Paulsson, Inc. (PI)

New Subsurface Signals are Needed for Improved Imaging of Subterranean Reservoirs & Resources

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December 18, 2014

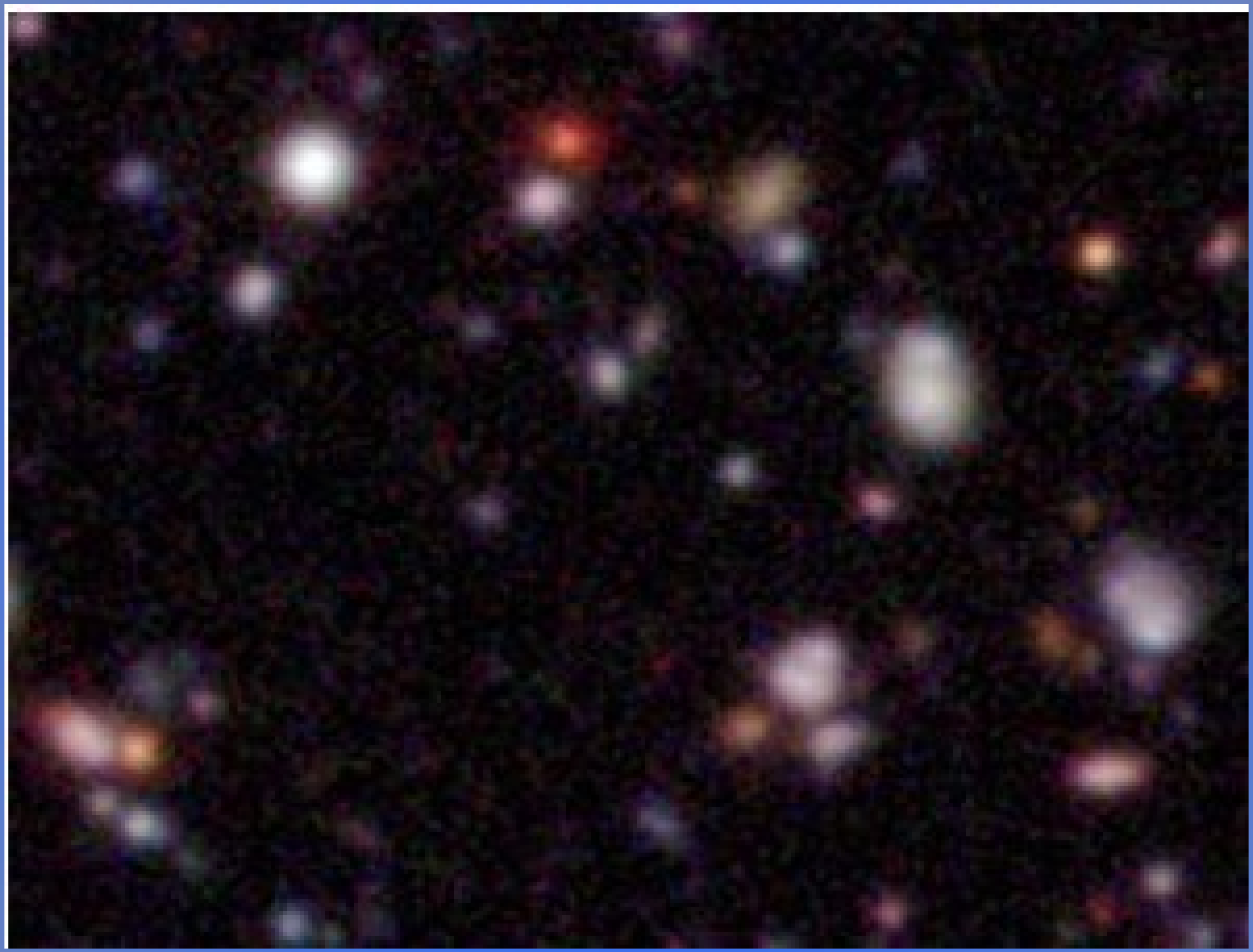
Why are New Subsurface Signals needed

Example from Space

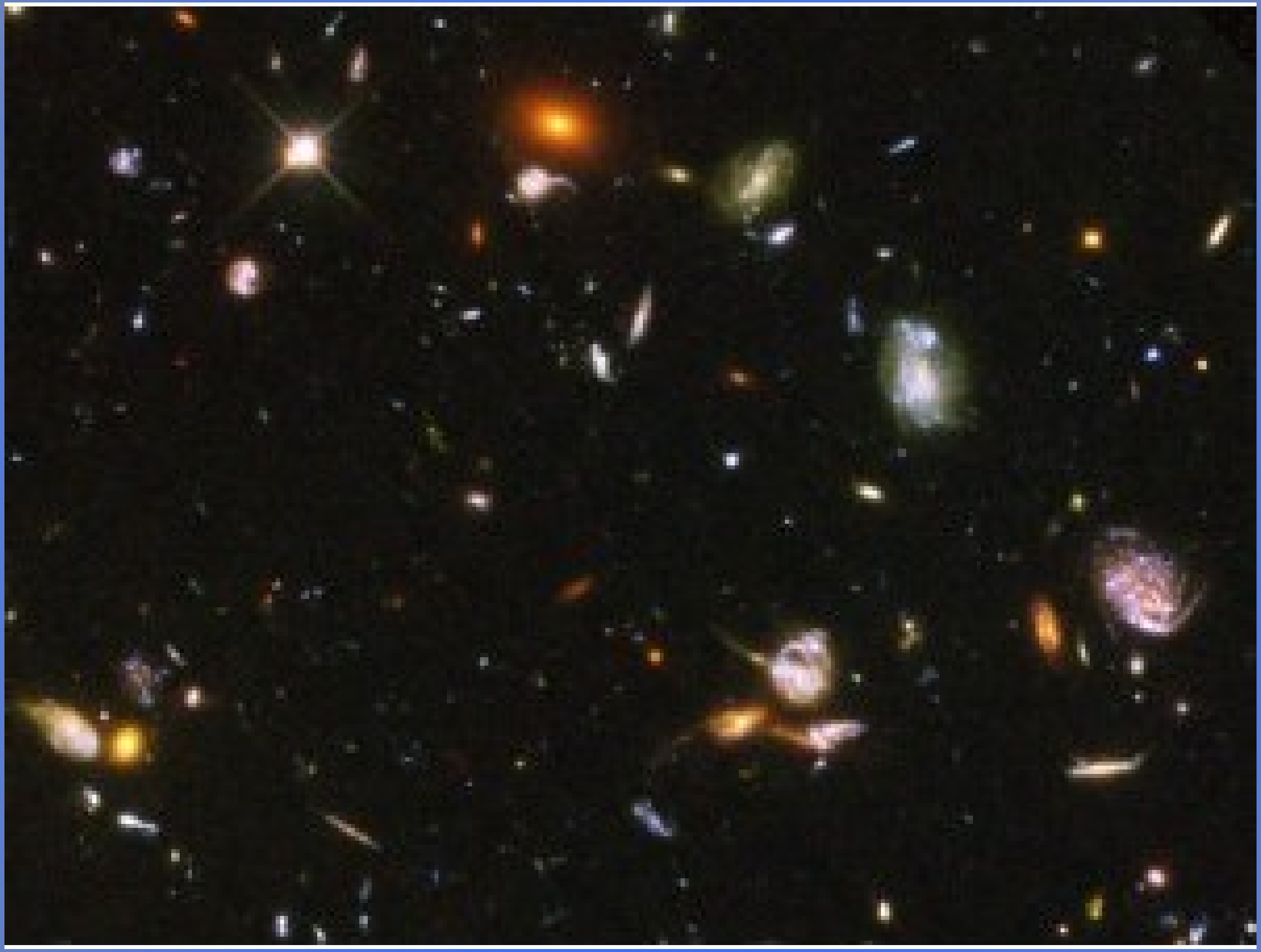
The Brilliant Idea of the Hubble Telescope:

Avoid the Noisy Atmosphere

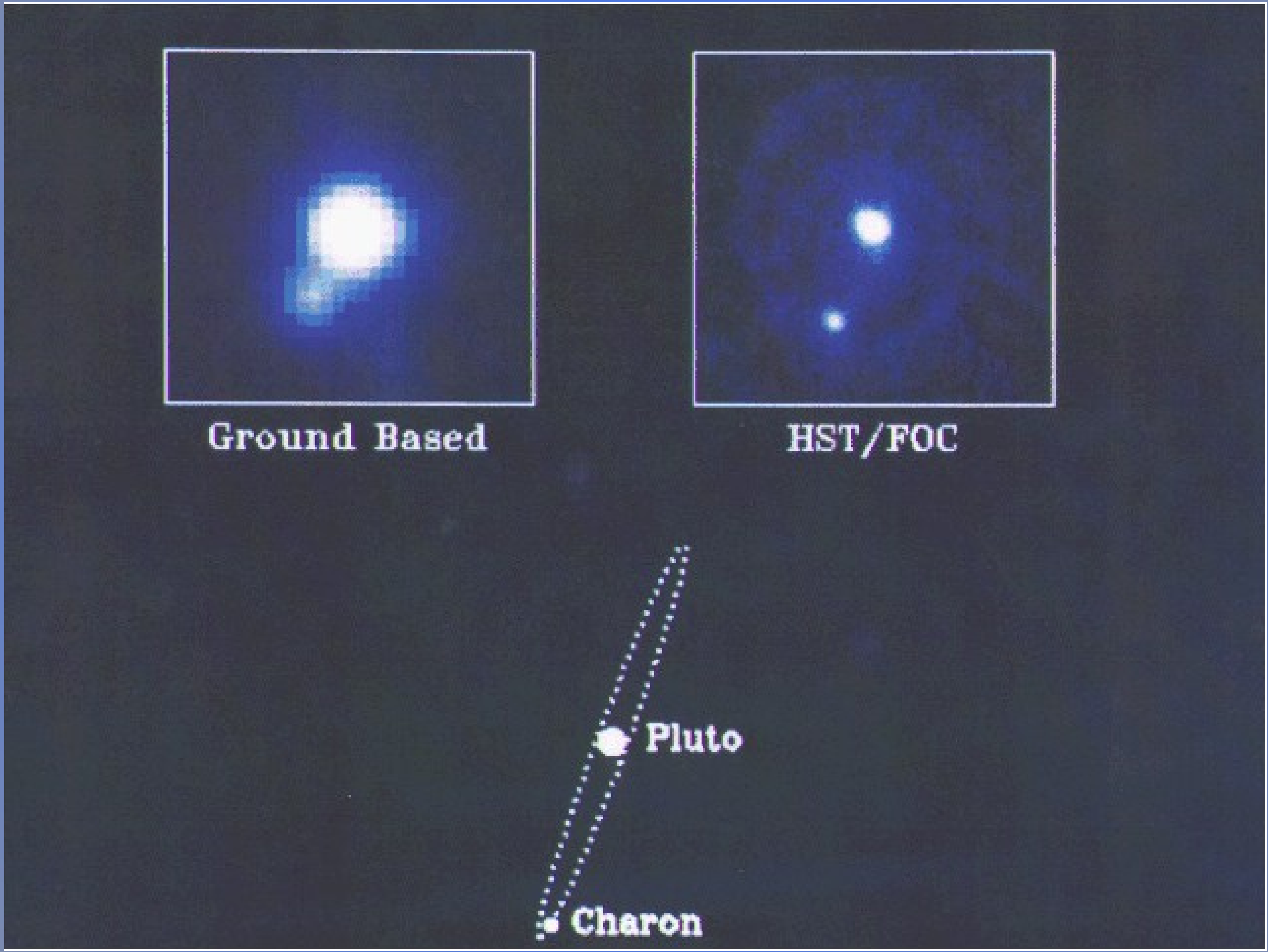
Turning this from an Earth telescope



Into This from the Hubble telescope



and this - into this



How do we apply this lesson from Space-Imaging to Earth-Imaging

Avoid the Noisy Surface!

Use Wells for the Instruments!

Develop Better Sensors!

All Examples today are from CCUS and Oil & Gas!

Up to now – Borehole Seismic Arrays have not been qualified for Geothermal Applications!

Our New FOSS Array has changed that!

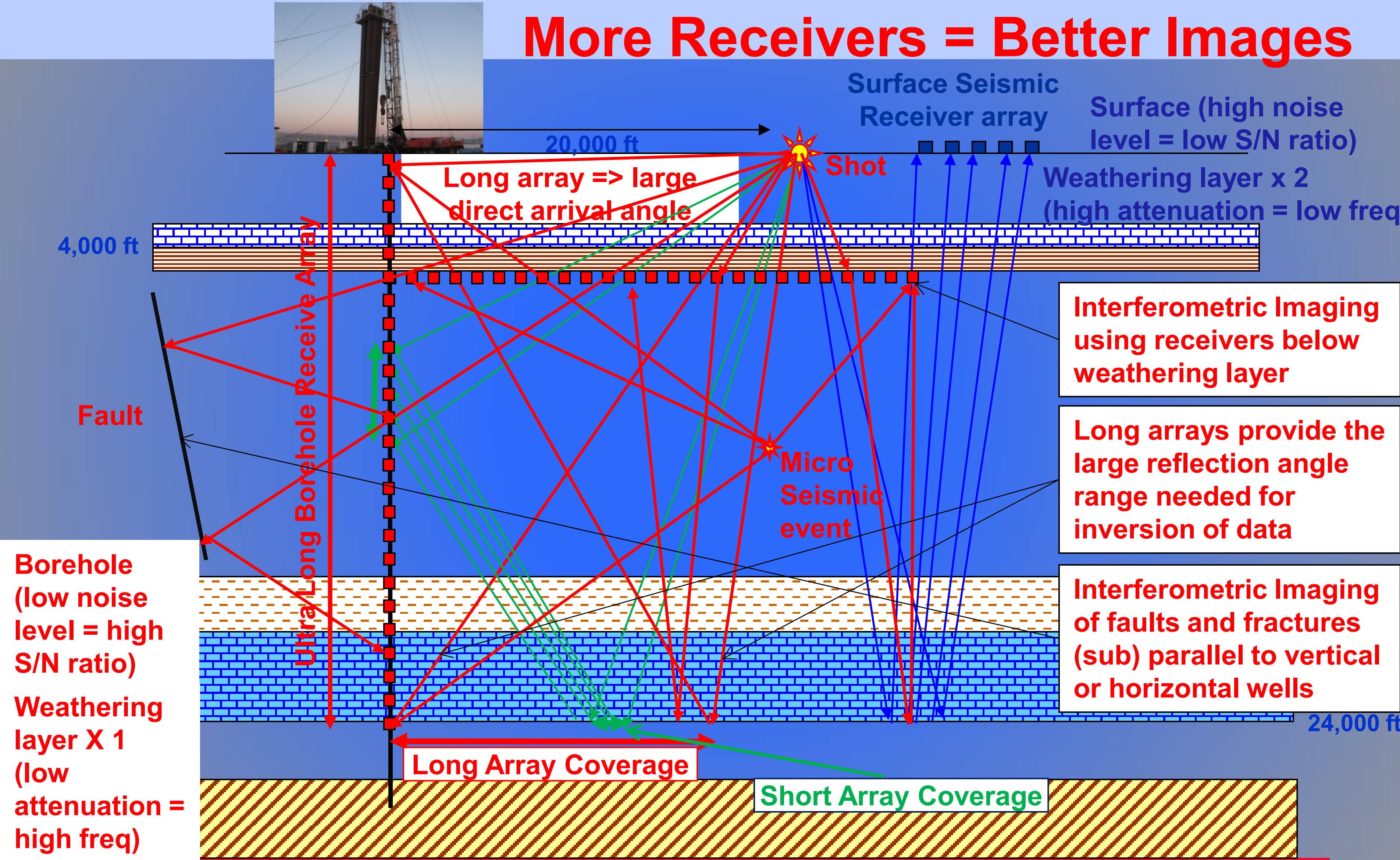
First Survey at the Geysers with Calpine & LBL in September 2015

Borehole Seismology

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

Borehole Seismic Imaging with Ultra long arrays

More Receivers = Better Images



Micro Seismic Monitoring of Fracking operations or Interferometric 3D VSP Imaging of Oil Production using Active and Passive Seismic Sources in Horizontal Wells

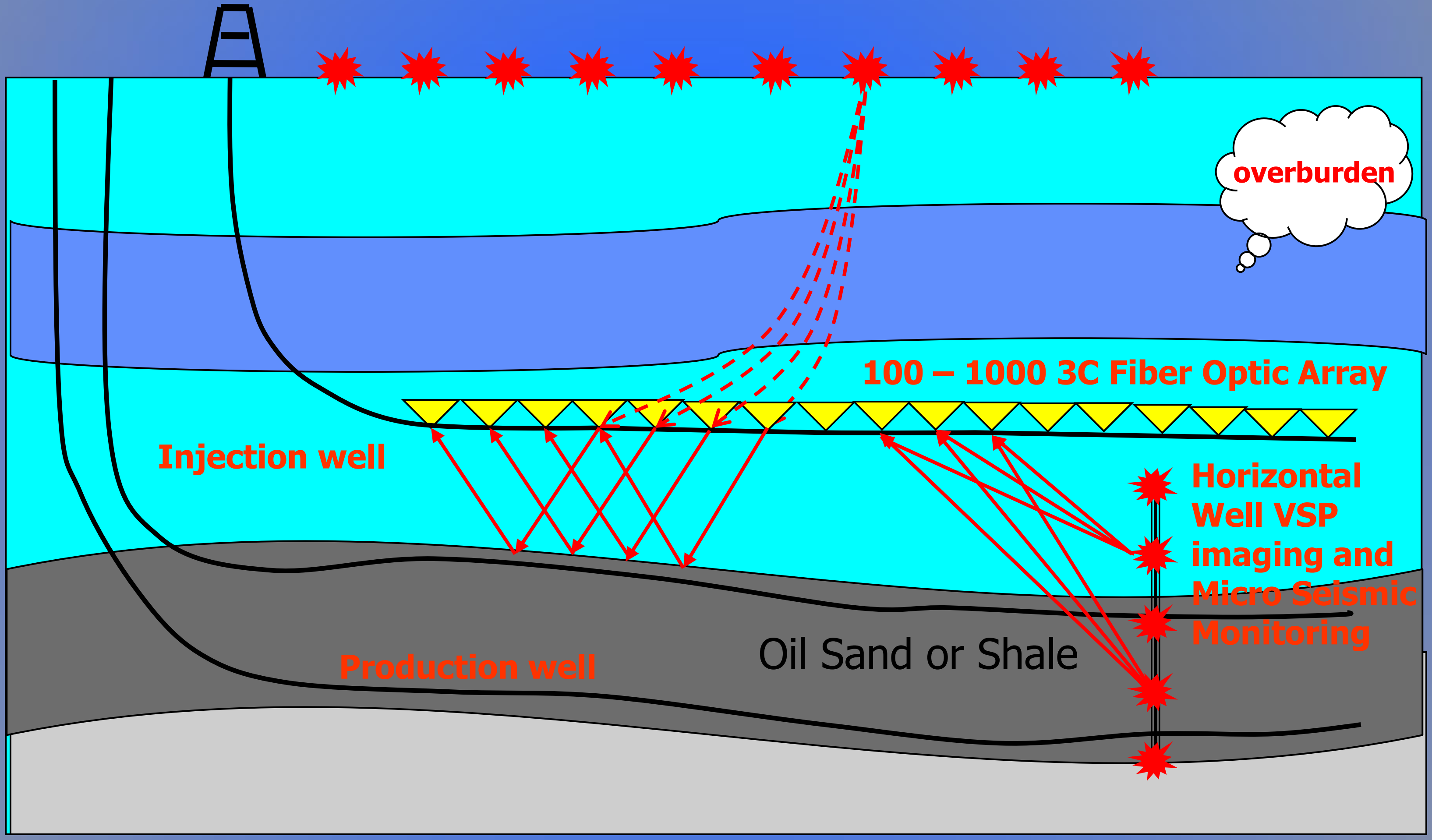


Image Shape from a vertical well 3D Borehole Seismic Survey

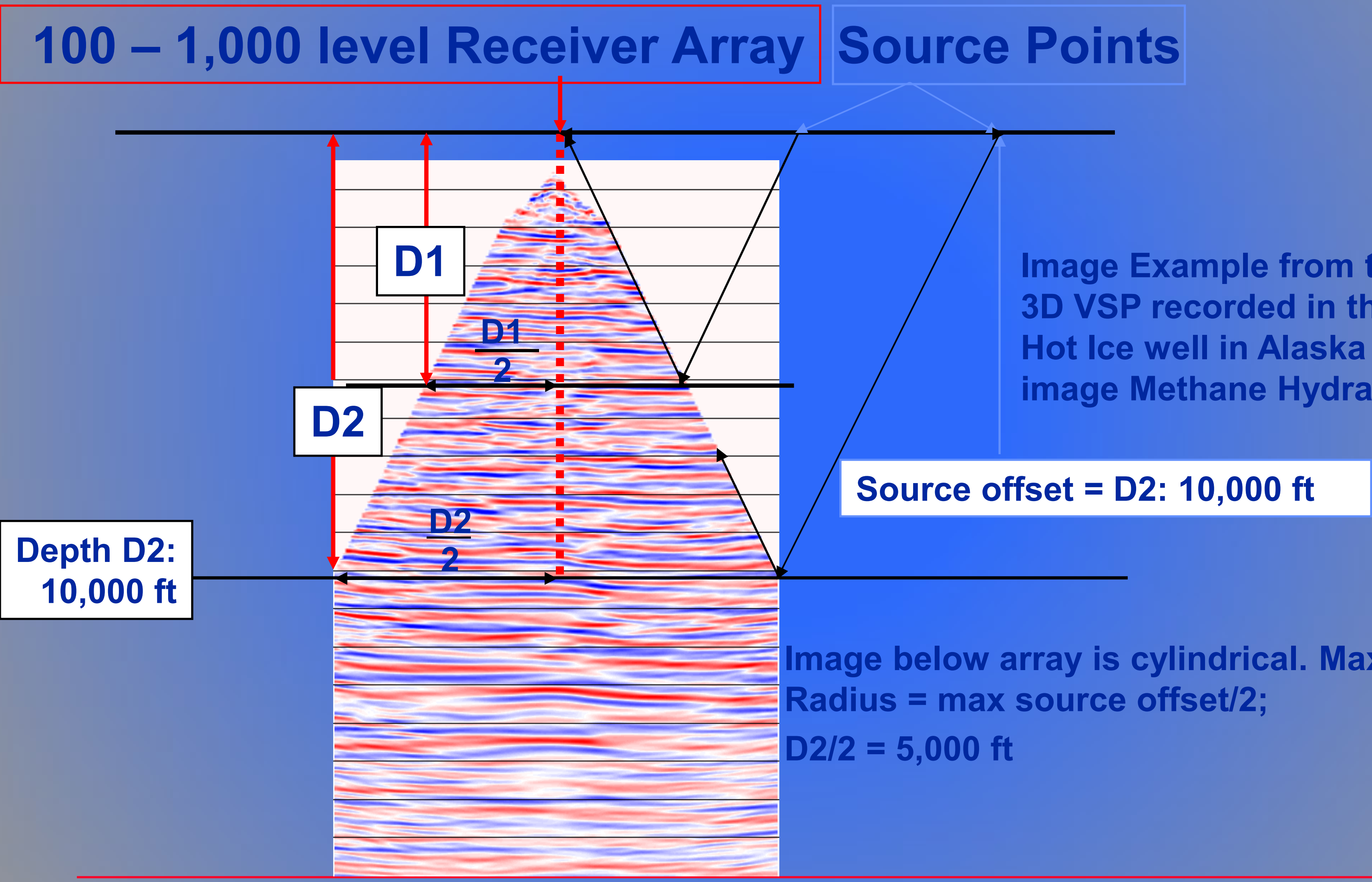


Image Example from the 3D VSP recorded in the Hot Ice well in Alaska to image Methane Hydrates.

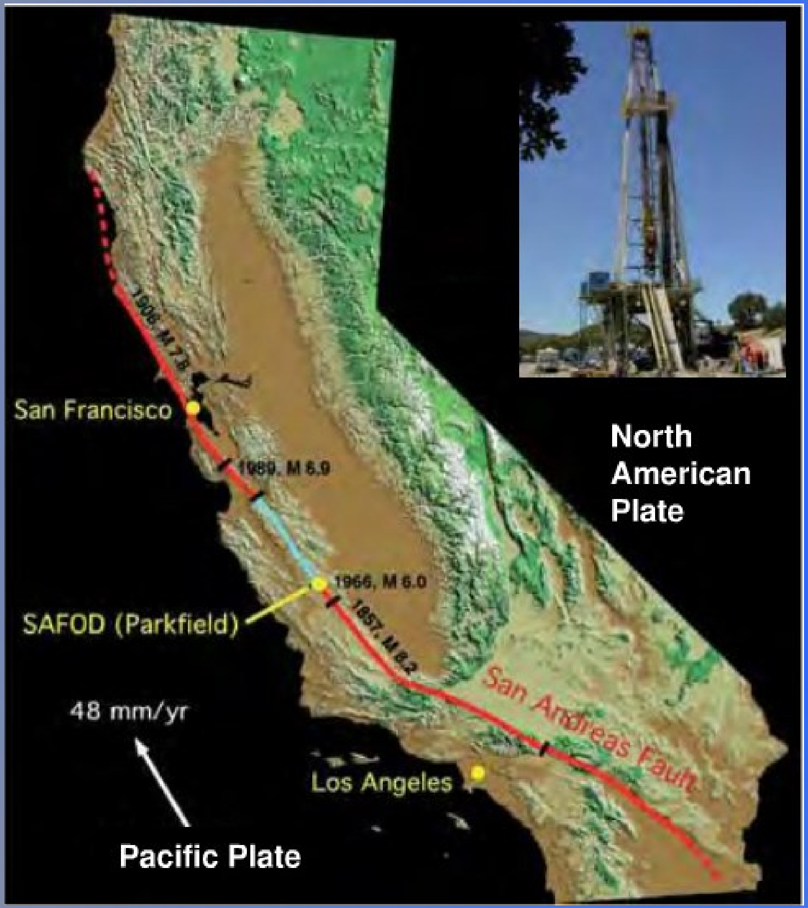
Image below array is cylindrical. Max Radius = max source offset/2;

D2/2 = 5,000 ft

Micro Seismic Applications For Long Arrays

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))

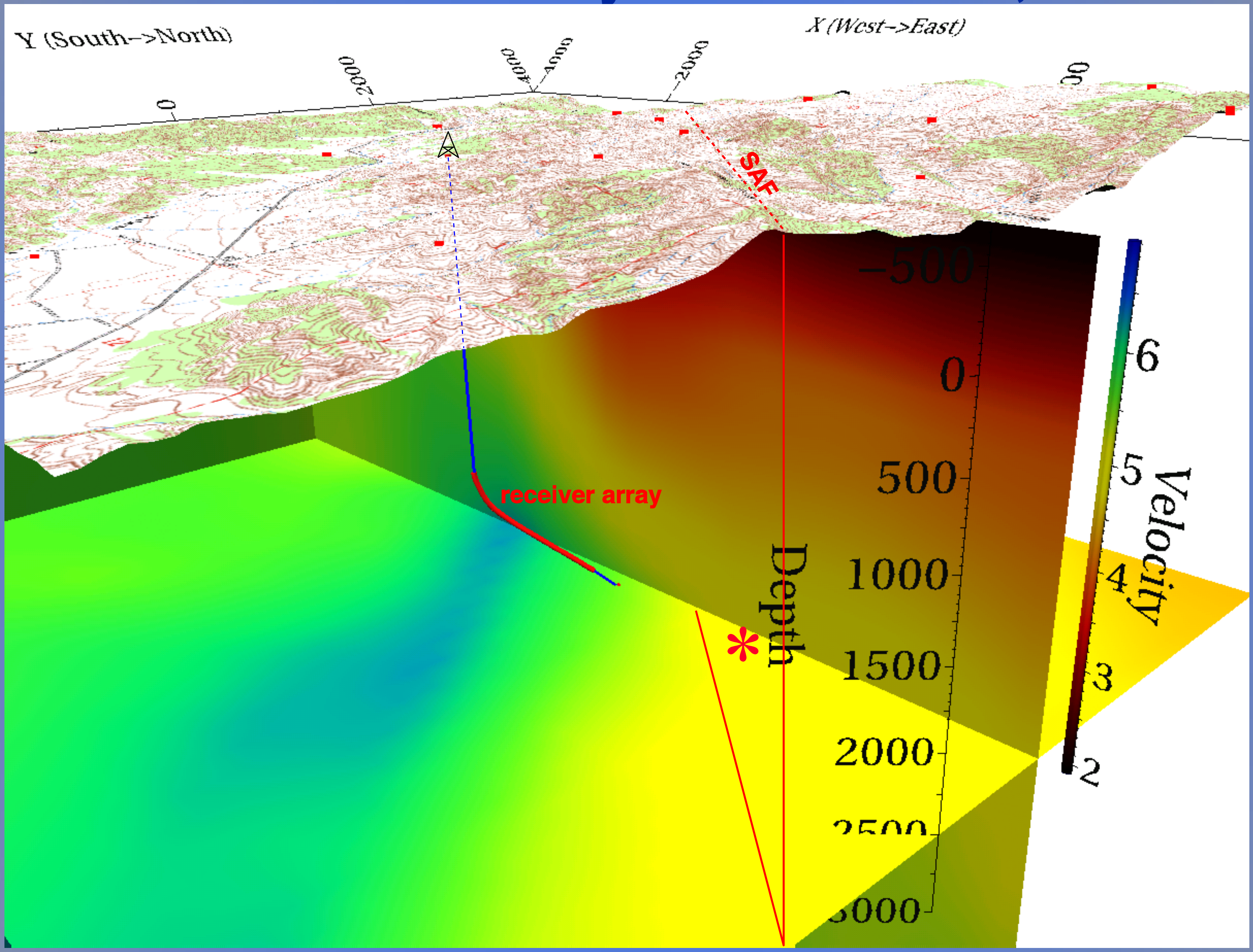
Zoback (2006)

Looking West @ Pacific plate heading north at 48 mm/year (~2”/year)

The Bridge over Sand Andreas Fault


The San Andreas Fault Zone from the Pacific Plate looking East
We are traveling North by 2”/year
We are going north – we are standing on the Pacific Plate

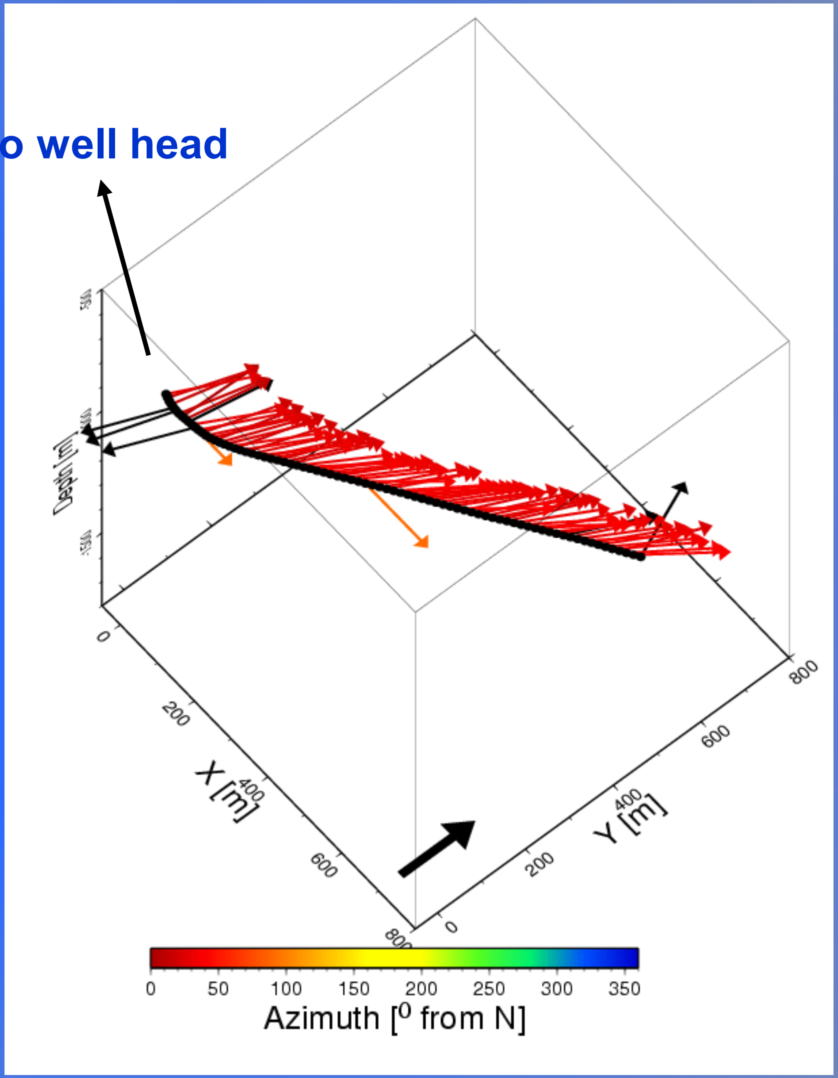
San Andreas Fault Survey Site – Parkfield, California



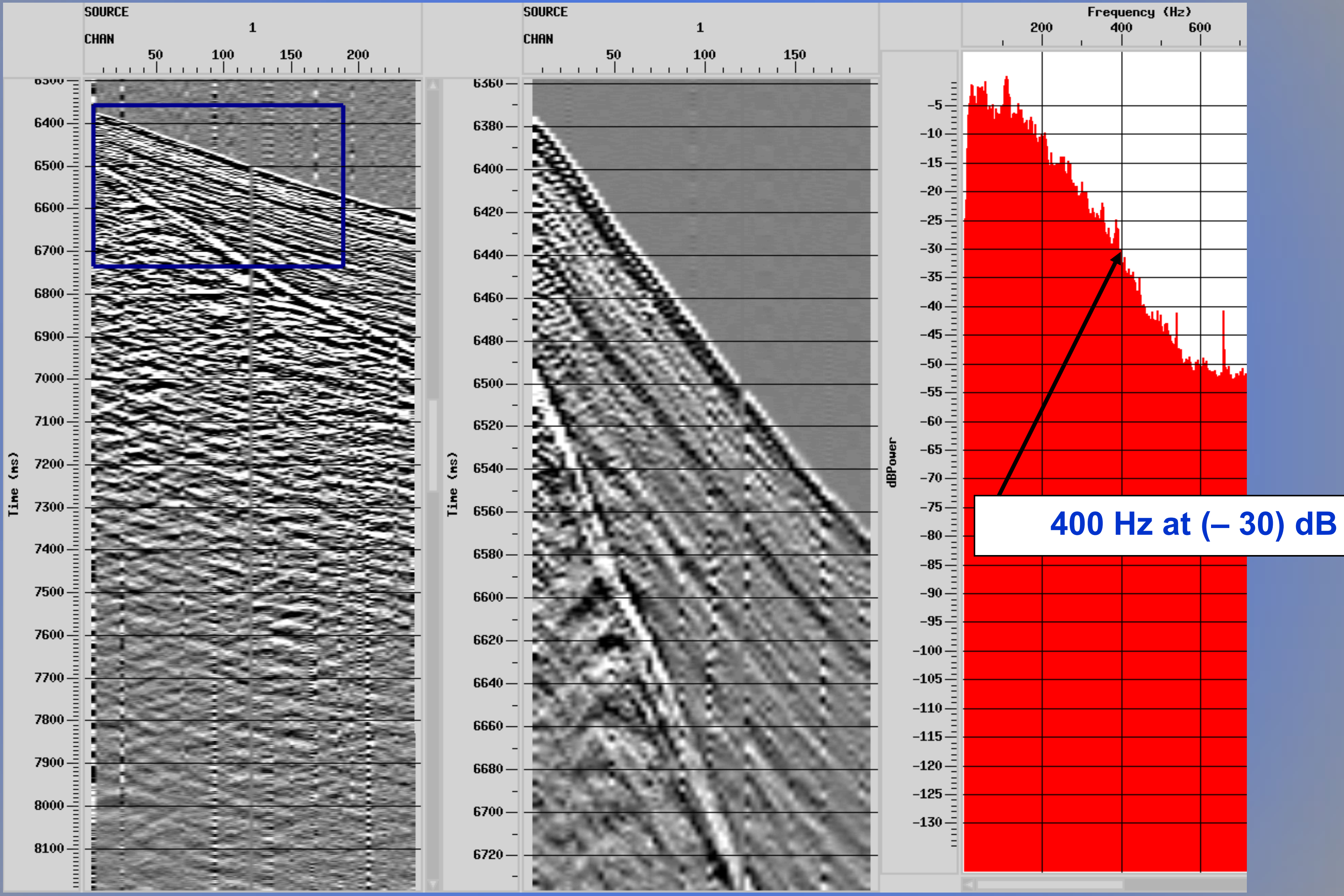
Mapping the seismic events using a large borehole seismic vector array.

Local emergence angle on each pod for selected earthquake event (M0.0)

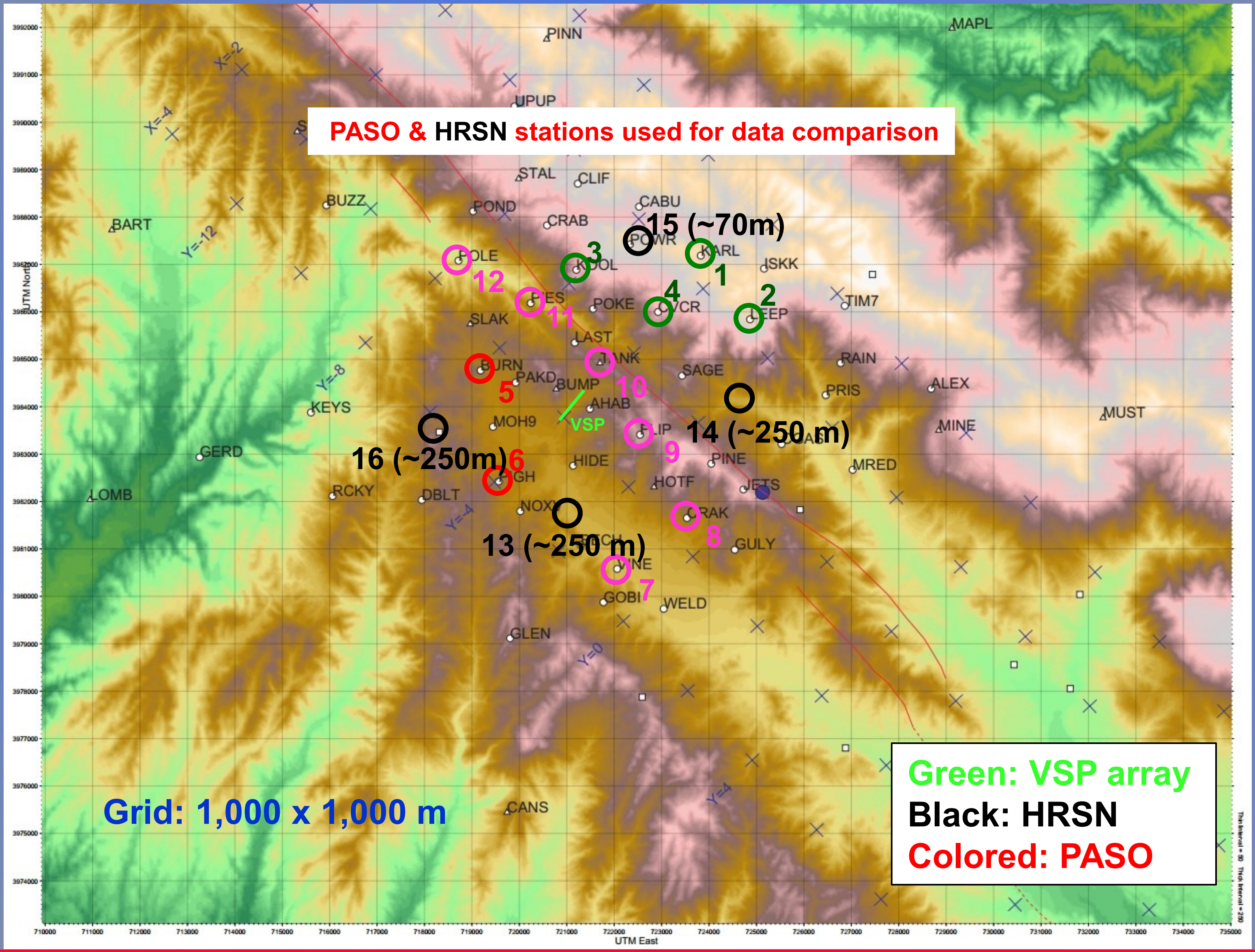
to well head



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



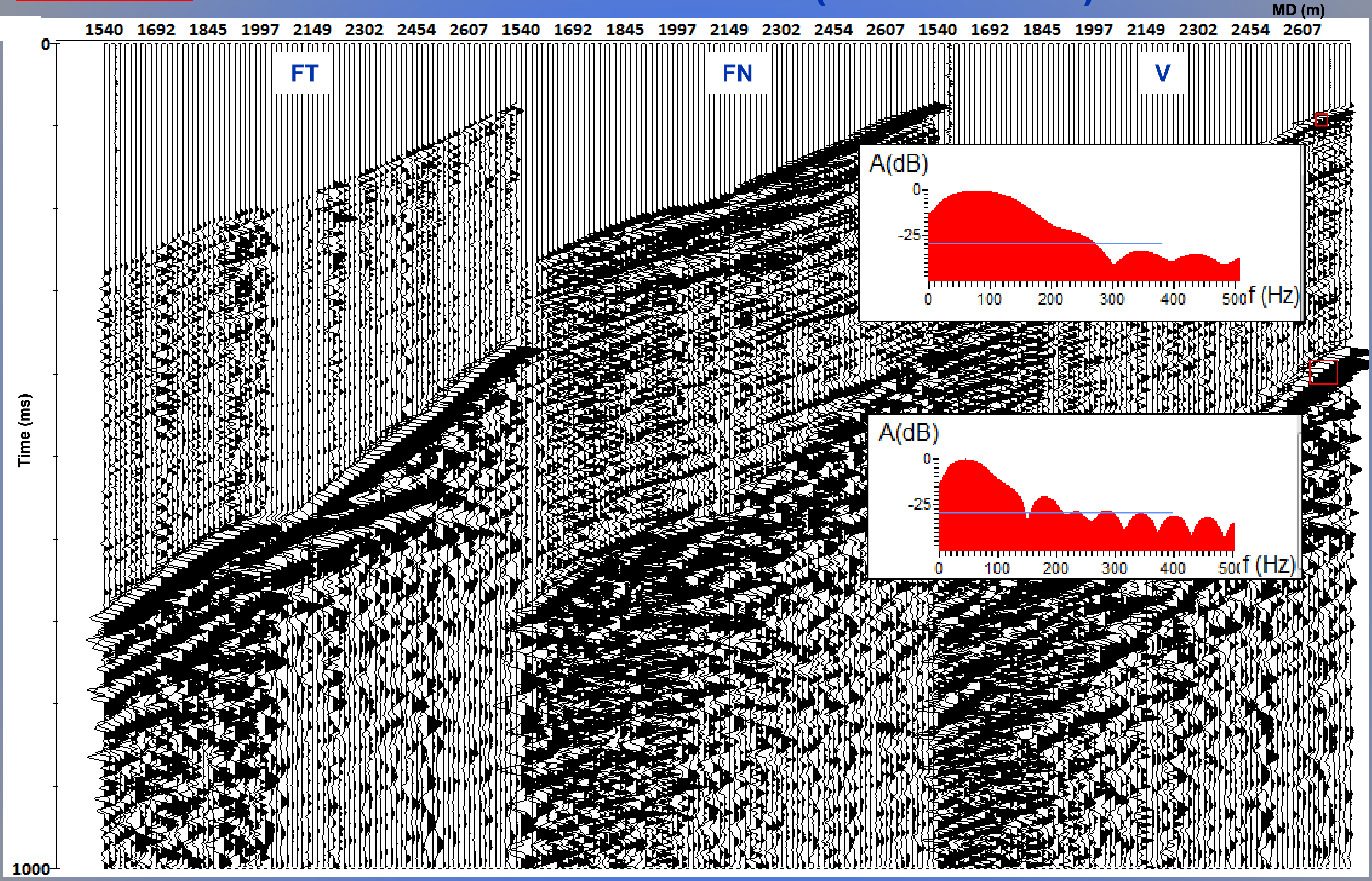
Parkfield Area Seismic Observatory (PASO)



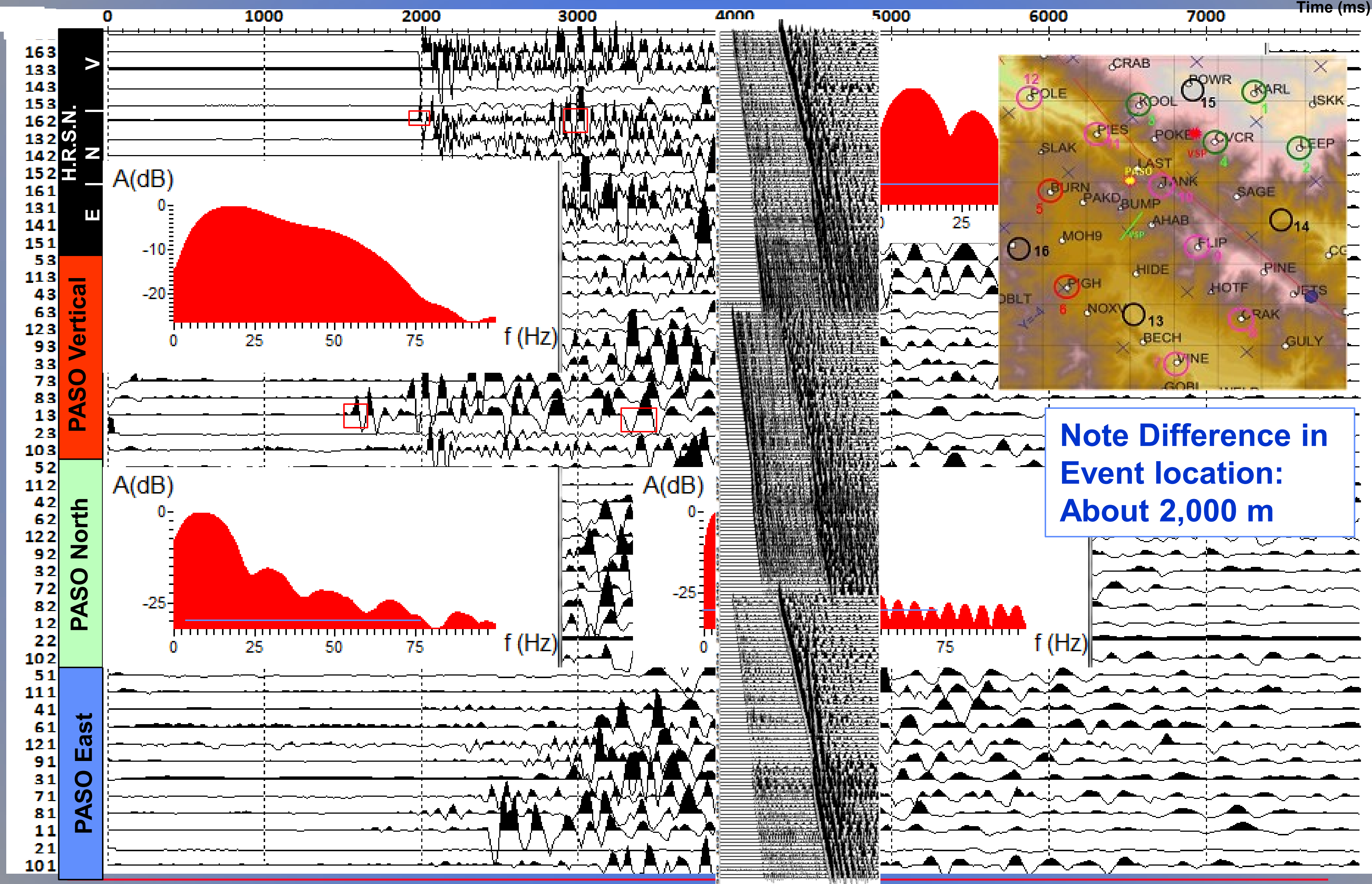
Why Sensor in Boreholes? Surface is so much easier!

A Micro-Seismic Event (5/8/2005 22:17:57)

USGS: M0.34



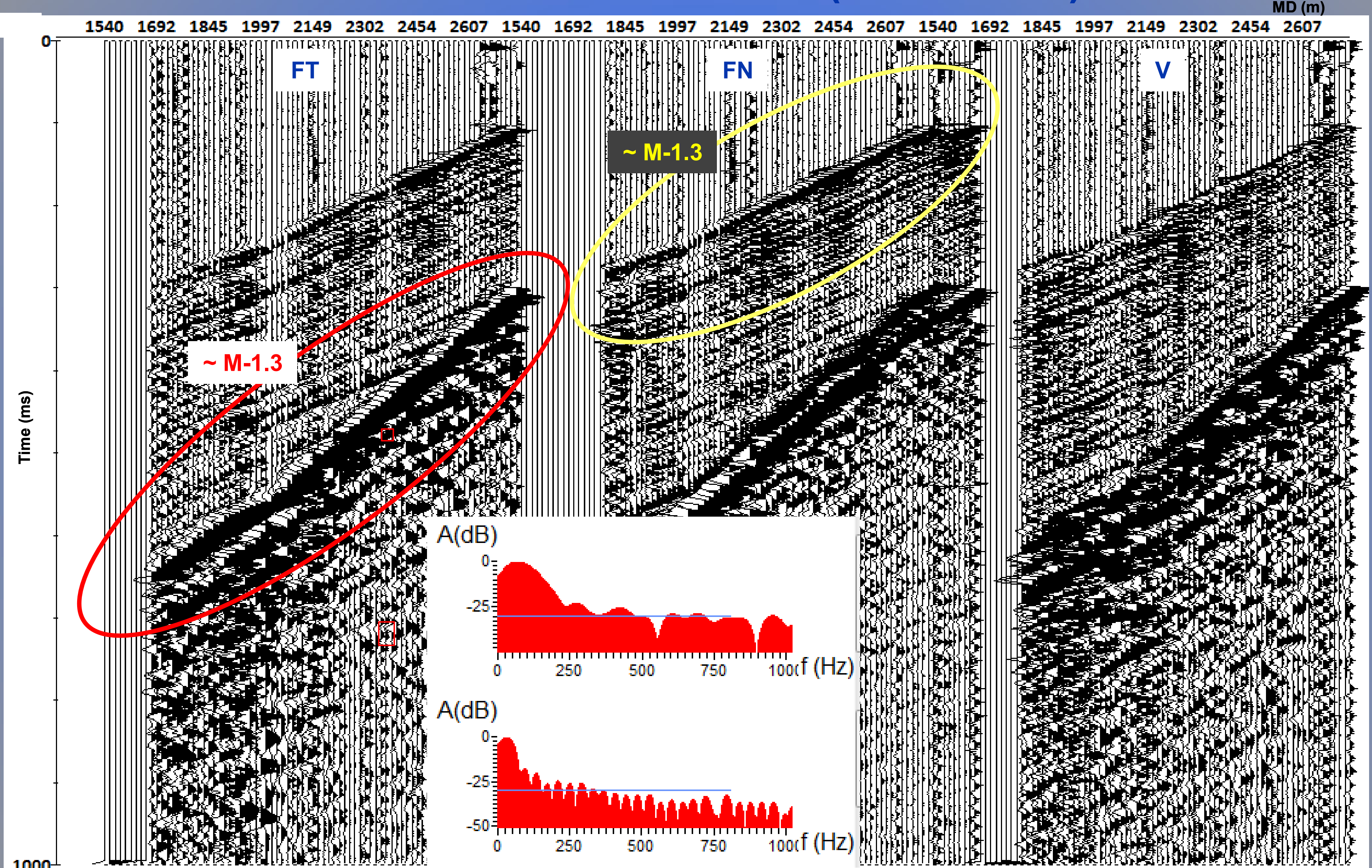
USGS: M0.34 — A Micro-earthquake Event in PASO (5/8/2005 22:17:57)



Note Difference in Event location: About 2,000 m

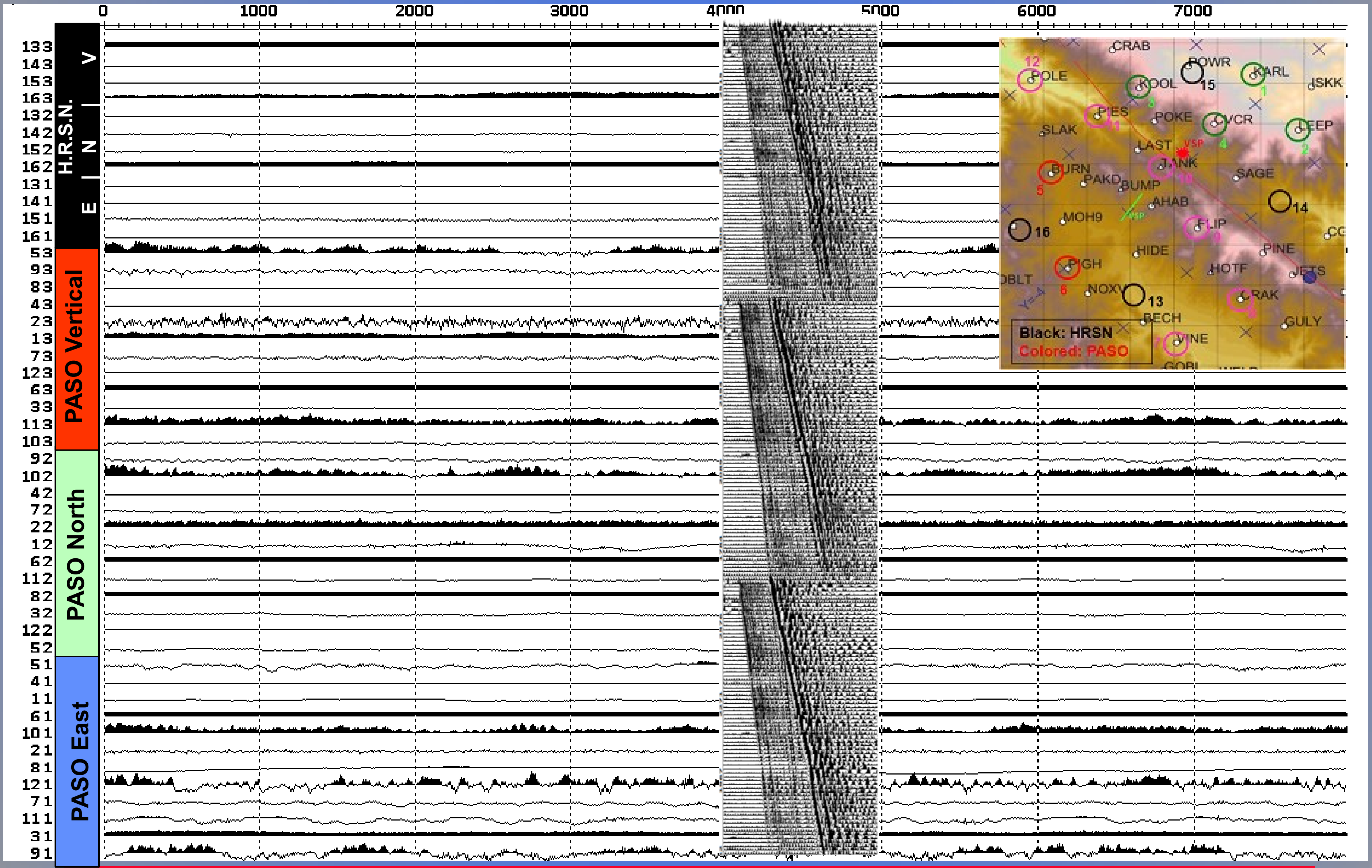
PI: M-1.3

A Micro-Seismic Event (4/30/2005 18:49)



PI: M-1.3

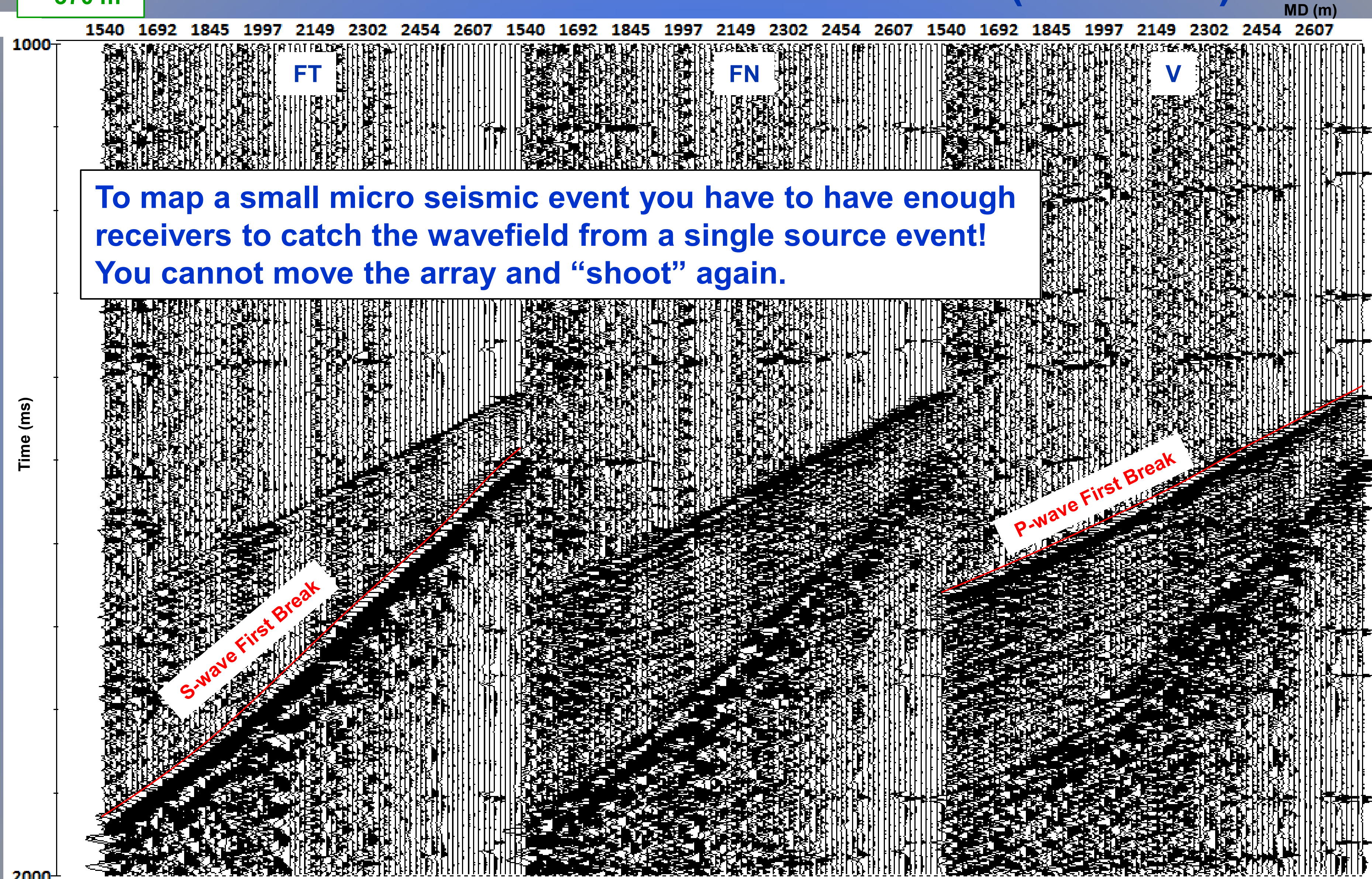
Micro-earthquake Event in PASO (4/30/2005 18:49:59)



Why Long Aperture Arrays?
Why tight Spatial Sampling?

PI: M-1.8
~370 m

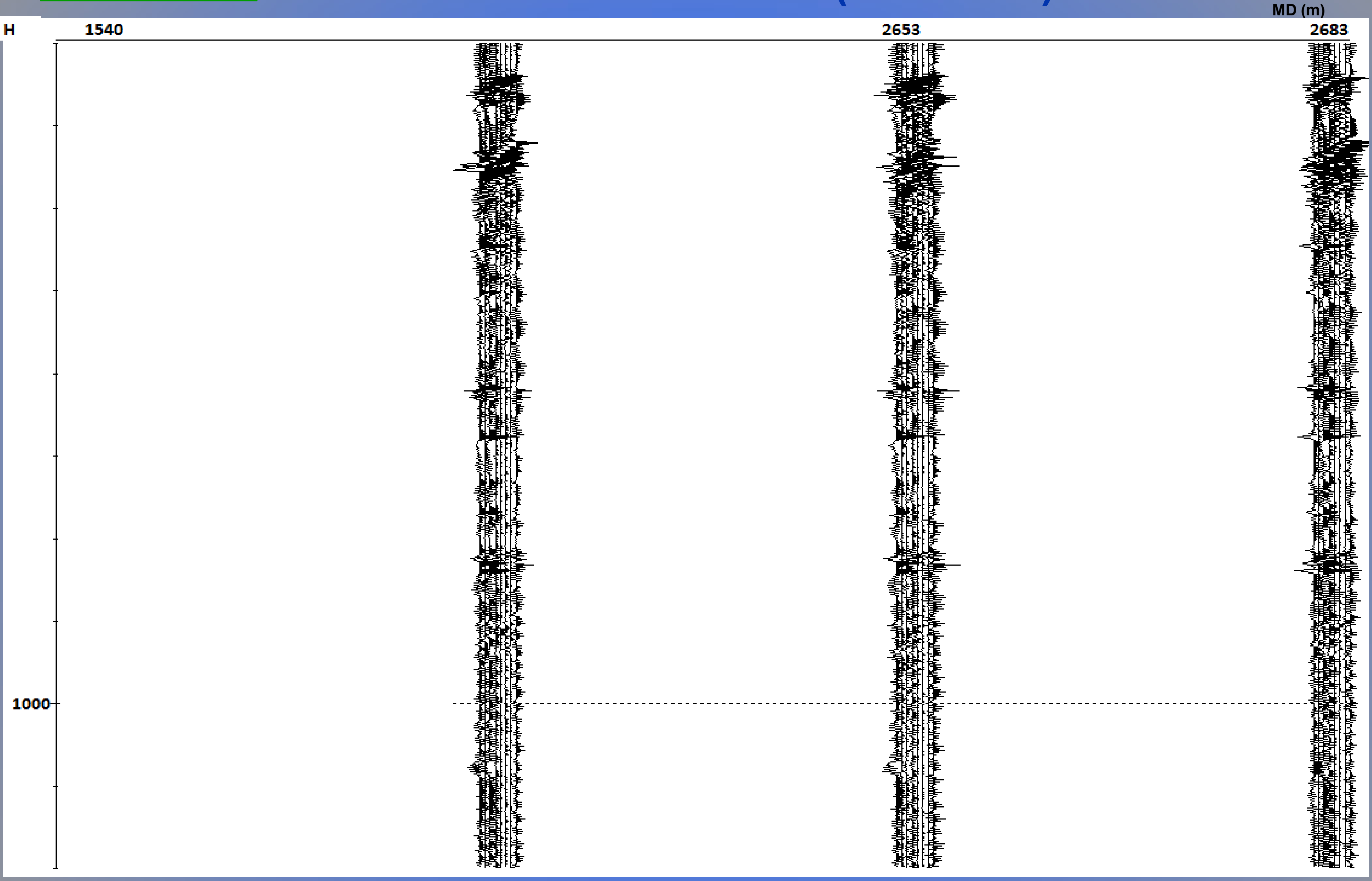
A "Zero-Offset" Micro-Seismic Event (5/7/2005 7:25)



To map a small micro seismic event you have to have enough receivers to catch the wavefield from a single source event! You cannot move the array and "shoot" again.

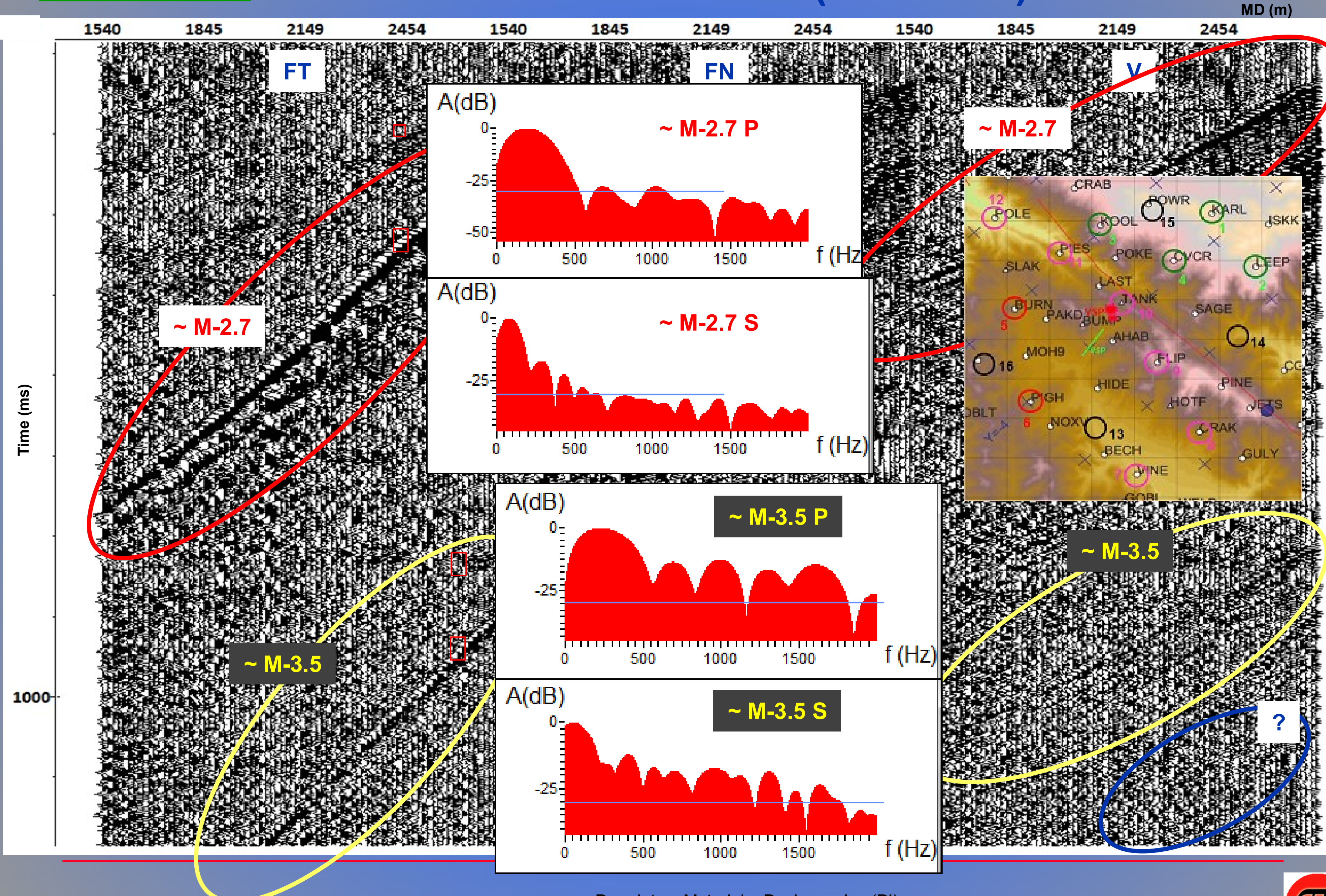
PI: M-2.7 & M-3.5

Micro-Seismic Events (5/7/2005 7:25)

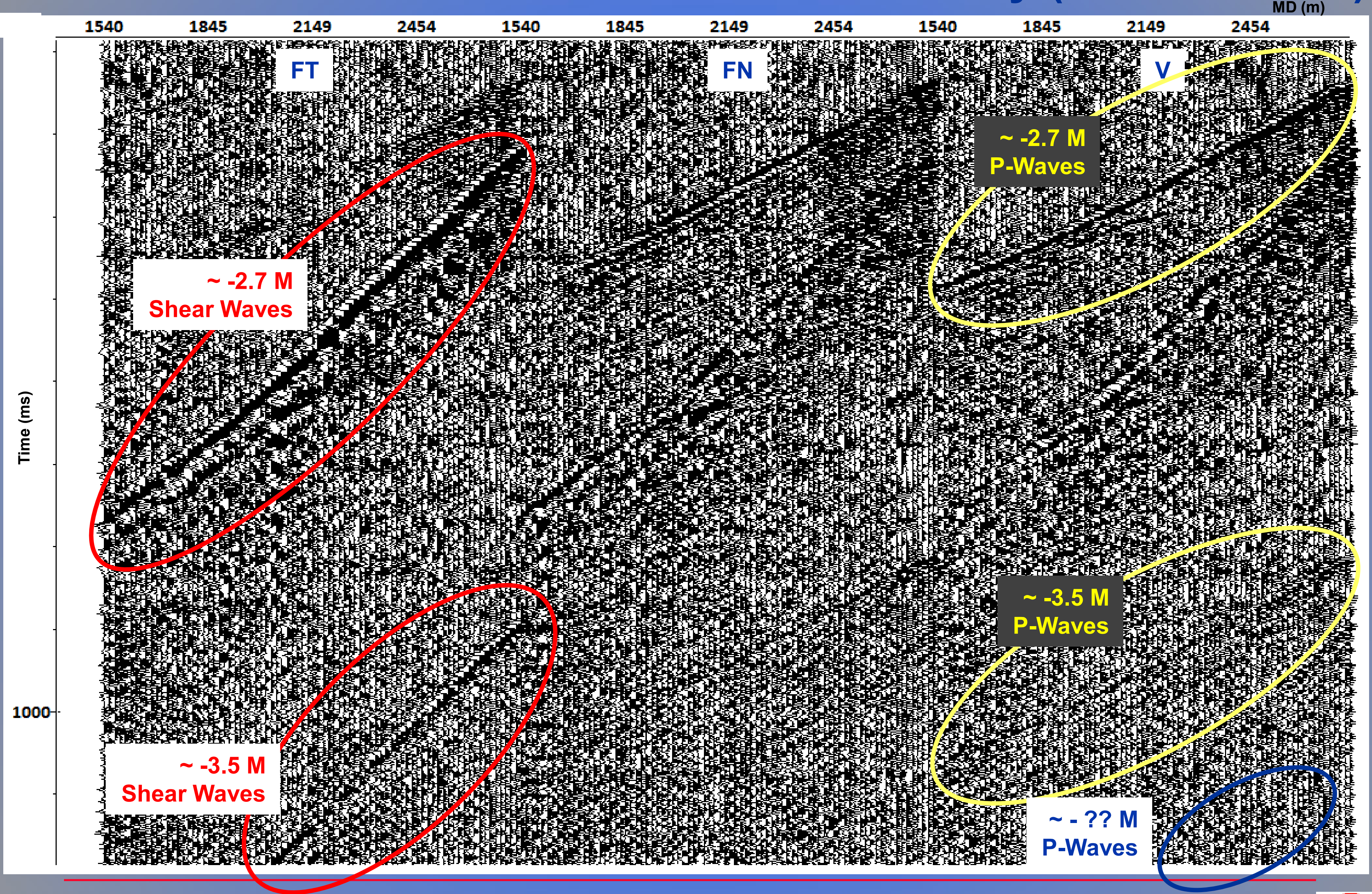


PI: M-2.7 & M-3.5

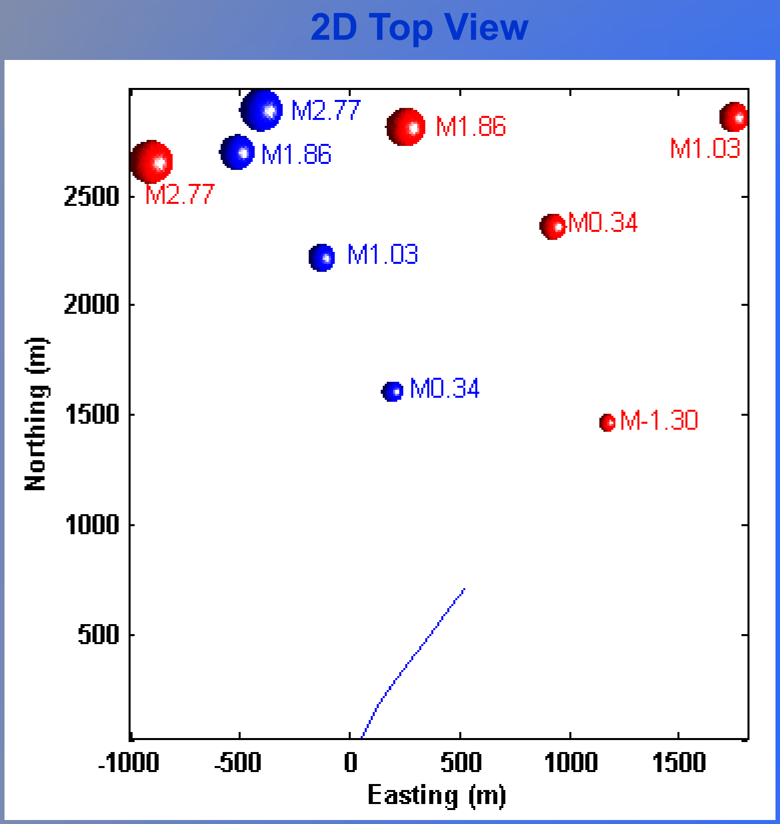
Micro-Seismic Events (5/7/2005 7:25)

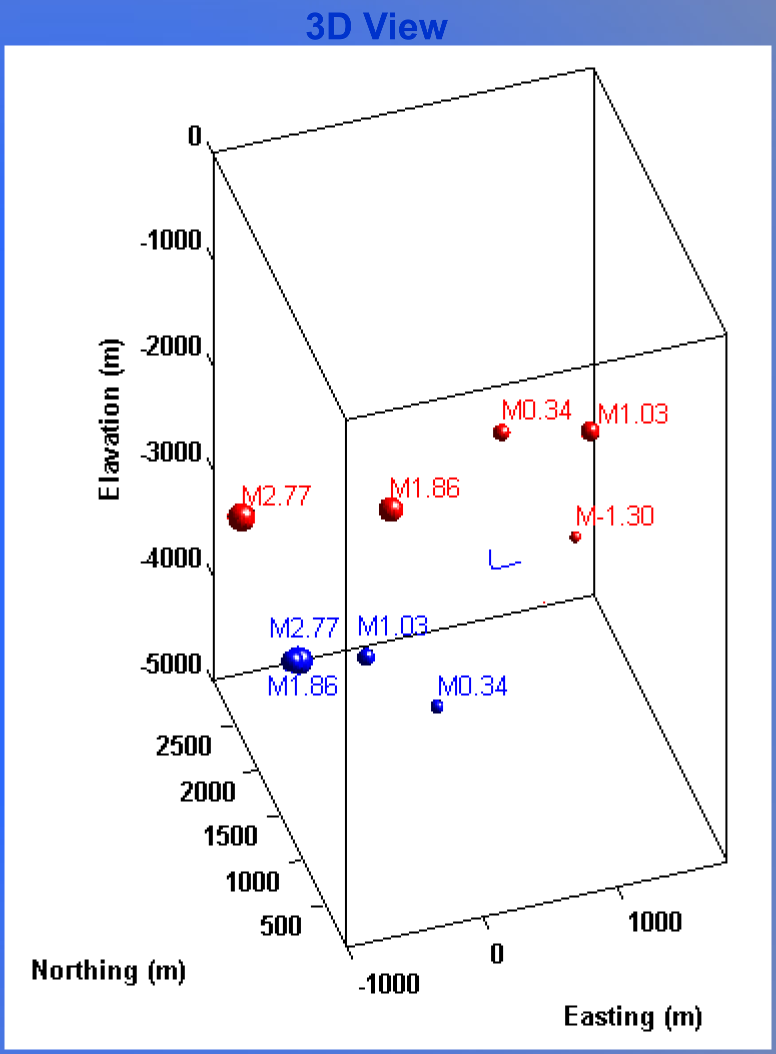


Micro-Seismic Events on an 80 level 3C Array (5/7/2005 7:25)



Long Array VSP vs. PASO & HRSN Results

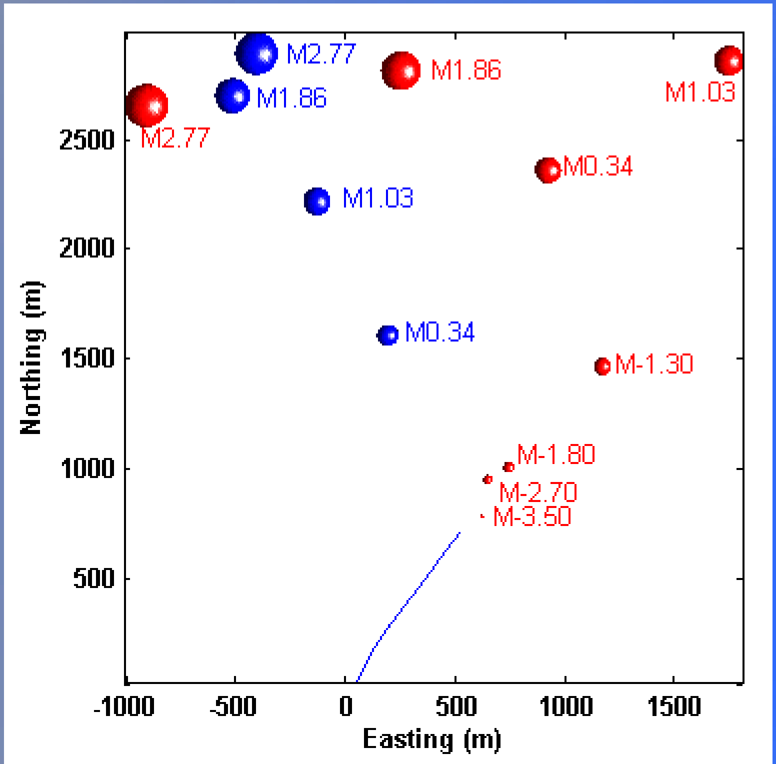




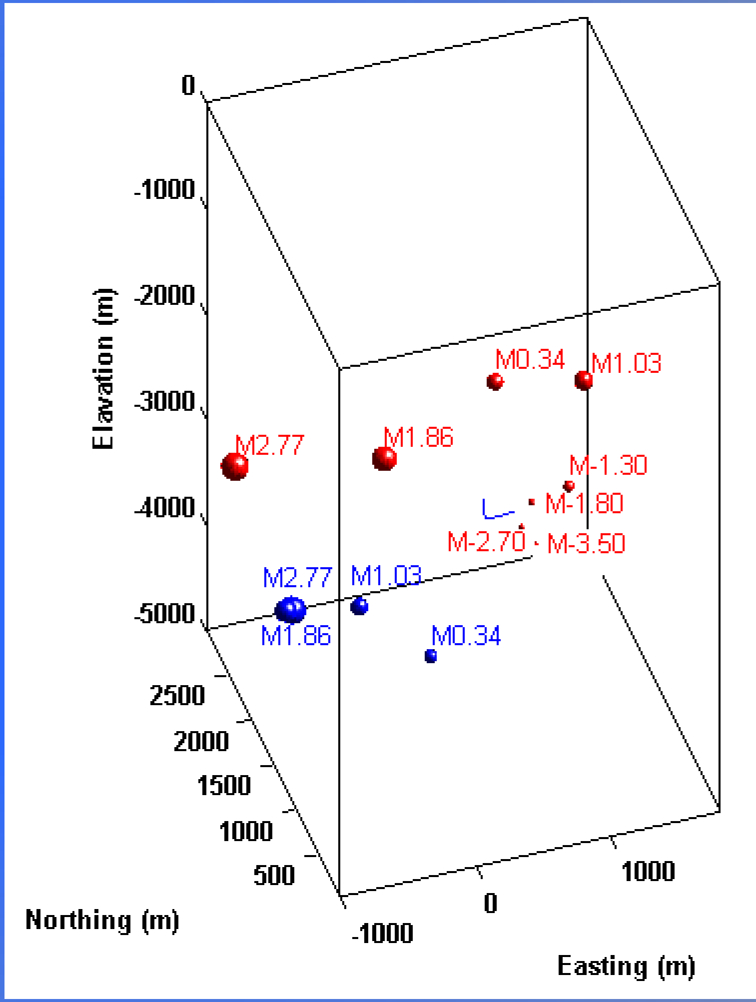
- **Event Locations: Surface**
- **Event Locations: Downhole**

Long Array VSP vs. PASO & HRSN Results

2D Top View



3D View

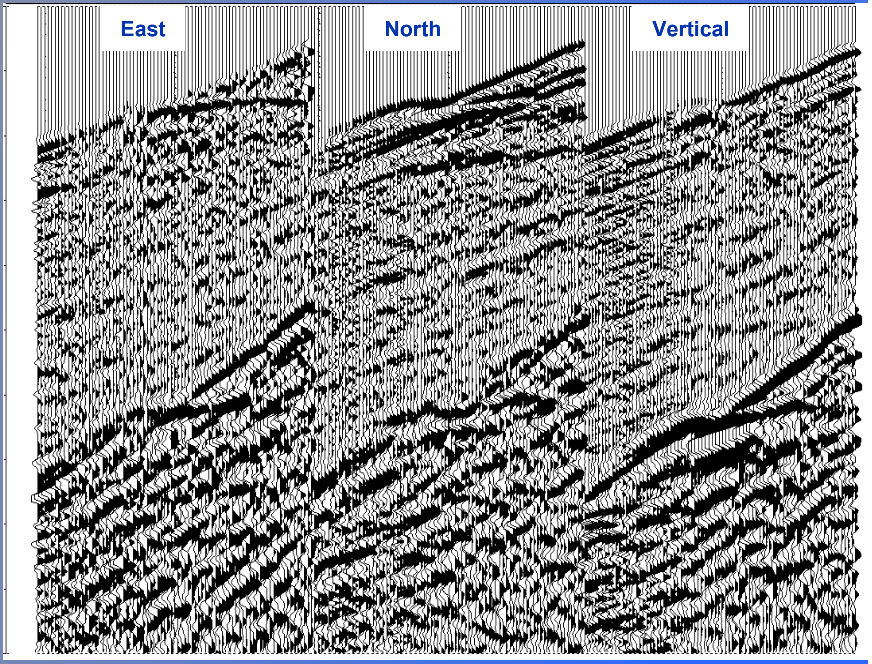


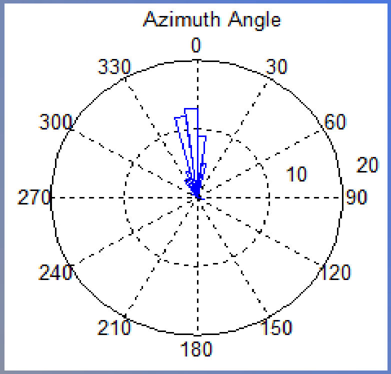
- Event Locations: Surface
- Event Locations: Downhole

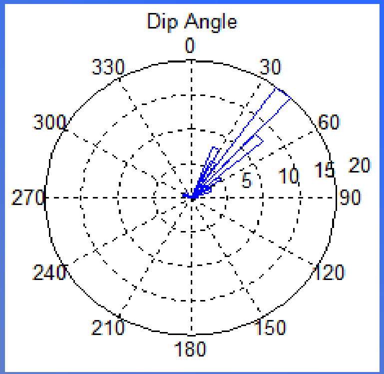
A Micro-Seismic Event

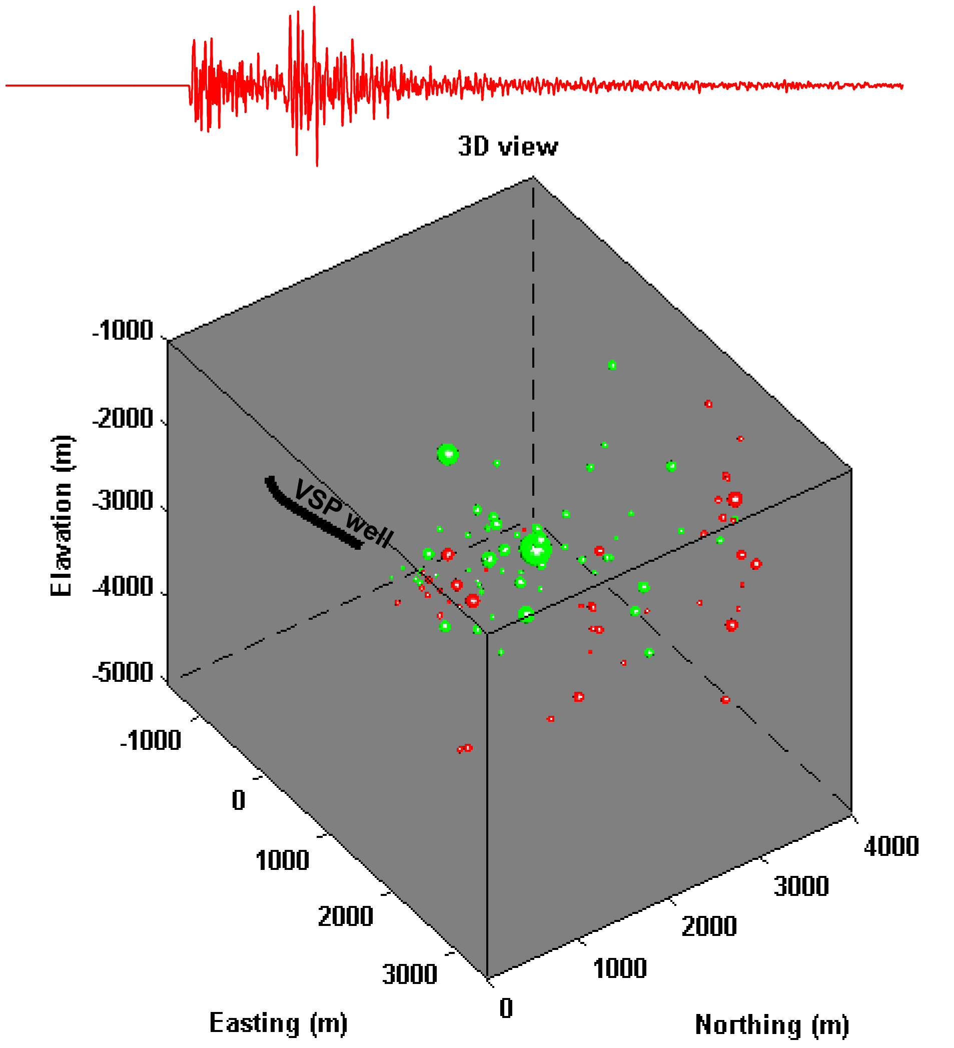
5/4/2005 9:23

USGS: M1.86



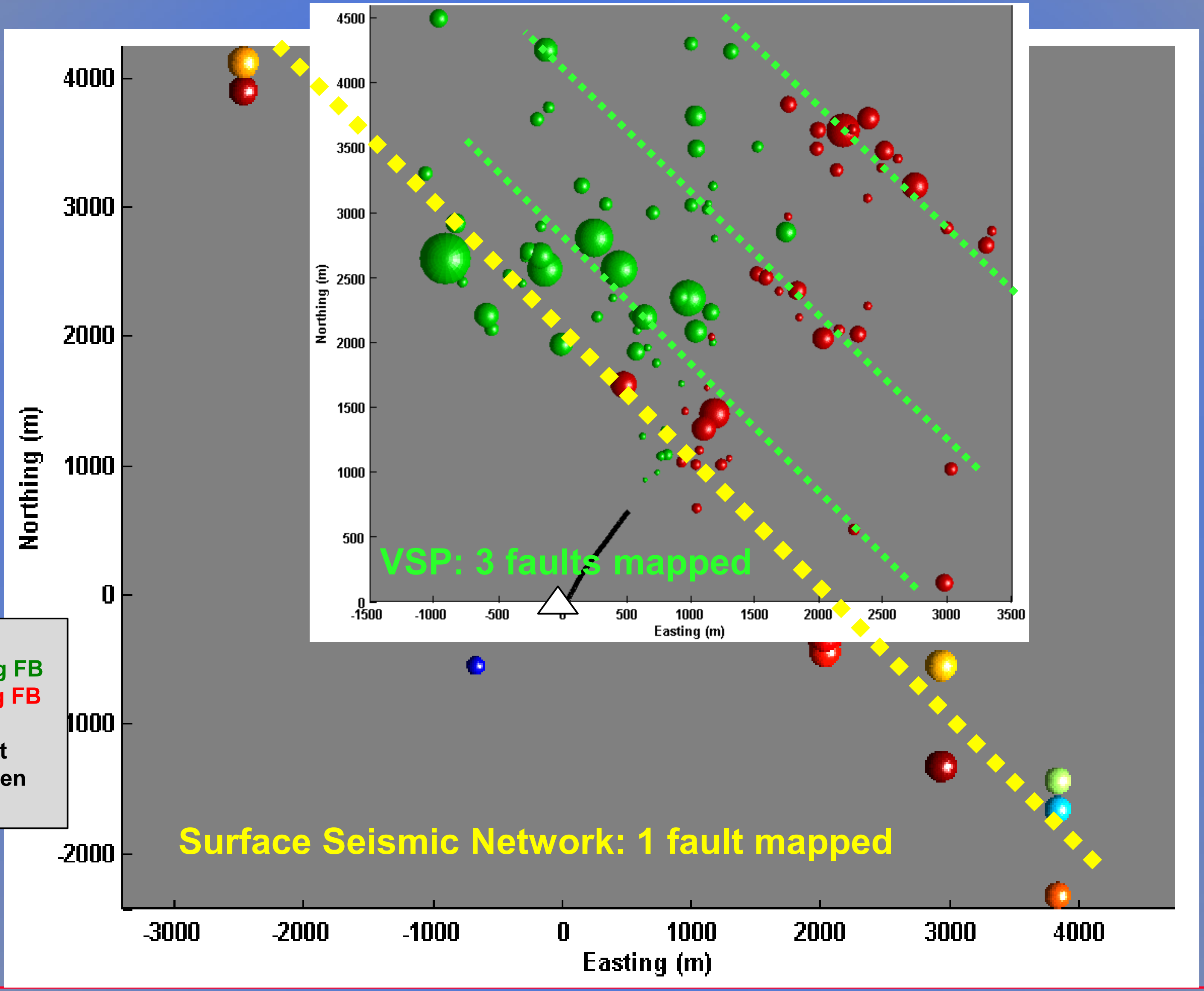






~ 80 km^3 monitored

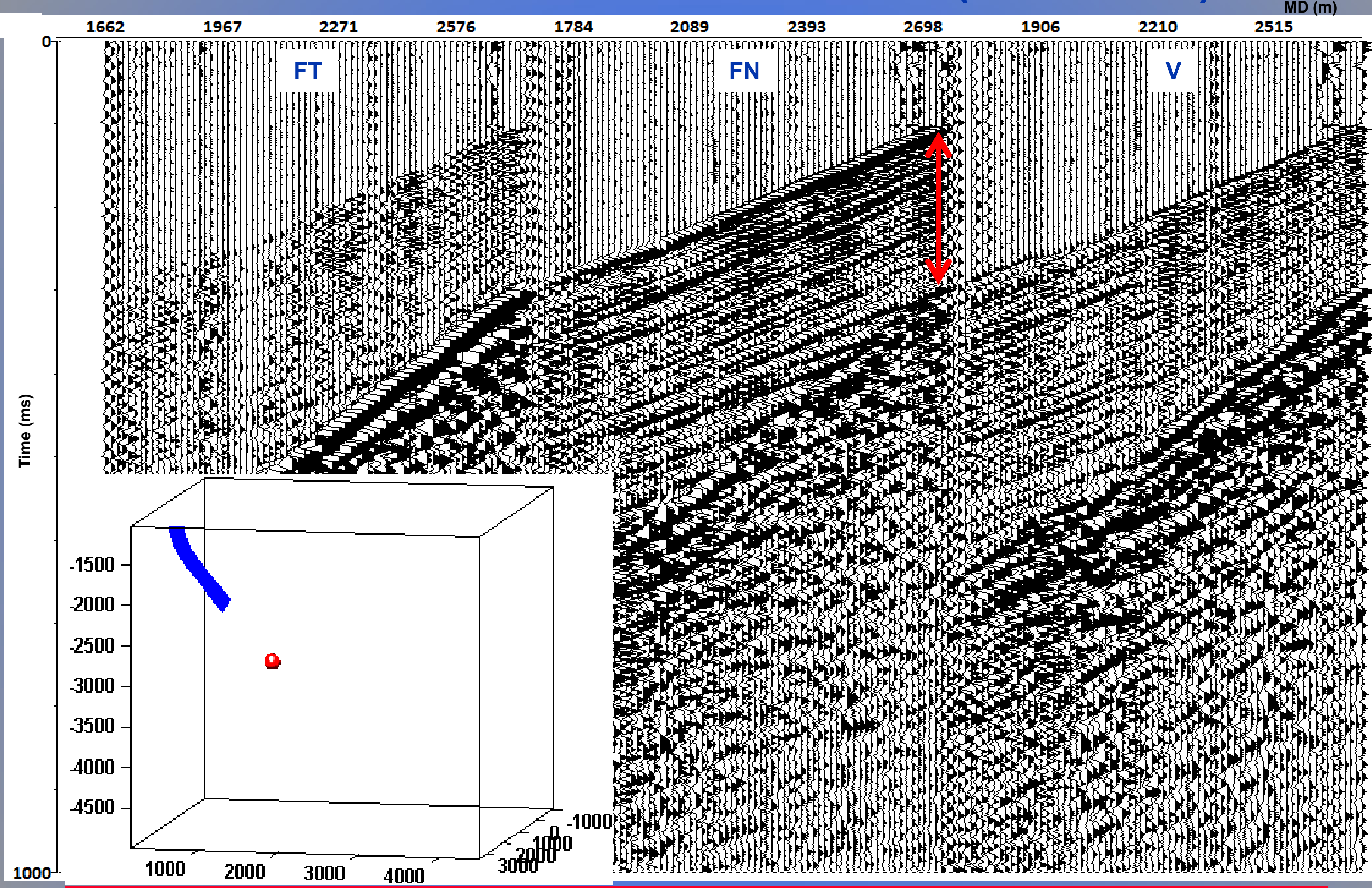
Surface Monitoring vs Borehole Monitoring



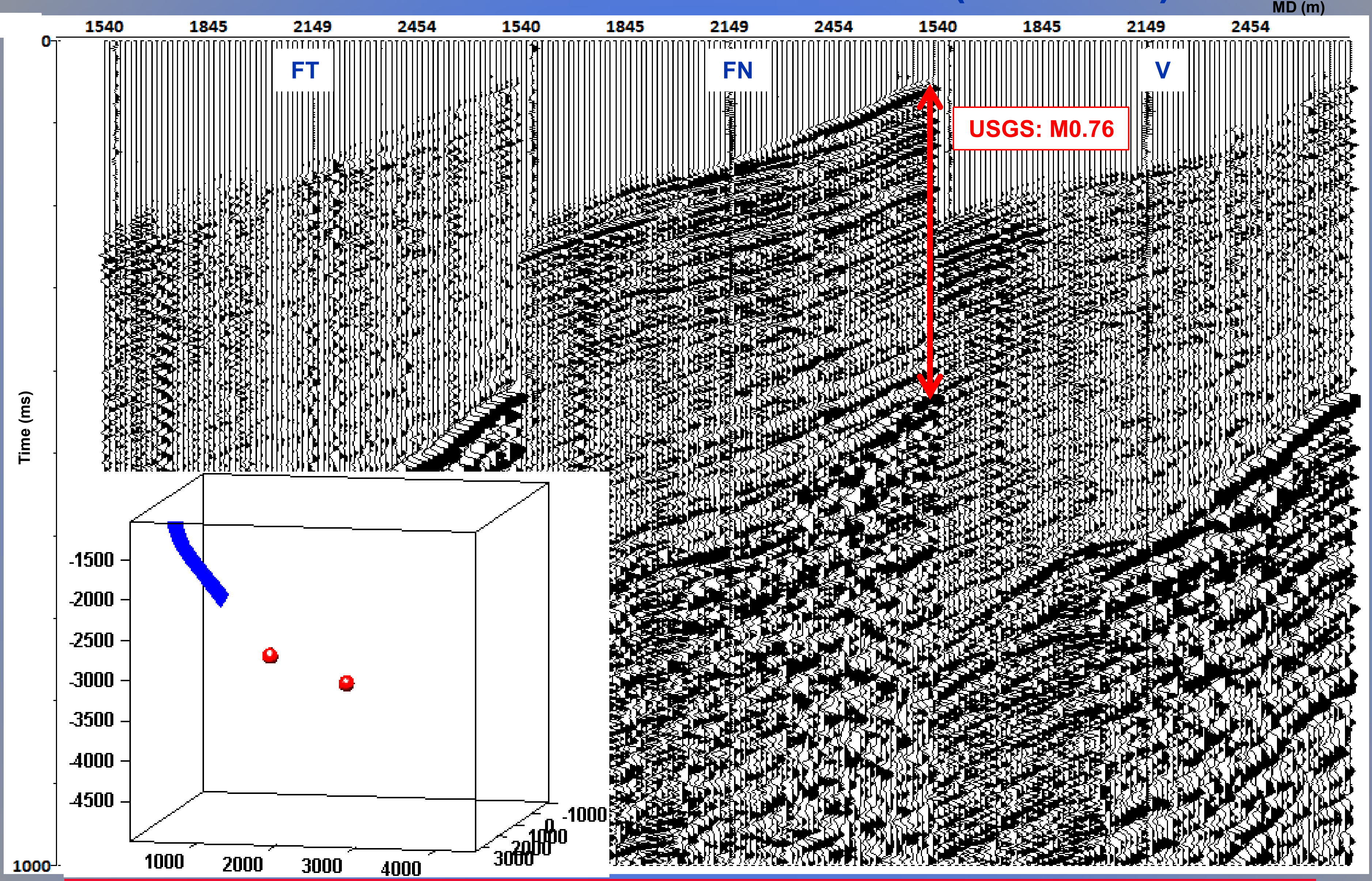
Blue: PASO
Green: VSP pulling FB
Red: VSP pushing FB

Amplitudes are not comparable between PASO & VSP

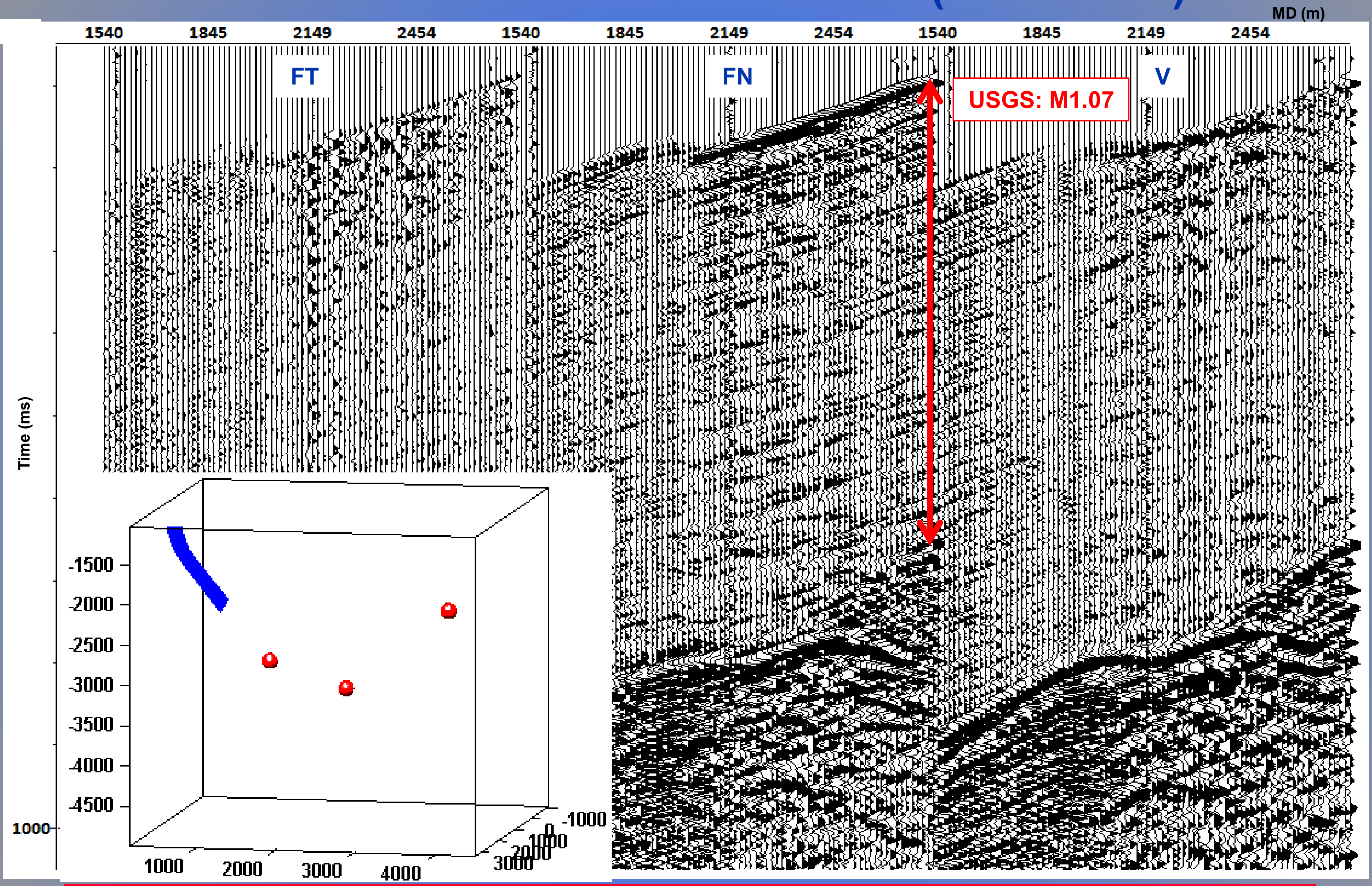
Evidence of The Near-offset Fault (4/30/2005 18:49)



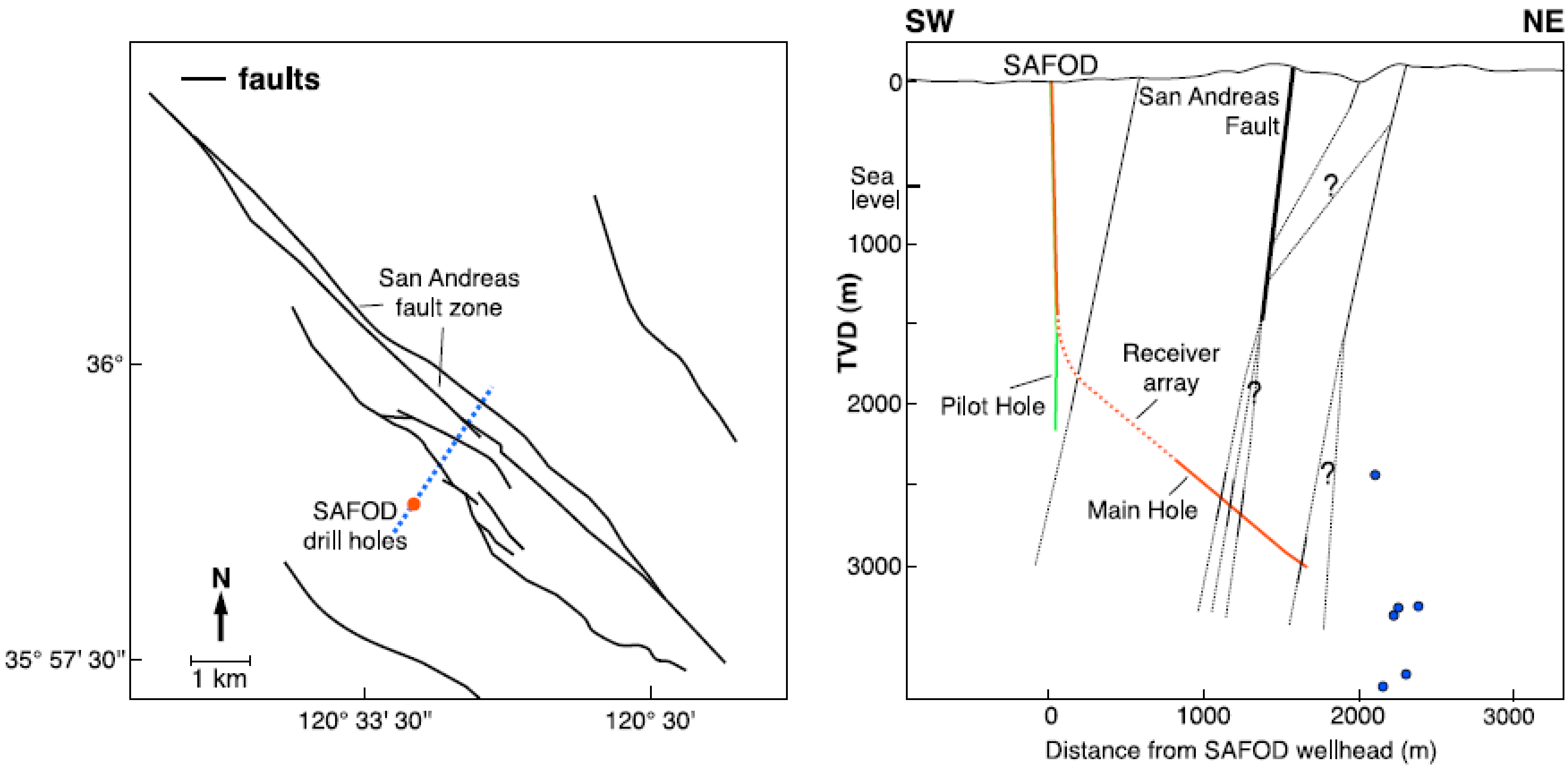
Evidence of The Mid-offset Fault (5/8/2005 4:54)



Evidence of The Far-offset Fault (5/10/2005 11:24)



Other References



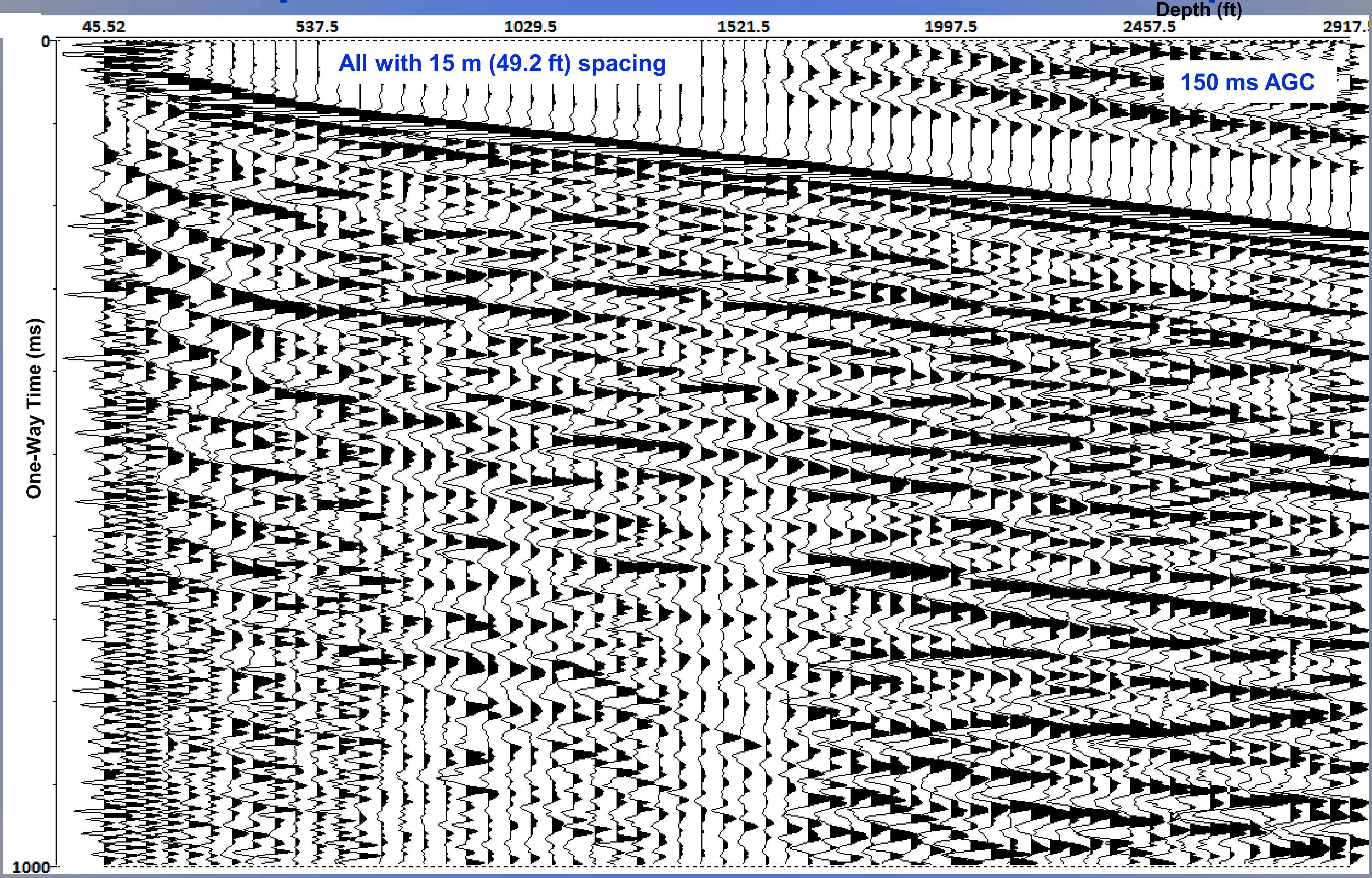
(a) (b)

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.

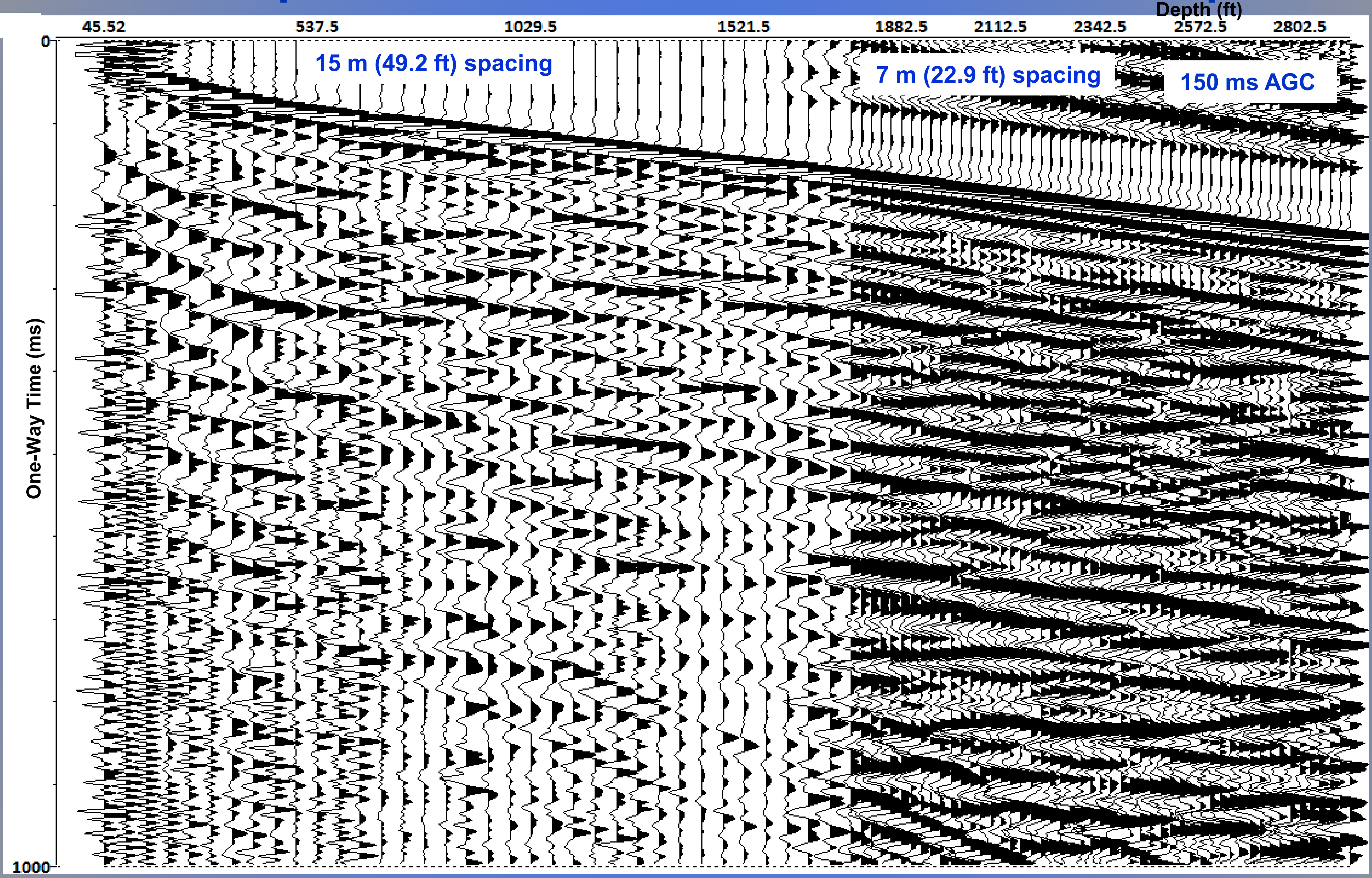
A. Reshetnikov, et al., (2010)

3D/4D Imaging Results using Long Arrays

Field Example 49.2 ft vs 22.9 ft: ZO VSP Vertical Component

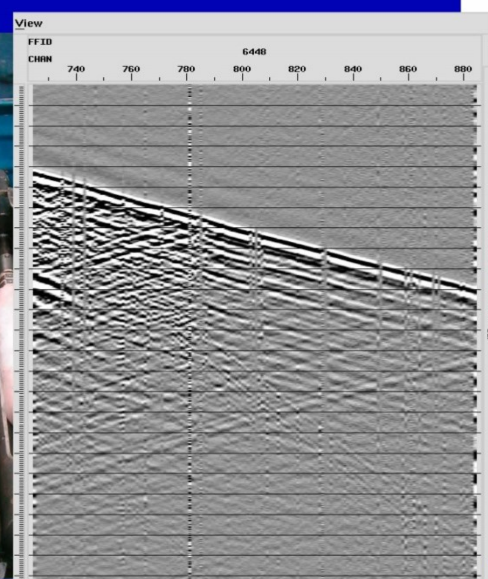


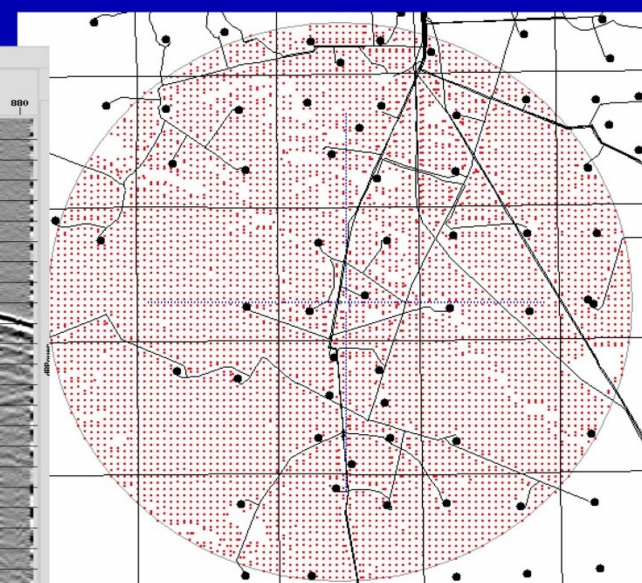
Field Example 49.2 ft vs 22.9 ft: ZO VSP Vertical Component



Imaging an Onshore Gas Reservoir

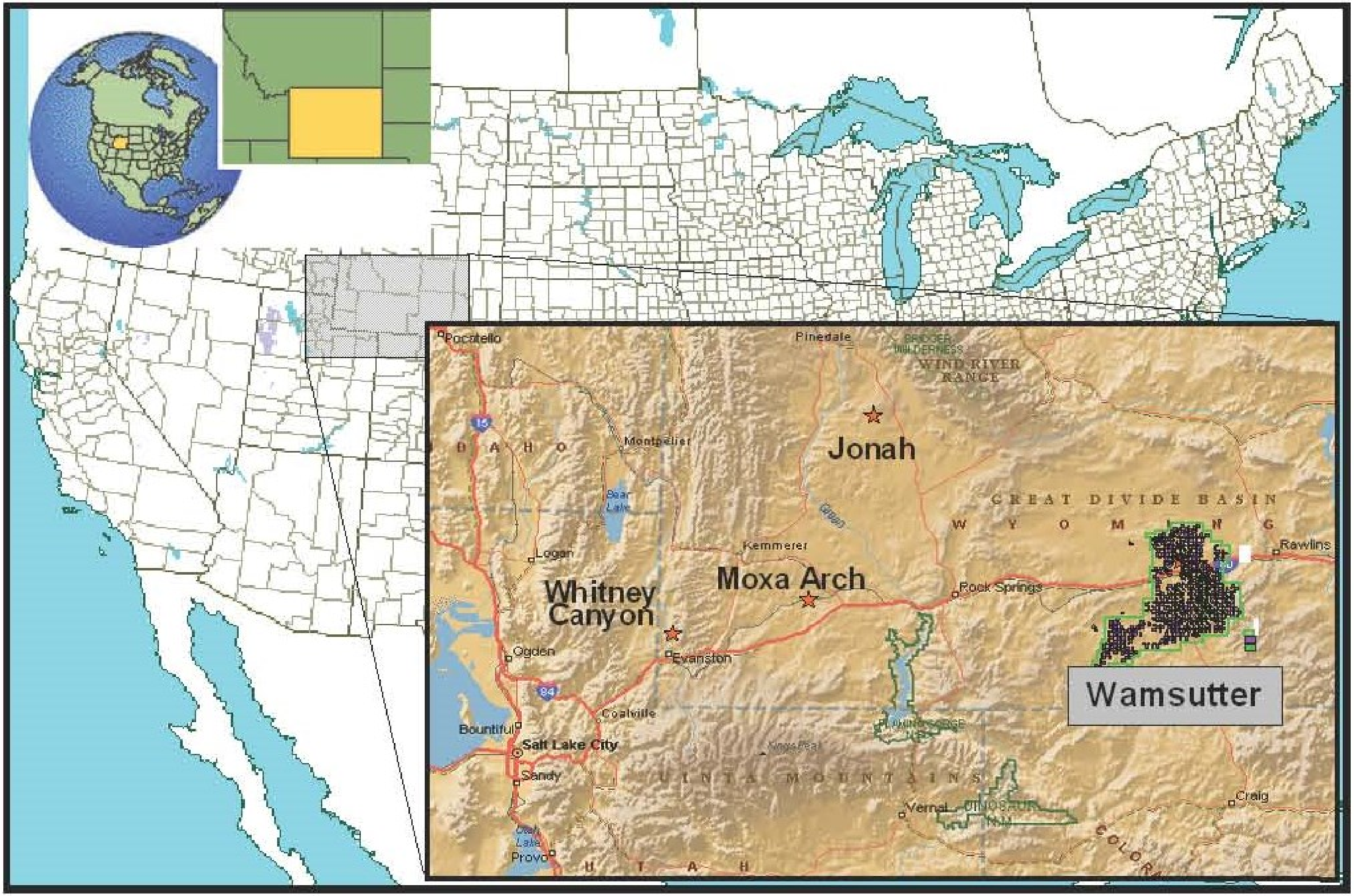
“Massive” 160 level 3D VSP at Wamsutter





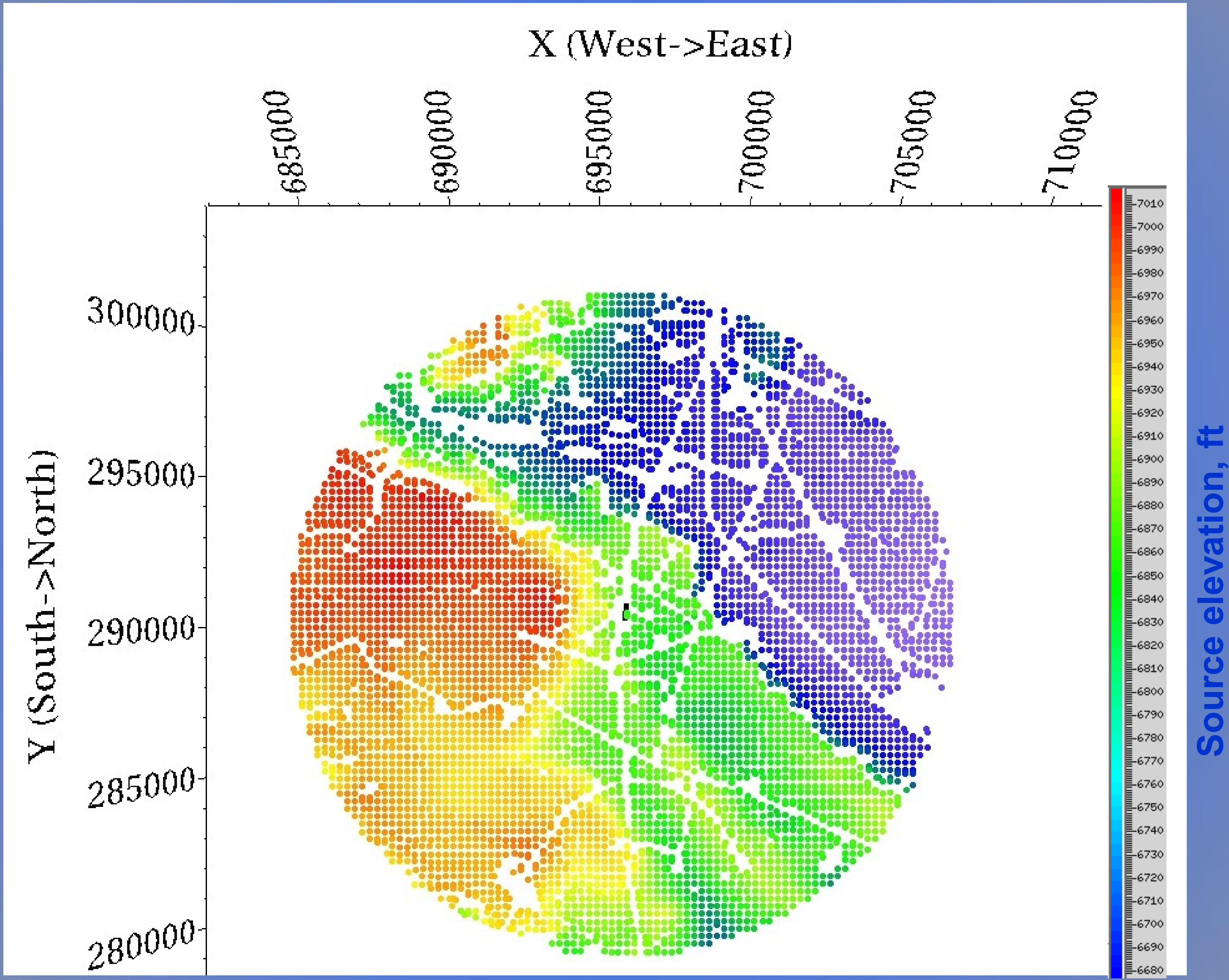
Geetan et al., 2011

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



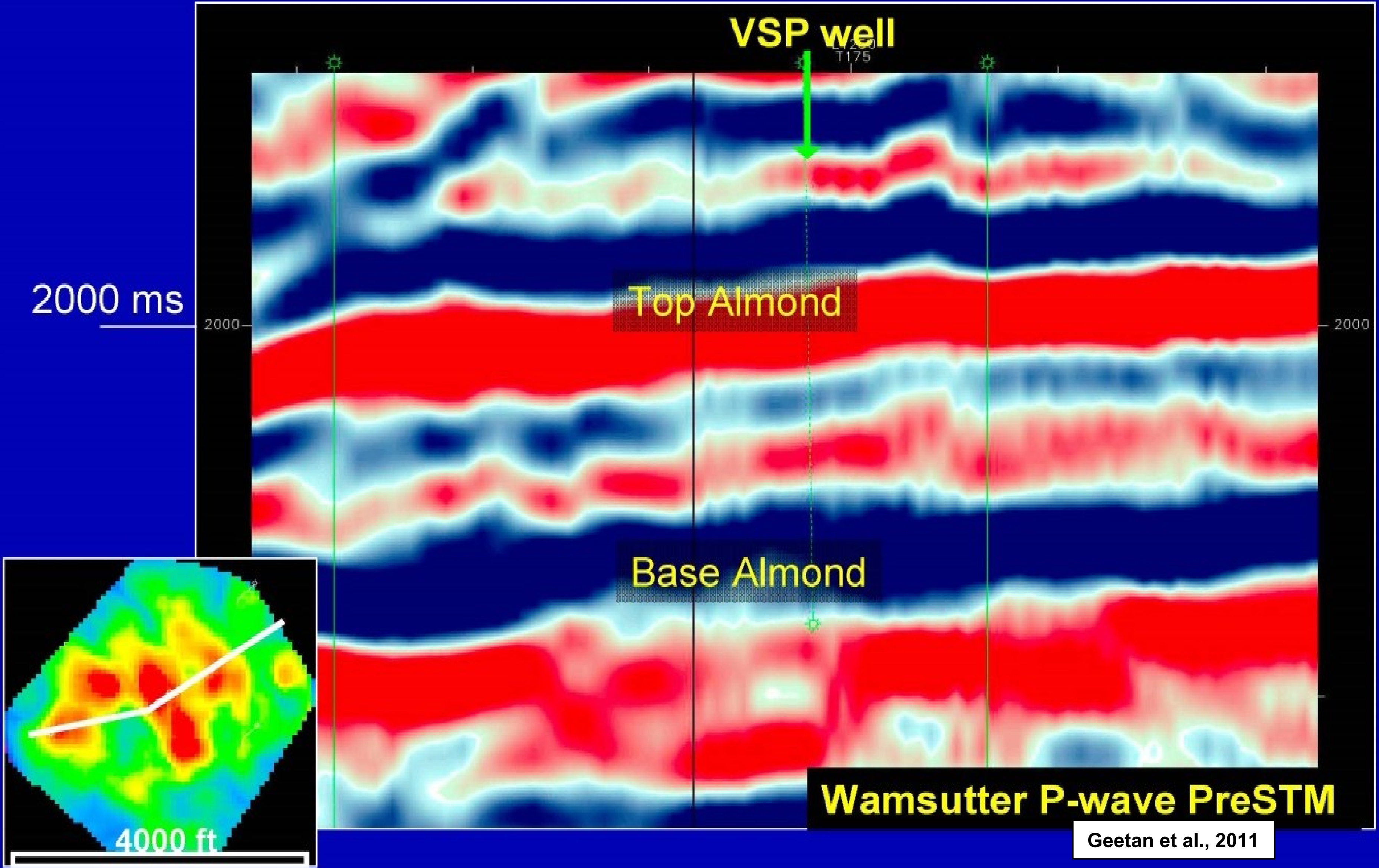
Ramkhelawan et al., 2008

3D VSP, 6000 source pts, 160 levels 2,500 – 10,500 ft



Ramkhelawan et al., 2008

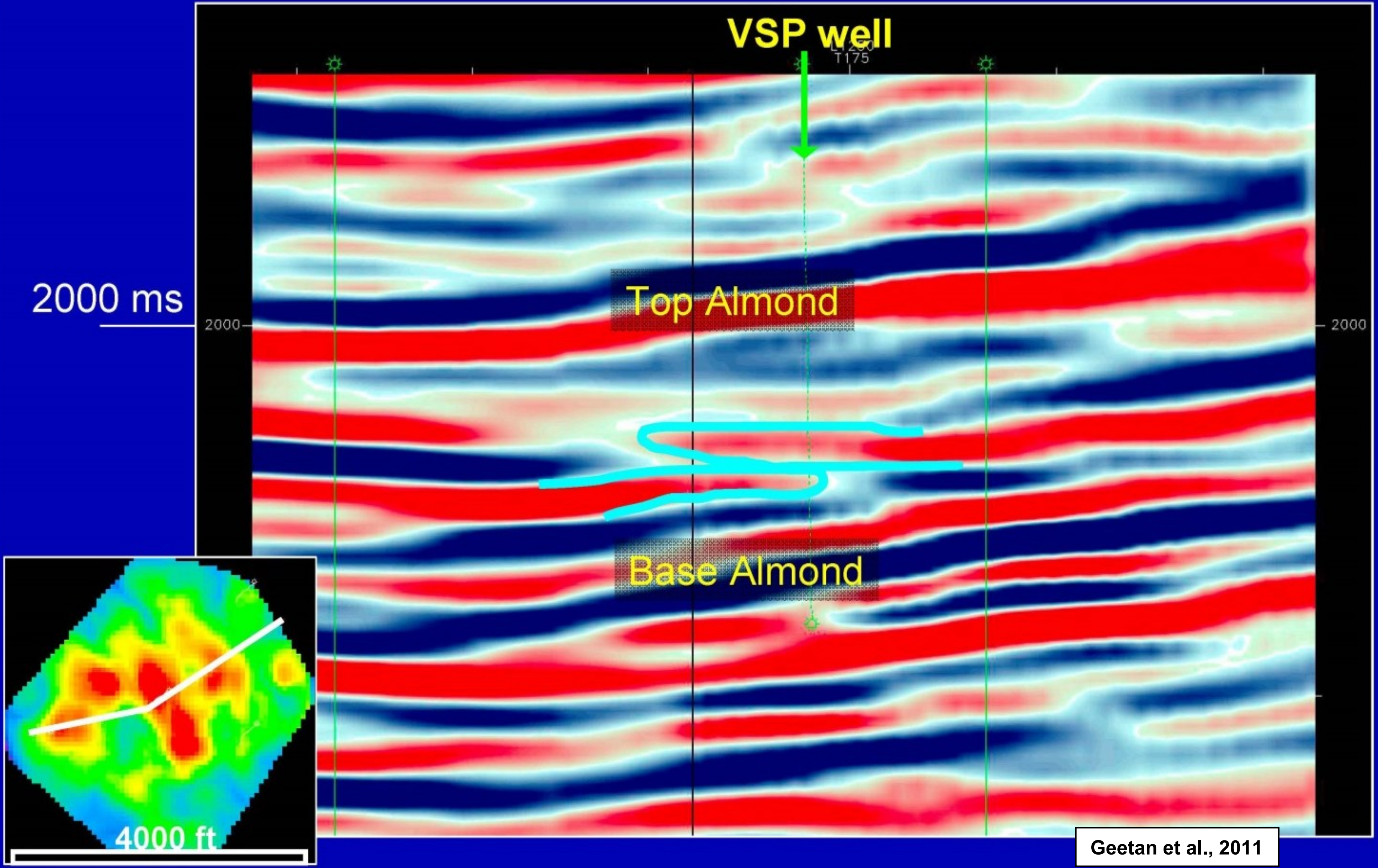
A look at the data- comparison to surface seismic data



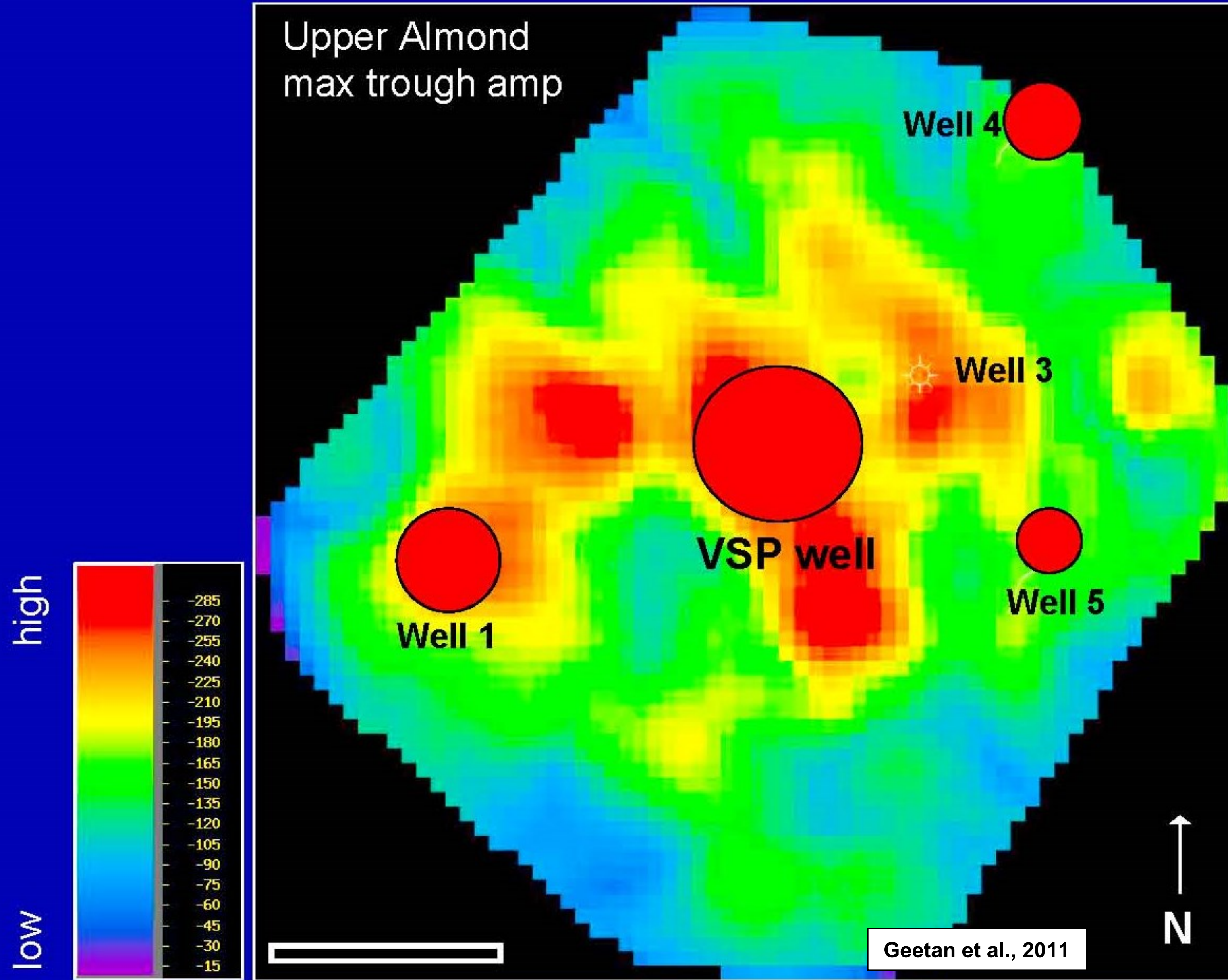
Geetan et al., 2011

VSP Data

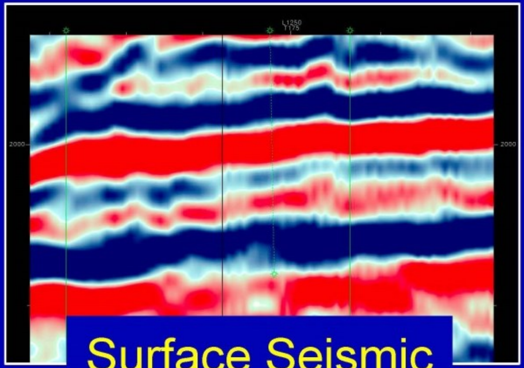
clearly visible terminations that tie into the depositional framework

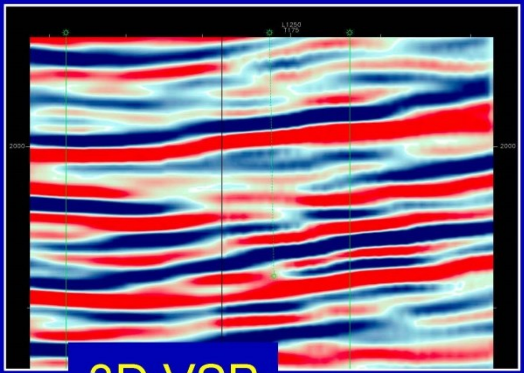


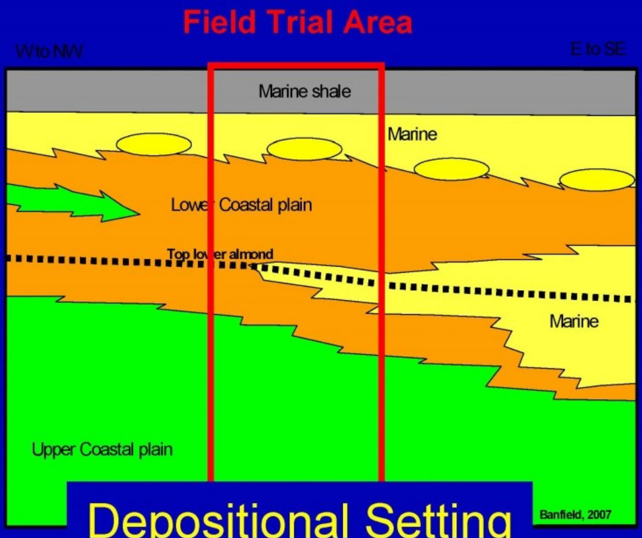
Almond reservoir 3D VSP and Production overlay

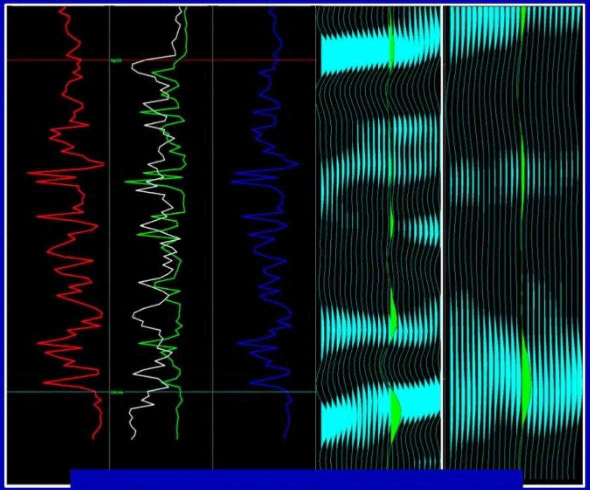


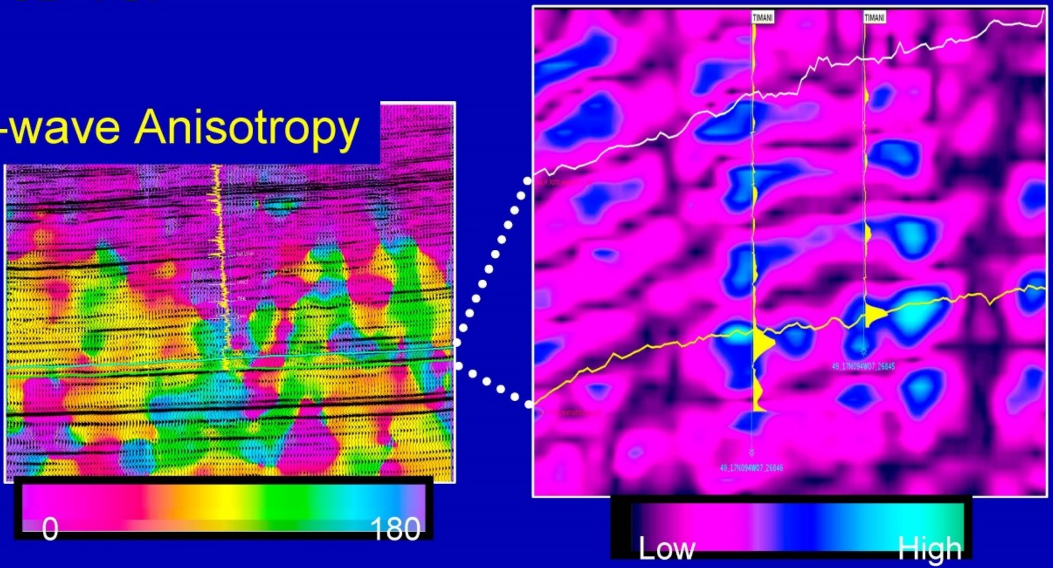
Integration

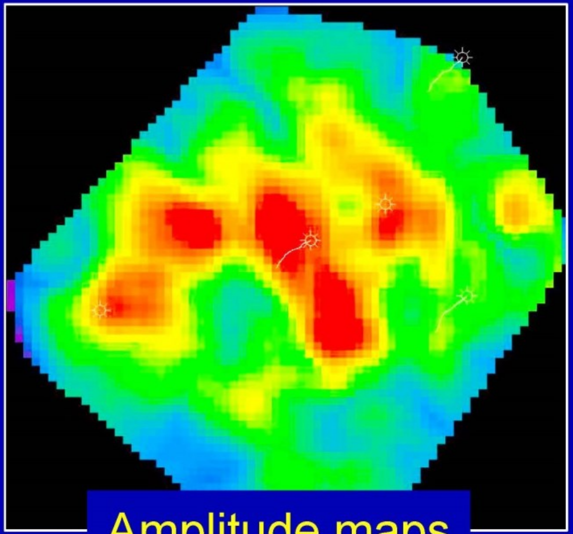








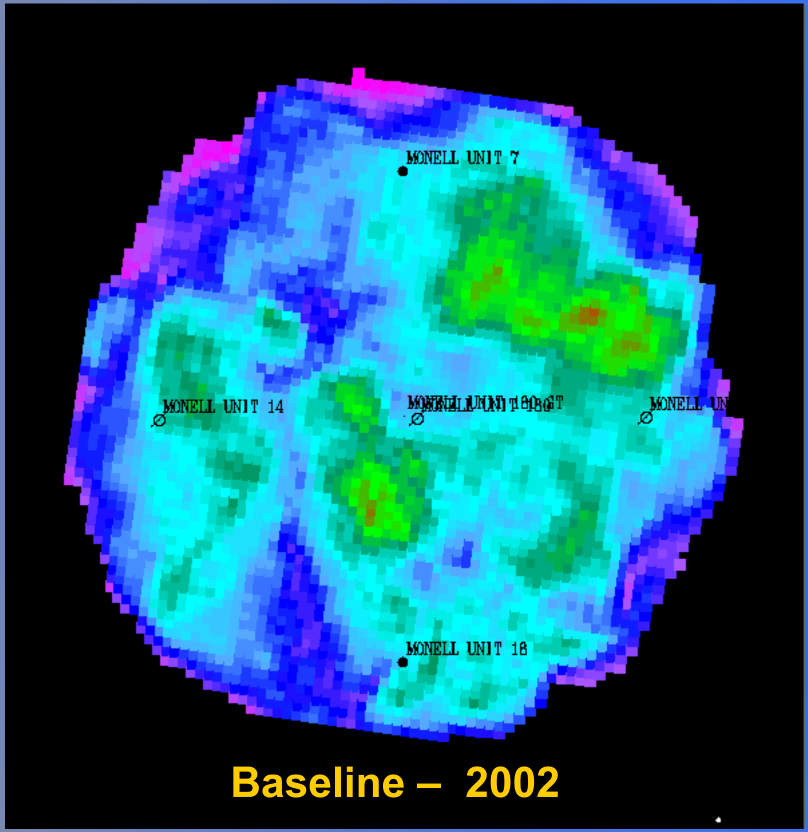


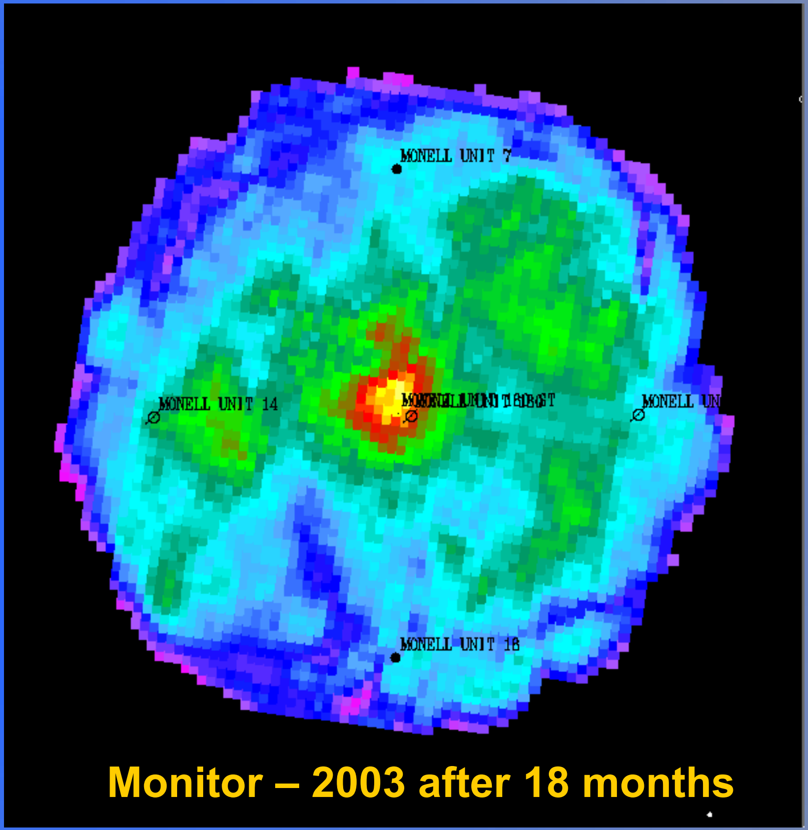


Geetan et al., 2011

Time Lapse Data Monitoring of CO_2 injection for Enhanced Oil Recovery in 2002 - 2003

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



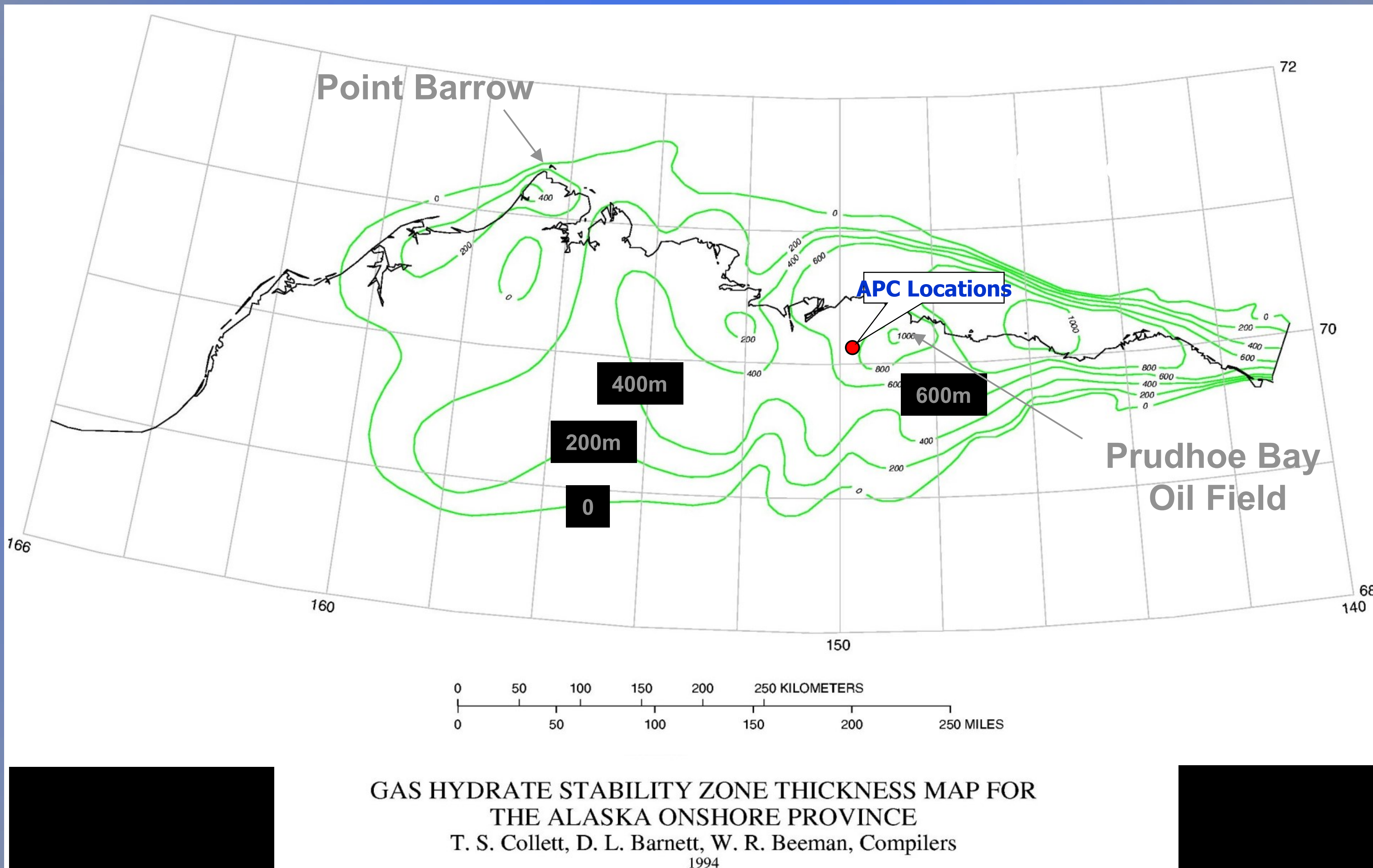


Increased reflectivity in the Monitor Survey 2003 at a depth of 4,800 ft at the well is due to the injected CO_2. Also seen is the increased reflectivity around the water injector wells.

O'Brien et al., 2004

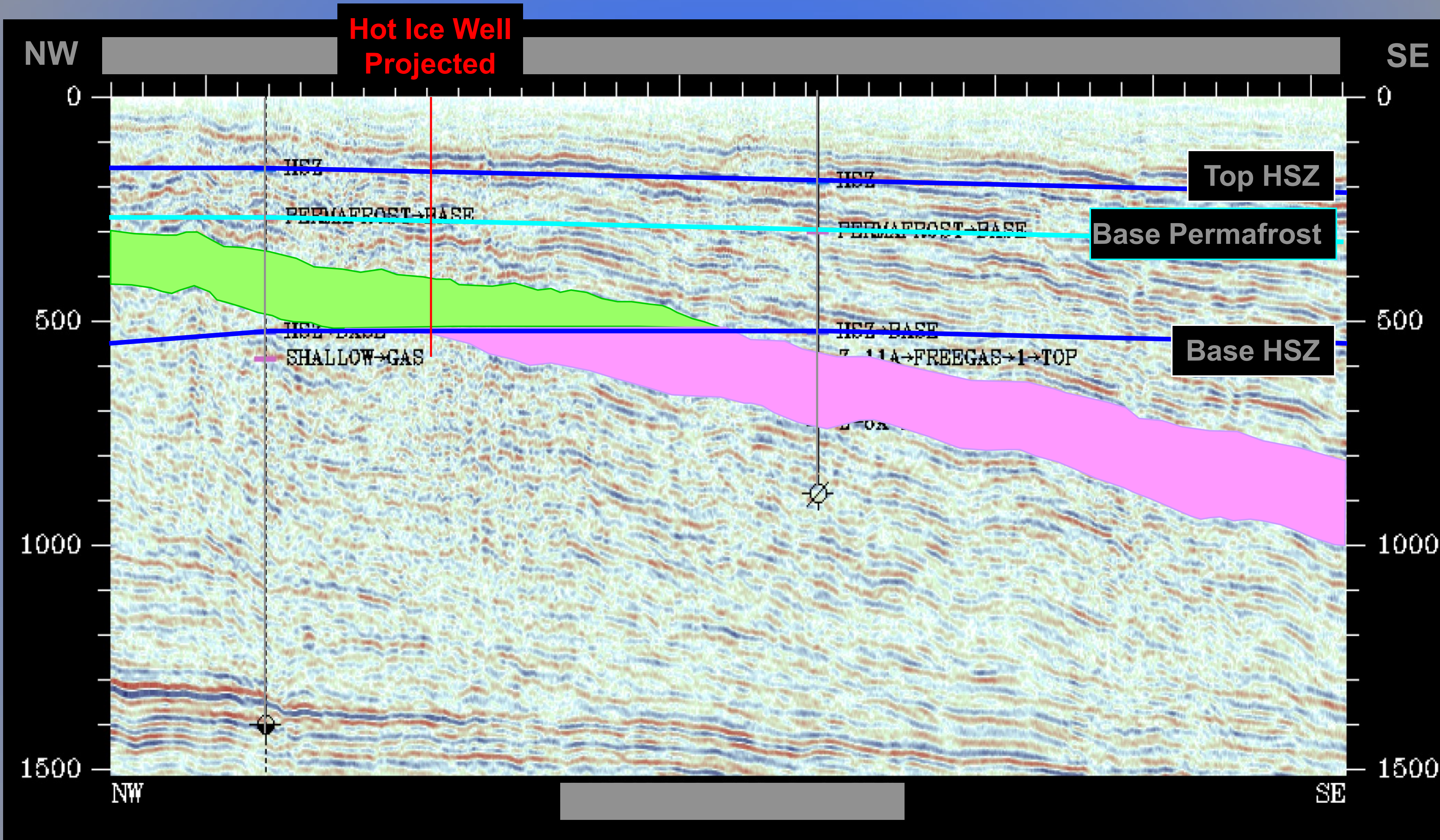
Imaging of Methane Hydrates on the North Slope, Alaska

Gas Hydrate Stability Zone Thickness



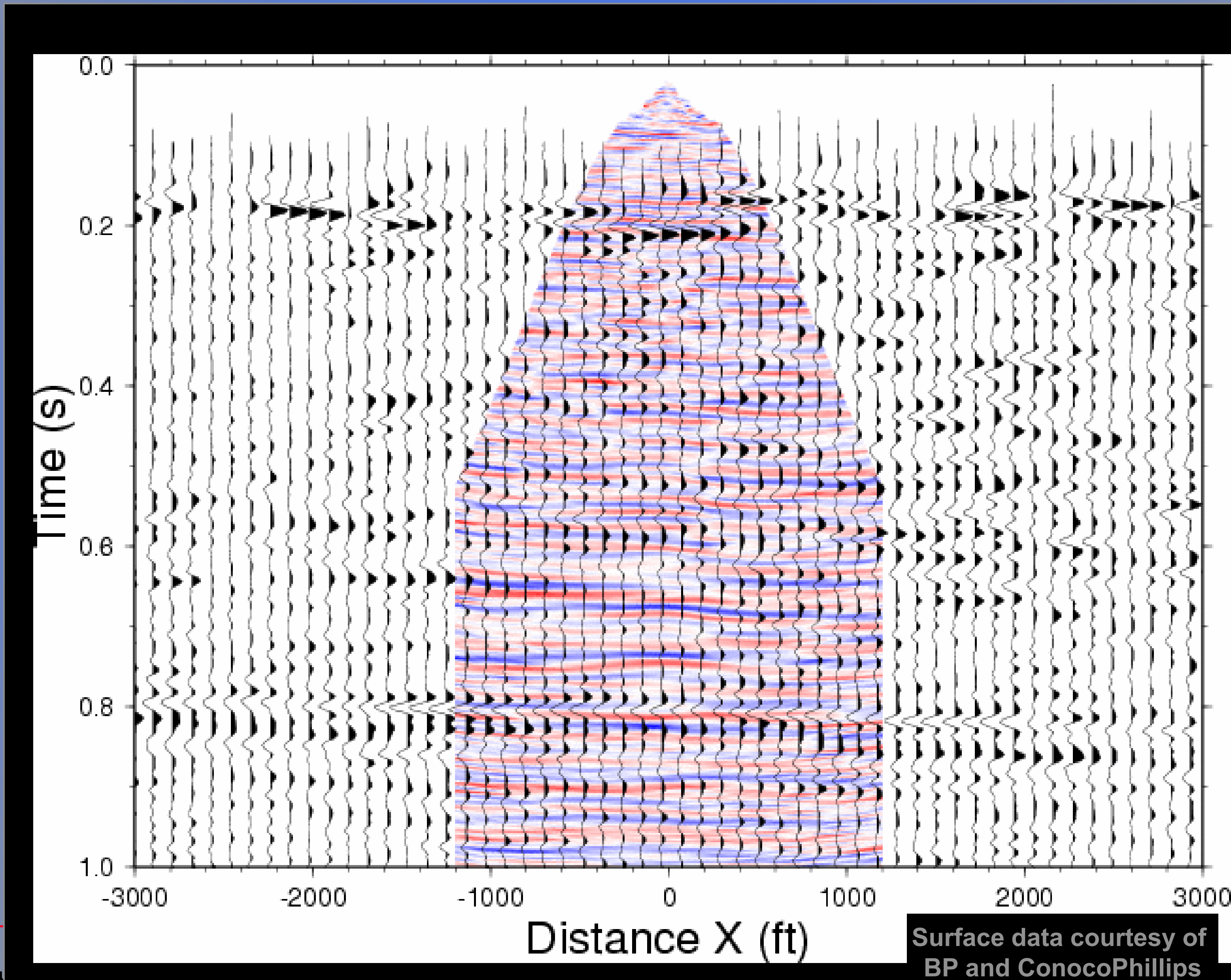
Map courtesy of USGS

2D Seismic Section

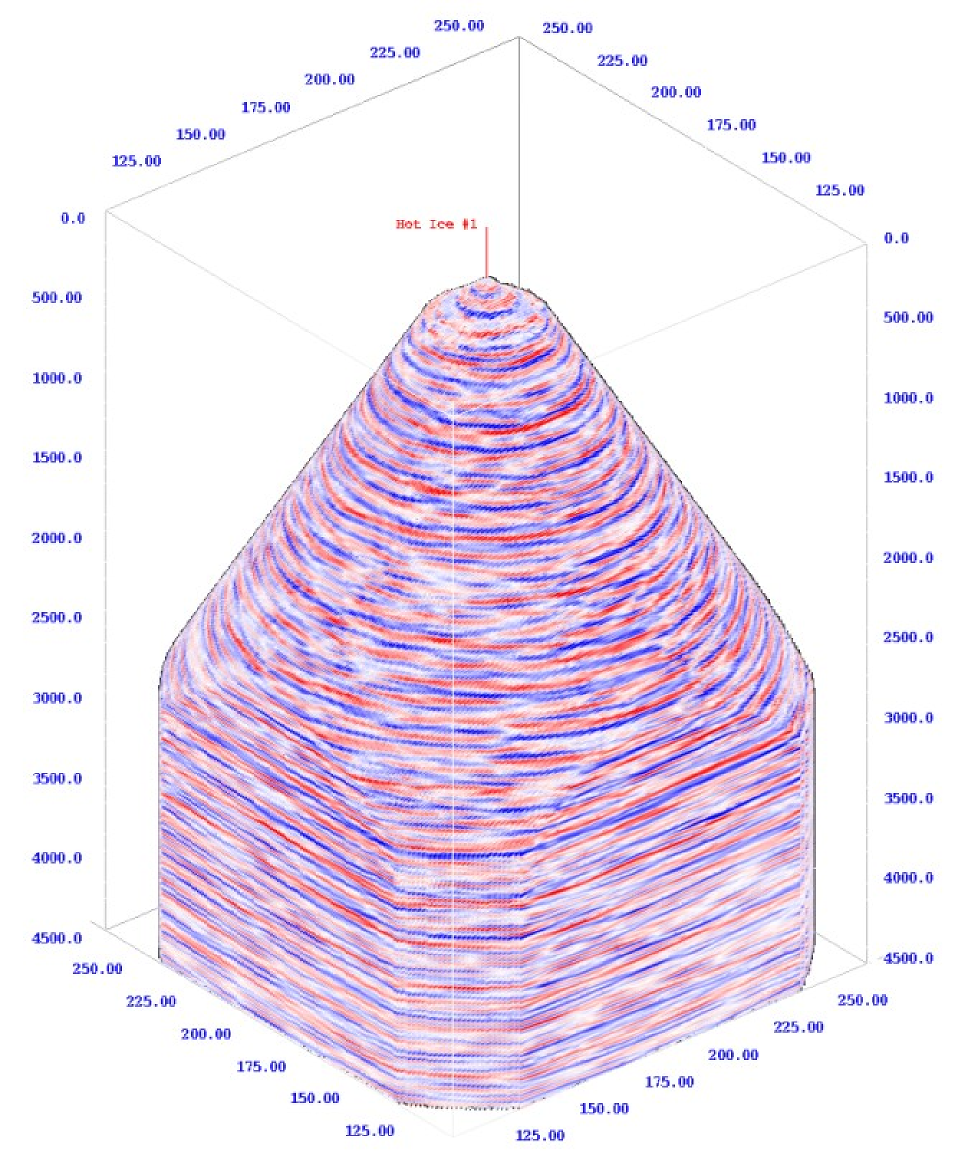


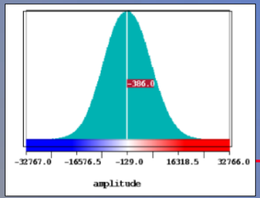
Data courtesy of WesternGeco

Comparison of VSP and Surface Seismic

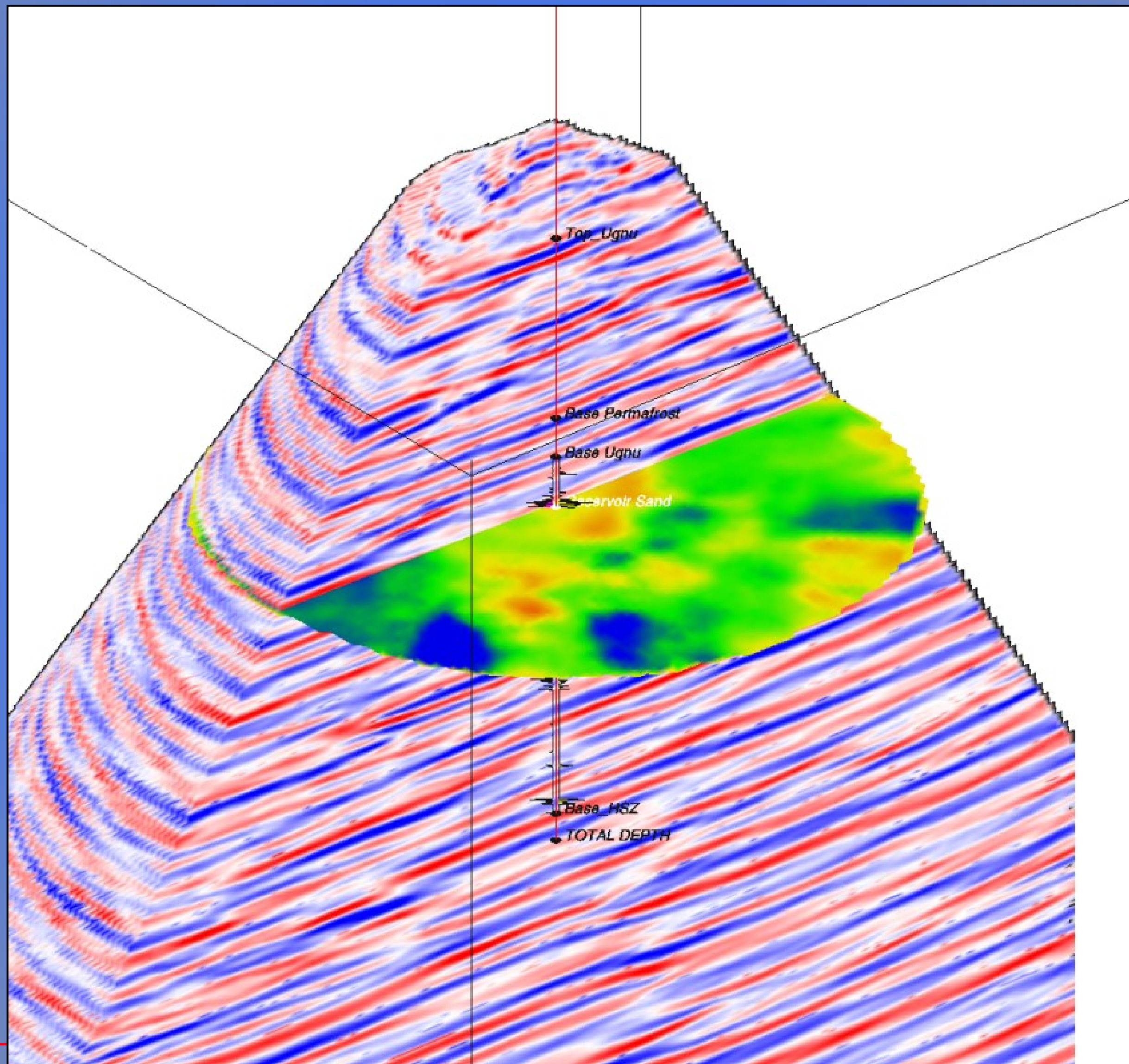


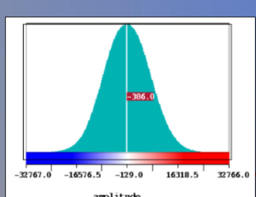
3D VSP Seismic Volume

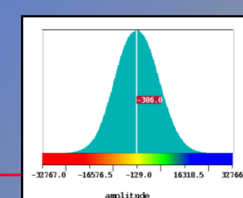




Amplitudes on Geologic Marker at Top of Sand A

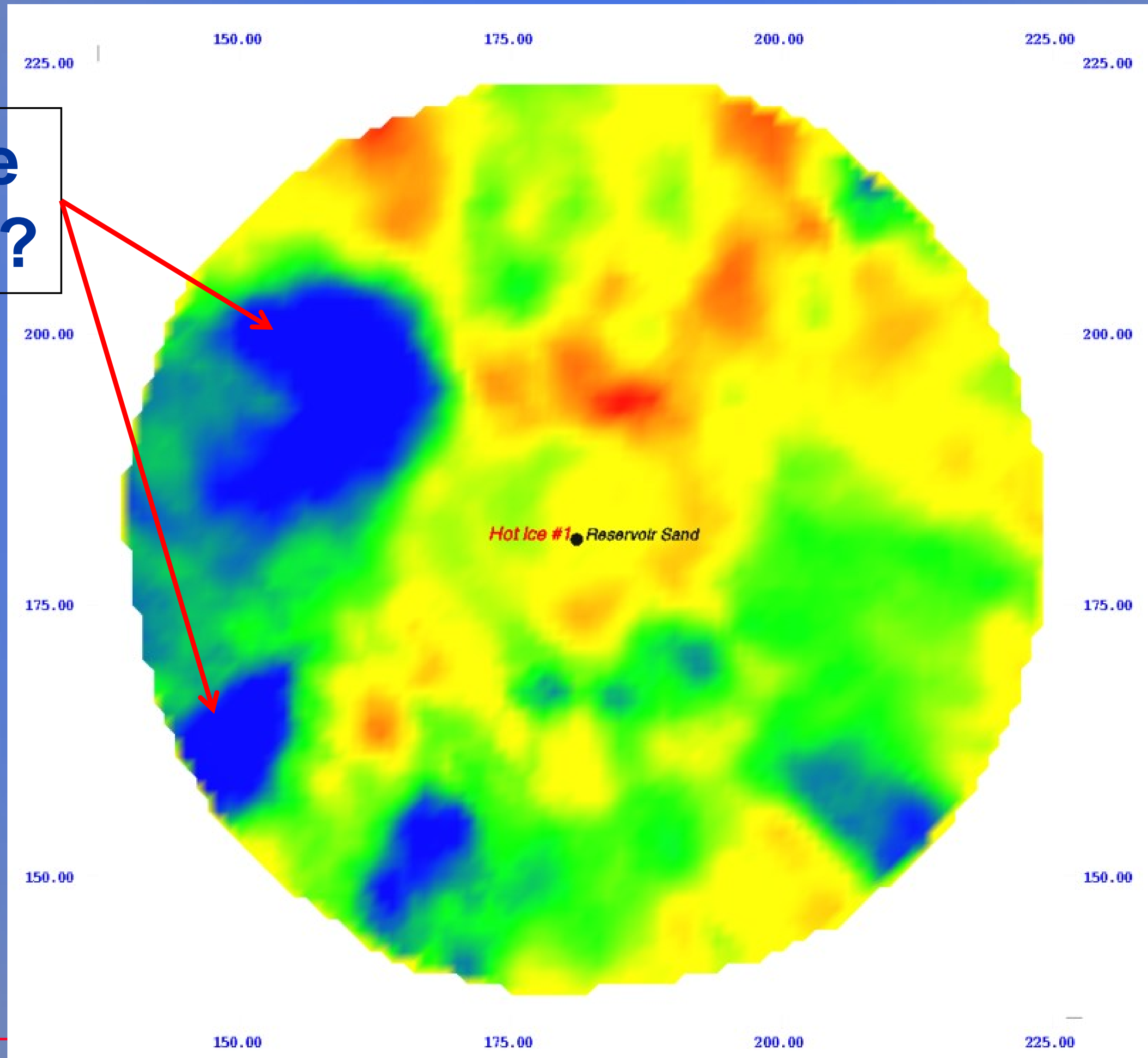


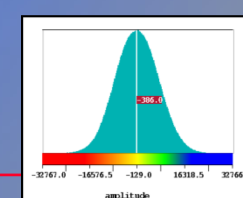




Amplitudes on Geologic Marker at Top of Sand A

Methane Hydrate?

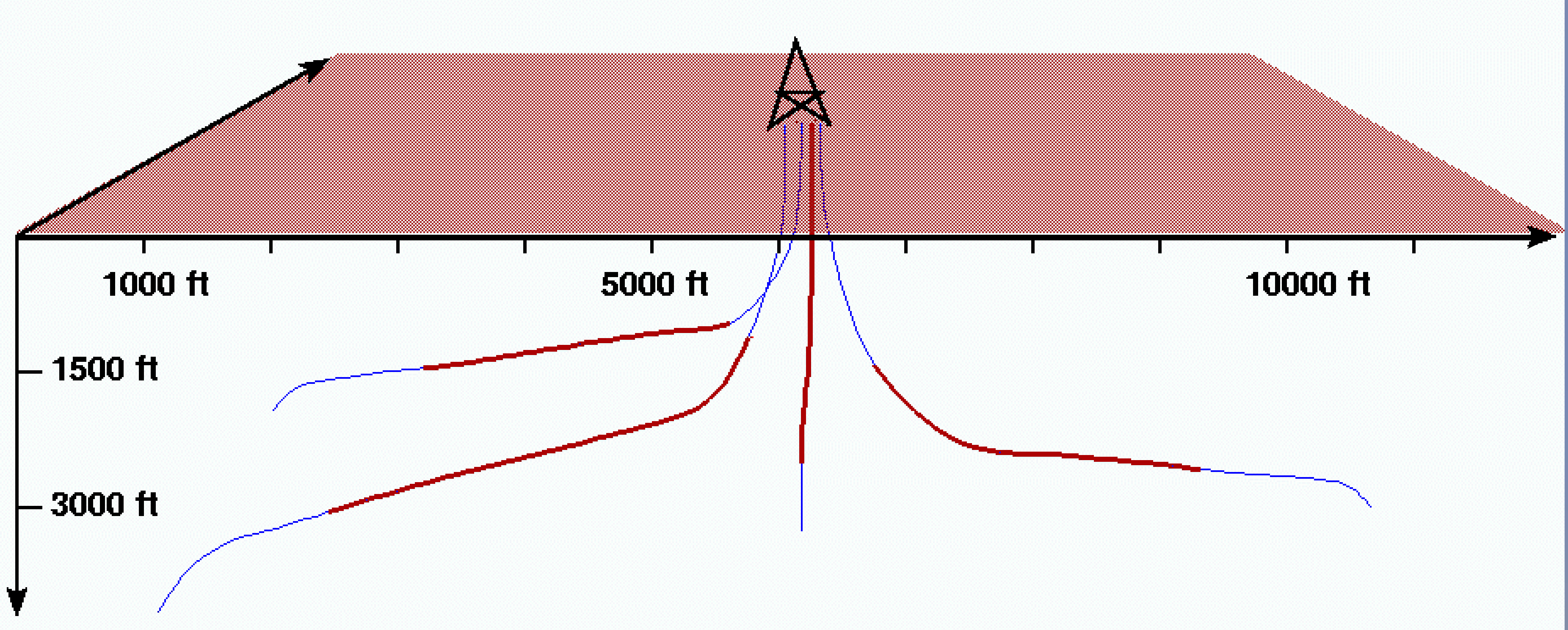




Multi well 3D VSP of thin reservoir to drill horizontal wells

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

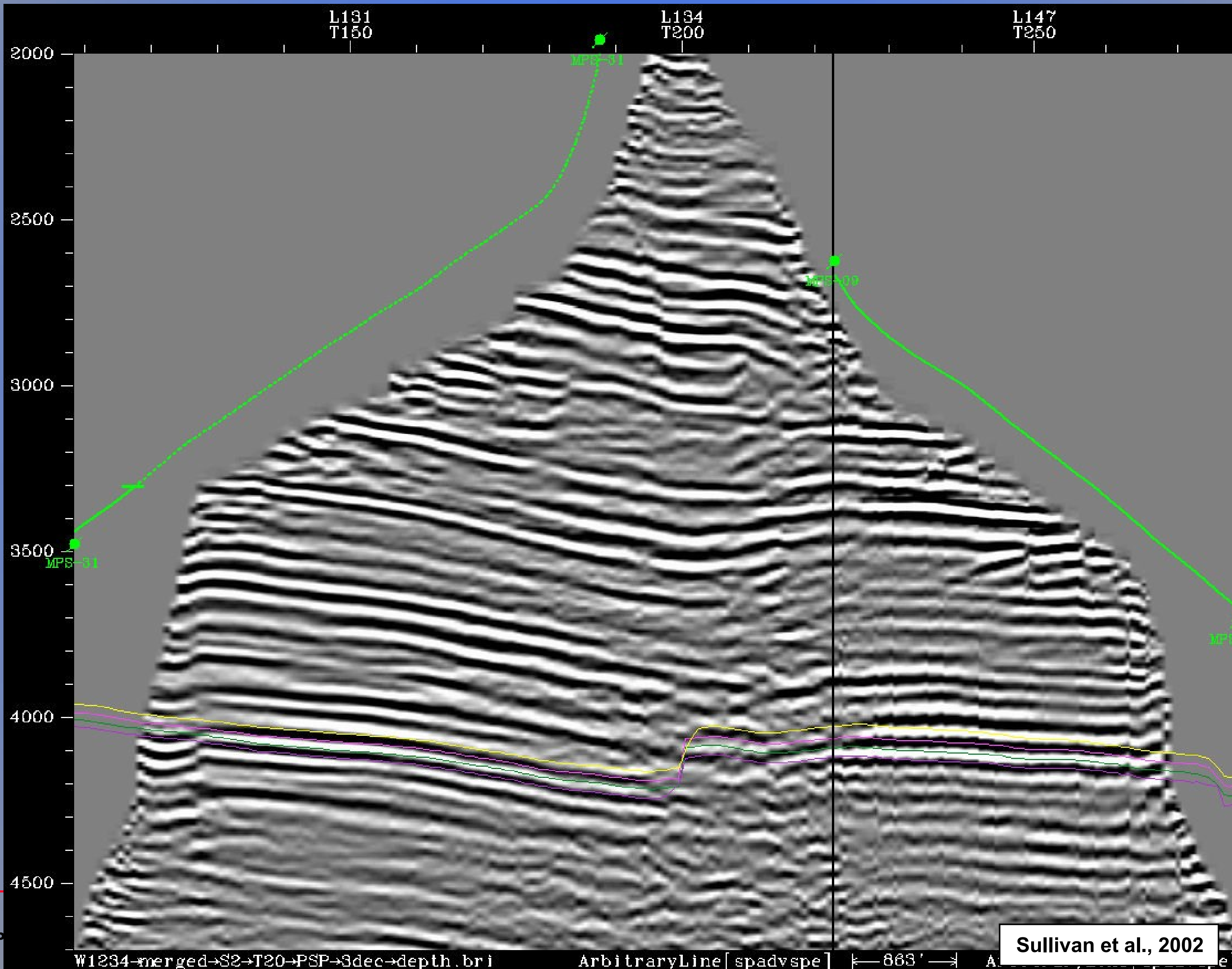
Surface Seismic Failed to Image the Reservoir



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

Paulsson et al., 2004

Massive 3D VSP / W-E Profile



Great Results - but Limited by the Sensor Response and Bandwidth

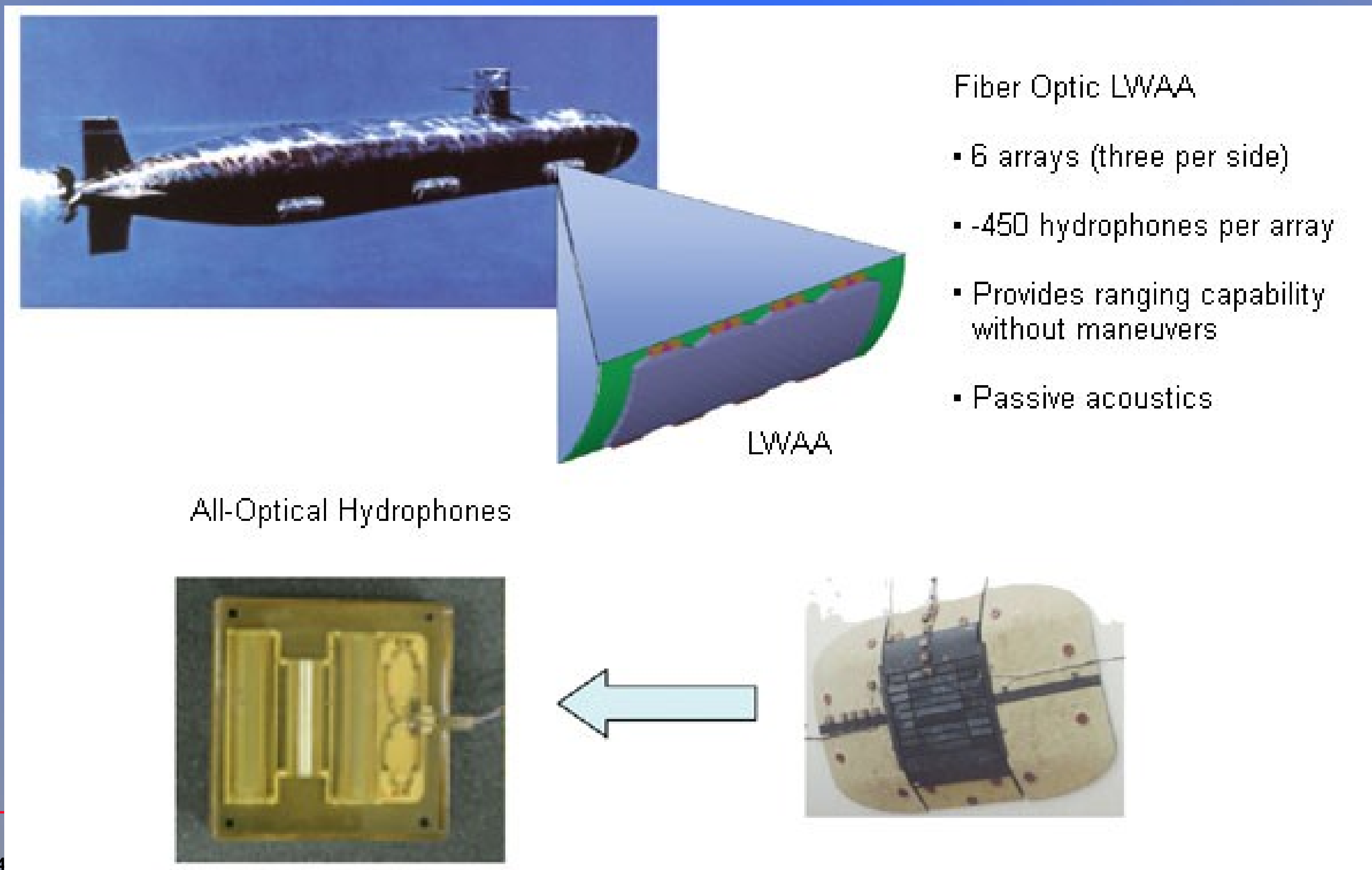
Borehole Seismology

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

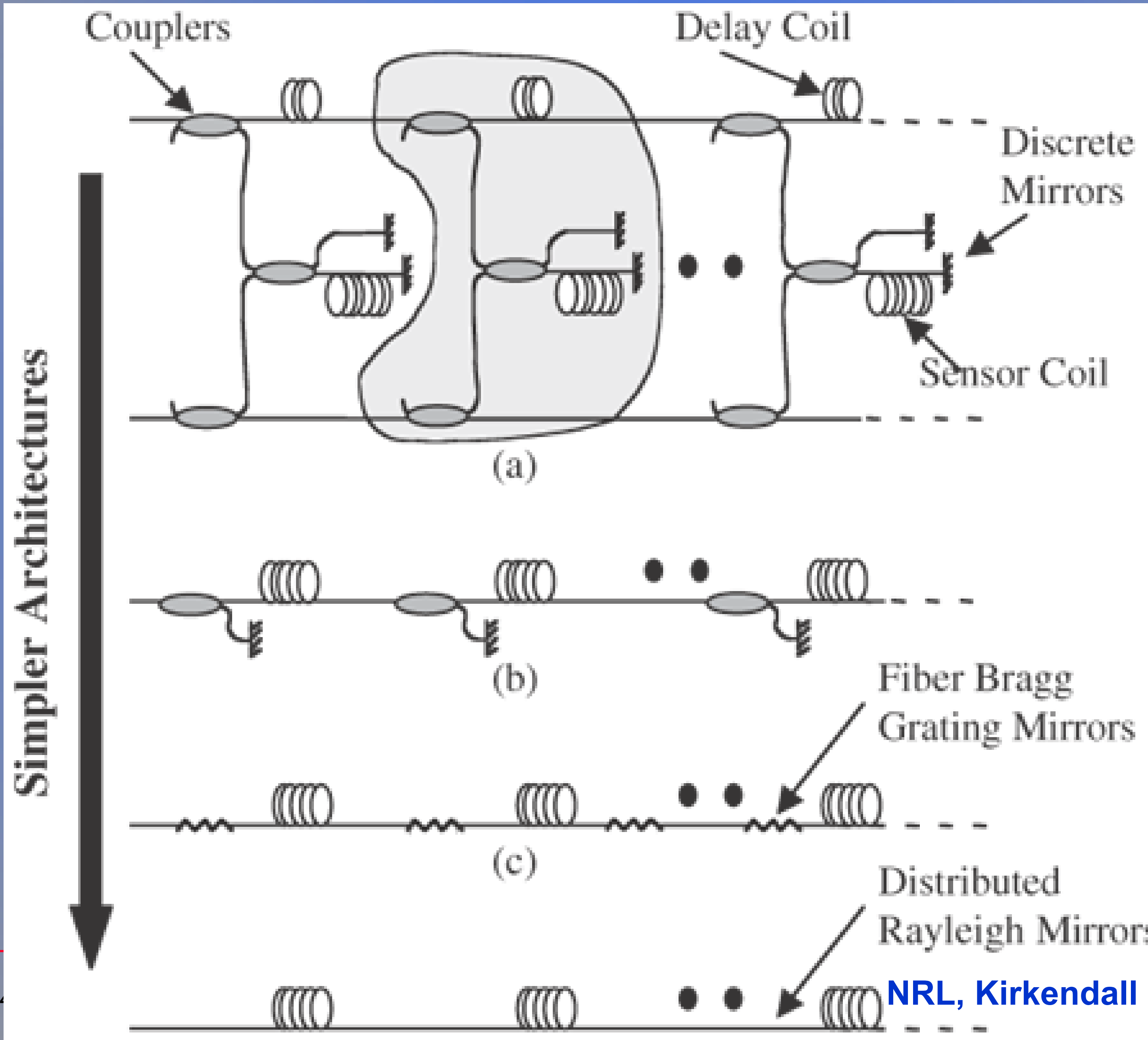
Fiber Optic Seismic Vector Sensor Technology

NSSN 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 has developed and demonstrated fiber optic methods based on the Michelson interferometry technique which measure the strain in fiber from dynamic signals (acoustic).

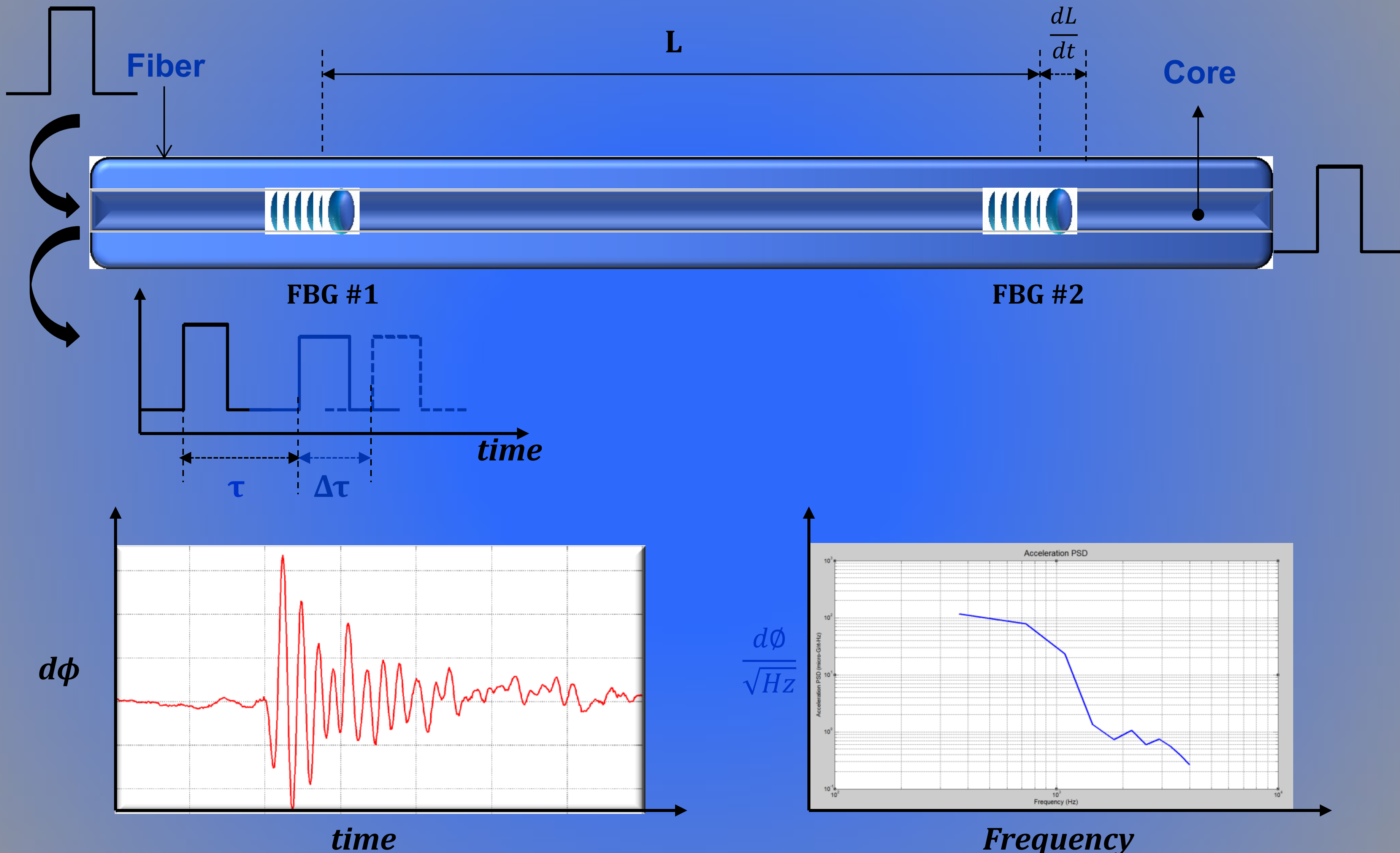


Interrogator Optical Specifications



NRL, Kirkendall et al. (2004)

Fiber Bragg Grating: Theory

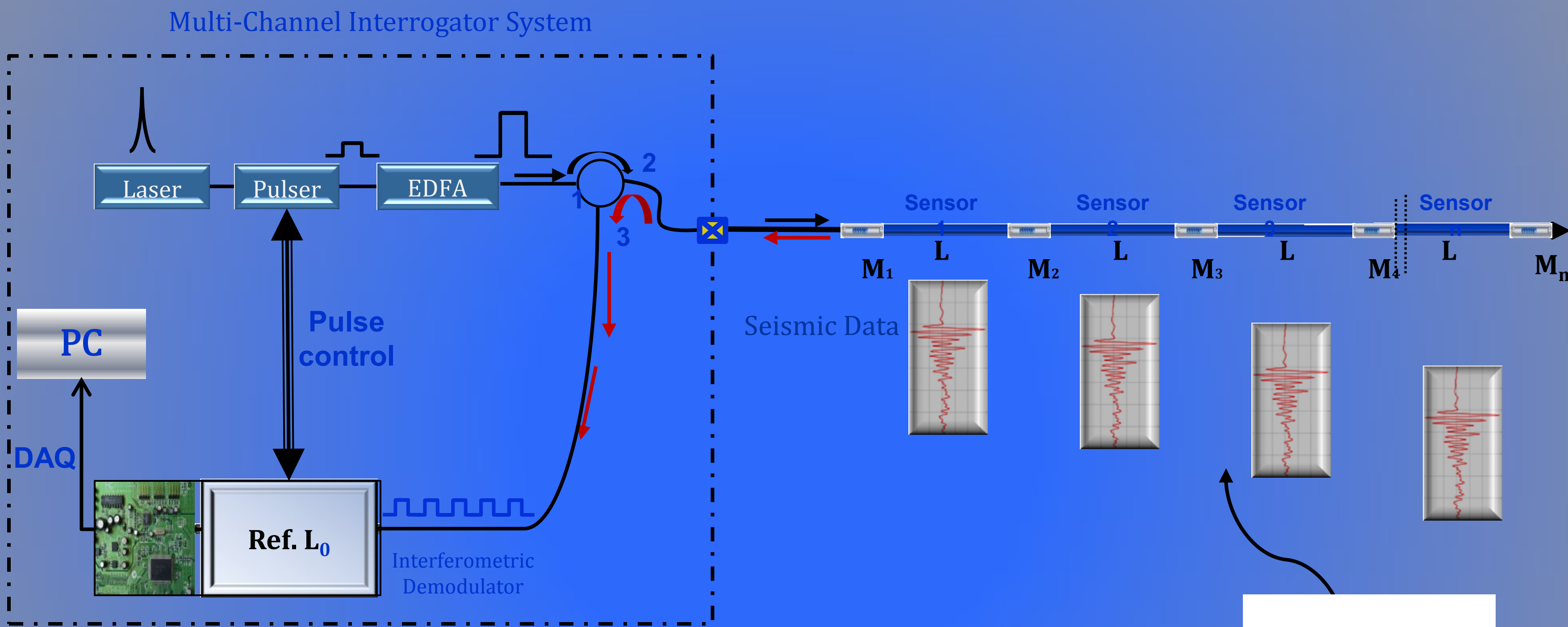


1. Fiber Optic Seismic Sensor (FOSS)™ Development

2. Deployment System Development

Interrogator Optical Specifications

Time Domain Multiplexing (TDM): Interrogator System Overview



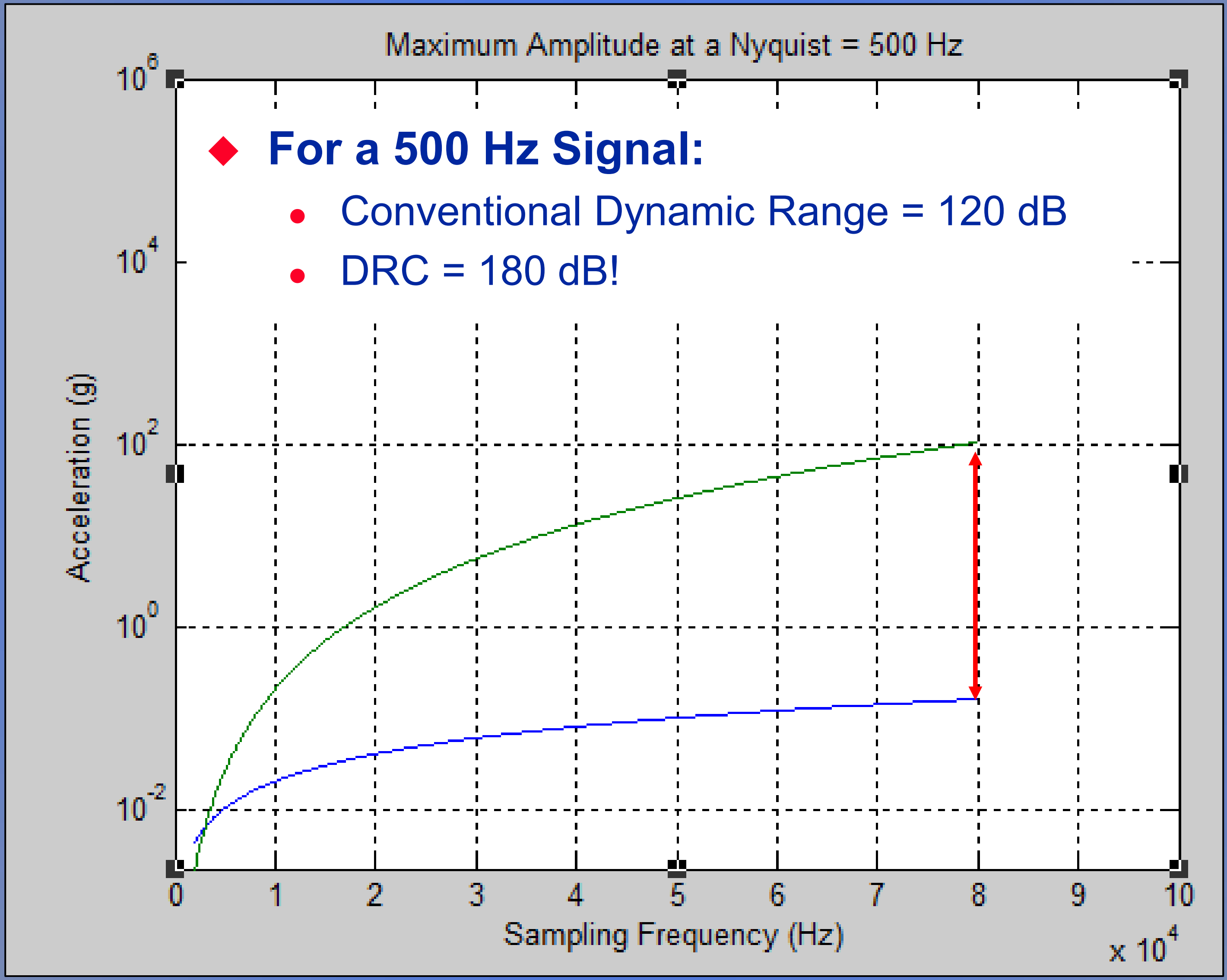
Basic Process:

1. A highly coherent laser source is used to generate a modulated laser pulse that corresponds to the length of the fiber sensor L.
2. The pulse reflects from each partially reflecting mirrors M_1, M_2, M_3, M_4, ...M_n(Fiber Bragg Gratings) generating multiple interfered pulses that are compared to **reference distance Ref L_0.**
3. **In the event of a seismic event, the returned** interfered pulses are demodulated to extract the induced change in **phase** , **dϕ , due to the change in length (strain)**

$$d\phi = 2\pi \frac{n\Delta L}{\lambda}$$

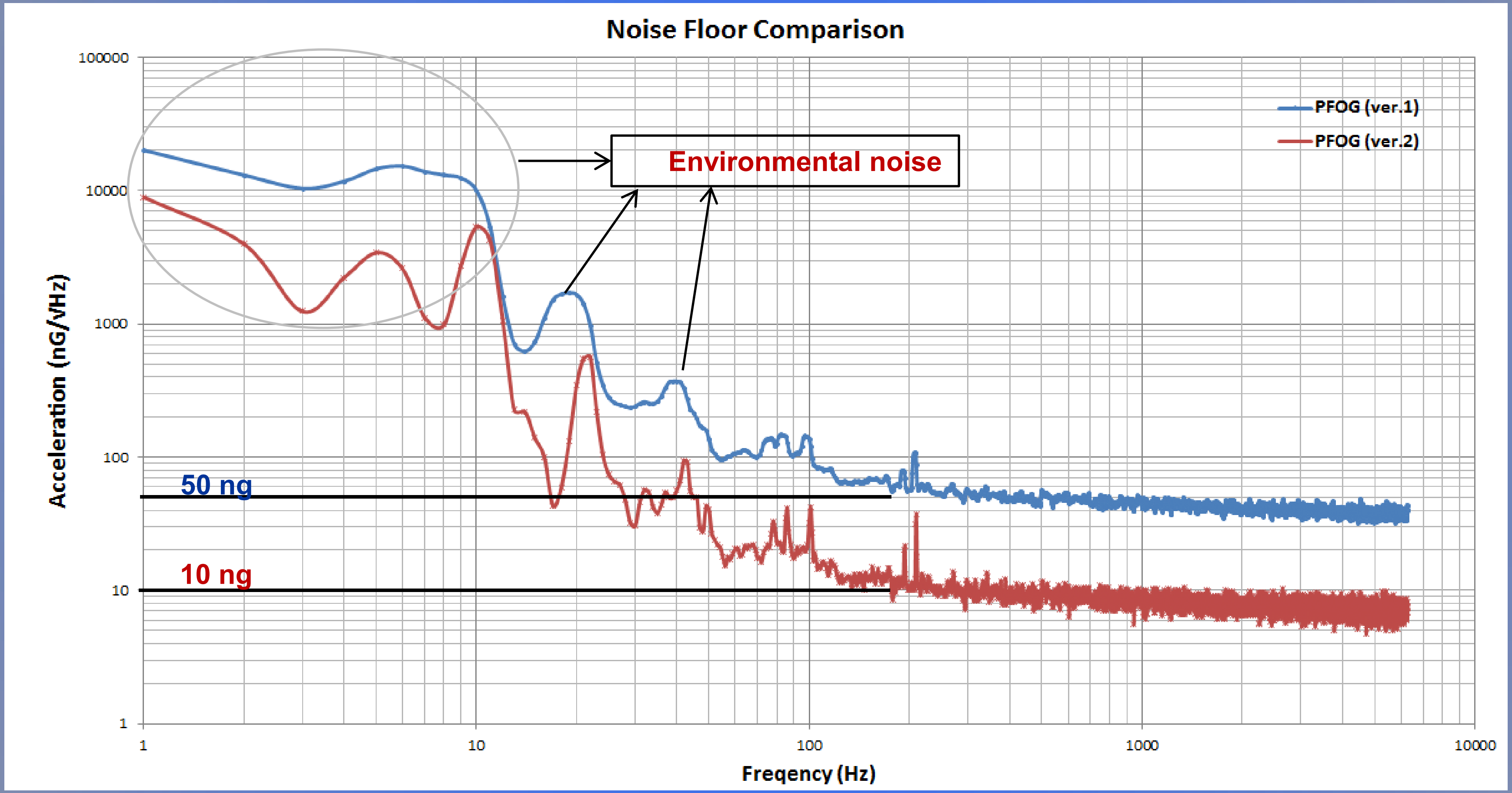
FOSS® Dynamic Range

Dynamic Range Enhancement Correction (DRC)



FOSS® Sensitivity

Fiber Optic Sensors and Interrogator Noise Floor Sensor's Sensitivity and noise floor improvement

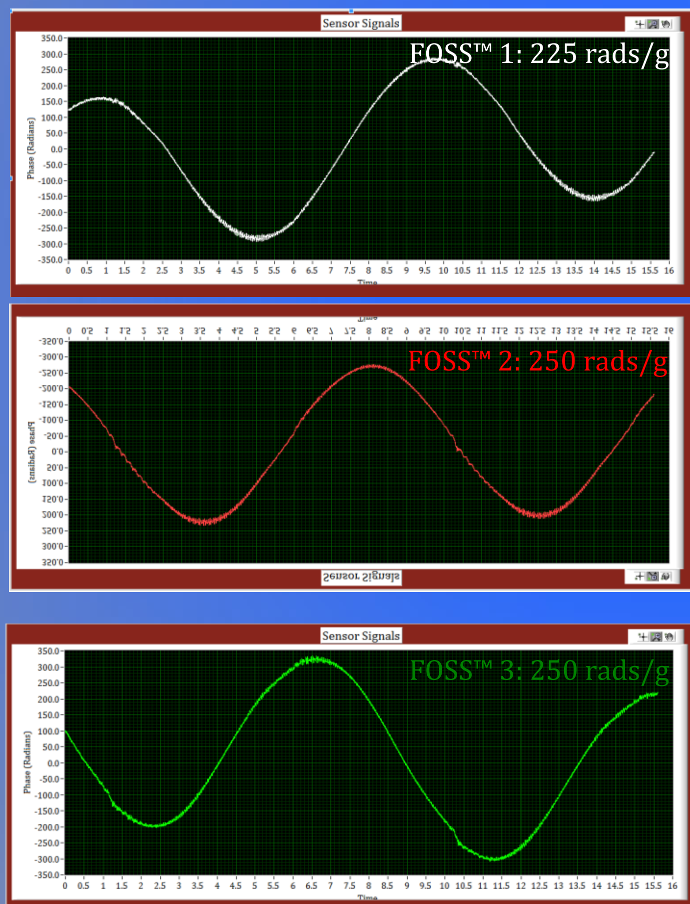


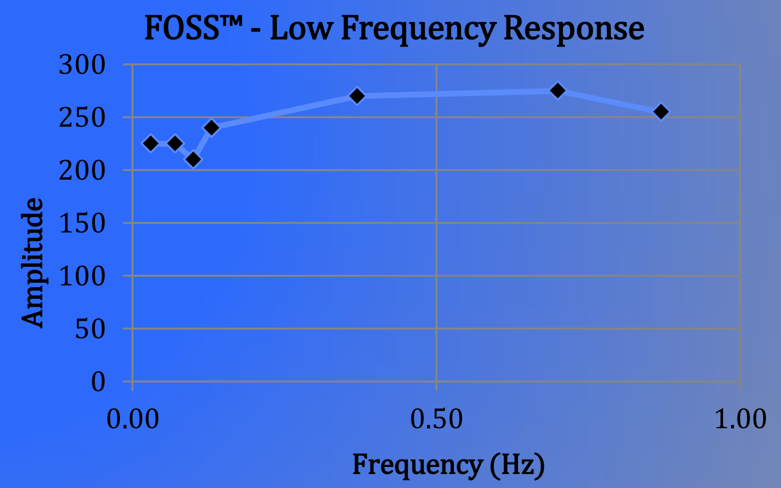
The Dynamic Test Station for the Fiber Optic Seismic Sensors (FOSS)™

Making and Testing of 3C FOSS™

- ## FOSS™ Testing - Sensitivity: 0.03 – 0.9 Hz
  - The sensor design in the 6-level prototype array has an sensitivity ~230 radians/g
  - The sensor design in the 15 level system will have a sensitivity >300 radians/g
  - Sensitivity of the FOSS™ has proven to be constant even at very low frequencies (sub-hertz)

FOSS™ Accel. Sensitivity





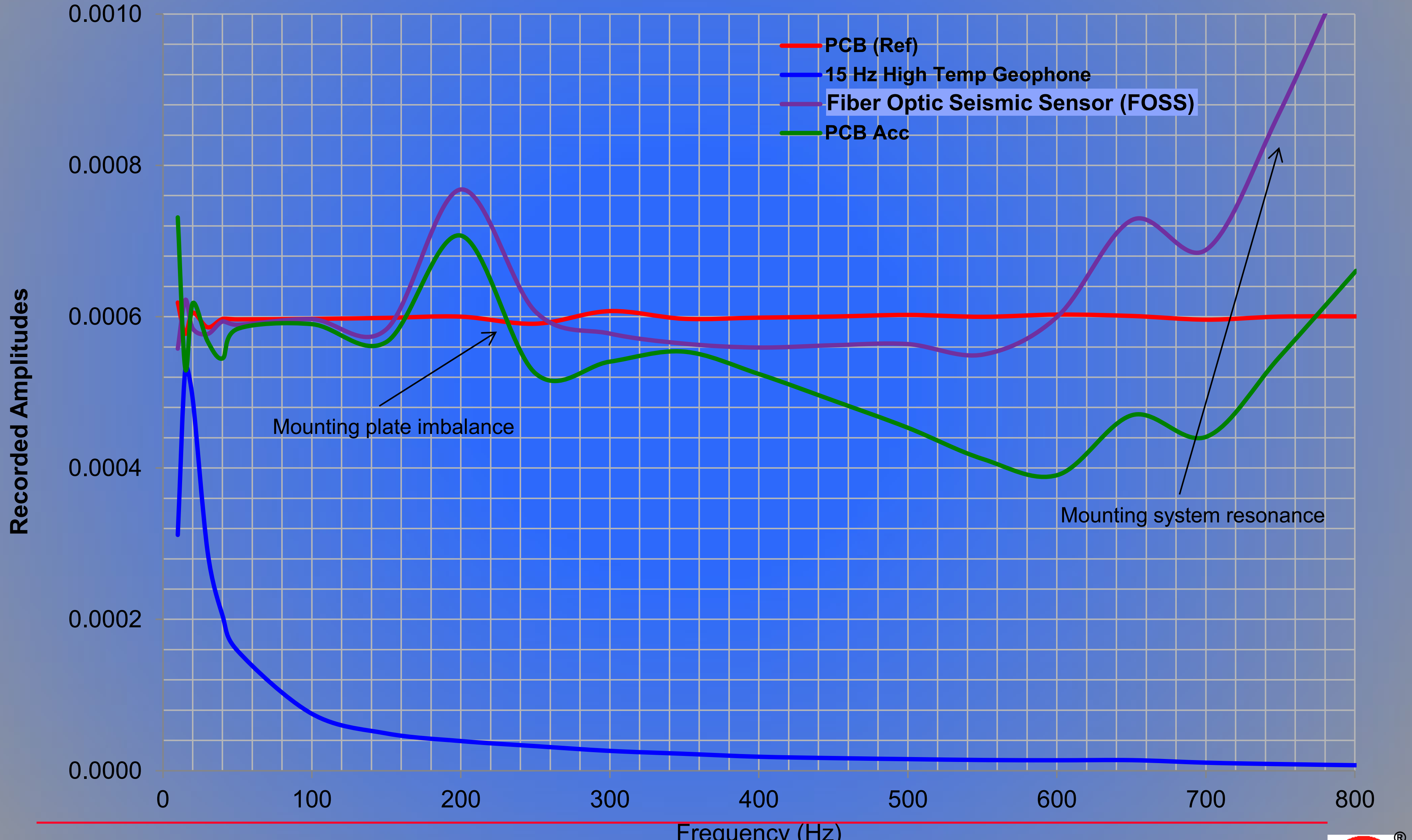
THE FIBER OPTIC SEISMIC SENSOR (FOSS)™

VS.

OTHER SENSORS @ 200°C

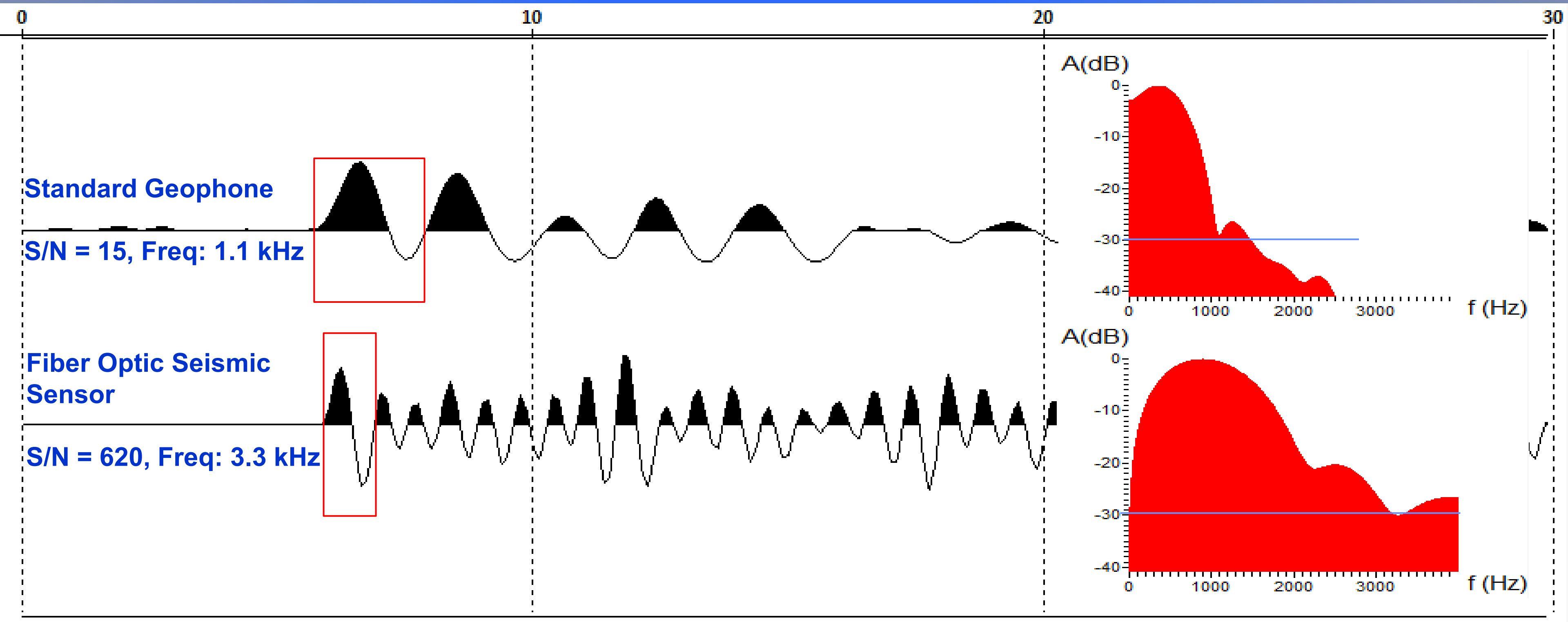
All Sensors - Frequency Response

10 to 800 Hz 600 μG Sweep @ 200°C



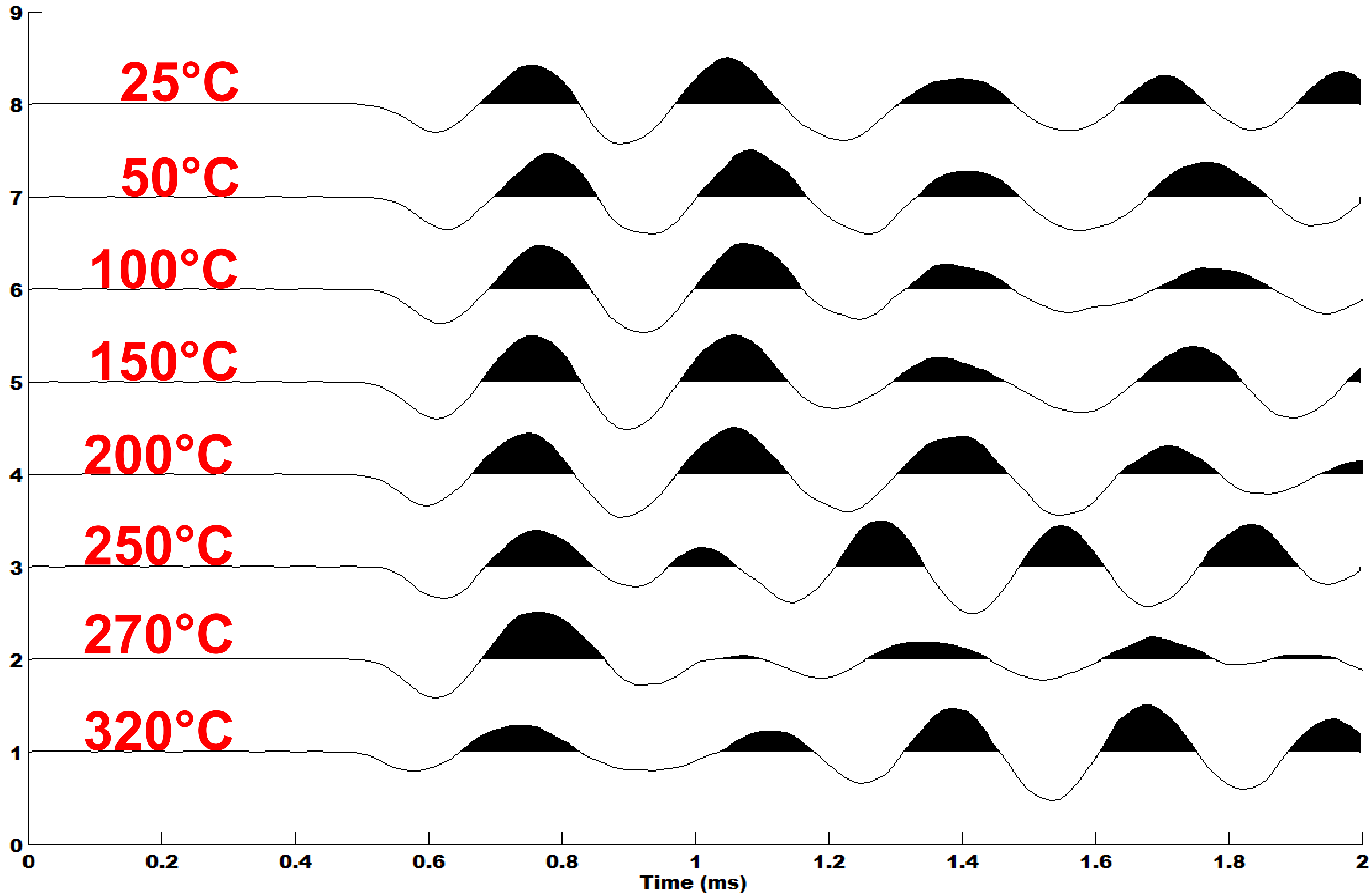
Fiber Optic Seismic Sensor (FOSS)™ vs. Standard Geophone
Data recorded simultaneously from a single tap test
Sampling rate: 8,000 Hz. High cut filter at 2,500 Hz.

- FOSS S/N ratio is 41 times higher than S/N for Geophone
- FOSS -30 dB point is 3,300 Hz vs 1,100 Hz for Geophone

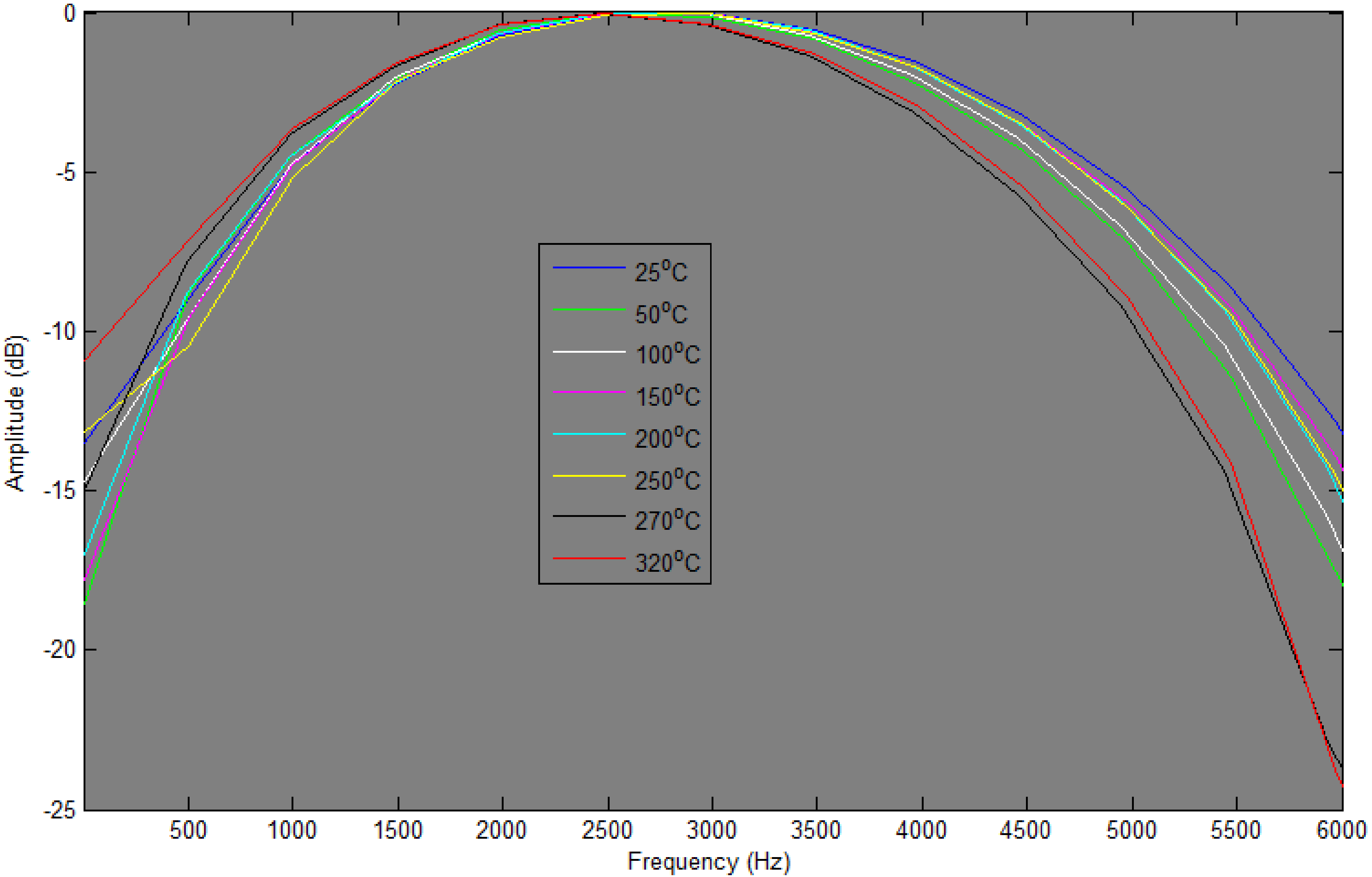


Tap Test of
Fiber Optic Seismic Sensor
Inside a Geophone Pod
@
Temperatures: 25°C - 320°C

FOSS: Optical Radial Component over Temperatures



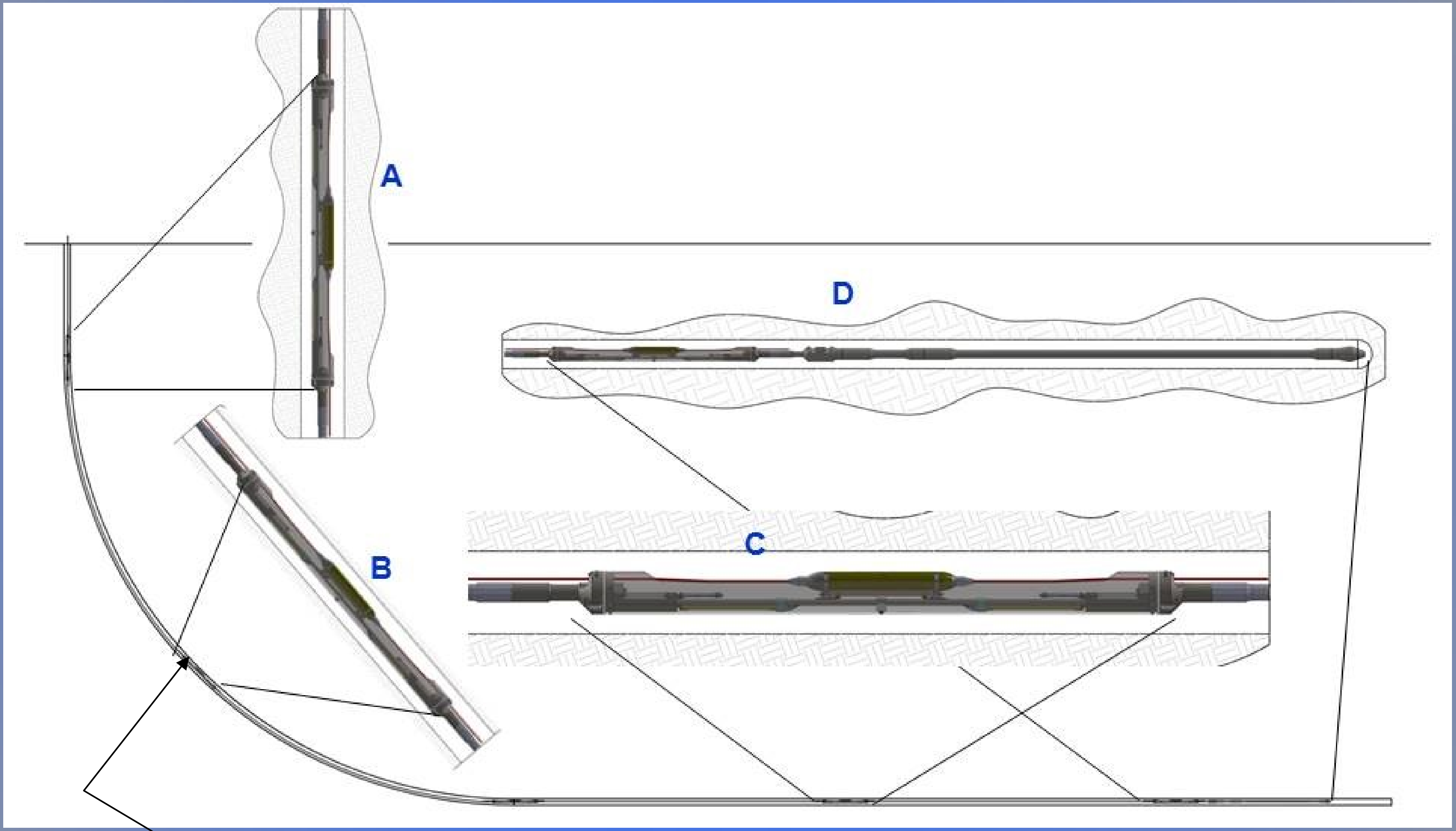
Fiber Optic Seismic Sensor (FOSS)™, Radial Compo. Tap Tests at 25°C - 320°C – Spectra plots



1. Fiber Optic Sensor Development

2. Deployment System Development

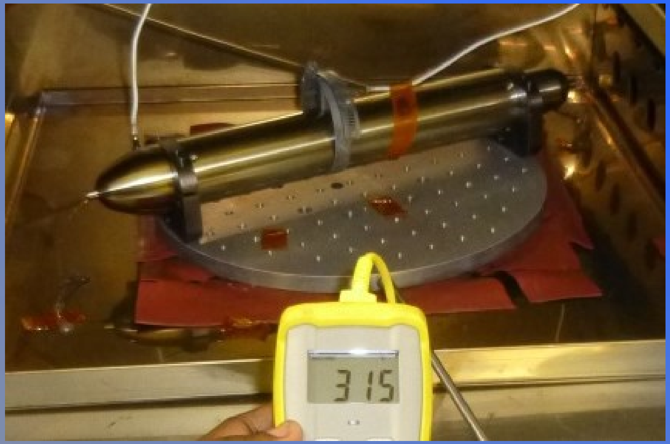
Drill Pipe Deployed System – Housing and Clamping



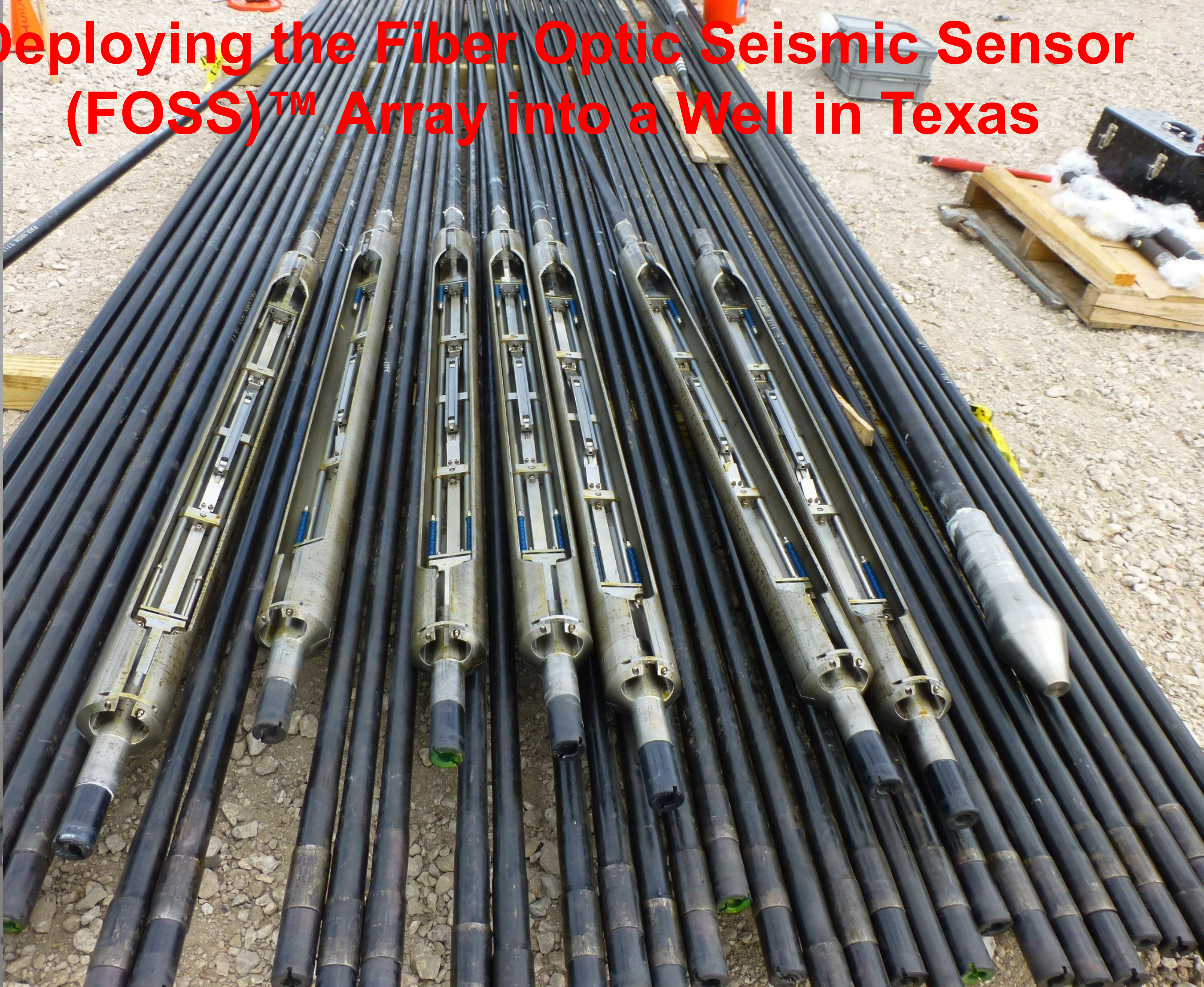
Clamping system operates by increasing the pressure inside the drill pipe and manifolds and uses the bore hole fluid as a medium

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

Fiber Optic Seismic Sensor Deployment



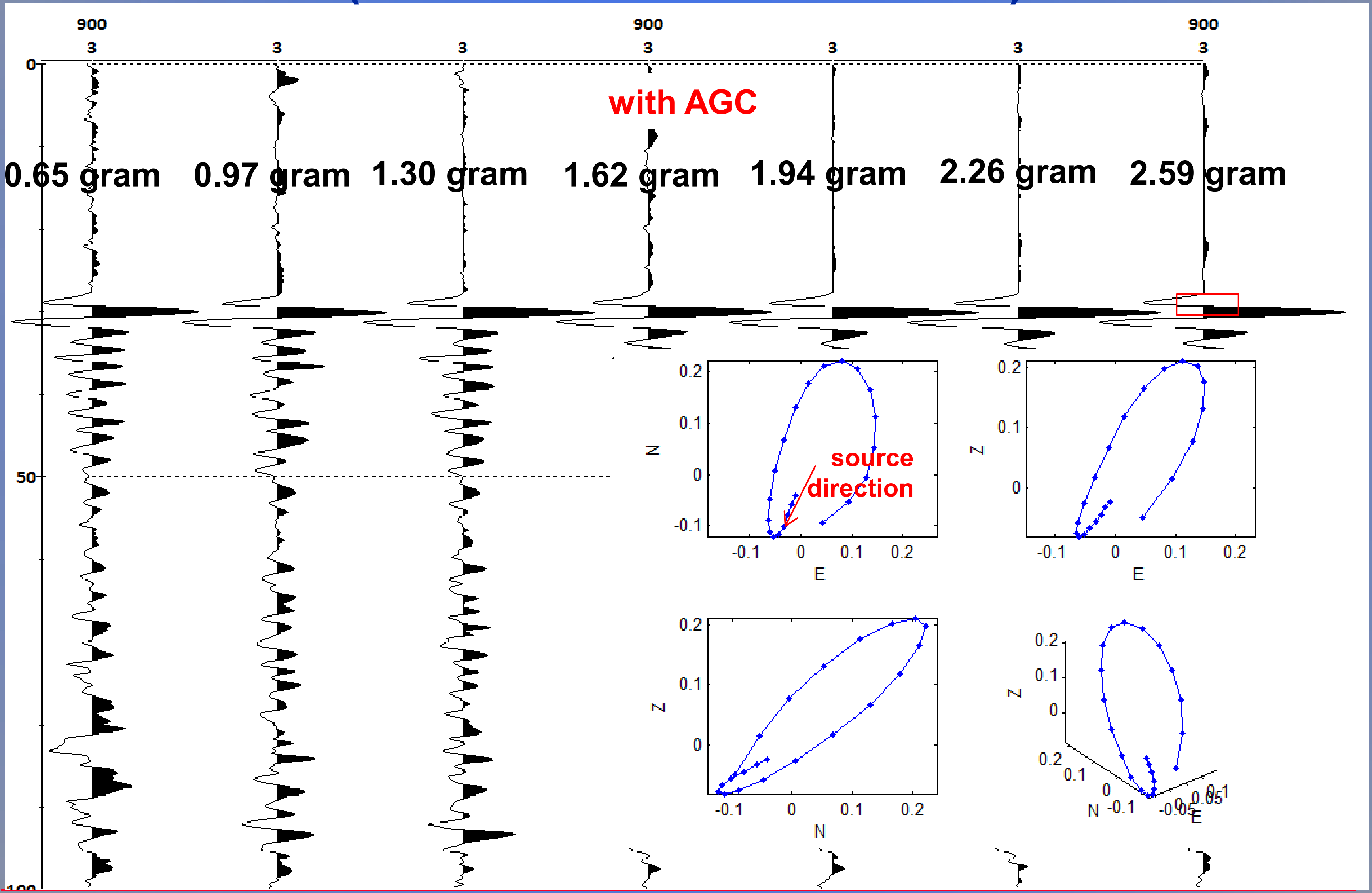
Deploying the Fiber Optic Seismic Sensor (FOSS)™ Array into a Well in Texas



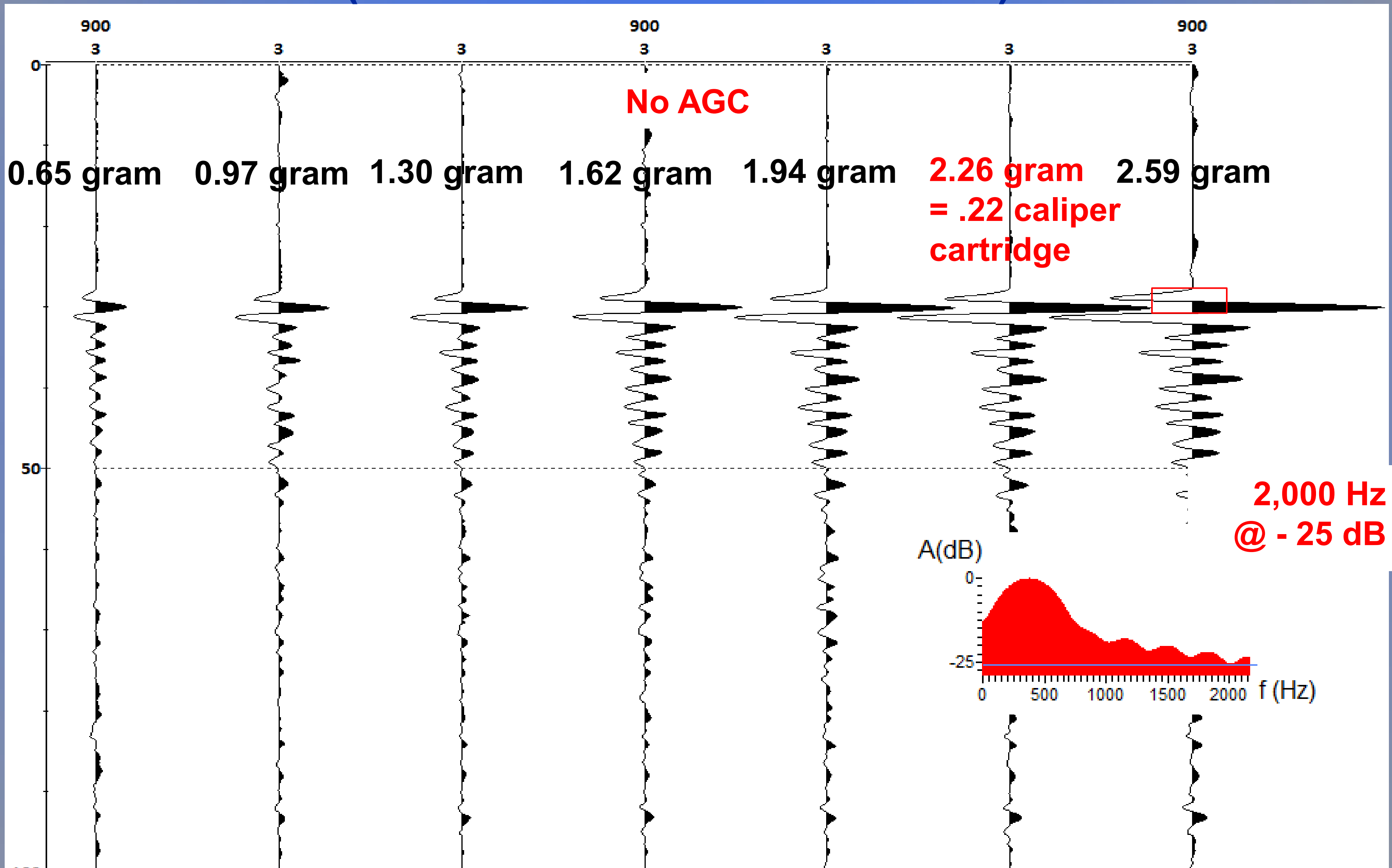
Deploying the Fiber Optic Seismic Sensor (FOSS)™ Array into a Well in Texas

Processing of Field Test Data Recorded with Fiber Optic Seismic Sensor (FOSS)™ System

Shots for POD 5 Principle Component, 1,200 ft (Filter: 80-100-1500-2000 Hz)

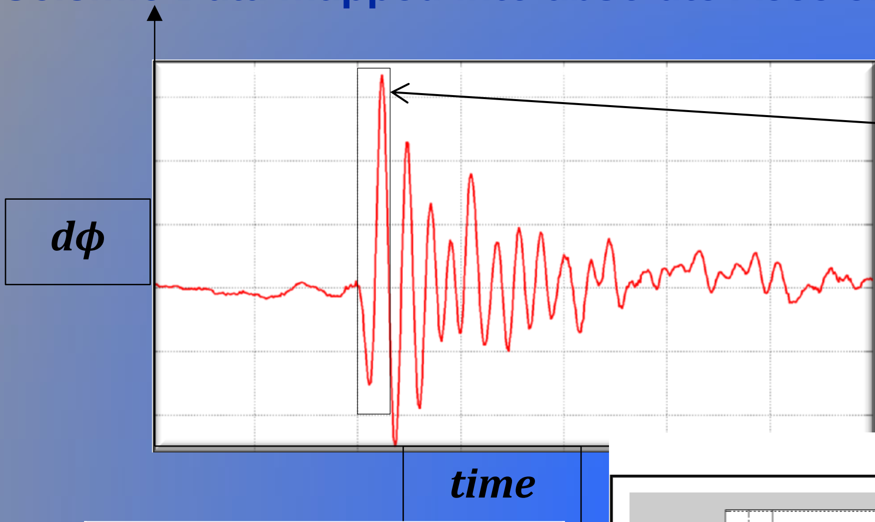


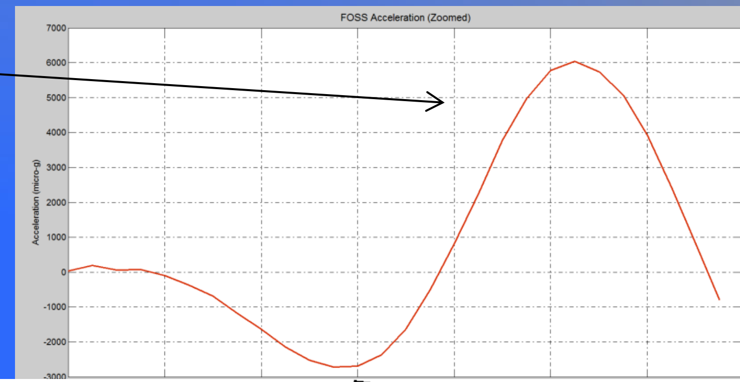
Shots for POD 5 Principle Component, 1,200 ft (Filter: 80-100-1500-2000 Hz)

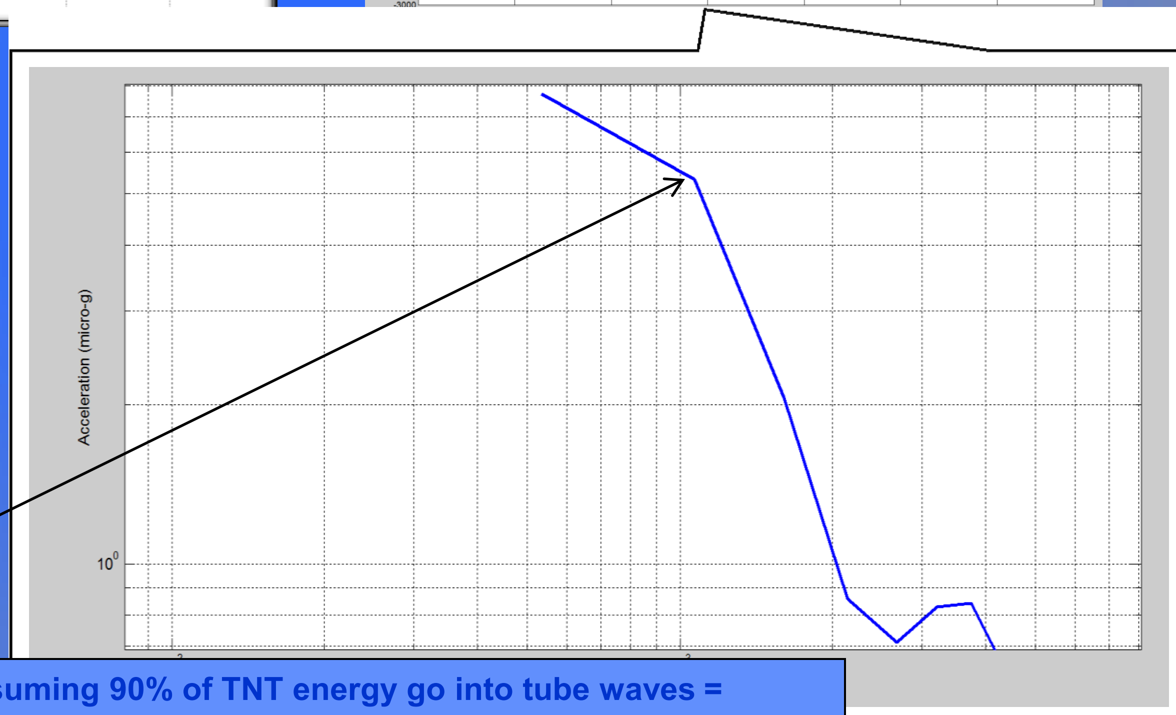


Seismic data Recorded on a Fiber Optic Seismic Sensor (FOSS)

Seismic Data mapped into absolute Acceleration using Calibrated Sensor Transfer Function







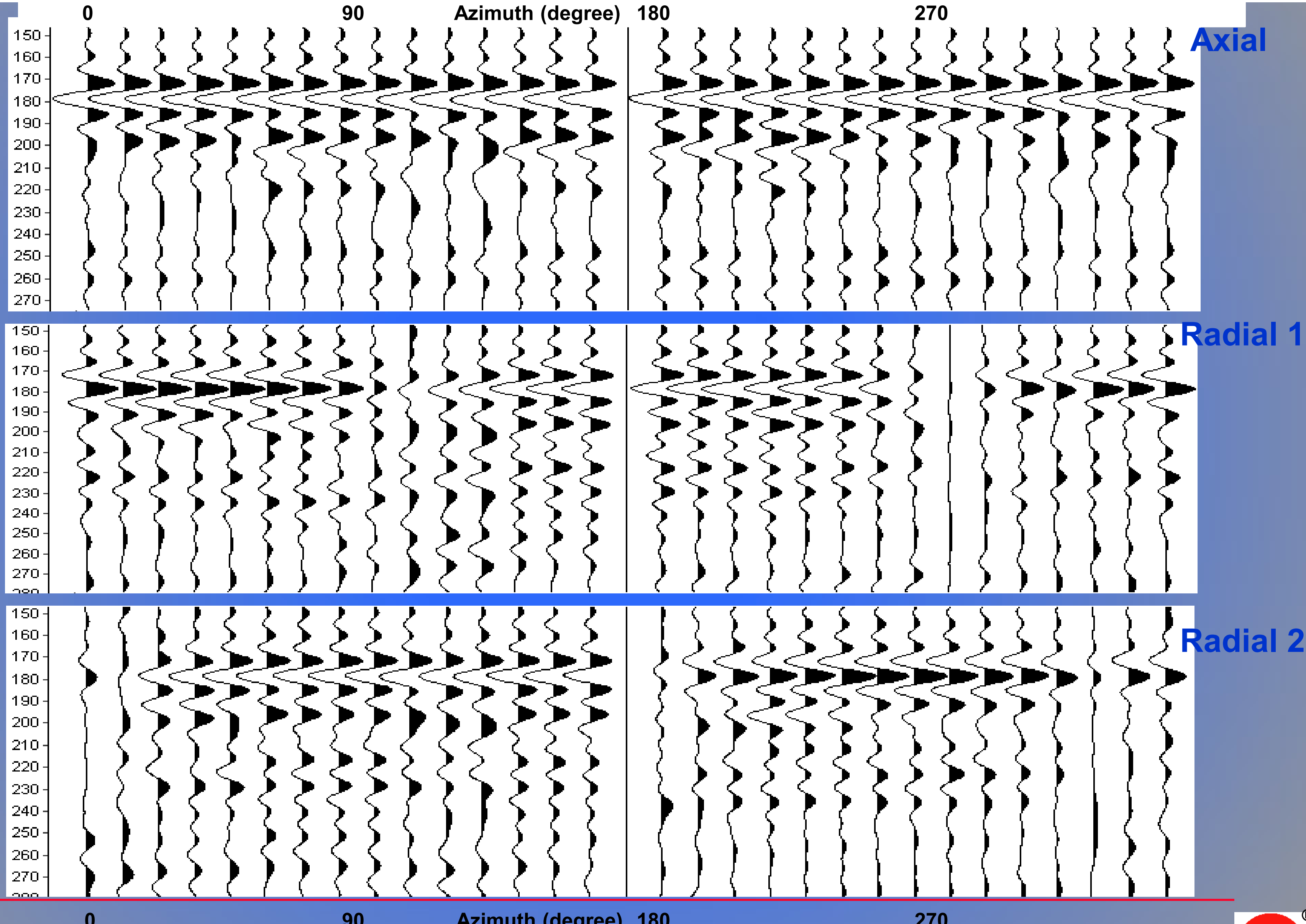
Quantitative Analysis of Data from 0.65 gram of TNT At a distance of 1,200 ft (366 m)

Frequency (Hz)	Acceleration (μG)
600	7.3
700	6.7
800	6.2
900	5.8
1,000	5.5
2,000	2.0

Assuming 90% of TNT energy go into tube waves = 200 Joules from 0.65 gram of TNT = Magnitude M-2.6

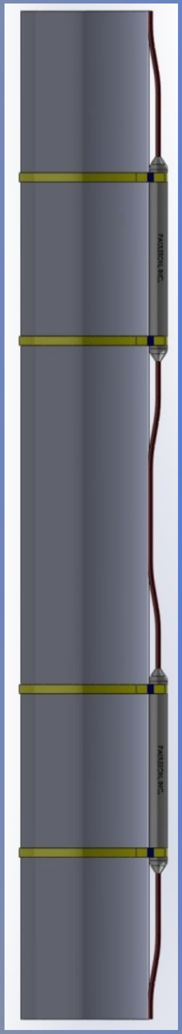
Vibrator walking around the receiver well

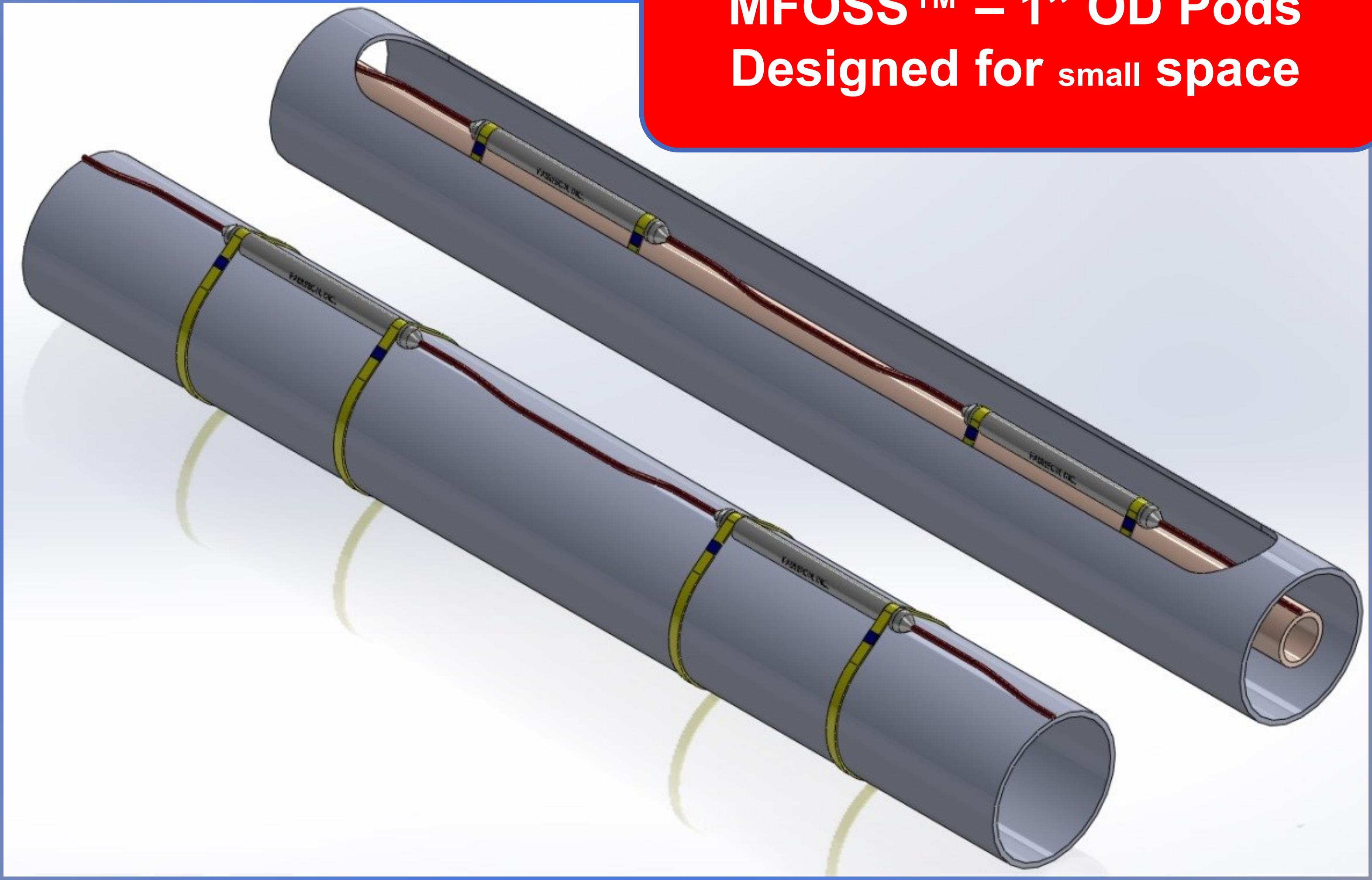
(Data aligned for waveform and phase analysis, Filter: 4-6-96-120 Hz)



Mini FOSS®

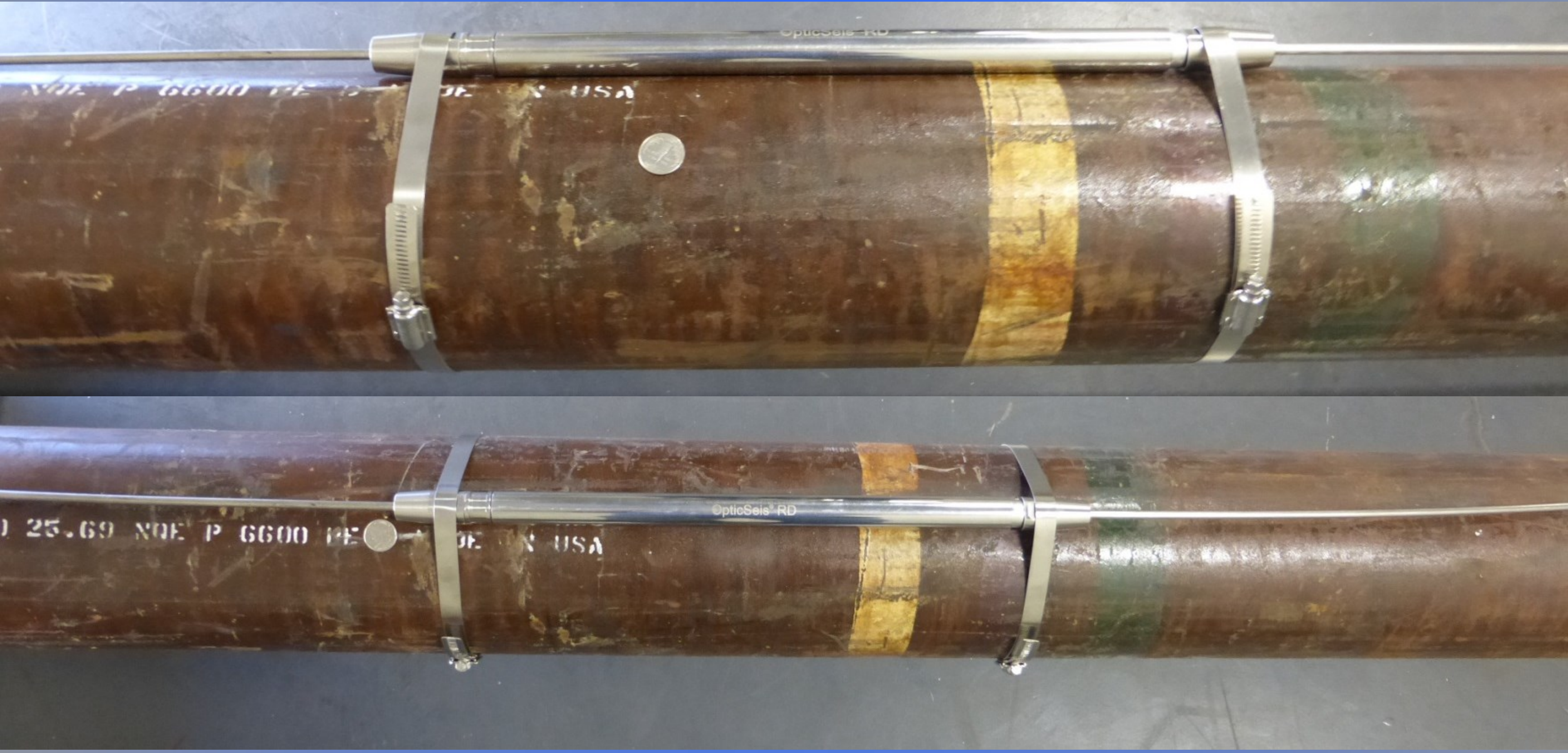
Mini FOSS™ – Pods 1” OD



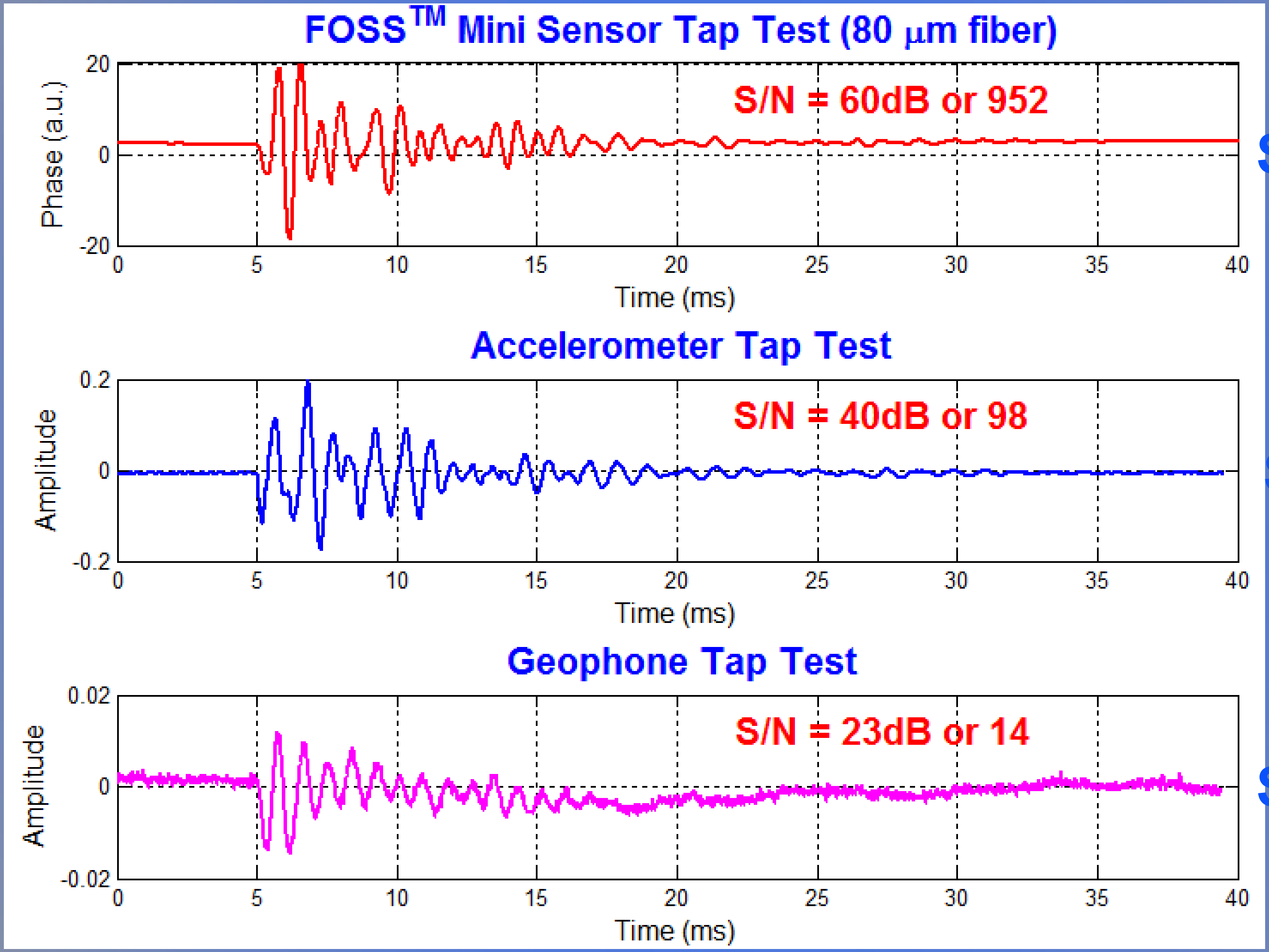


MFOSS™ – 1” OD Pods
Designed for small space

Mini FOSS™ – Pods 1" OD
Designed for small space
Shown on 7" casing – Note Quarter: 0.955"



Simultaneous Tap Test on 3 sensors

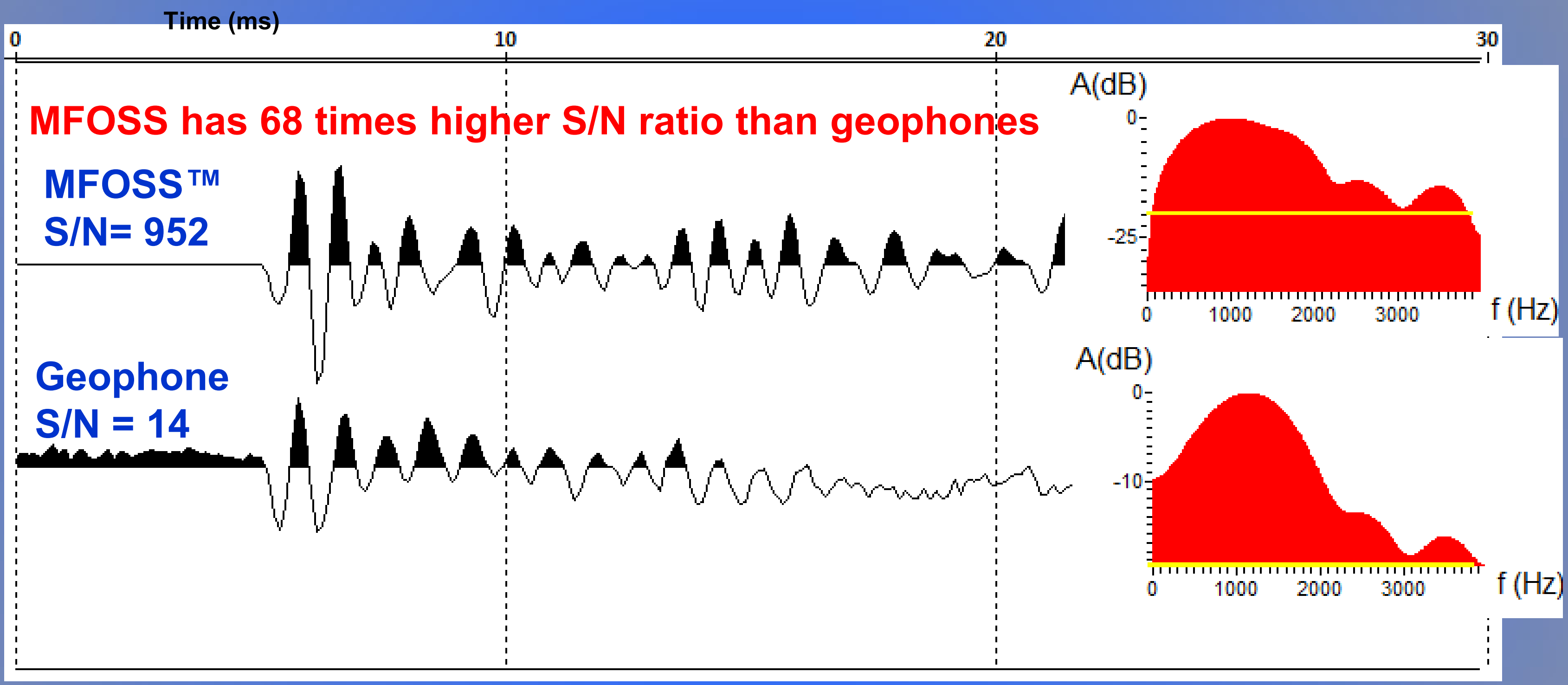


S/N= 952

S/N= 98

S/N= 14

Simultaneous Tap Test on Two Sensors Fiber Optic Seismic Sensor (FOSS) vs Geophone



Borehole Seismology

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

Smart
Acoustic Micro Emitters

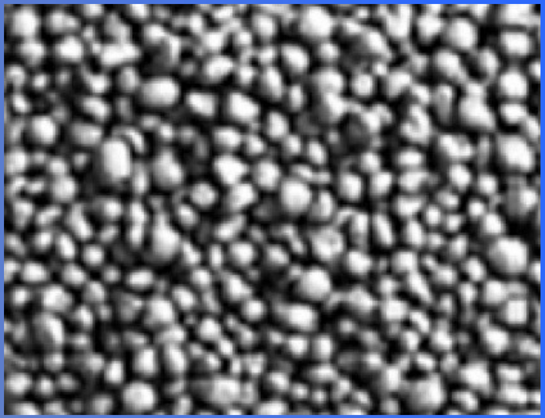
A technology for monitoring fracture geometries in-situ

www.fluidion.com
contact@fluidion.com

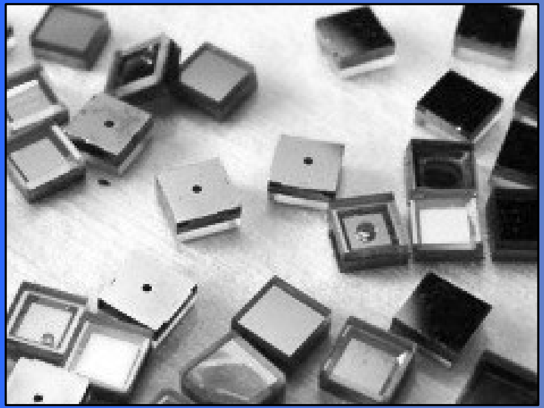
Getting most out of fracture monitoring

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

Answer: Embedding smart microsystems within standard proppant formulations

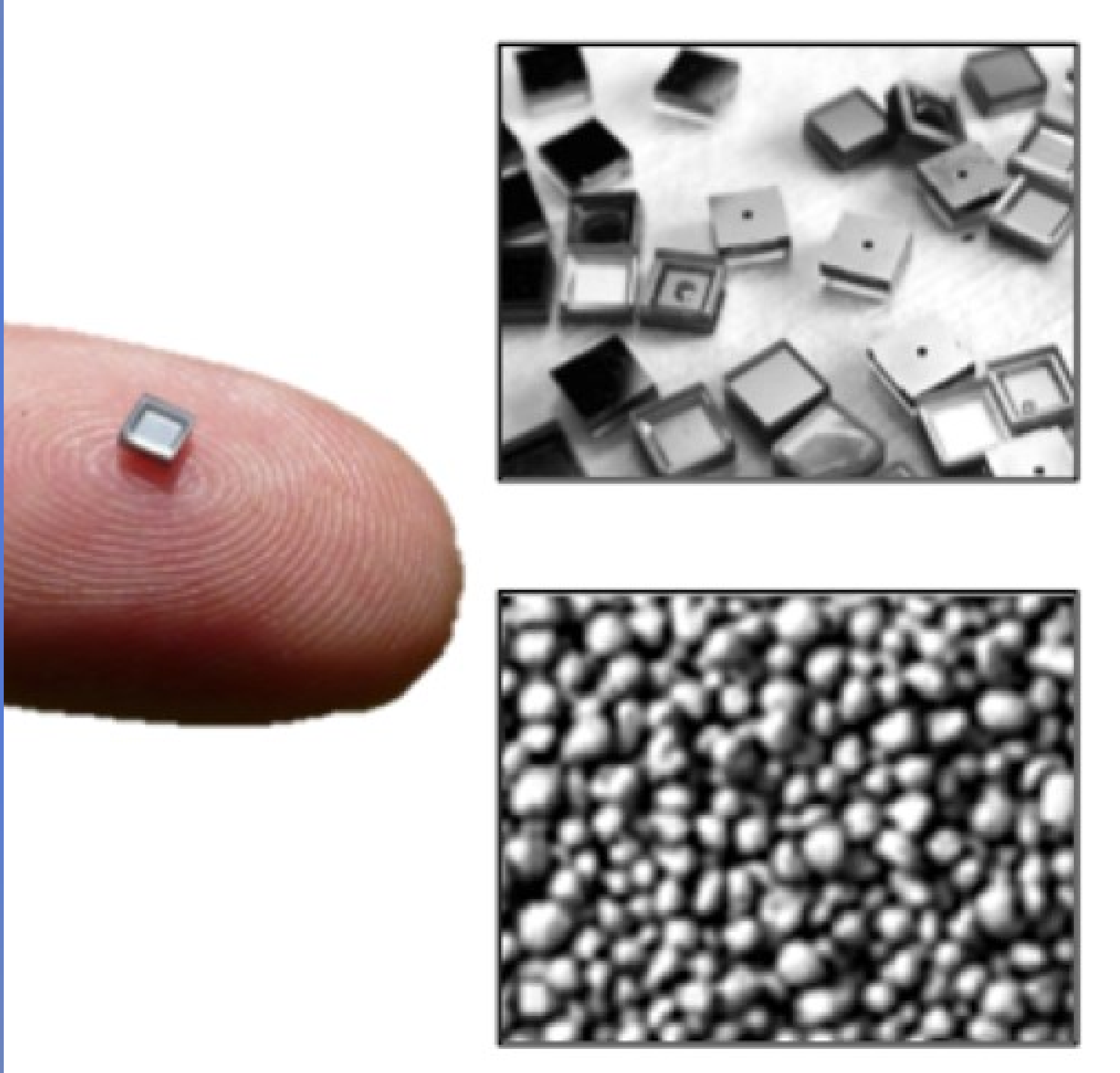


Typical ceramic proppant 20/40

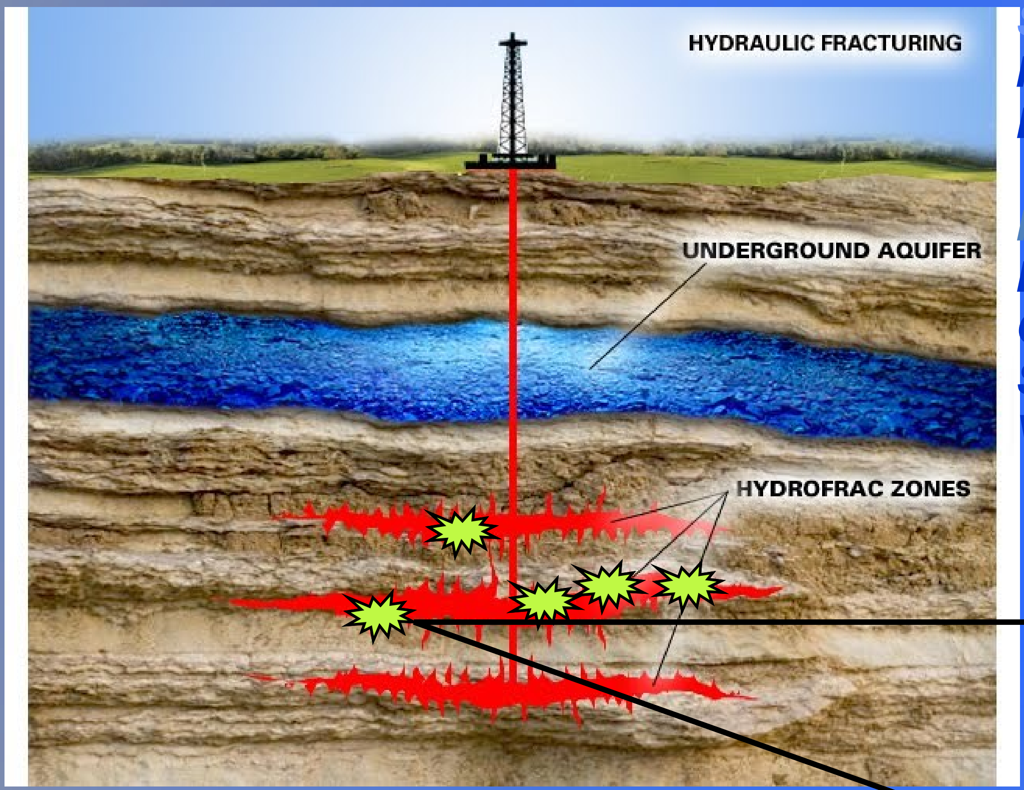


fluidion smart micro-emitter (prototype stage)

Acoustic Micro Emitters – Evolving Technology

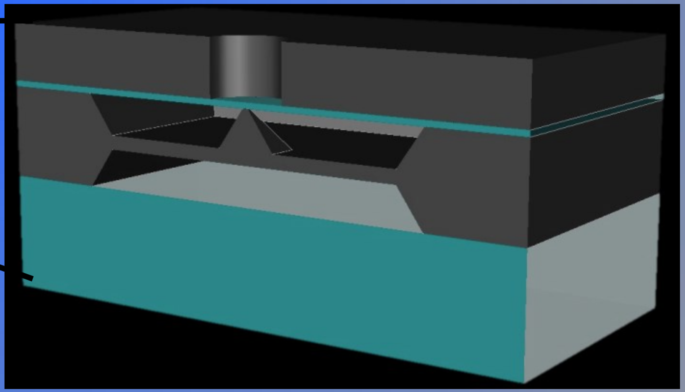


Using smart Acoustic Micro Emitters (AME)

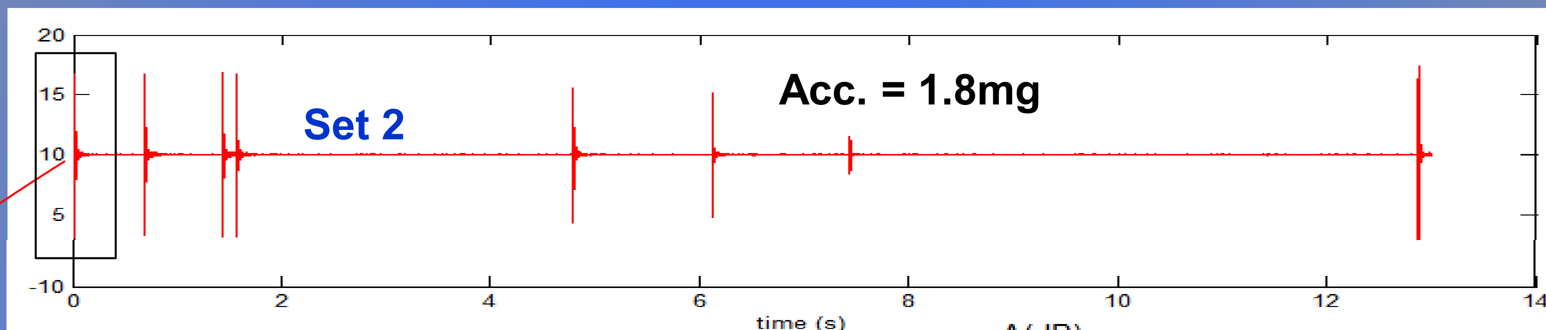


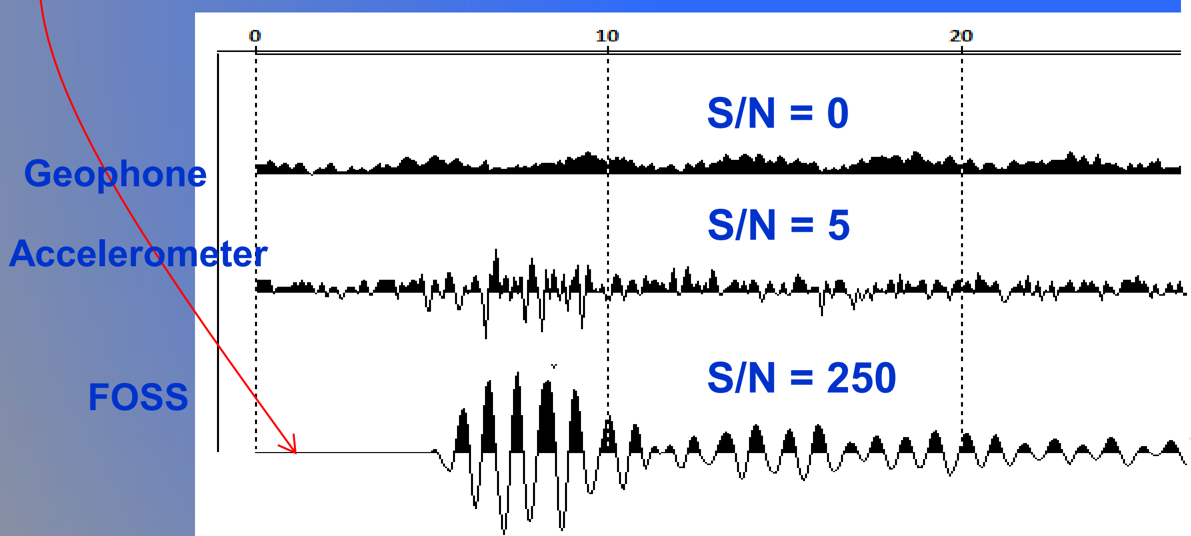
Simple logistics:
Injected in well along with proppant
Detected using fiber optic sensor array

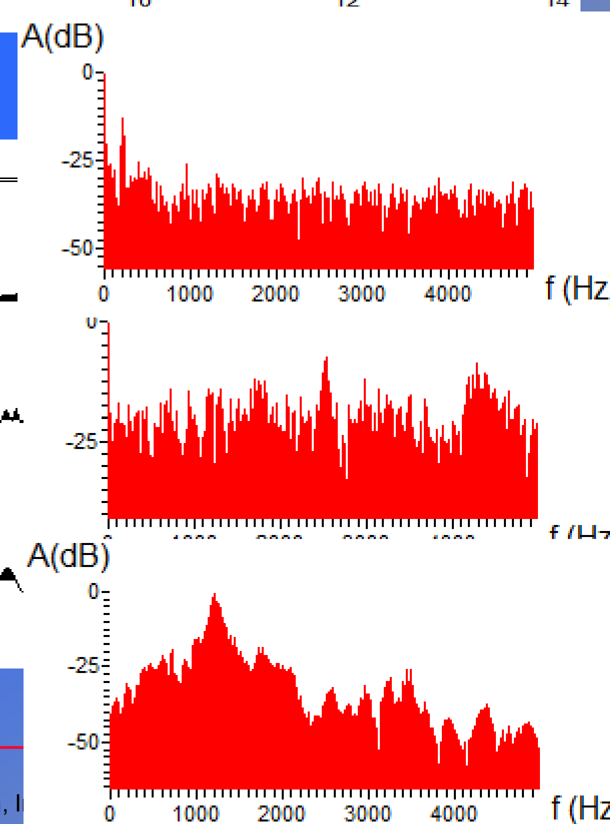
High added value:
Delayed acoustic emission – high S/N
Guaranteed in-fracture signal
Specific acoustic signature
Various sizes – mapping fracture width



Test of Acoustic Micro Emitters - Test #23







Game-changing potential

Smart acoustic micro-emitters (AME)

Allow high precision localization of fracture geometry

Avoids drawbacks of standard micro seismic analyses

Can produce valuable information on

- fracture width vs. position
- fracture orientation and size
- number of fractures per frac zone

Monitoring technology allowing effective fracture optimization

Data by Optical Sensor Systems

Today:

- Seismic – Fiber Optic Vector Sensors (Sensitivity: 100 x Geophones and 1000 x DAS)
  - P-wave Velocities
  - SH and SV Velocities
  - Reflections
- Acoustic – Distributed (DAS) for velocity
- Temperature – Distributed along the fiber
- Pressure – Point Sensors

Future:

- Chemical Sensors
- Pressure sensor – Distributed
- Other

What can we learn from the “New Signals”

- High Resolution images – much better than surface seismic
- Large volume images – much larger volumes than well logs
- 3D Velocity model to be used for surface seismic processing
- Anisotropic velocity information to focus imaging
- Outstanding structural/stratigraphic images
- Much better understanding of the dynamic processes of producing and injecting fluids and gases
  - Monitor Fracturing (Fracking) Operations
- Volumetric rock-mass stress distribution – not just a the well
- Faults & Fracture distribution and directions
- 3D Maps of diapiric salt bodies
- Type of fluids in the reservoirs:
  - Gas vs Oil vs Water vs CO_2 vs Steam
- Temperature distribution
- REAL TIME PROCESSING - allow control dynamic processes

Borehole Seismology

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

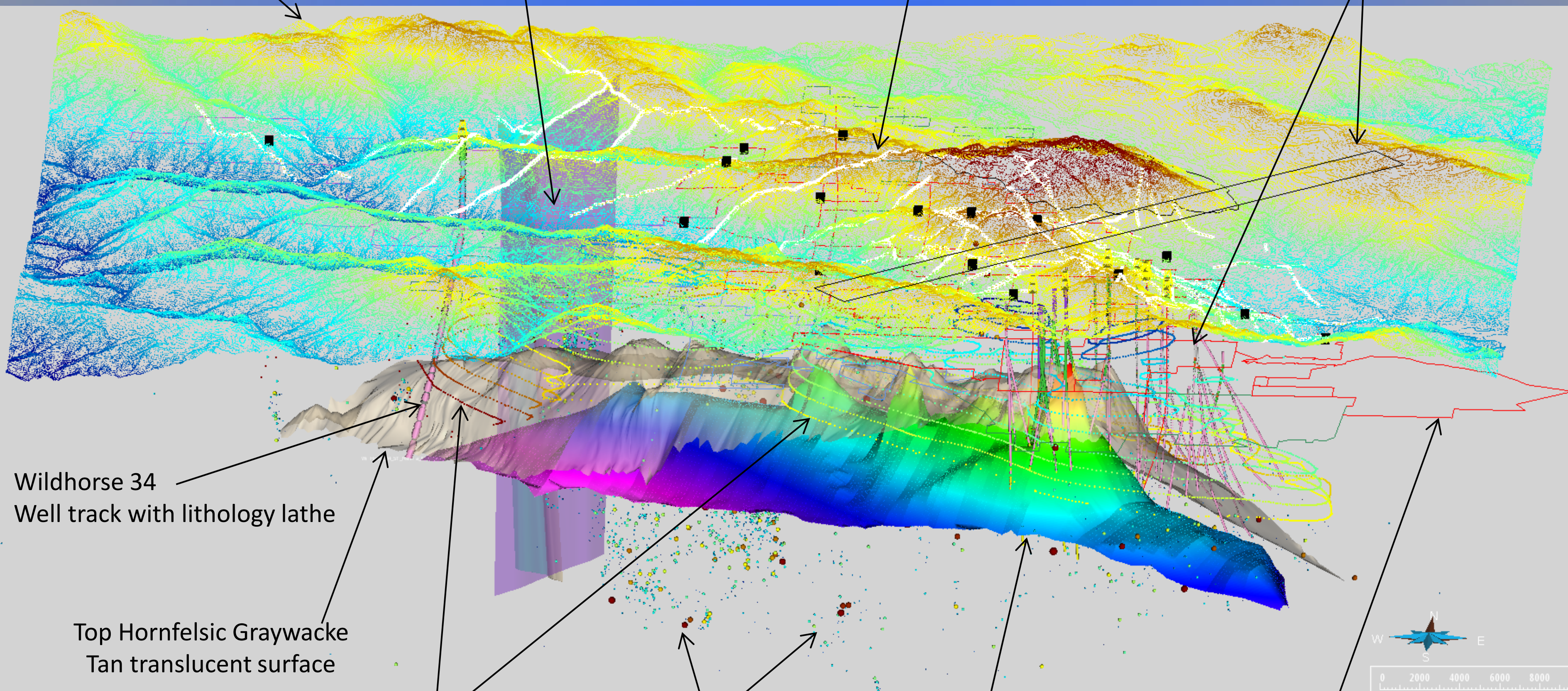
CALPINE
NYSE CPN

Preliminary fault zones
Single colored near-vertical surfaces

Topographic surface
Color scaled surface points

Mapped inactive surface faults
White lines

"Corridor" of displayed wells



Wildhorse 34
Well track with lithology lathe

Top Hornfelsic Graywacke
Tan translucent surface

Top of Steam Reservoir
Color scaled contour lines

Microseismicity
hypocenters

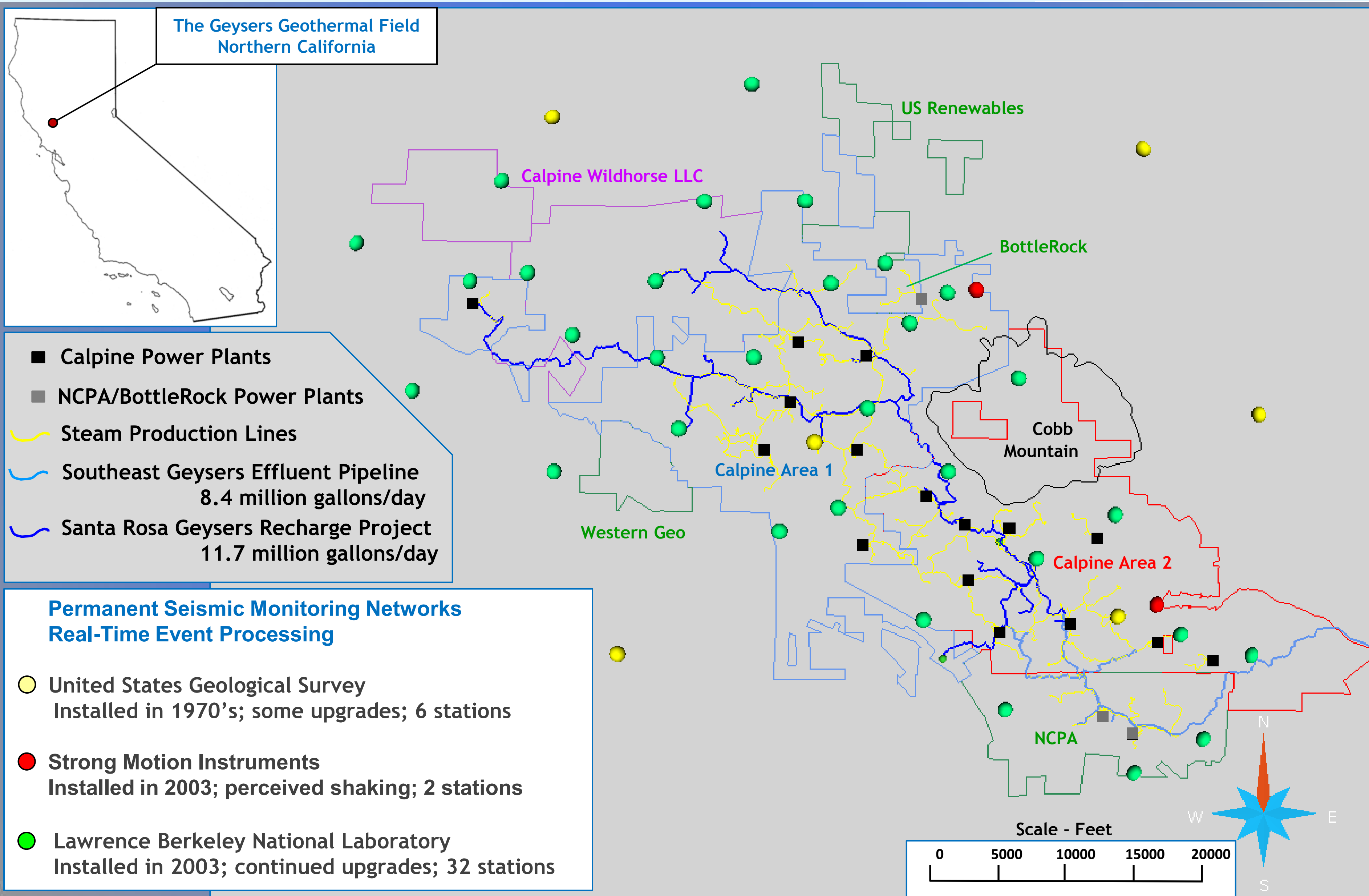
Preliminary Top Felsite
Color scaled surface

Field boundaries (at sea level)

■ Calpine Power Plants

The Geysers
Permanent Seismic Monitoring Networks

CALPINE NYSE CPN



■ Calpine Power Plants

■ NCPA/BottleRock Power Plants

Steam Production Lines

Southeast Geysers Effluent Pipeline 8.4 million gallons/day

Santa Rosa Geysers Recharge Project 11.7 million gallons/day

Permanent Seismic Monitoring Networks
Real-Time Event Processing

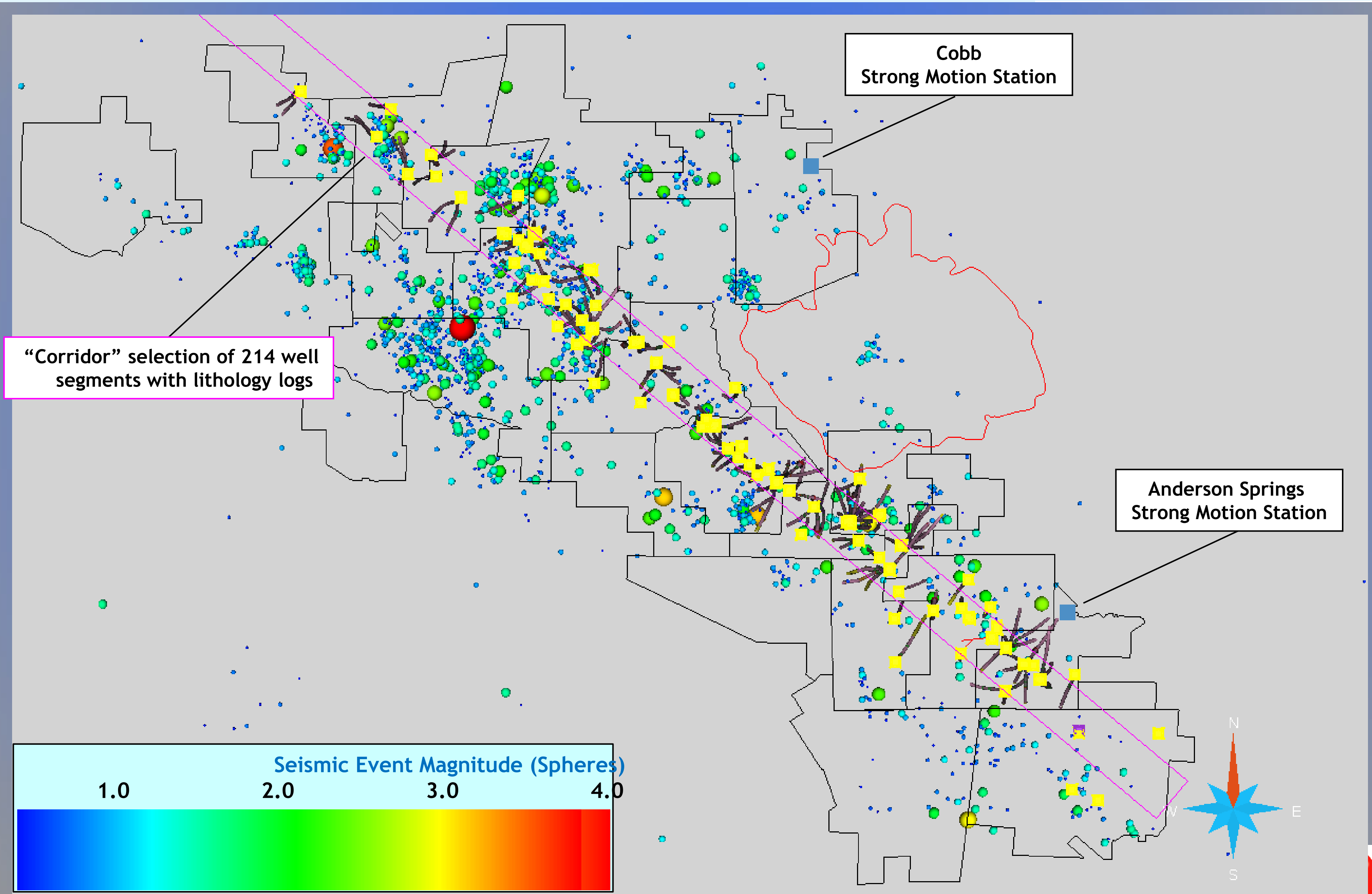
United States Geological Survey
Installed in 1970's; some upgrades; 6 stations

Strong Motion Instruments
Installed in 2003; perceived shaking; 2 stations

Lawrence Berkeley National Laboratory
Installed in 2003; continued upgrades; 32 stations

The Geysers

Field-wide Seismicity Analysis
01 October 2014 to 31 March 2014

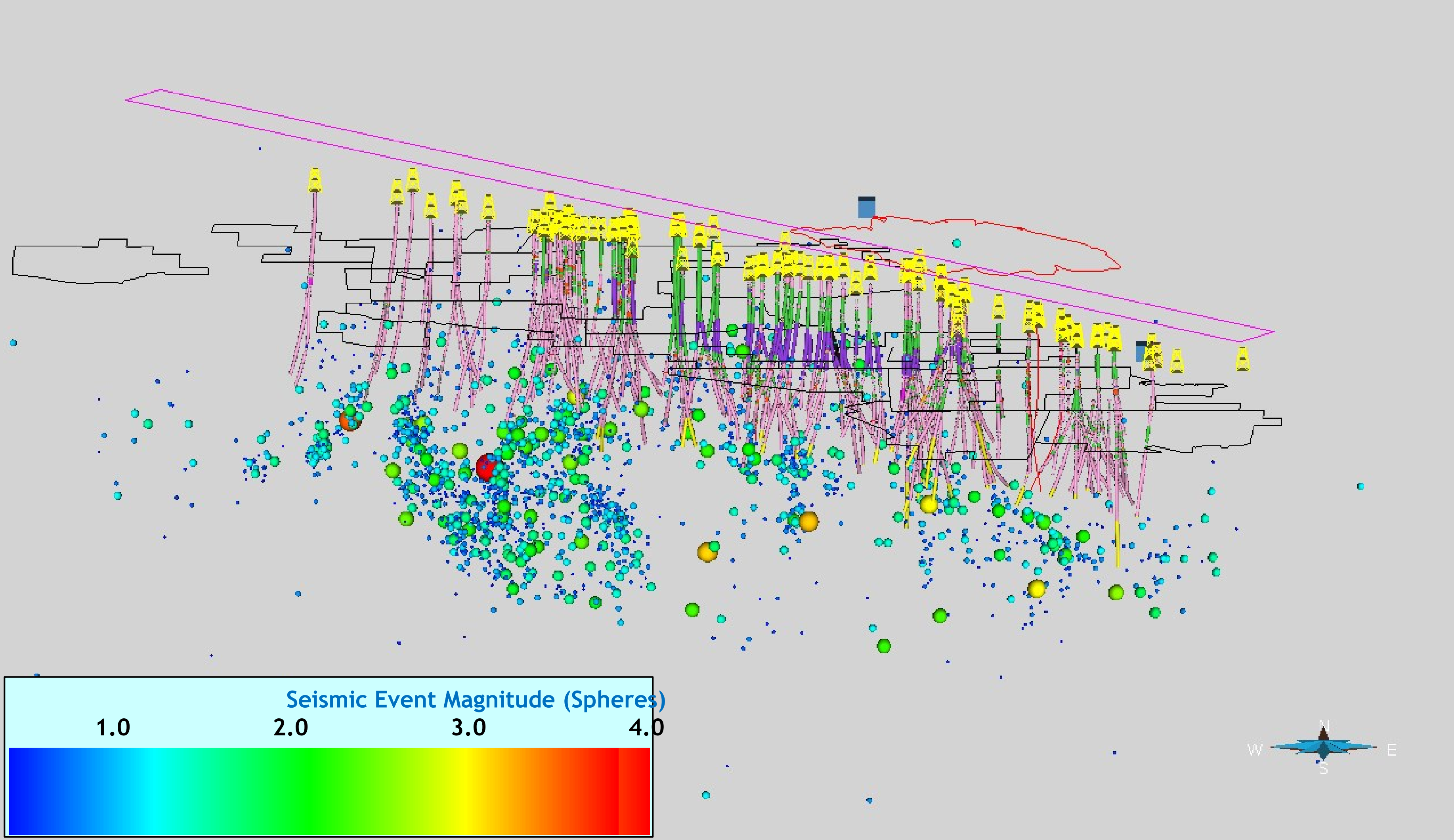


The Geysers

Field-wide Seismicity Analysis

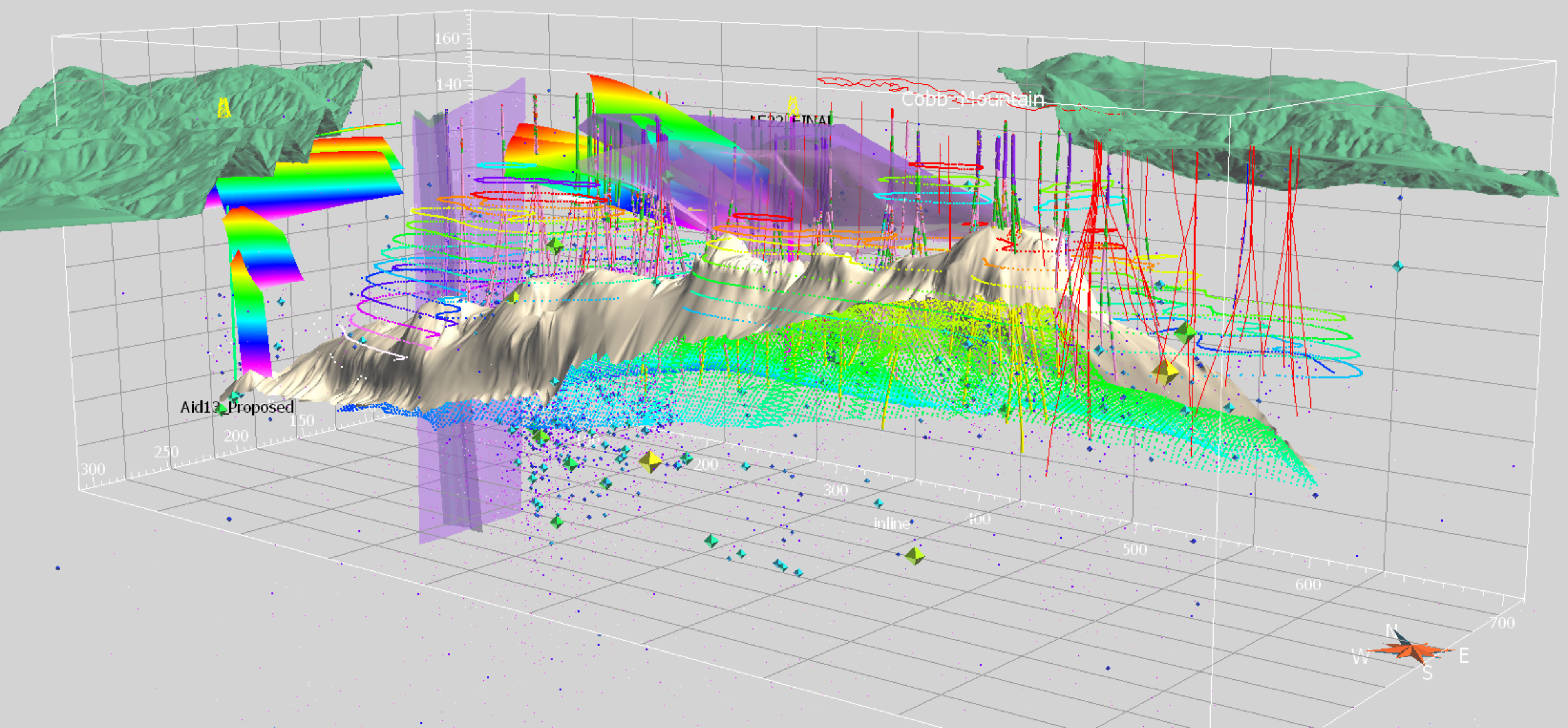
01 October 2014 to 31 March 2014

Software advances for seismicity analysis, along with 3D modeling constraints from lithology logs, surface geology, temperature logs, pressure logs, tracer analysis, heat flow and reservoir history matching are improving Calpine's ability to develop a 3D Structural Model for The Geysers.



The Geysers
3D Visualization and Model Building

The developing **3D Structural Model** (including pre-existing fault zones and fractures) will assist in understanding and potentially mitigating induced seismicity at The Geysers. **The goal is to better match water injection flow rates with local geologic conditions.**



Well Tracks 1042 segments In 3D Project	Lithology and/or Steam Entries for 839 Wells	3D Surfaces (in progress)	3D Contours Top Steam	Fieldwide Seismicity	Fault Zones (in progress)	Well Planning Aidlin-13	Real-Time Drilling Assessment LF-22

Borehole Seismic Survey Expectations

Calpine, the operator The Geysers Geothermal field needs:

- **Improved Micro Seismic locations with improved signal/noise ratios**
- **Refined understanding of the physical mechanisms of faulting**
- **Improved subsurface imaging with multi-level high-temperature tolerant fiber-optical sensors**
- **Apply improved hypocenter determination and improved imaging to refinements of our 3D structural model**
- **Refine our understanding of fault zones and fractures**
- **Develop improved models for fluid flow and fluid boundaries**
- **Mitigate seismicity at The Geysers to the degree possible, based on a better understanding of fault mechanisms and fluid flow**

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Borehole Seismology

- Large Seismic Array Technology
- Fiber Optic Seismic Sensors
- Acoustic Micro Emitters
- Geothermal Applications
- Offshore Applications

DeepStar Project

Improved Imaging of Offshore GOM using 3D VSP

SEAM GOM Model VSP Survey

General:

- Acquisition parameters – Elastic 15 km by 8 km grid shot set
- Velocity Model: Isotropic

Sources:

- Source grid centered on East 11200 m, North 23900 m
- SP interval: 100 m
- Grid size: 15 km EW by 8 km NS
- Number of SPs: 12,231 (151 EW by 81 NS)
- Grid location: East 3700 to 18700 m, North 19900 to 27900 m
- Source Depth: 15 m
- Source Bandwidth: 1 – 30 Hz

Receivers:

- VSP 4 Components: pressure, acceleration in vertical, east, north
- **Receiver levels: 467 in each well**
- Receiver depth range: 1000 to 7990 m
- Receiver interval: 15 m
- Well Locations:
  - Well 1: East 10075 m North 23900 m
  - Well 2: East 12025 m North 23900 m
  - Well 3: East 15025 m North 23900 m
  - Well 5: East 15025 m North 22900 m
- Record length: 16.0 seconds
- Sample interval: 8 milliseconds/sample, Nyquist = 62.5 Hz

SEAM GOM Model VSP Survey

General:

Acquisition parms – Elastic 15 km x 8 km grid

Velocity Model: Isotropic

Sources:

SP interval: 100 m

Grid size: 15 km EW by 8 km NS

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Receivers:

VSP 4 C: pressure, 3C acceleration sensors

Receiver levels: 467 in each well

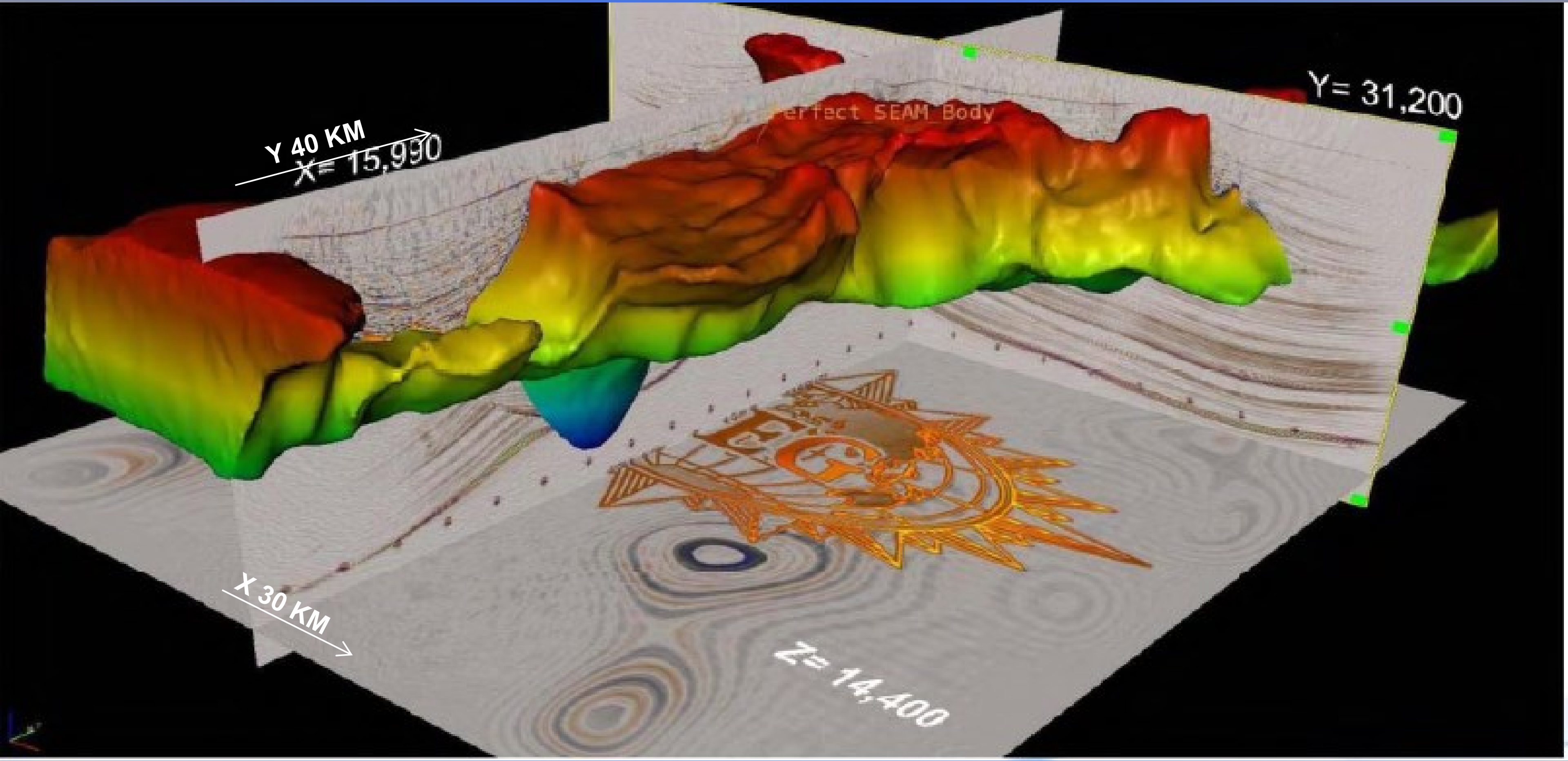
Receiver depth range: 1,000 to 7,990 m

Receiver interval: 15 m

Record length: 16.0 seconds

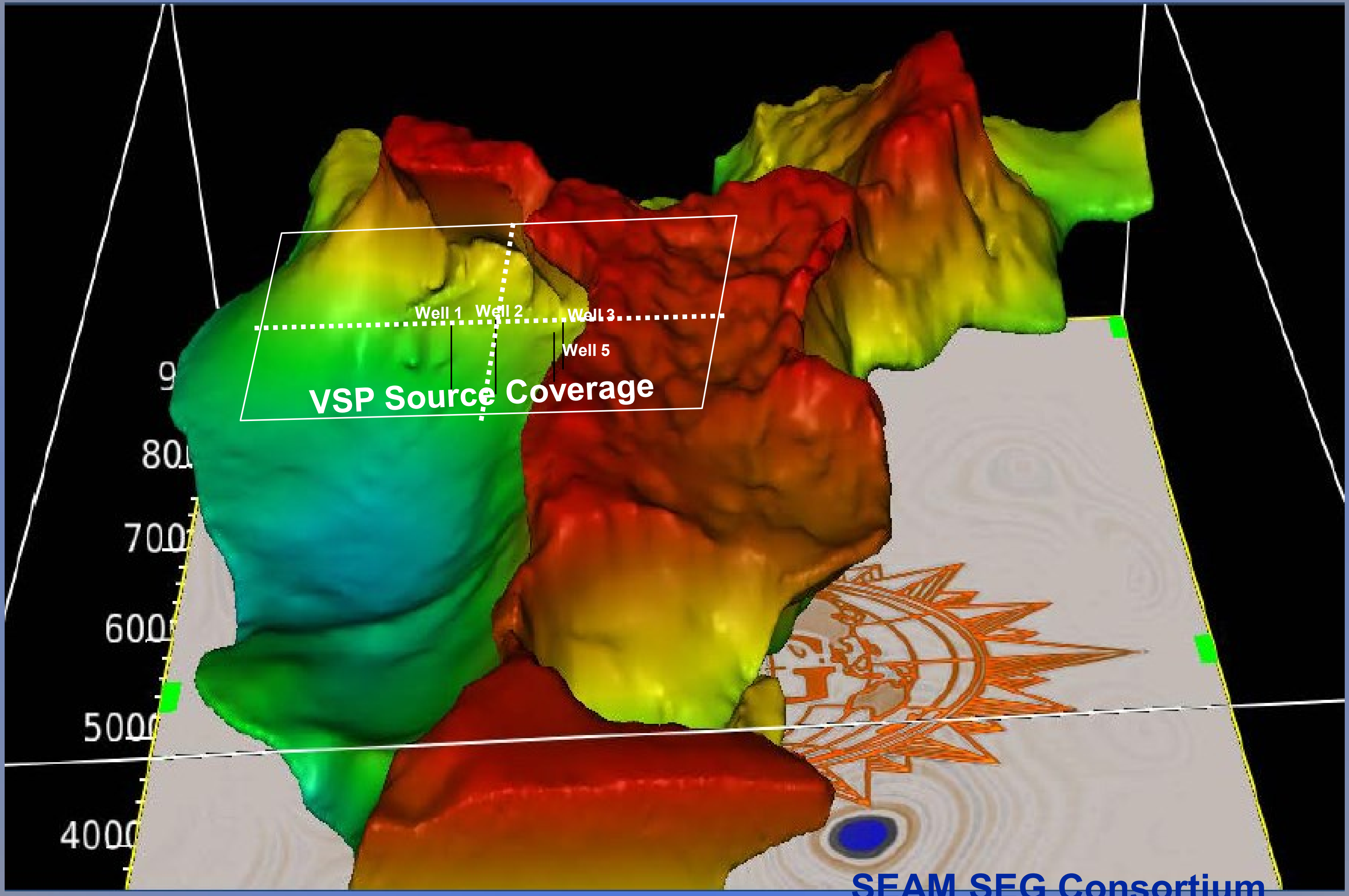
Sample interval: 8 msec., Nyquist = 62.5 Hz

High Resolution GOM Earth Model
40 x 30 x 15 km

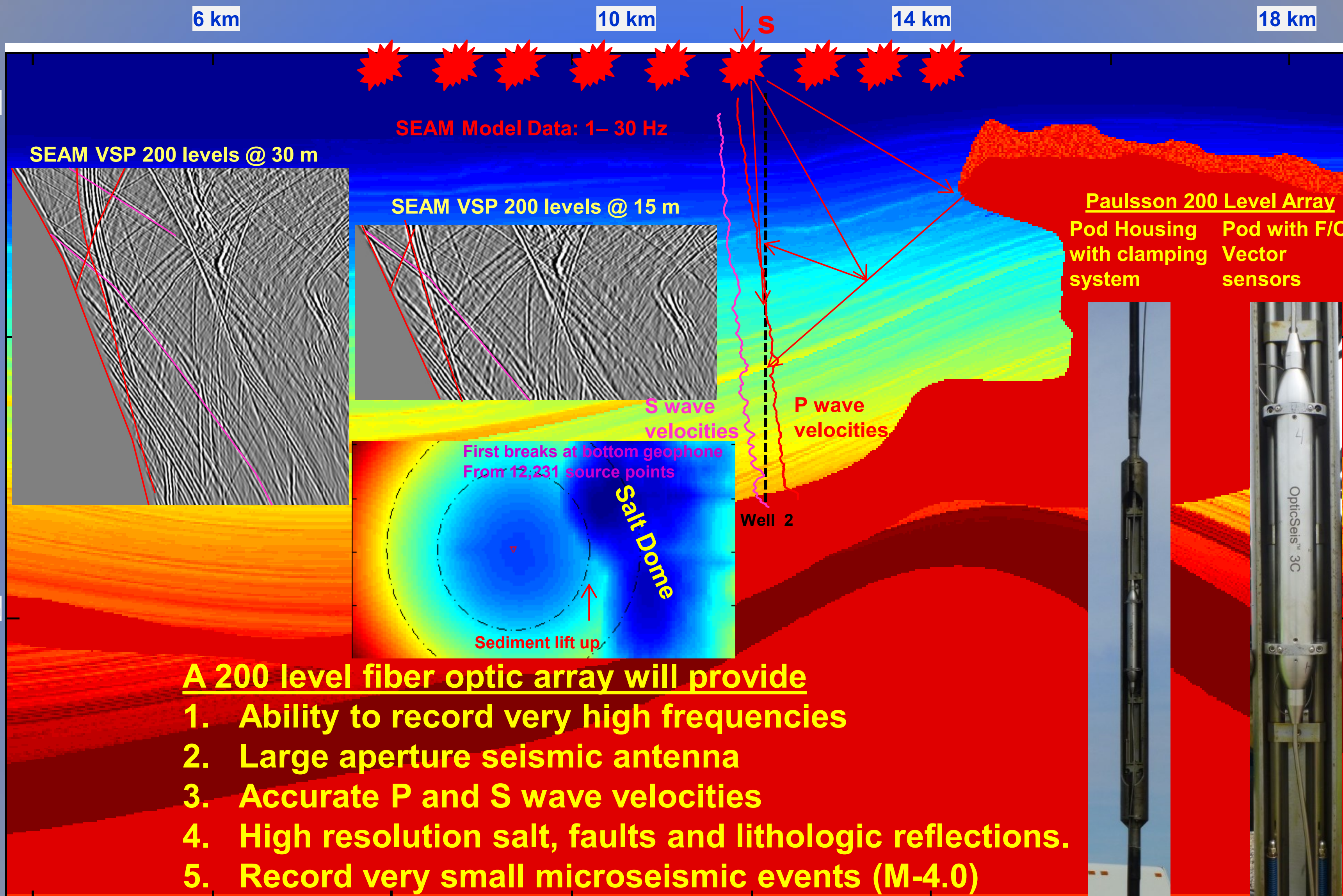


SEAM SEG Consortium

High Resolution Earth Model – close-up view



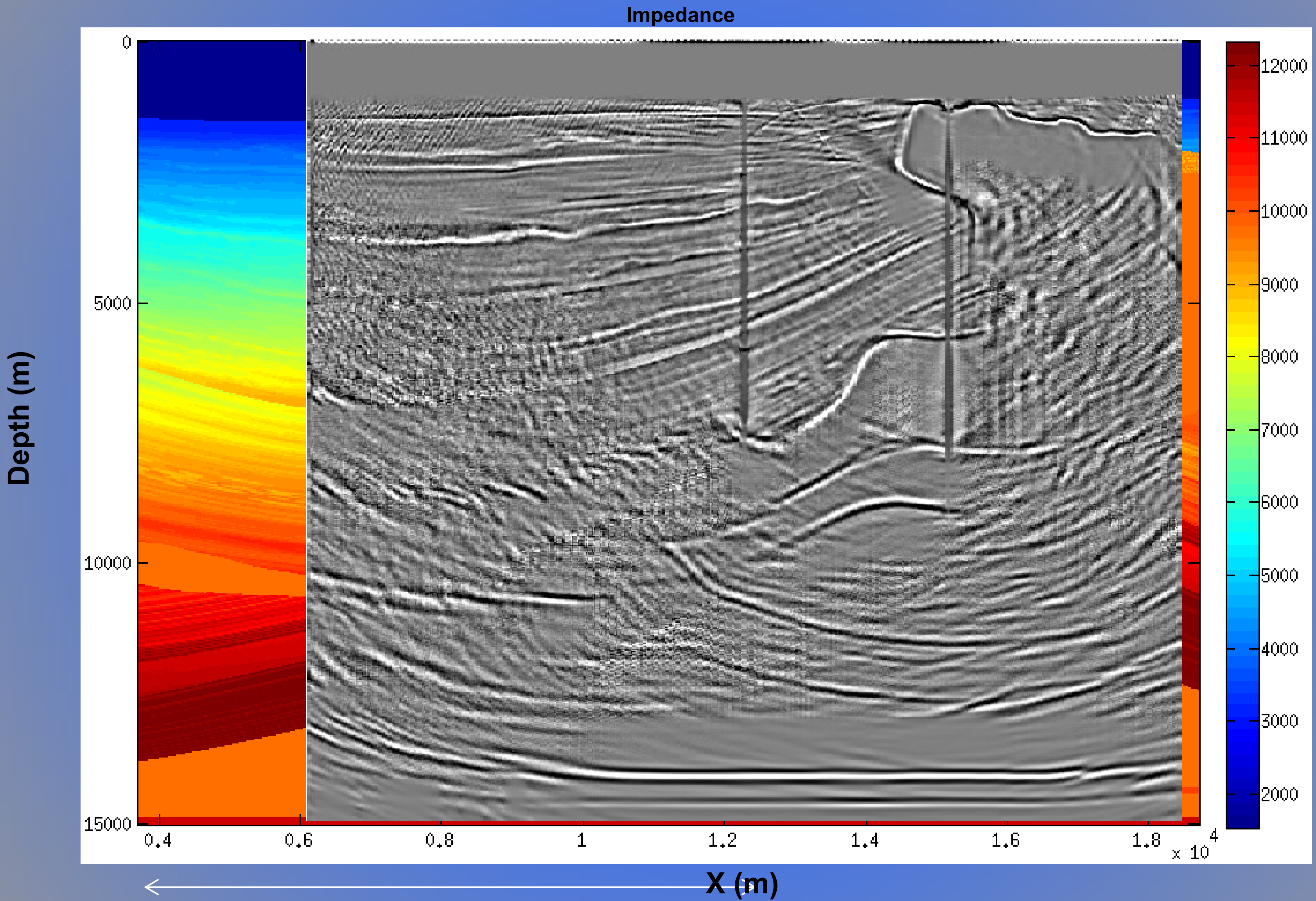
200 Level Fiber Optic VSP Tool and 3D VSP Data



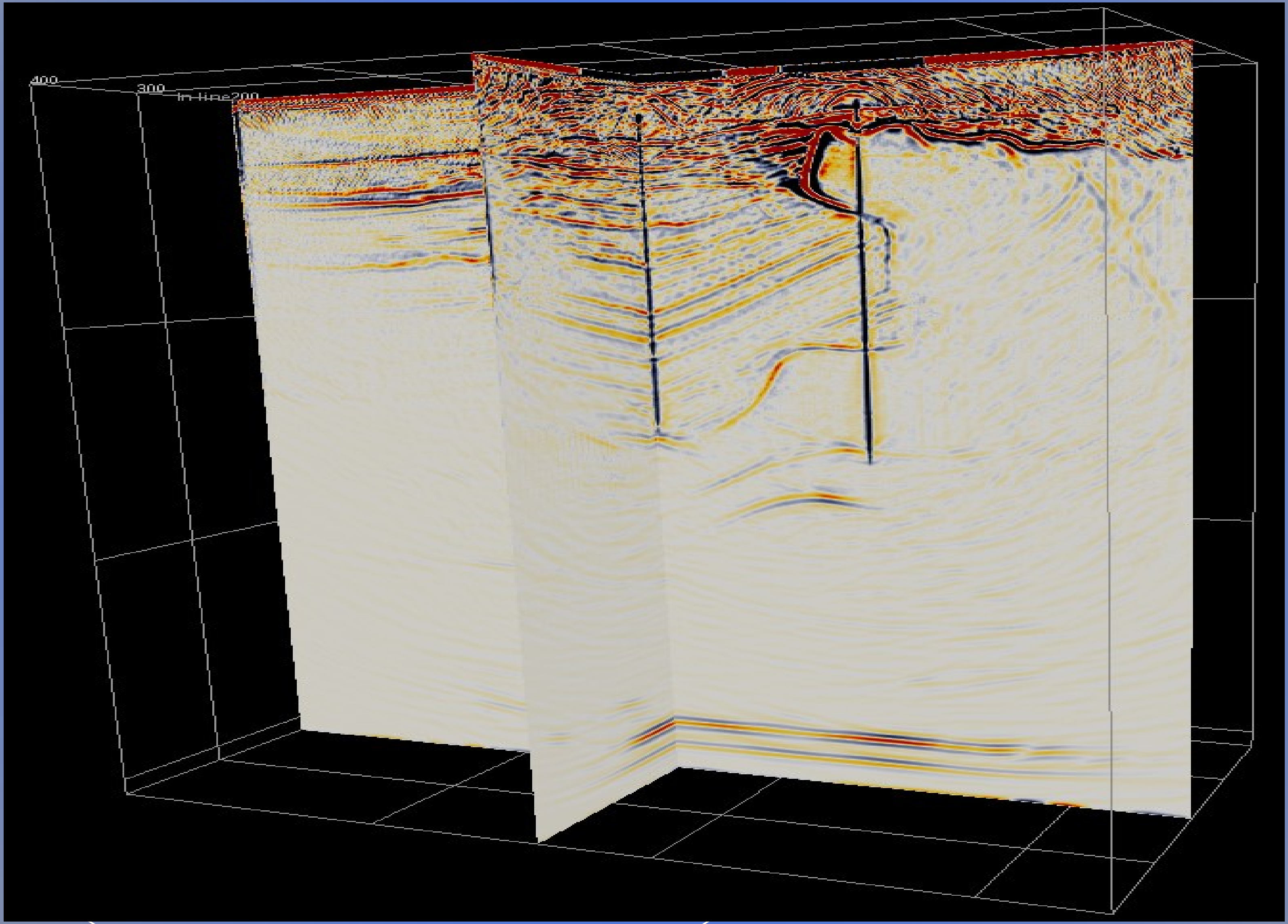
A 200 level fiber optic array will provide

1. Ability to record very high frequencies
2. Large aperture seismic antenna
3. Accurate P and S wave velocities
4. High resolution salt, faults and lithologic reflections.
5. Record very small microseismic events (M-4.0)

RTM Inline Well 2 & 3



VSP RTM Well 2 & 3



Offshore 3D VSP Summary

- Surface Seismic Images contain today about 10 - 15 Hz
- Long Array Borehole Seismic
  - Will Record 80 – 120 Hz
  - Will Allow Building a Much Better Velocity Model

Acknowledgement

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Thank You!

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