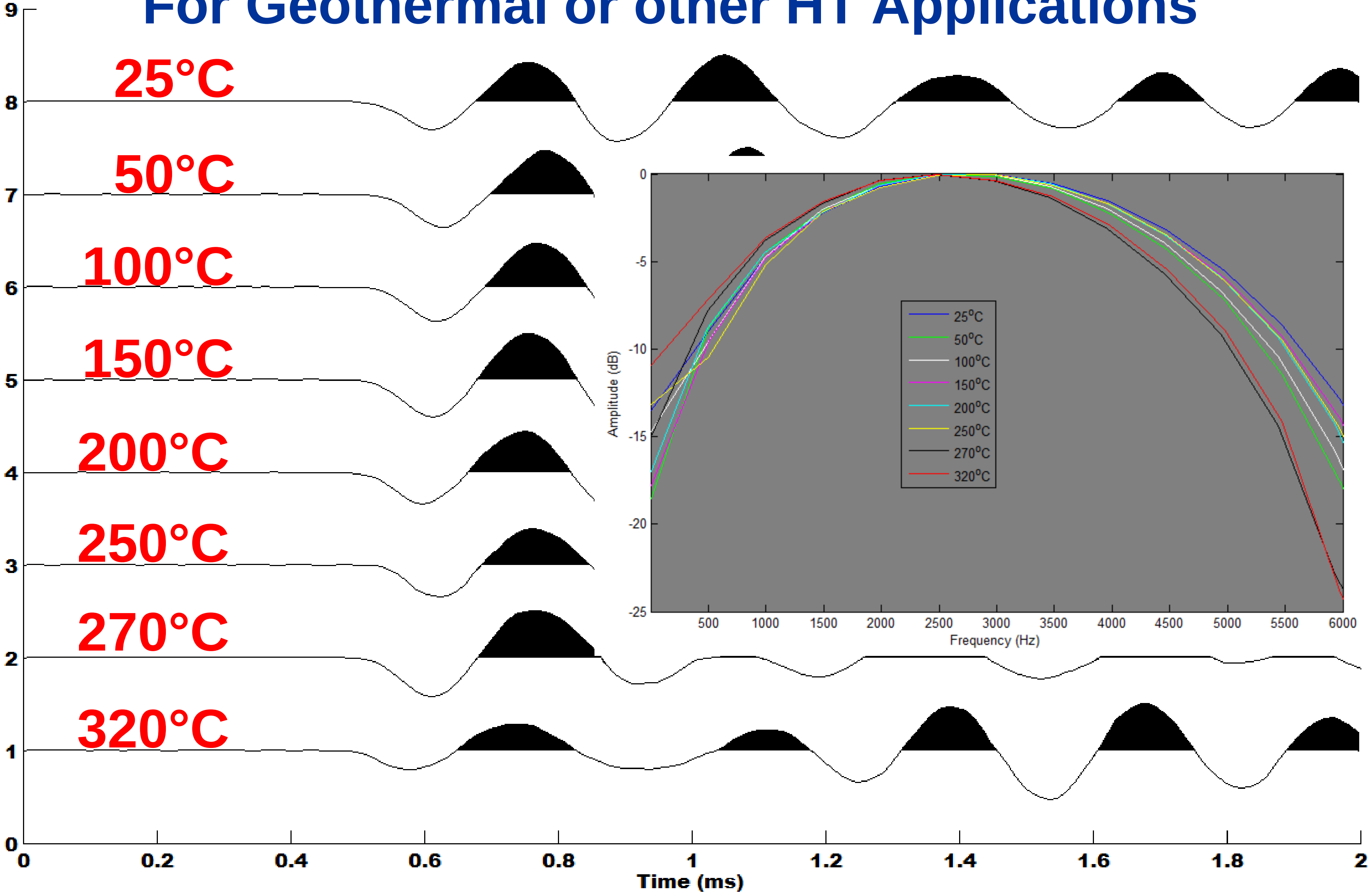


FOSVS Test: OD: 0.011”, 24.8 mg Pin Drop 1 cm:

2.5 µJ kinetic energy (M-7)

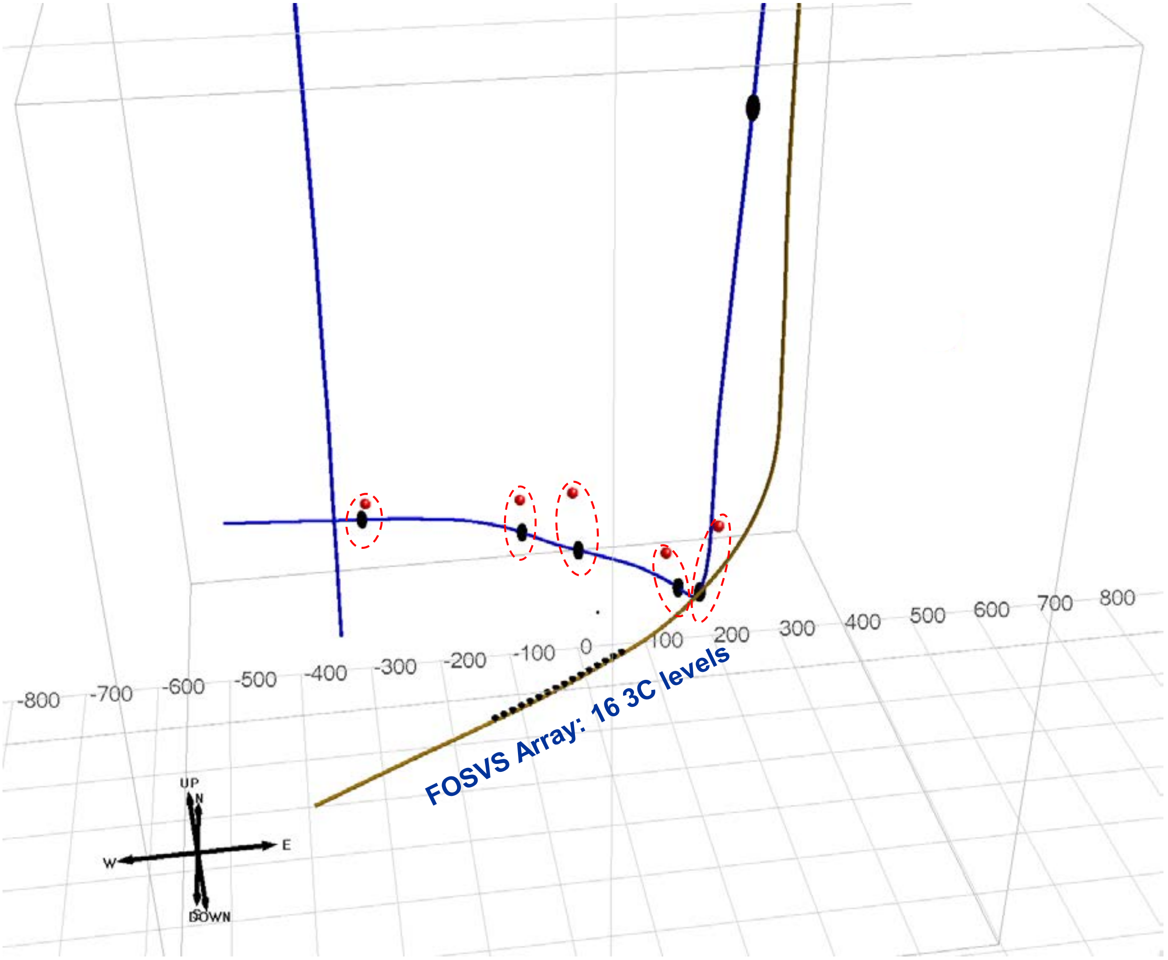


FOSVS: Optical Radial Component @ 25°C - 320°C For Geothermal or other HT Applications



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

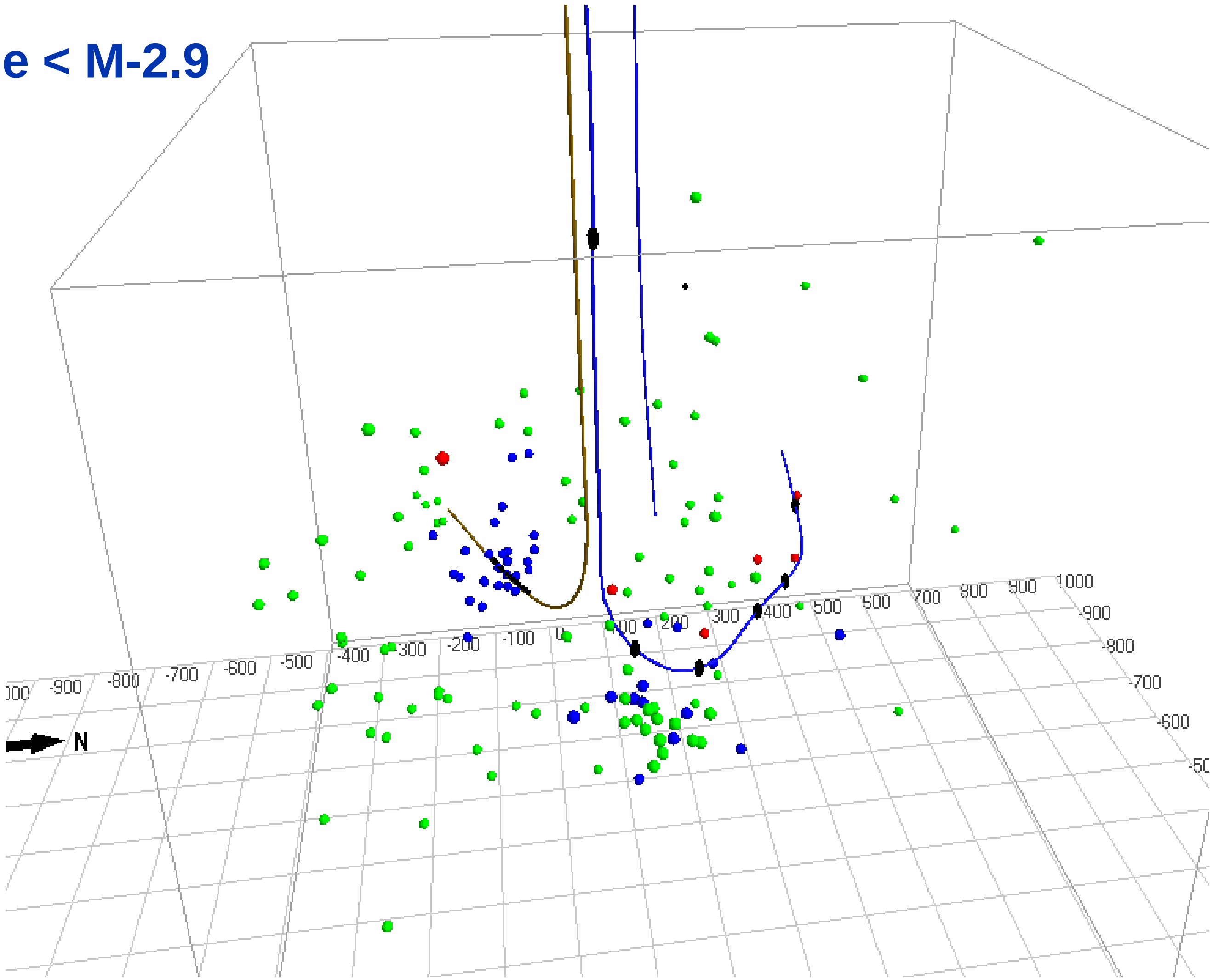
Results from Locating 0.5 gram String Shots During a Survey Recorded for Battelle in June 2016



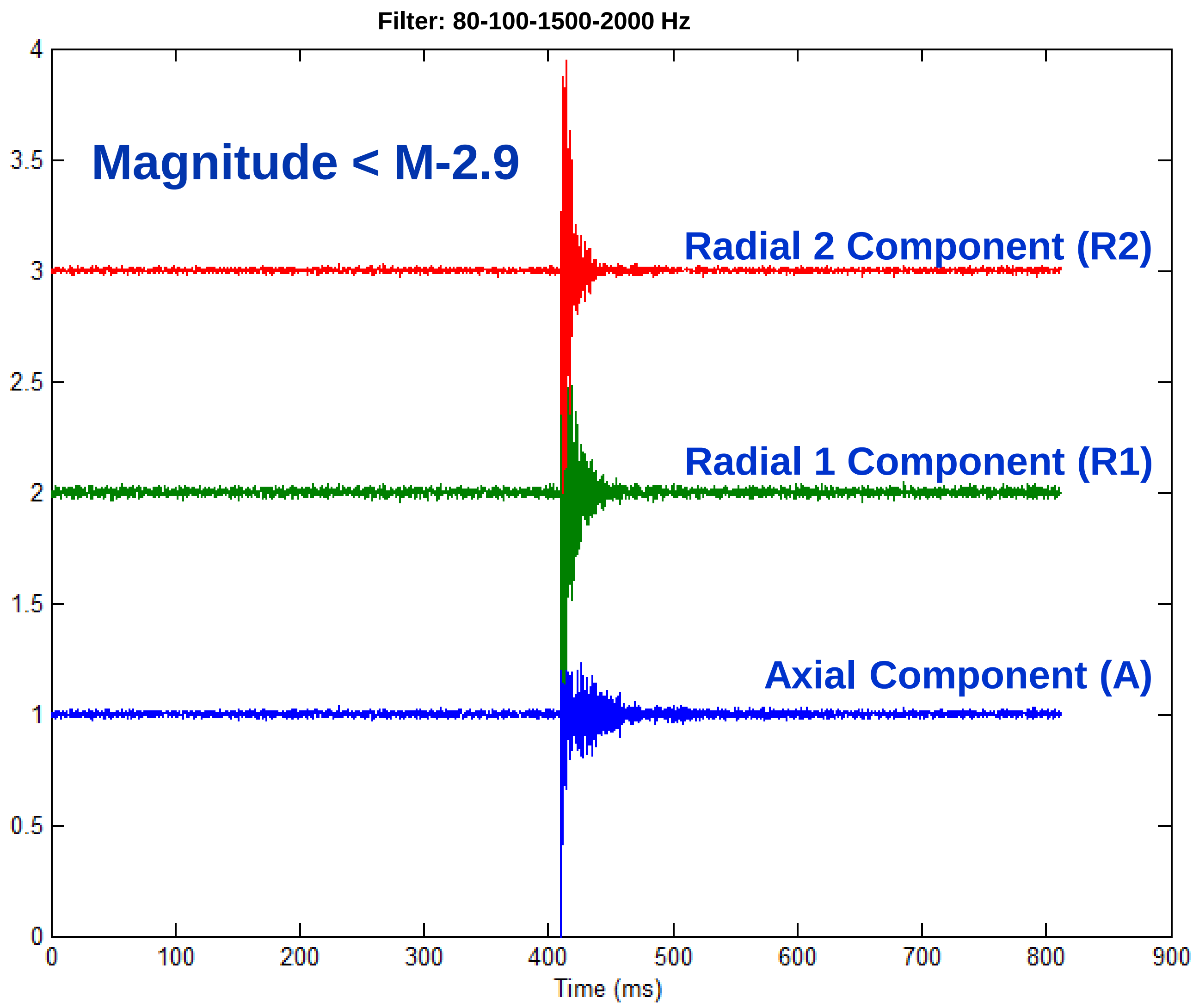
Survey for Battelle - Locating String Shots and Micro Seismic Events
Recorded >20,000 events in four weeks. Displayed here are 130 events.

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

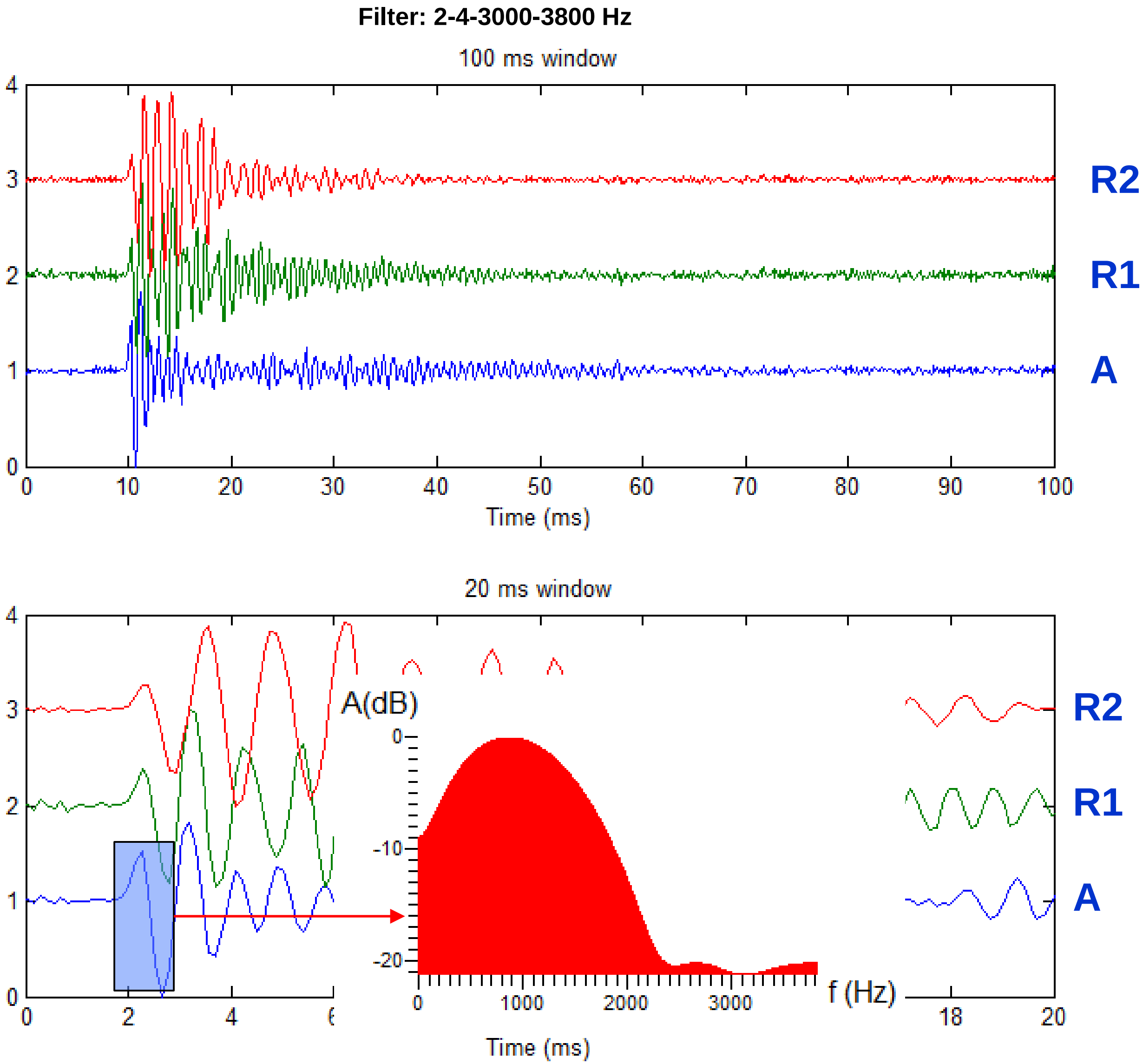
Magnitude < M-2.9



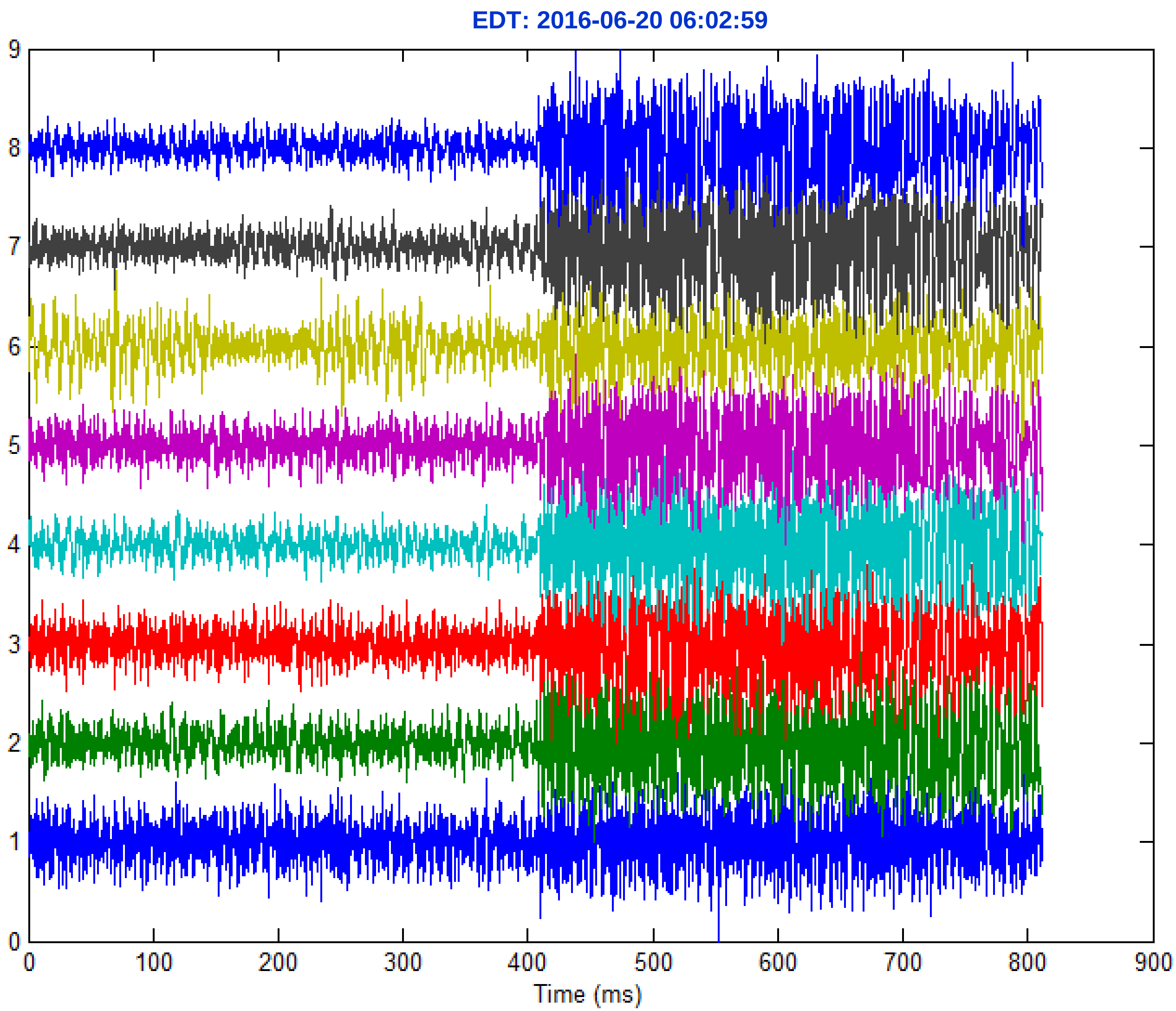
Sound of A Focused MS in 3C, Survey for Battelle, June 2016



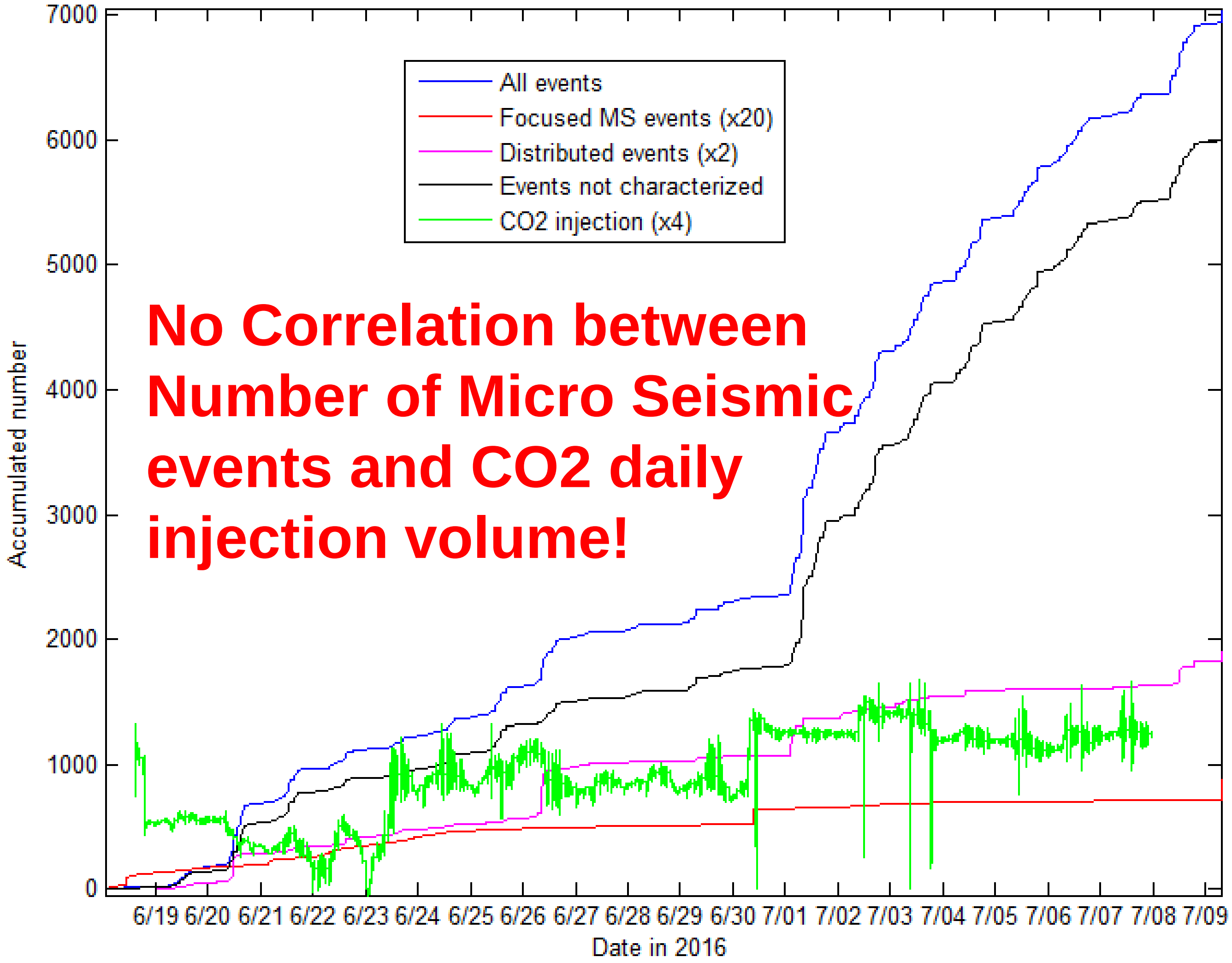
Zoomed-In Focused MS in 3C- Filter: 2-4-3000-3800 Hz



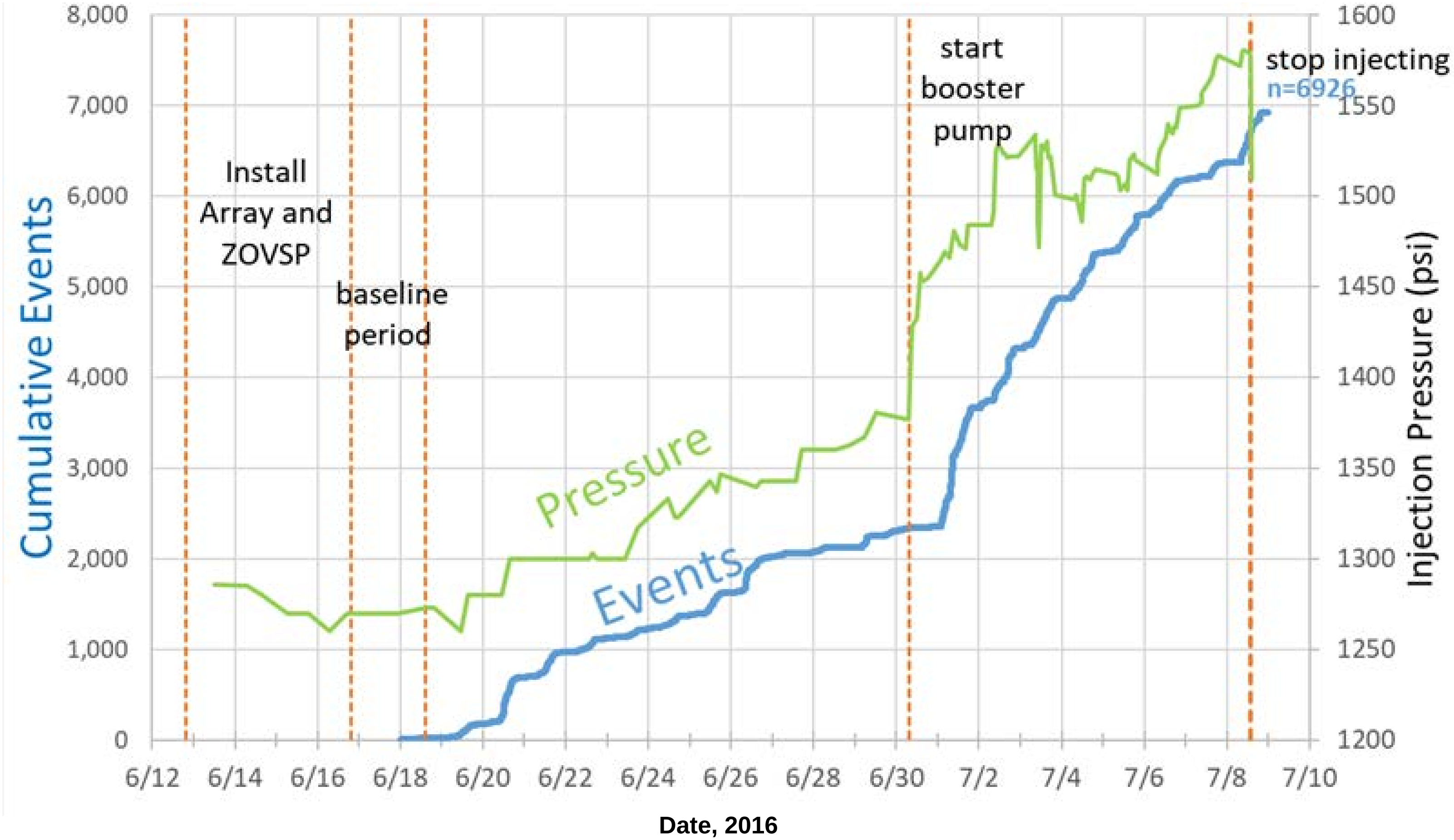
Sound of A Long Duration Event (<M-5.0) – Maybe Fluid Flow



Updated Search: Distribution of Different Events during CO2 Injection (6/18/2016 – 7/8/2016)



Micro Seismic Events and Pressure of Injected CO2

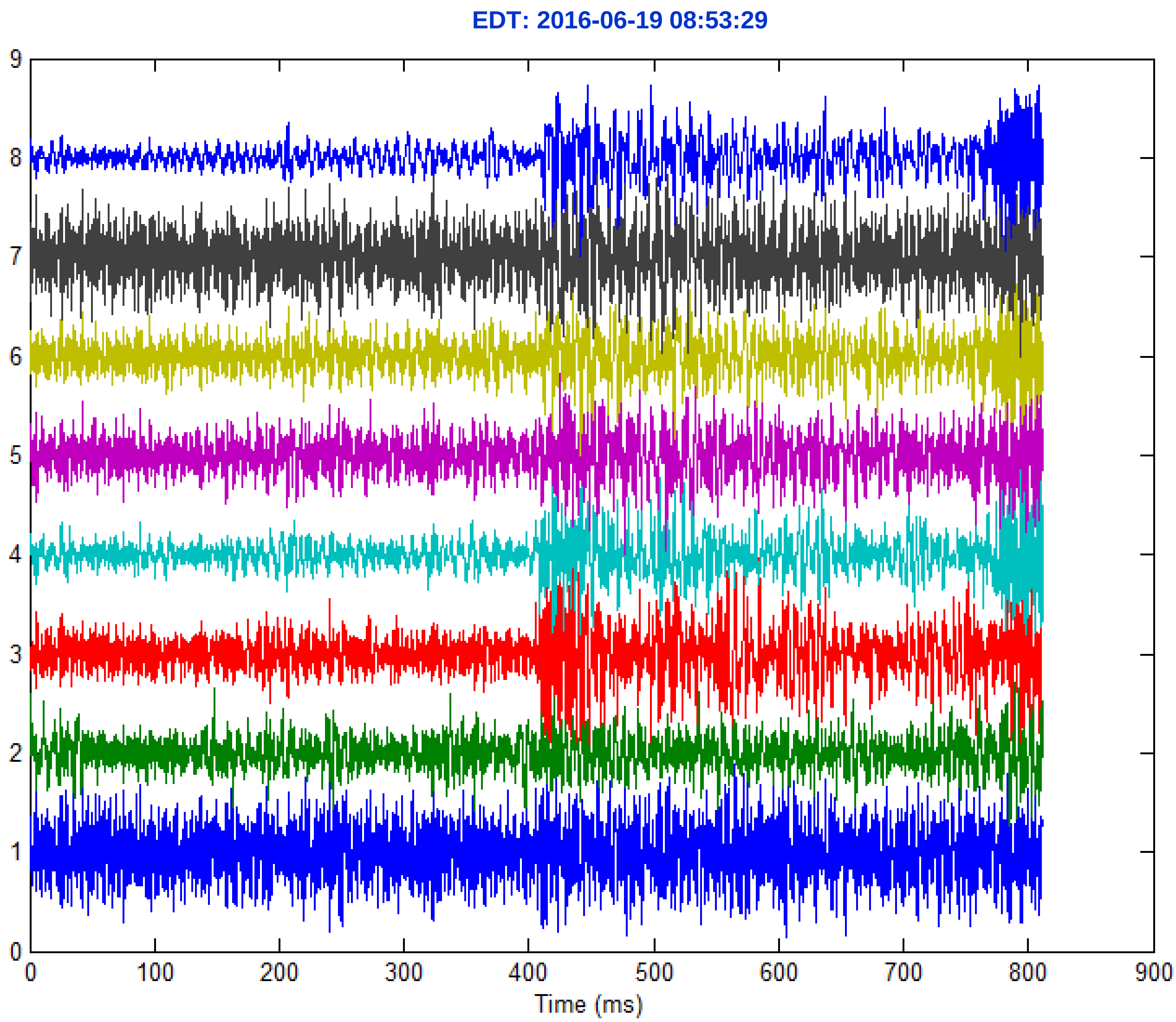


Great Correlation between Micro Seismic and CO2 Pressure!

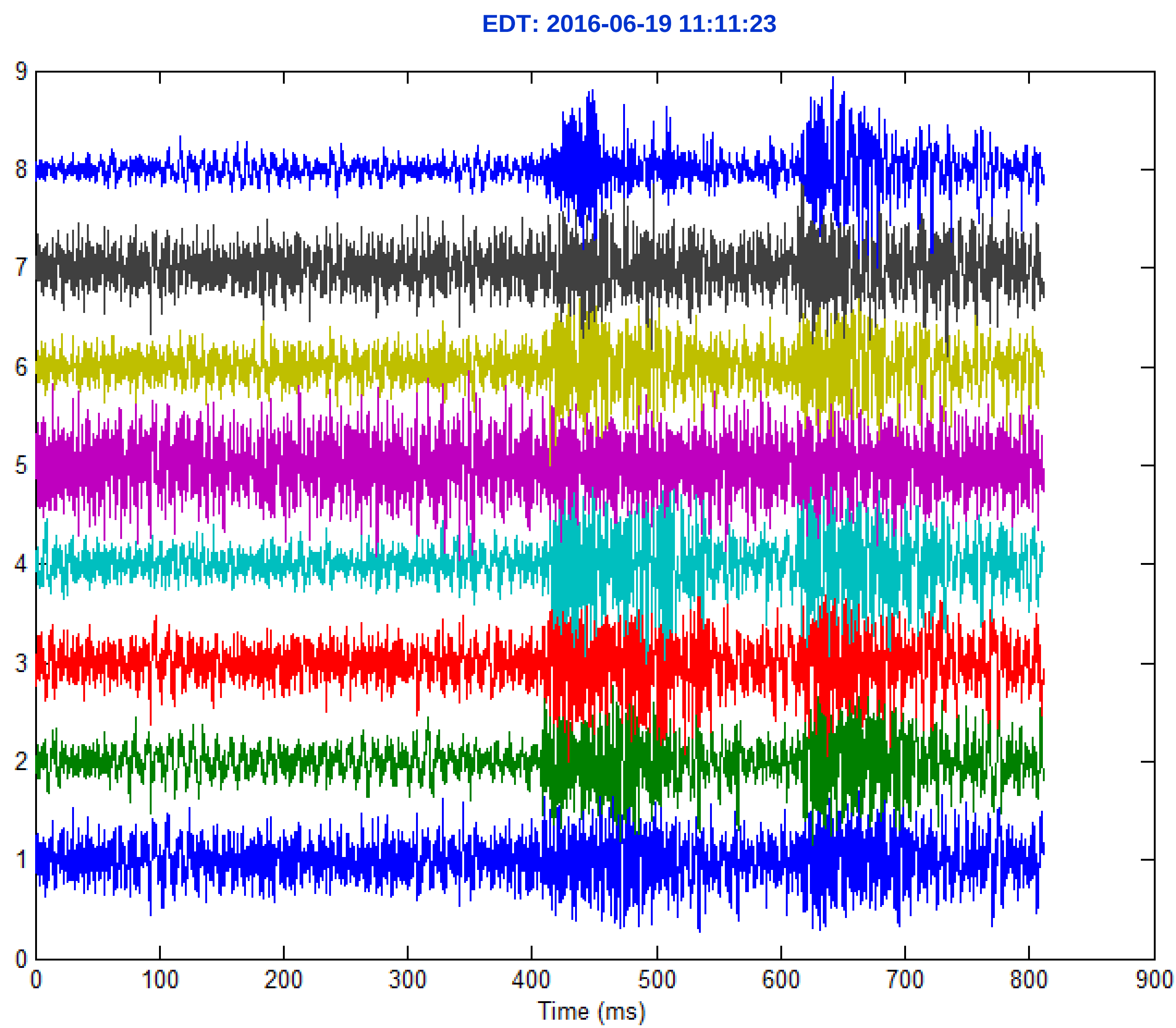
2019 Discovery by Mark Kelley, Battelle

Courtesy Mark Kelley, Battelle, 2019

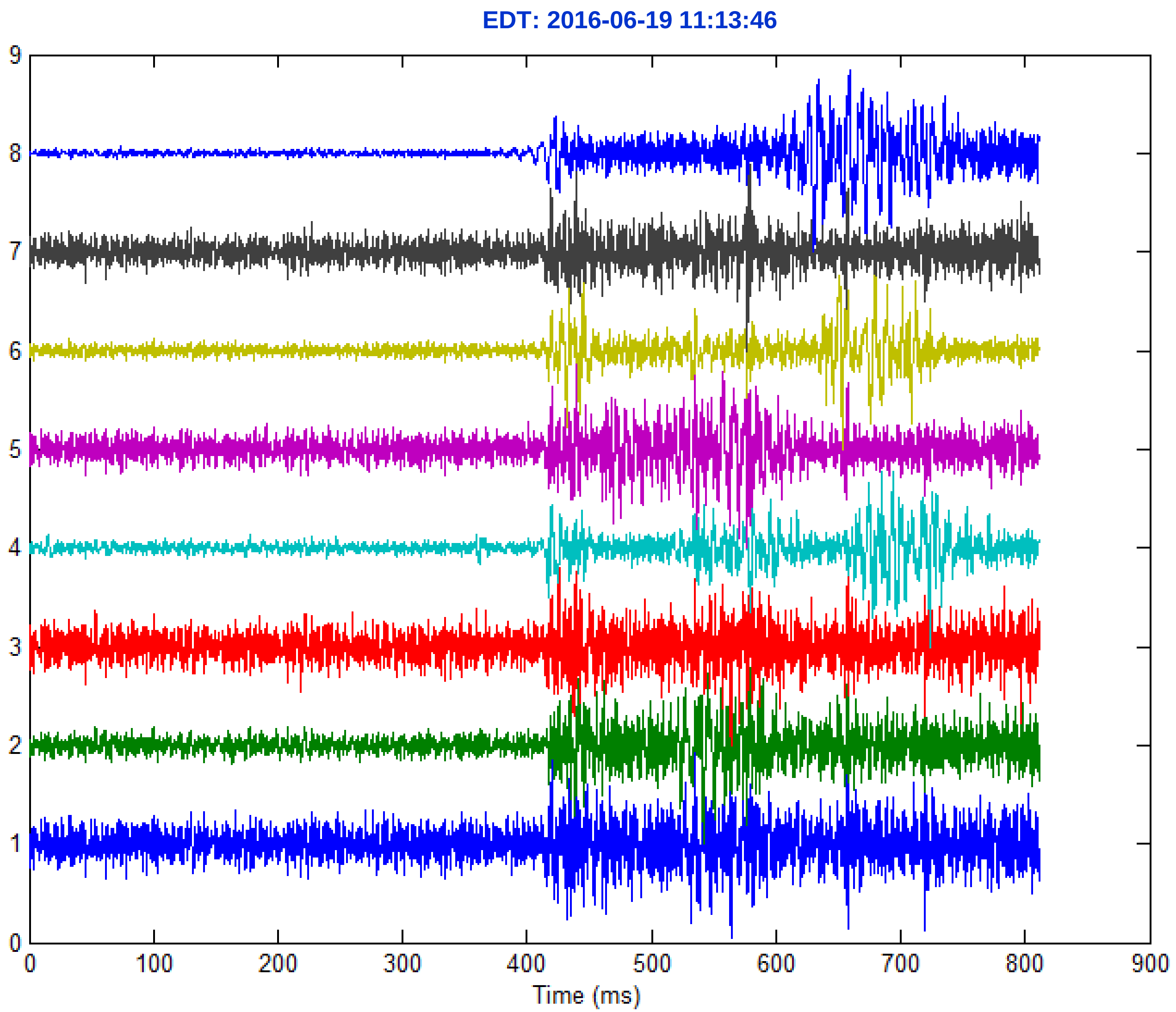
The Sound of a Long Duration Event on many Sensors



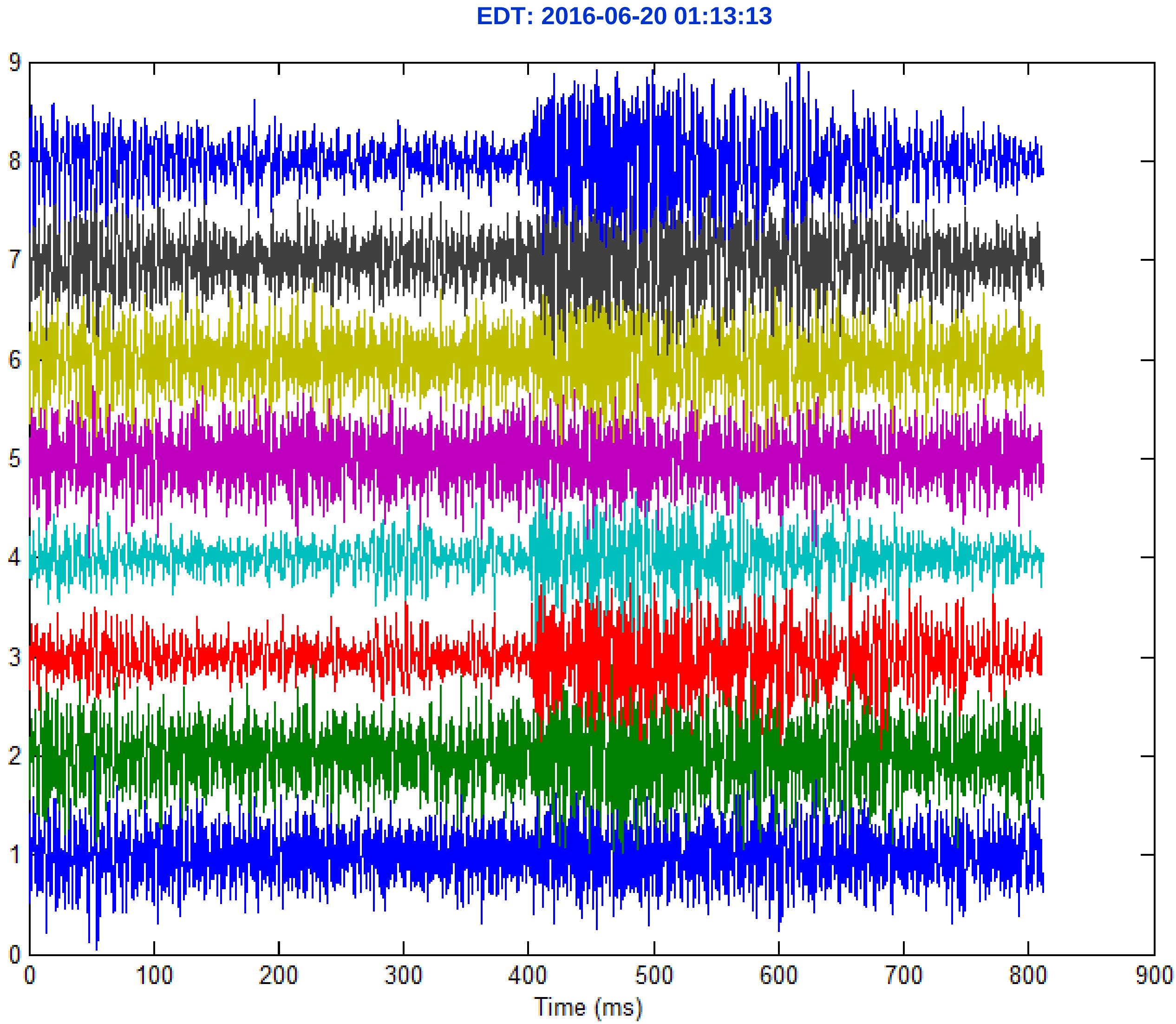
The Sound of a Long Duration Event on many Sensors



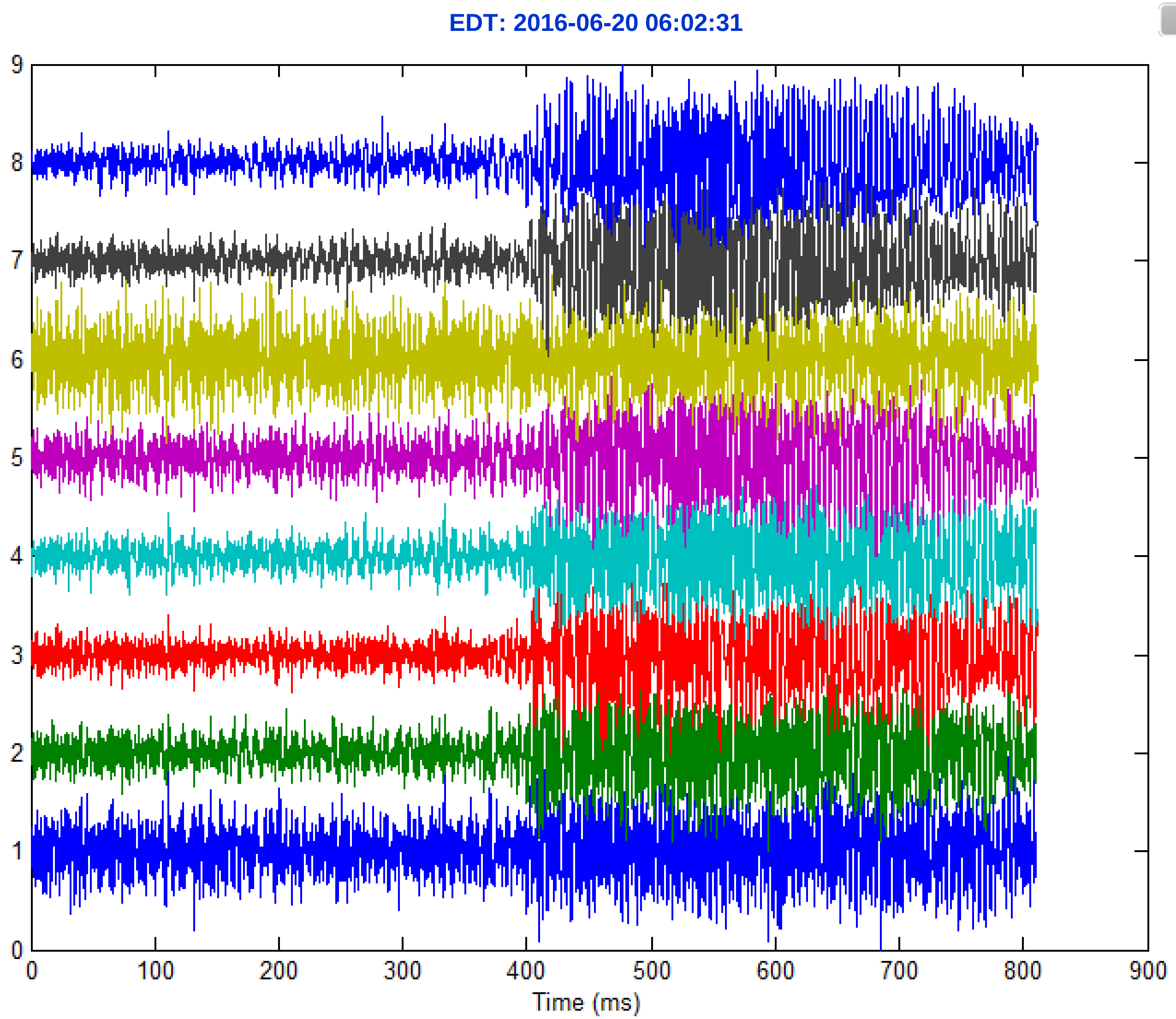
The Sound of a Long Duration Event on many Sensors



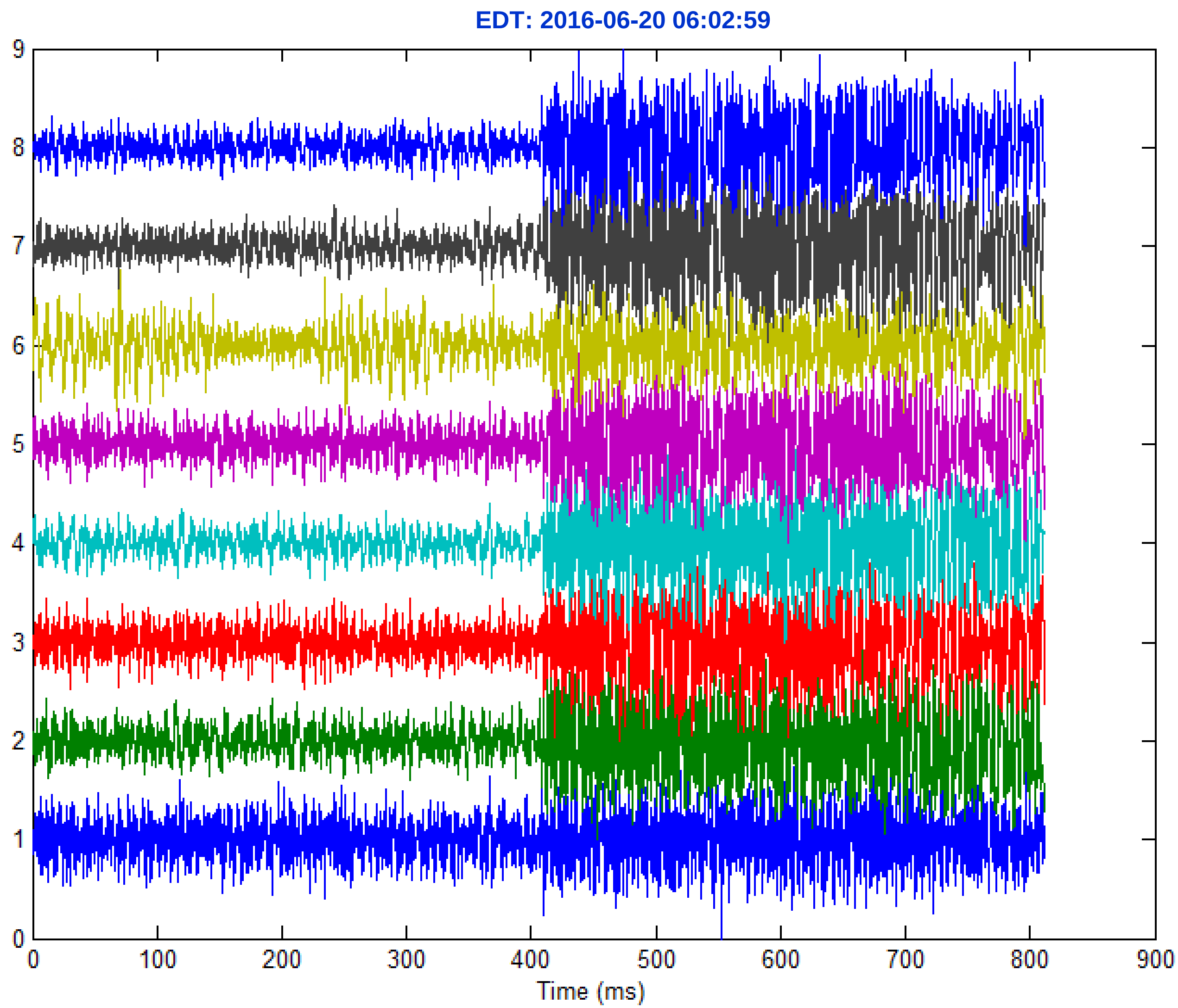
The Sound of a Long Duration Event on many Sensors



Sounds of Long Duration Events Consistent between Sensors

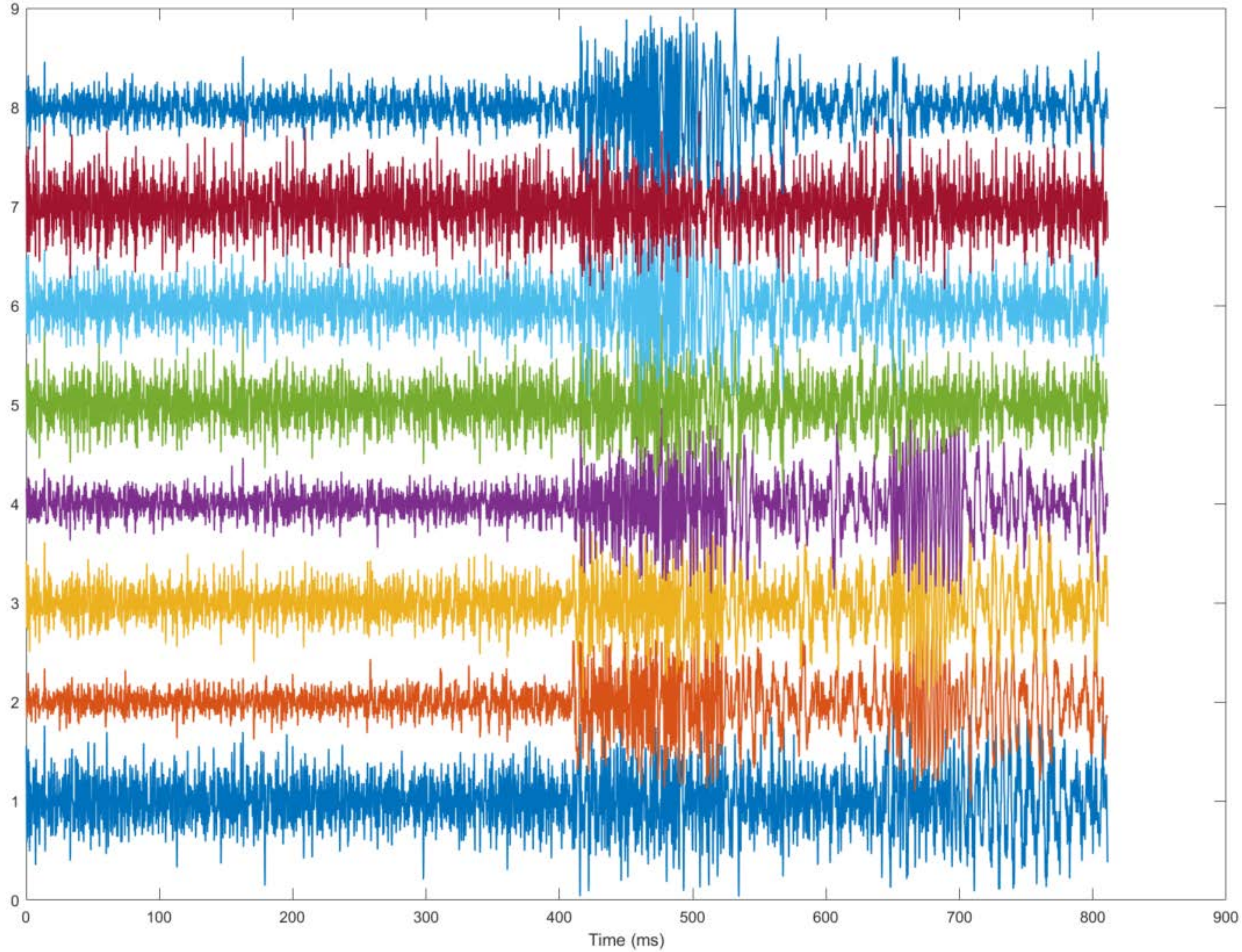


Sound of A Long Duration Event (<M-5.0) Definitely Fluid Flow

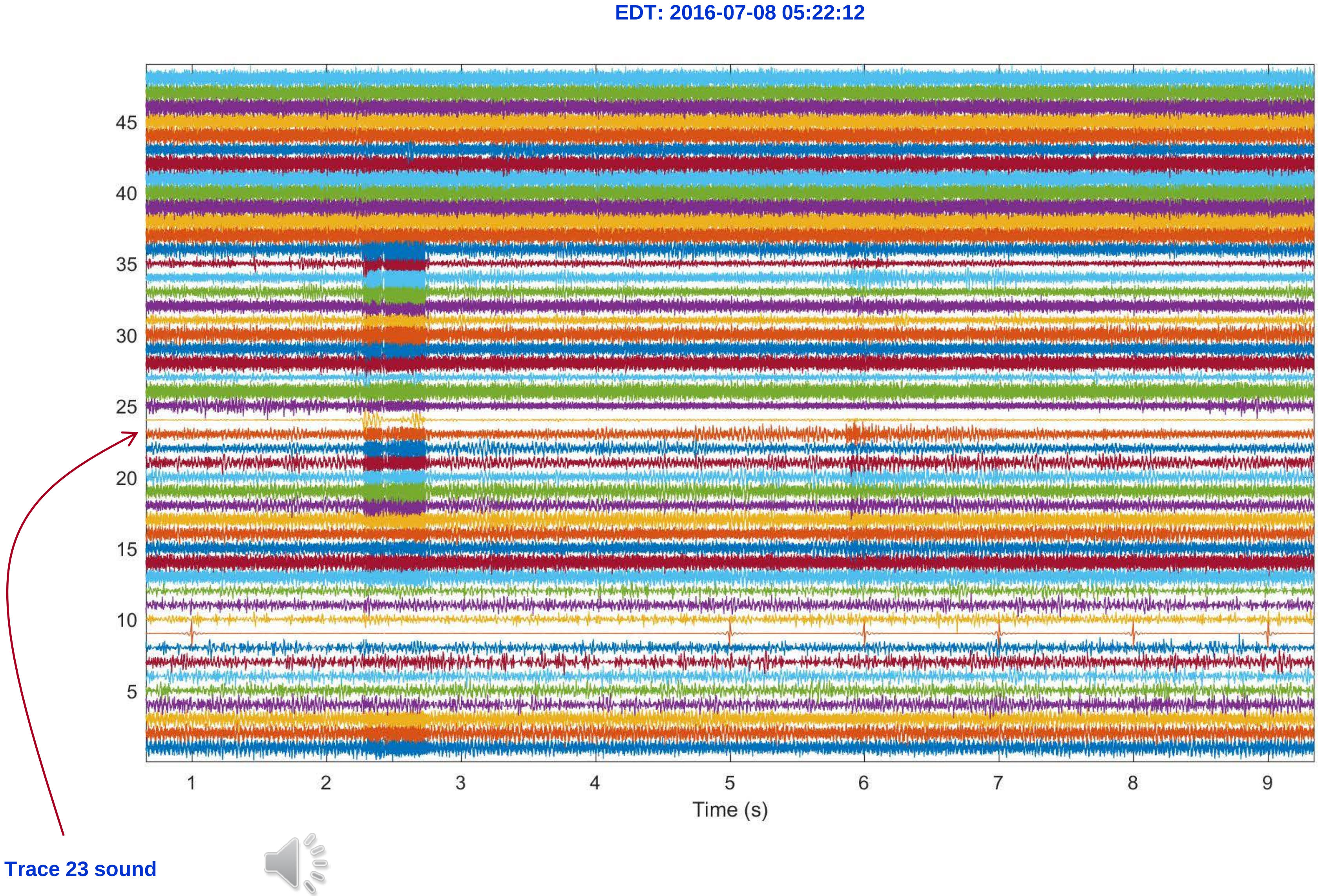


Sound of A Long Duration Event

EDT: 2016-07-02 00:45:53

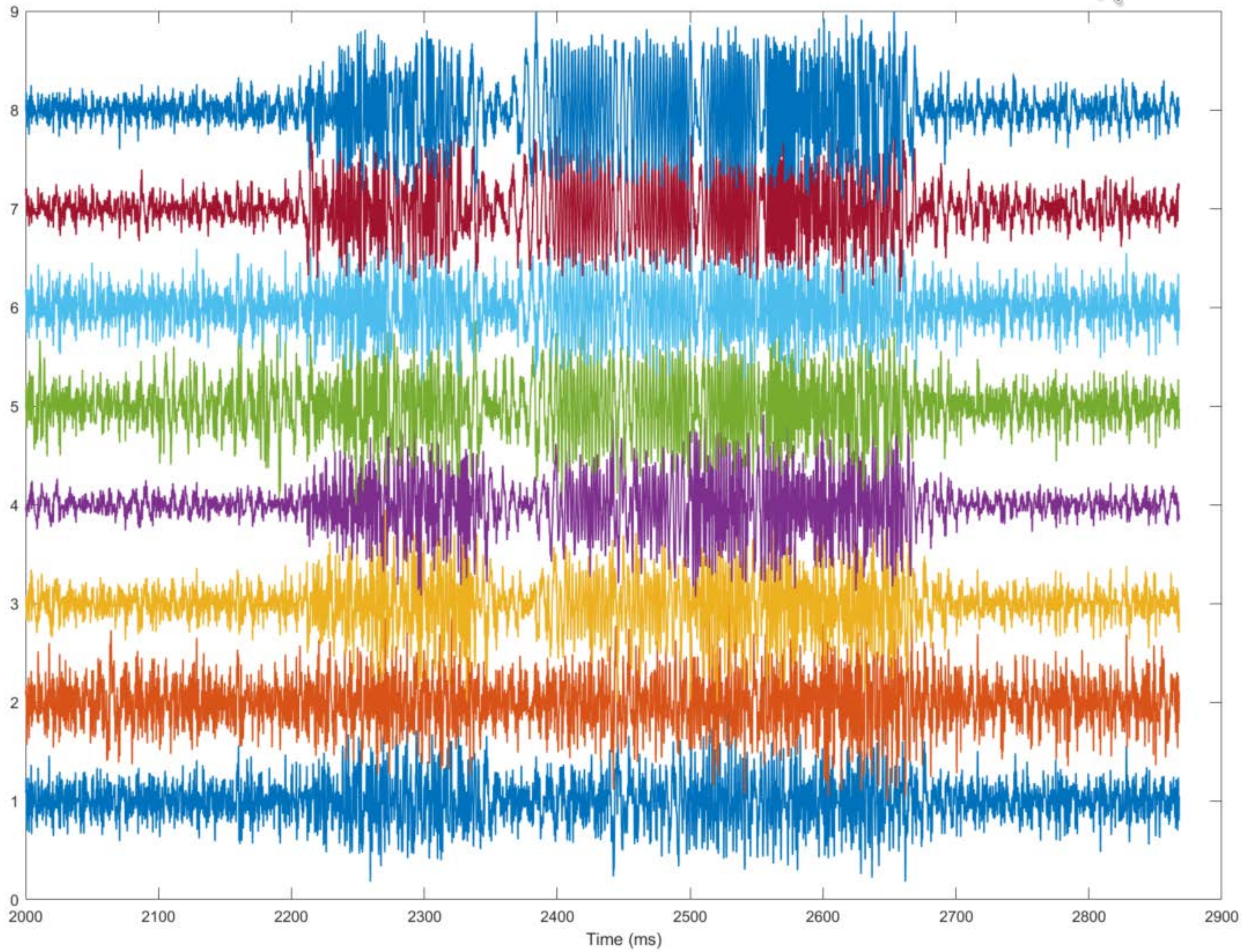


The Sound of a Long Duration Flow Event on many Senors

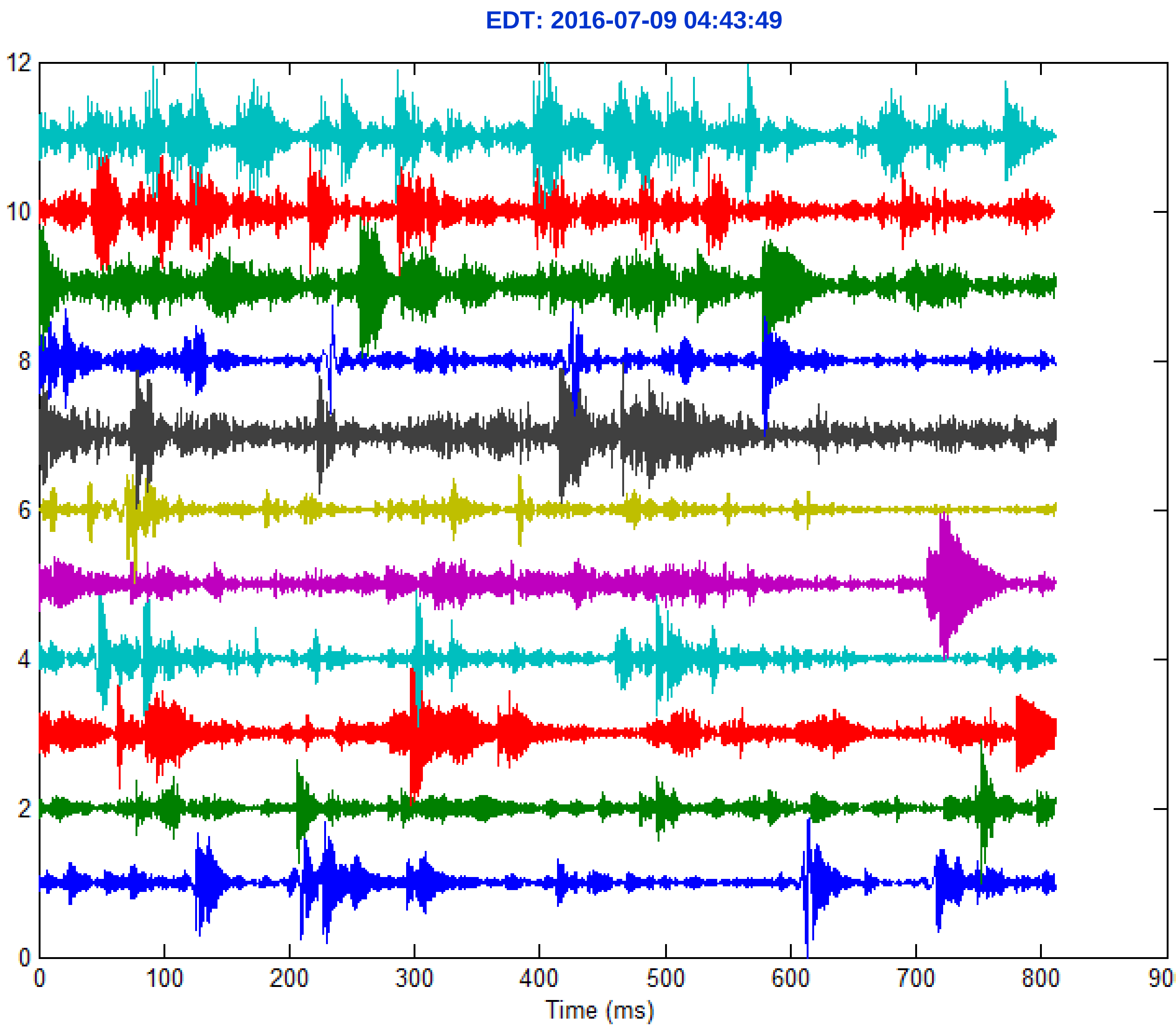


Sound of A Long Duration Event Zoomed In

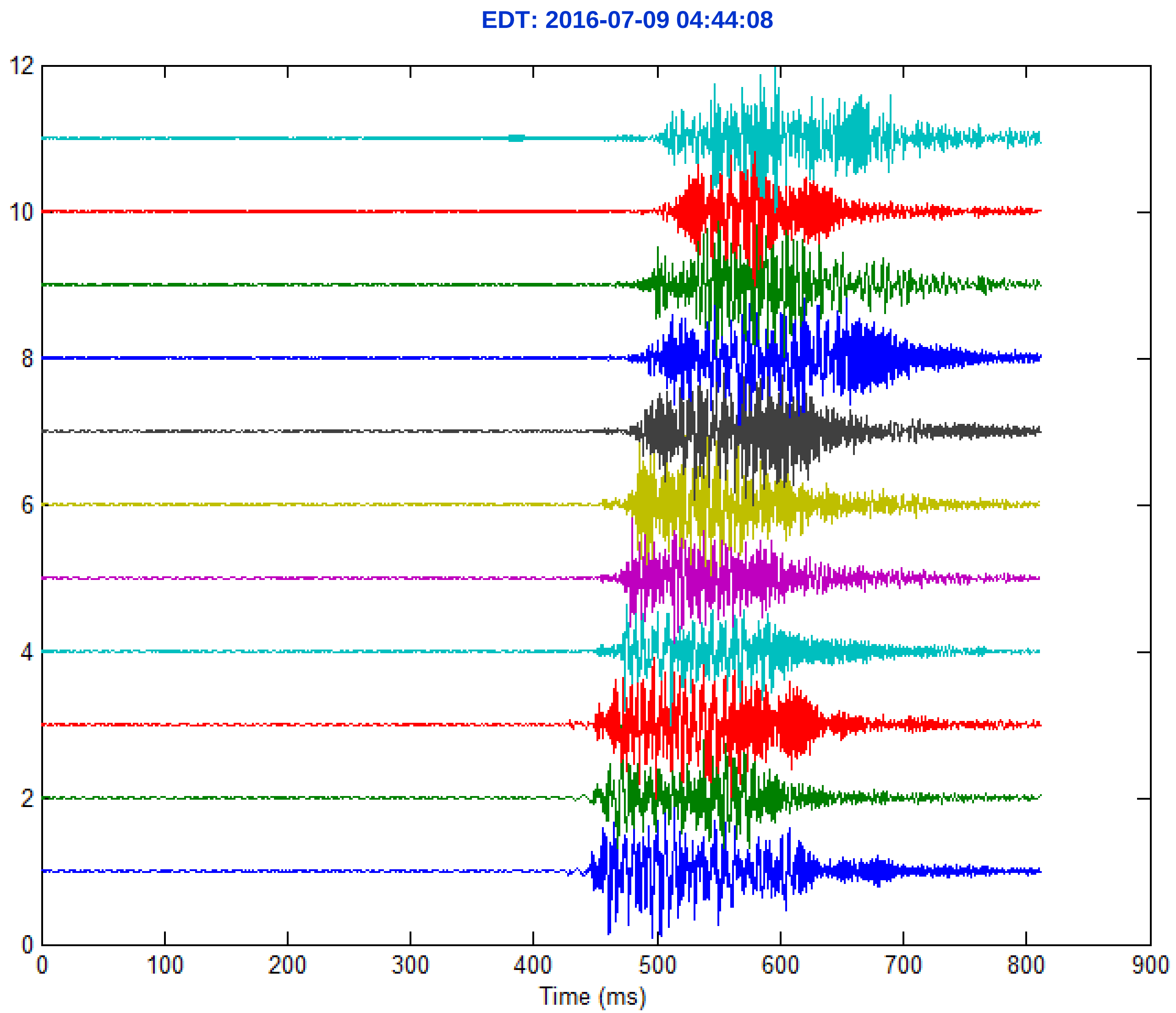
EDT: 2016-07-08 05:22:12



Sound of Building Up Pressure



Sound of Unclamping after breaking the Burst Disk

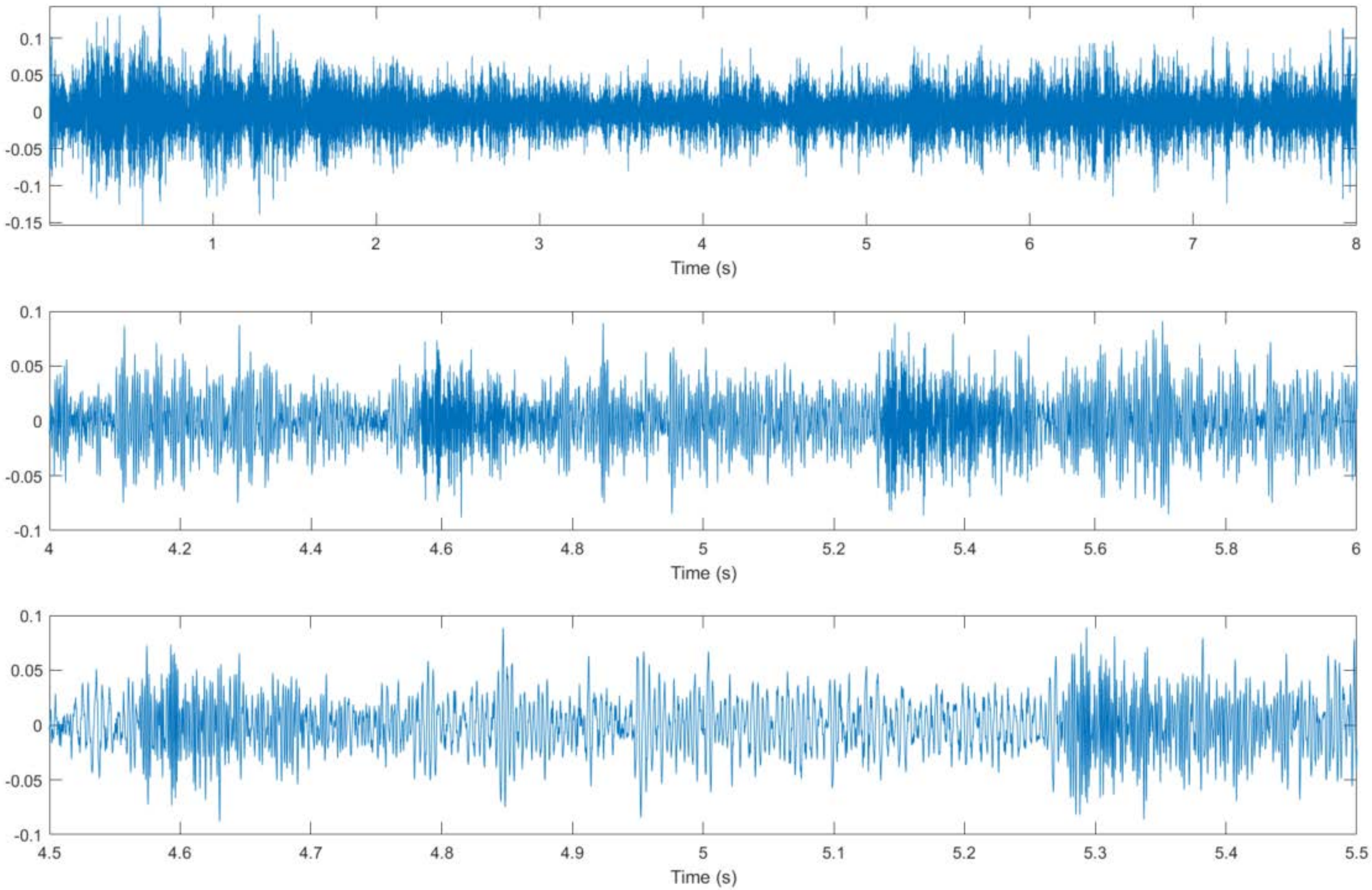


We looked for Analogs: Cardiac Blood Flow

8 seconds

Zoomed in 2 seconds

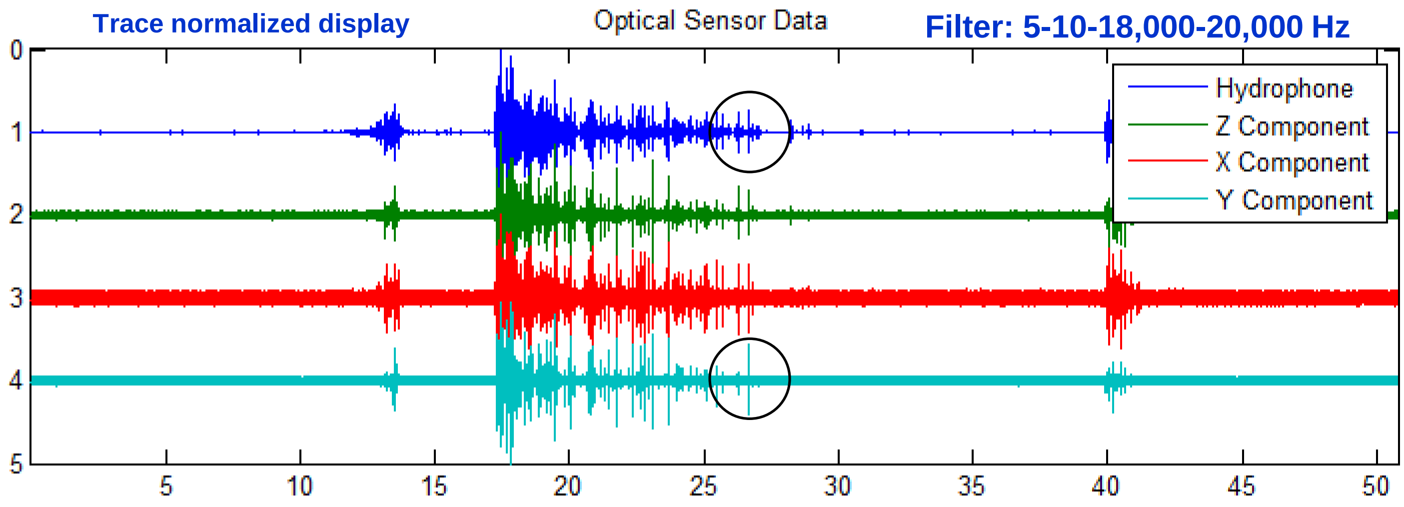
Zoomed in 1 second



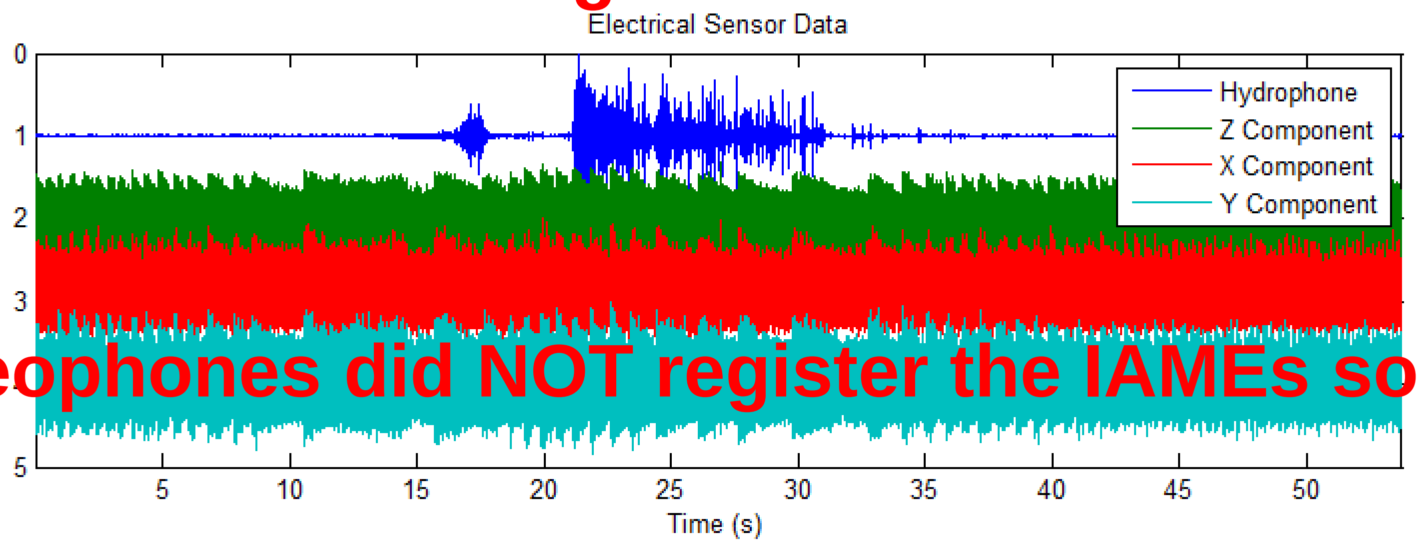
Pool Test of Micro Spheres – IAME's Size: 60 µm Matches 40/70 proppant

IAME Sources Recorded on FOSVS - Experimental Set Up

Pool Test 8: ~ 4gm Micro-Spheres (IAME) at 4,000 psi



The Optical Sensors registered the IAMEs sounds

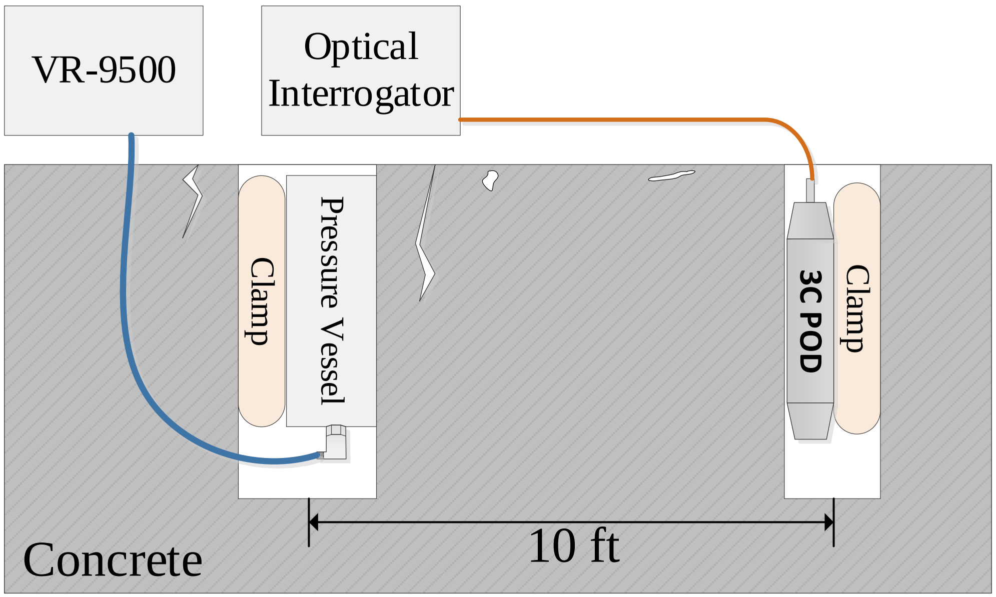


The Geophones did NOT register the IAMEs sounds

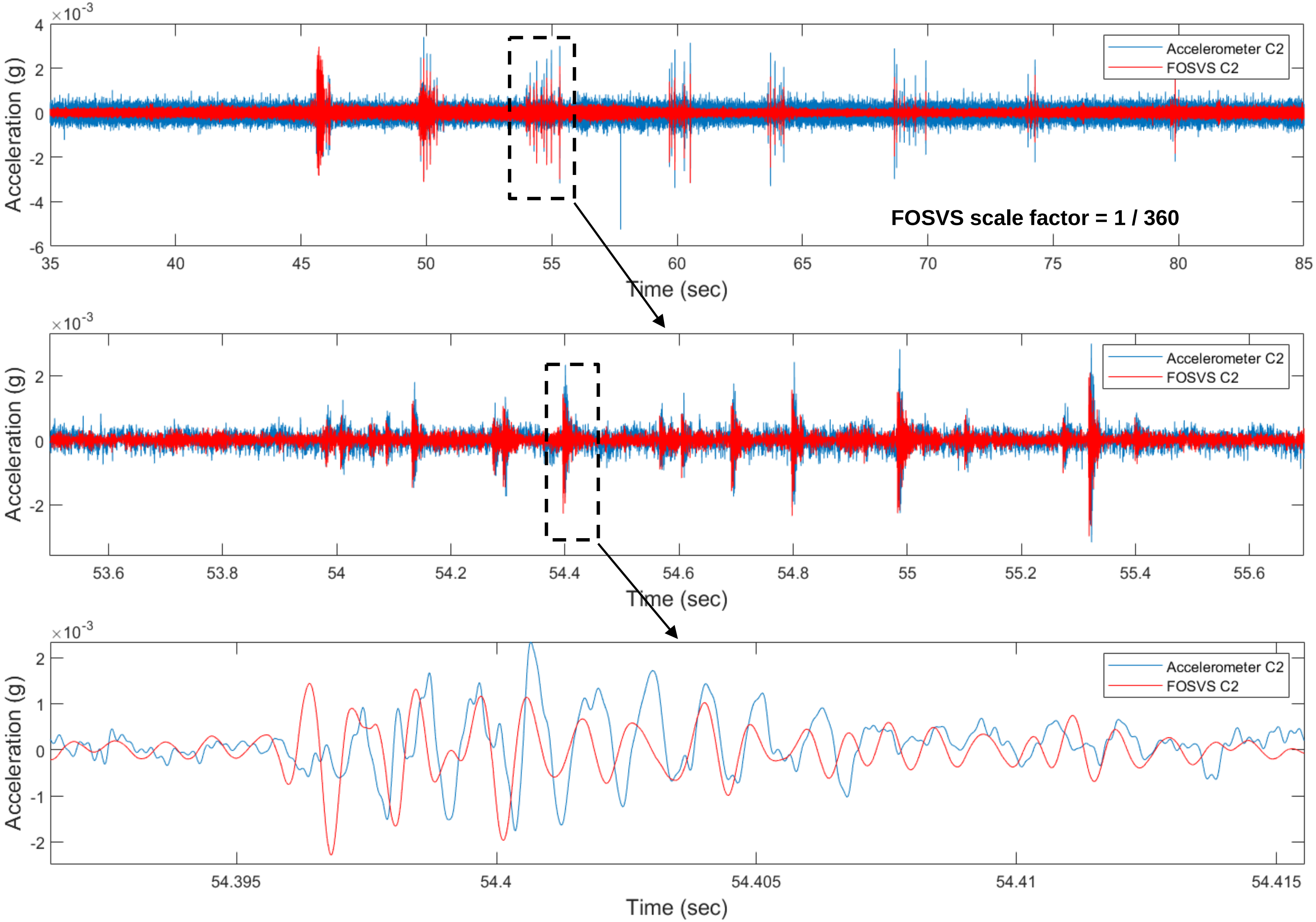
2019 Laboratory Tests of Micro Spheres as IME Size: 60 µm Matches 40/70 proppant

Terves Micro Emitters/ VisionFrax Lab Test Setup

- **Date: July 15 2019**
- **Mixture: 10% of poppers**
- **Offset: 10 ft through dry fractured concrete**
- **Receivers:**
  - **1C accelerometer on the bottom of the pressure vessel**
  - **3C FOSVS and 3C accelerometers in the same pod in concrete 10 ft away**



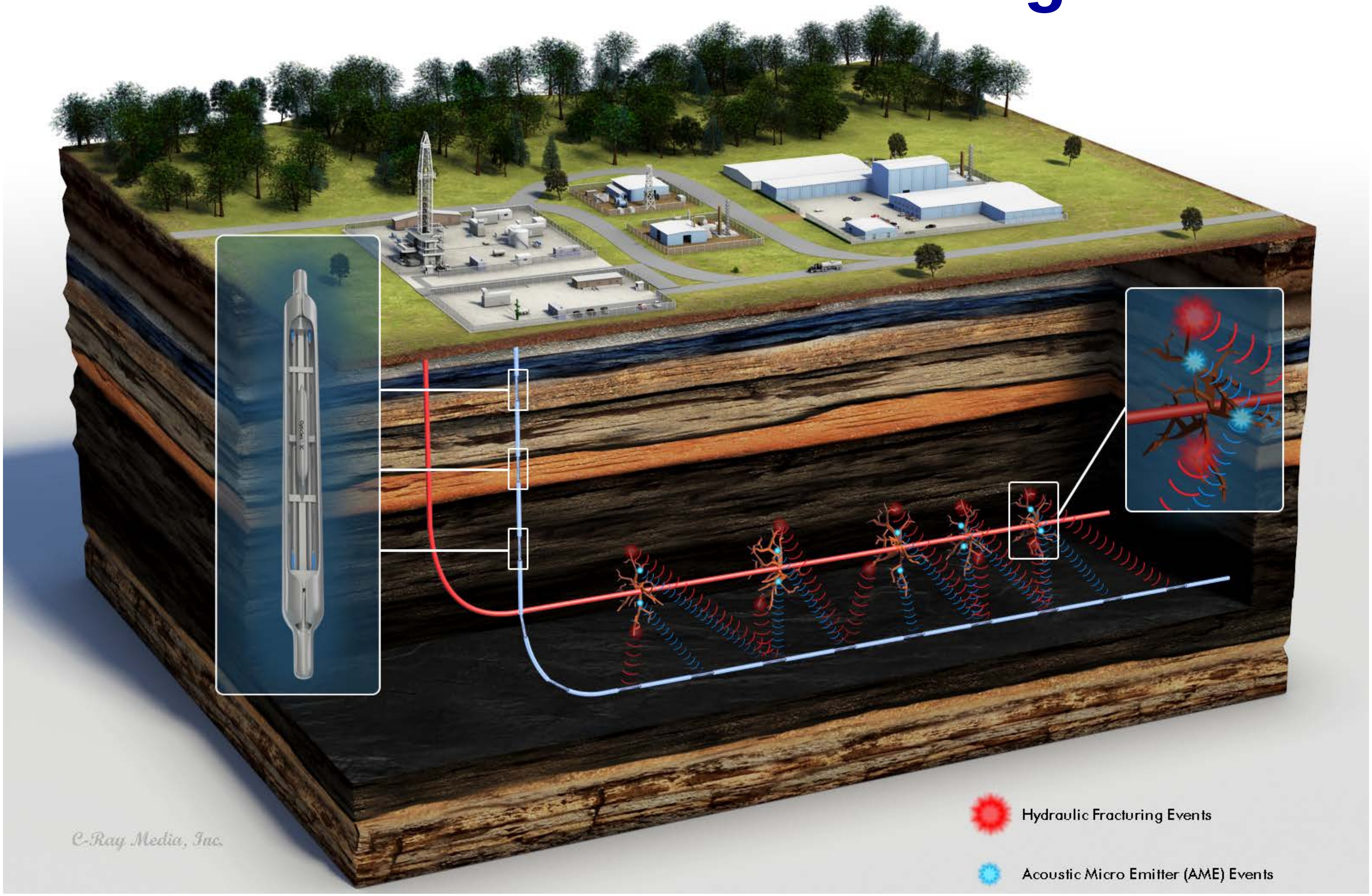
FOSVS Filtered R1 VisionFrax Data ([5-10-5k-6k] Hz)



So far we have tested VisionFrax Prototypes

Next Step is to Test the Actual VisionFrax to be Injected

Effective & Accurate Monitoring of UOG



Fiber Optic Seismic Vector Sensors (FOSVS): Applications Include

- Monitor UOG Fracturing & Proppant Injection Operations to Increase Production from Current 5 – 8 %, thus leaving 92-95% behind, to a much higher oil recovery
- Monitor Water, Steam, CO2 Injection
- Monitor Production of Conventional Oil&Gas
- Monitor Geothermal EGS Production

We will Address the Need to Monitor & Map:

- The Primary Fracturing for UOG and EGS
- The Injection of the Proppant in UOG
- Accurately Locate the fluid and proppant flow Micro Seismic events using Large Aperture FOSVS Arrays
- The location of the Delayed Events from the Injectable Micro Emitters (IME's) that are mixed with the Proppant
- Very small micro seismic events – to M-5.0 and smaller. The IME energy output is about M-3.5.

Also:

- Key to Successfully Apply the IAME Technology is Large Borehole Seismic Arrays Deployed in Horizontal Wells.

Injectable Micro Emitters (IME) for UOG & EGS

- Compliments standard micro seismic monitoring
- Find if there is fluid flows in fractures
- Find the location of fluid flows in fractures
- Find the location of proppant in the fractures
- Can produce valuable information on
  - fracture position and orientation
  - fracture width and opening
  - number of fractures per fracking zone
- Thus - In combination with effective monitoring technology the IAME technology has the potential to provide effective fracturing optimization thereby improving UOG and EGS production

Single Well Seismic Technology Made possible by Fiber Optic Seismic Vector Sensors

FOSVS + Borehole Seismic Source

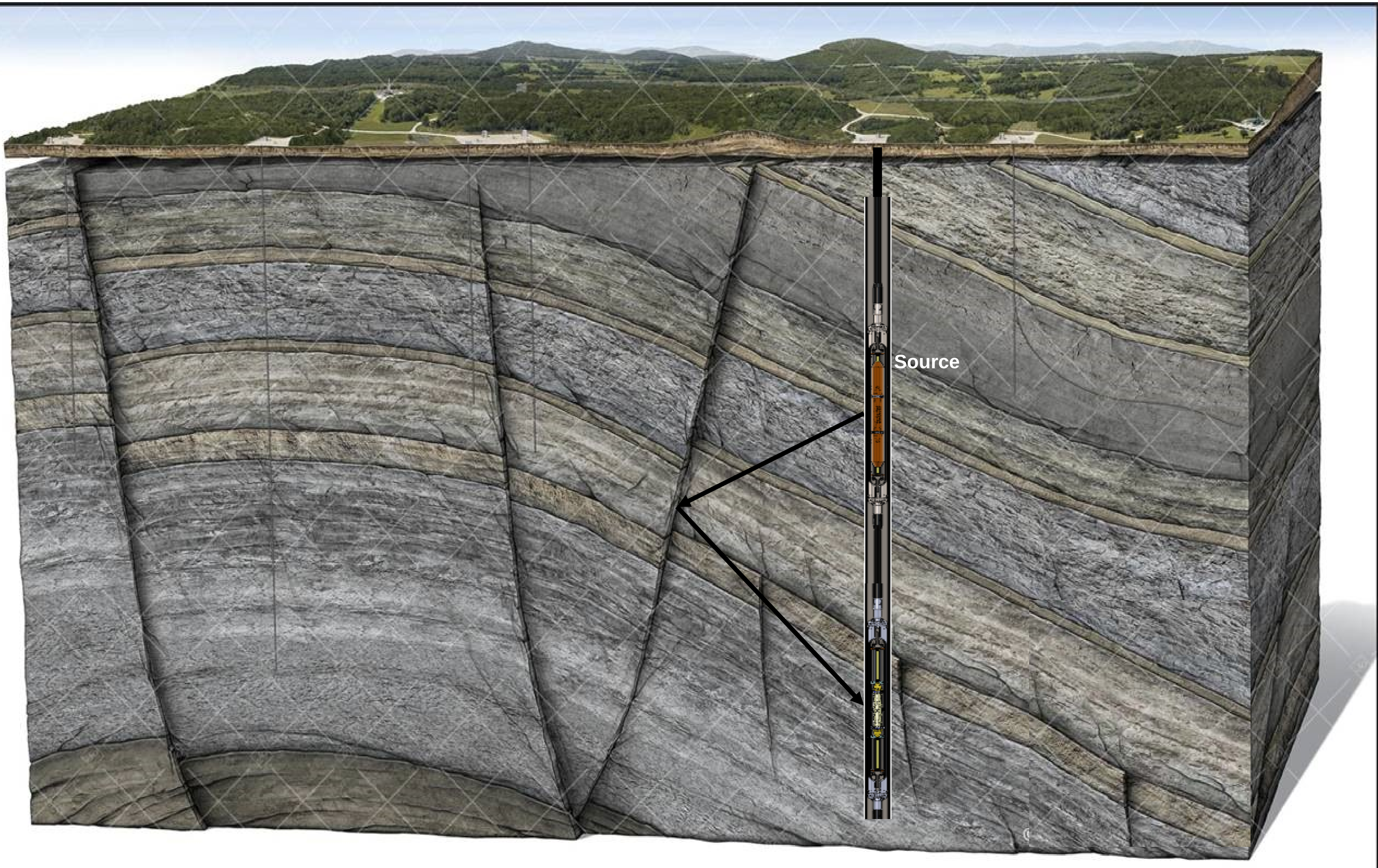
Creates an Extreme-Resolution Seismic System

- By placing only the Seismic Receivers in boreholes we get 2 – 10 times the resolution as compared with surface seismic!
- By placing both the Seismic Receivers and the Seismic Source we will get much better than 10 times the resolution as compared with surface seismic!

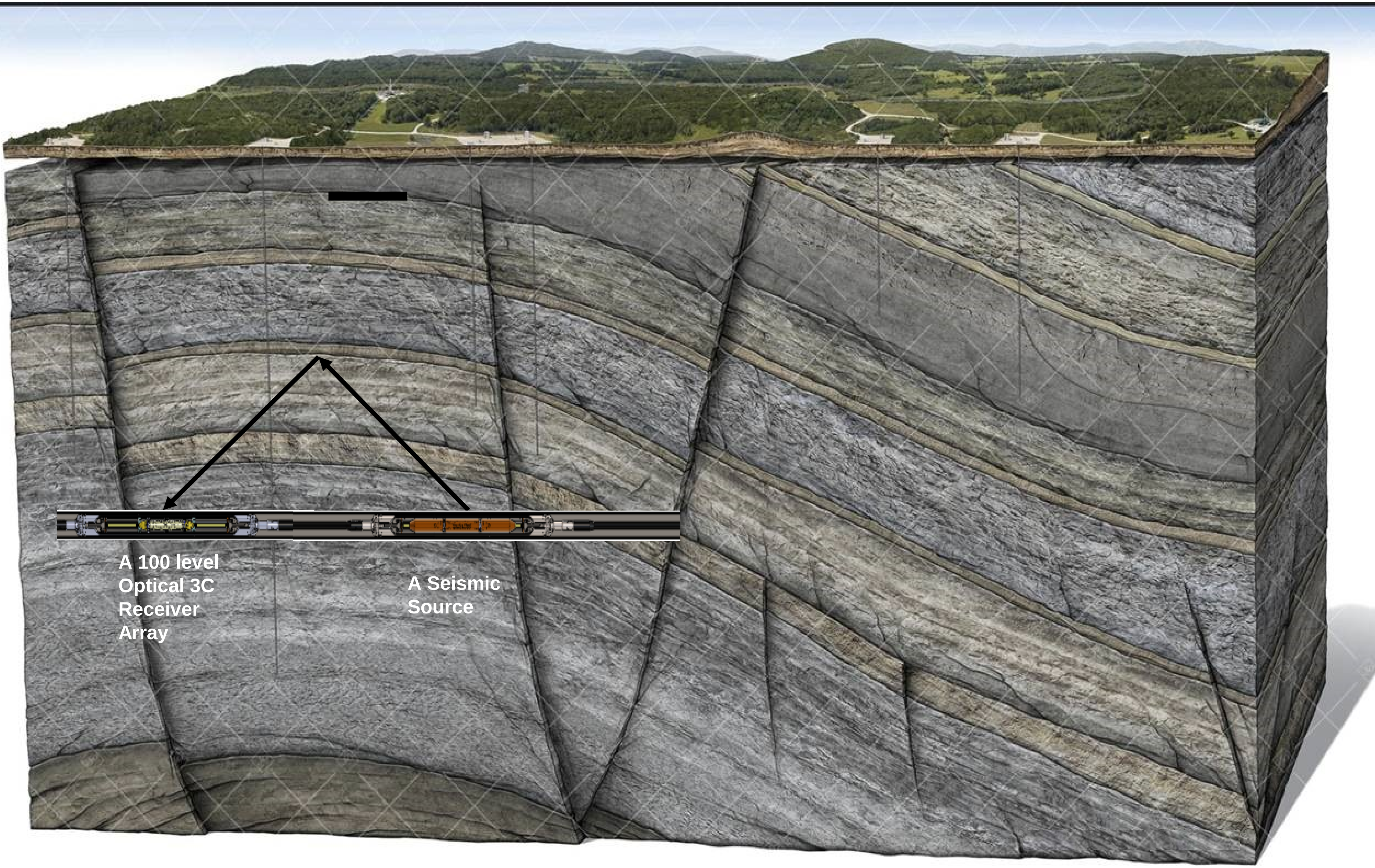
Single Well Seismic
Made Possible by FOSVS Sensors

- Much (>10x) Higher Frequencies than Surface Seismic
- Different View Perspective – Radial to Borehole
  - Horizontal Perspective in Vertical 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

Single Well Seismic Imaging of a Fault



Subsurface Geothermal Geology Imaging



30,000 Horizontal UOG Wells drilled/year

Laboratory test of a Downhole Seismic Vibrator

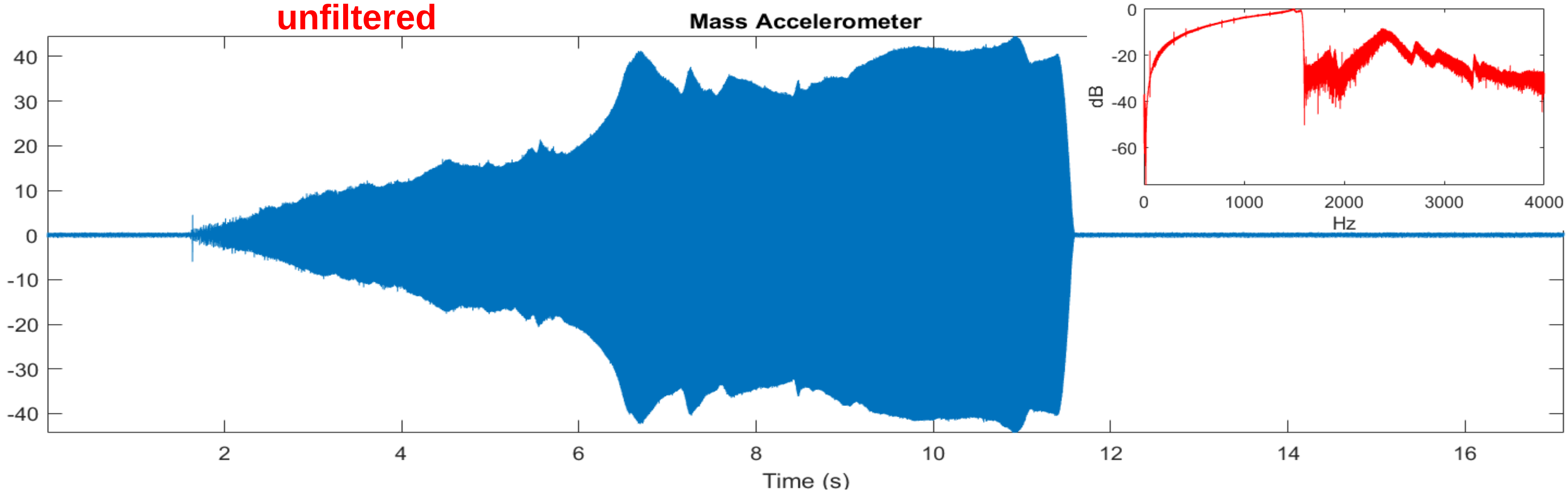
Source Test Setup

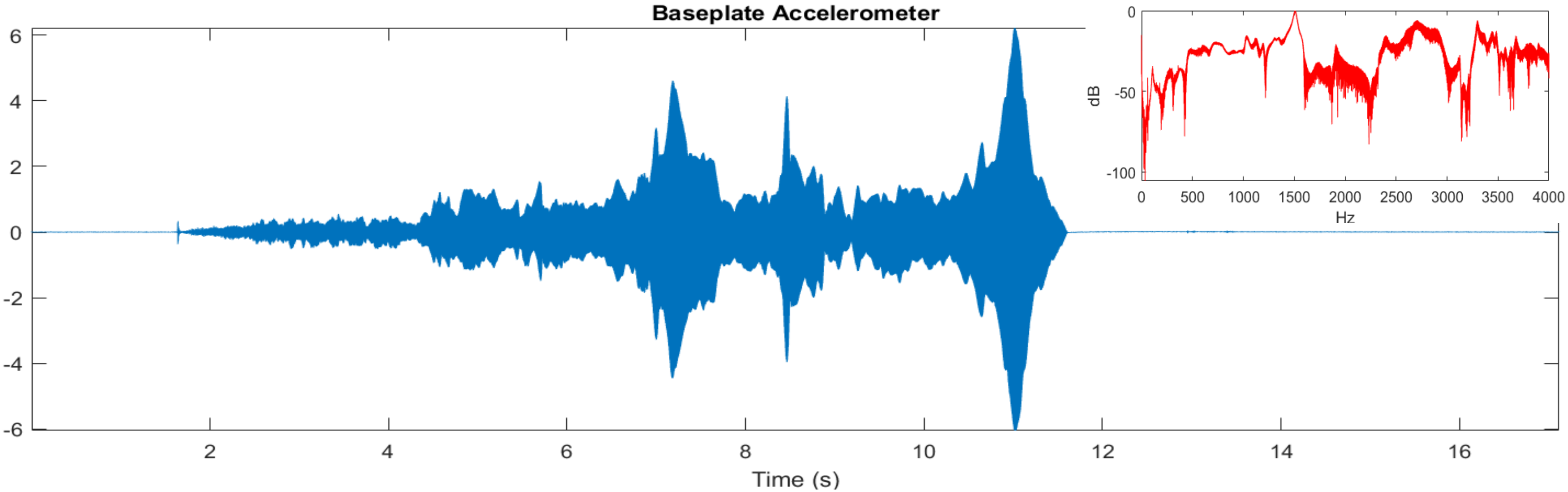
Test Fixture for a Downhole Seismic Vibrator

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

Uncorrelated Data: 10 – 1,610 Hz, 10 sec sweep, 5 Vpp drive (7.5 Octaves)

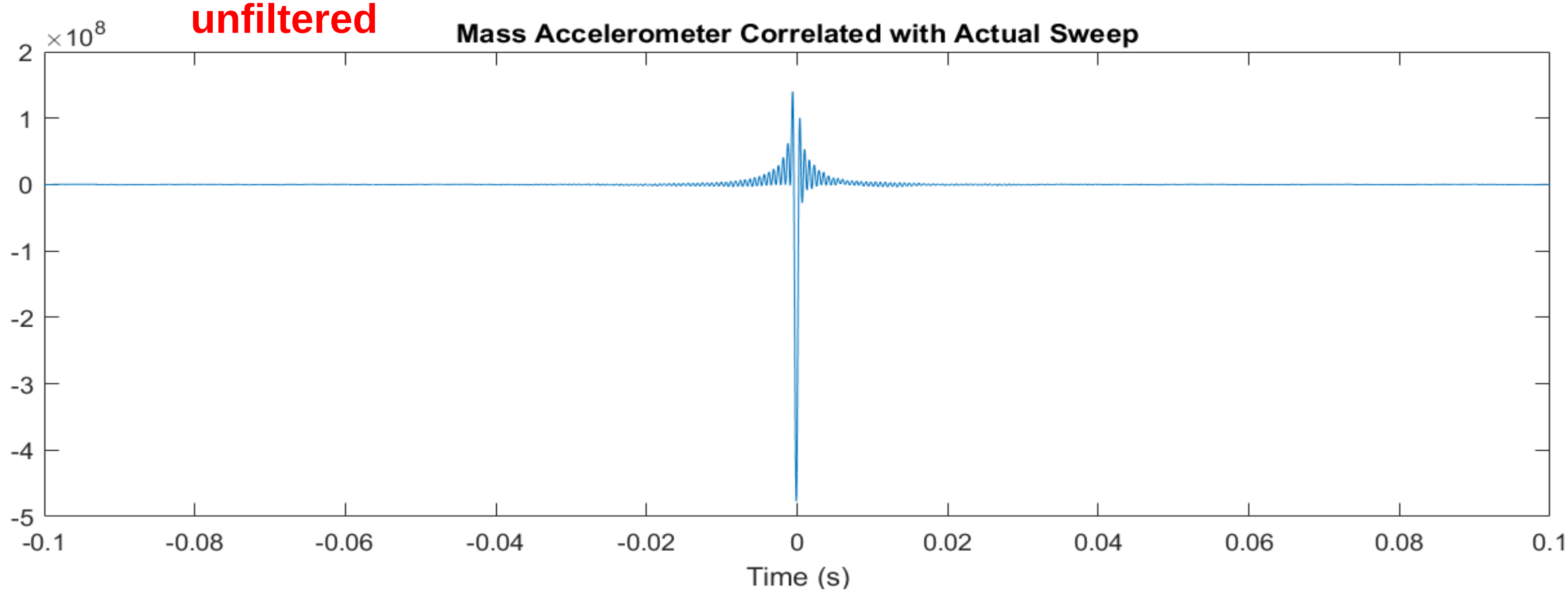
unfiltered

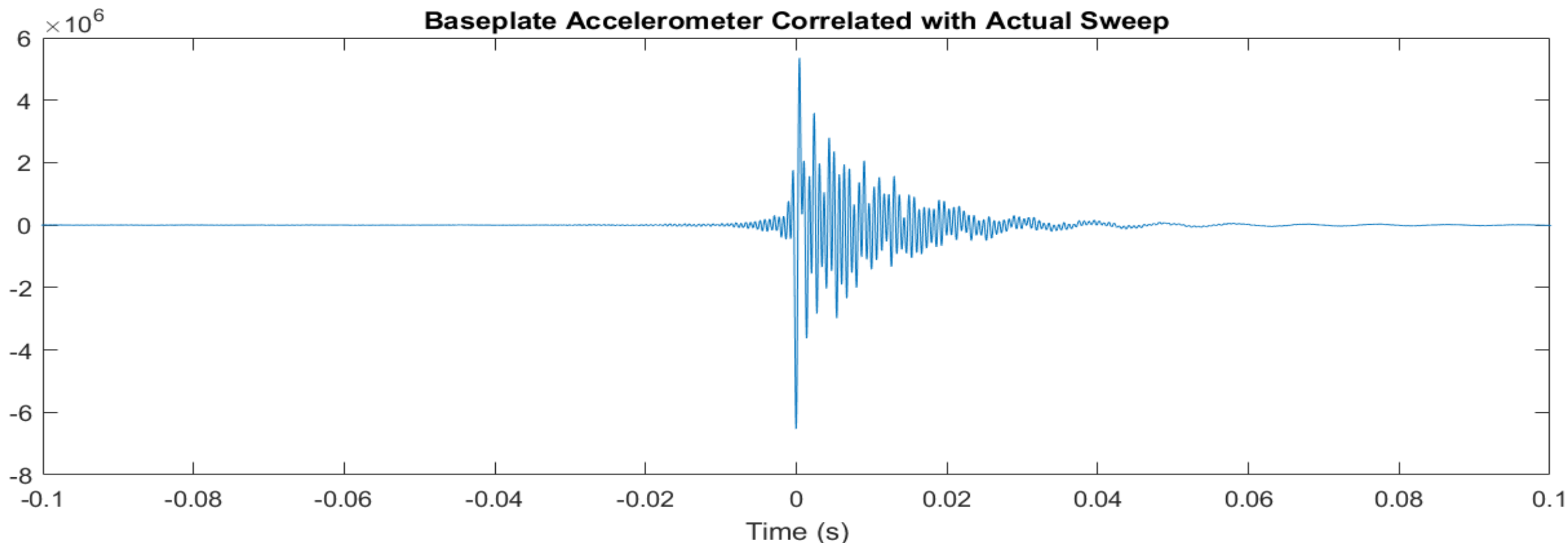




Correlated Data: 10-1610 Hz, 10 sec sweep, 5 Vpp drive

unfiltered





Final Thoughts

Next Step in Building More Effective Borehole Seismic Arrays:

Combine FOSVS with DAS

Precise Vector Data from FOSVS Combined with Large Aperture Data from DAS

FOSVS + DAS

Both FOSVS and DAS are optical sensors

- DAS are Rayleigh Scattering Based
  - Not Very Sensitive
  - Depth mapping not precise -> low res images
  - Nor a true Acoustic Receiver. Z-Sensitive
  - Supports Large Aperture Arrays

- FOSVS is Interferometric Based: 10^3 – 10^4 more sensitive than DAS. Has recorded <M-5 field events.
- FOSVS are vector sensors with an 80 dB cross axis rejection – Calibrates DAS data

Our Big Challenge is to Commercially Demonstrate our New Reservoir Survey & Monitor Technologies!

DOE is a Key Partner to Provide Opportunities to Demonstrate our New Technologies used to secure our National Energy Resources

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)
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  - DOE SBIR II Grant DE-SC0018613 (2018) Downhole Source

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Thank You!

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&

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