Development of a 1,000 Level 3C Fiber Optic Borehole Seismic Receiver Array Applied to Carbon Sequestration

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U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the Infrastructure for CO_2 Storage

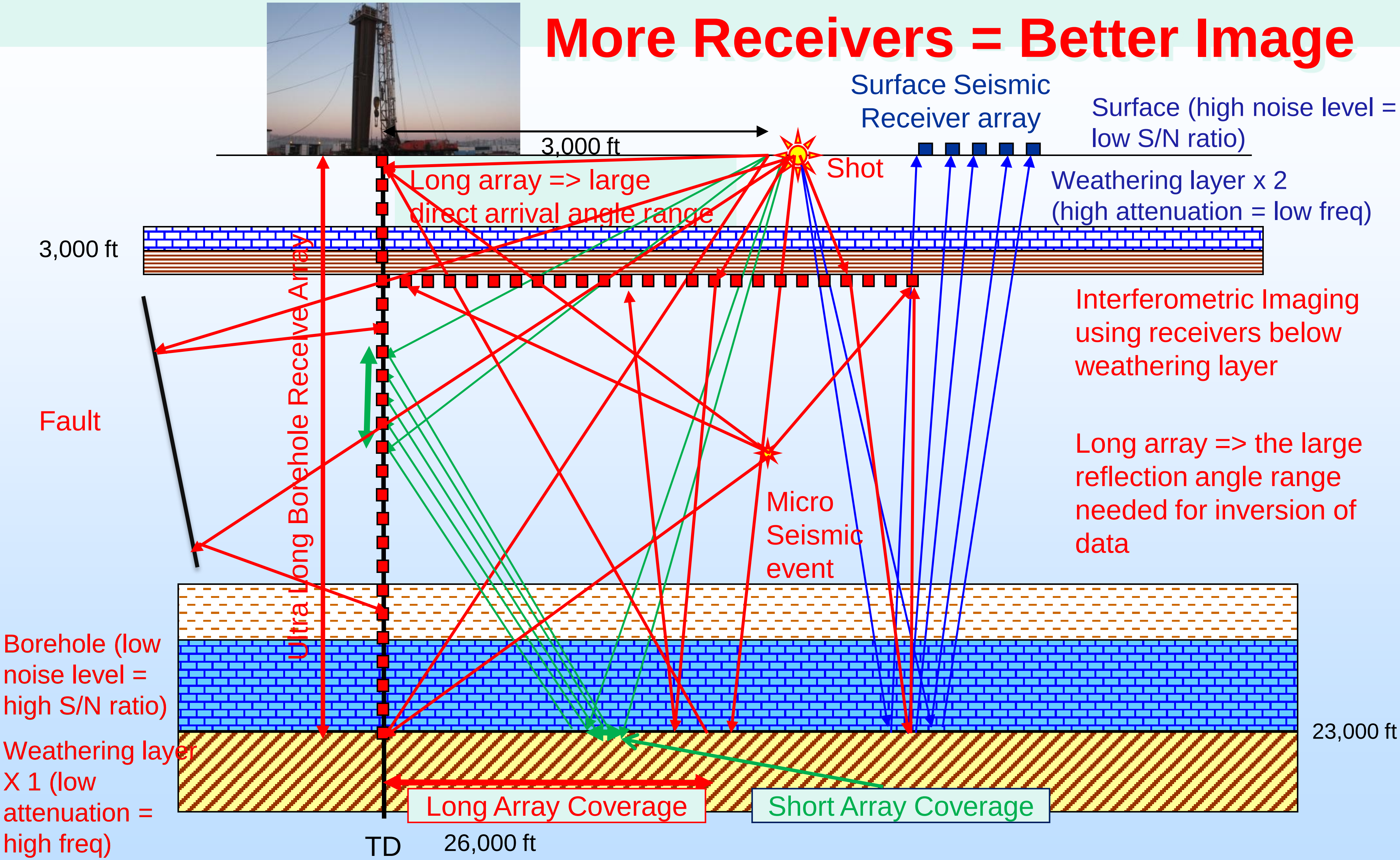
August 21-23, 2012

Project Overview: Goals and Objectives

- **Goals:** Design, build, and test a high performance borehole seismic receiver system to allow cost effective geologic Carbon Capture and Storage (CCS)
- **Objectives: A:** Develop technology to allow deployment of a 1,000 level drill pipe deployed 3C Fiber Optic Geophone (FOG) receiver array for deep boreholes. **B:** Build a 150 level 3C 15,000 ft long prototype system. Test the prototype system, and conduct a borehole seismic survey at a Carbon Capture and Storage site with the fiber optic borehole seismic prototype system

Borehole Seismic Imaging with ultra long arrays

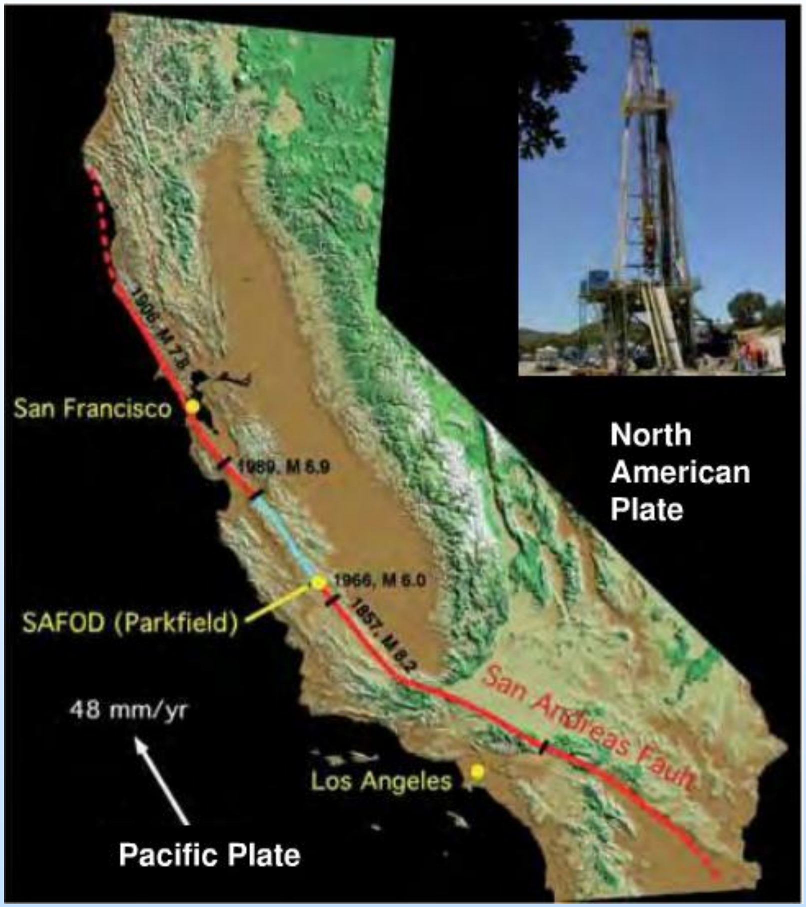
More Receivers = Better Image



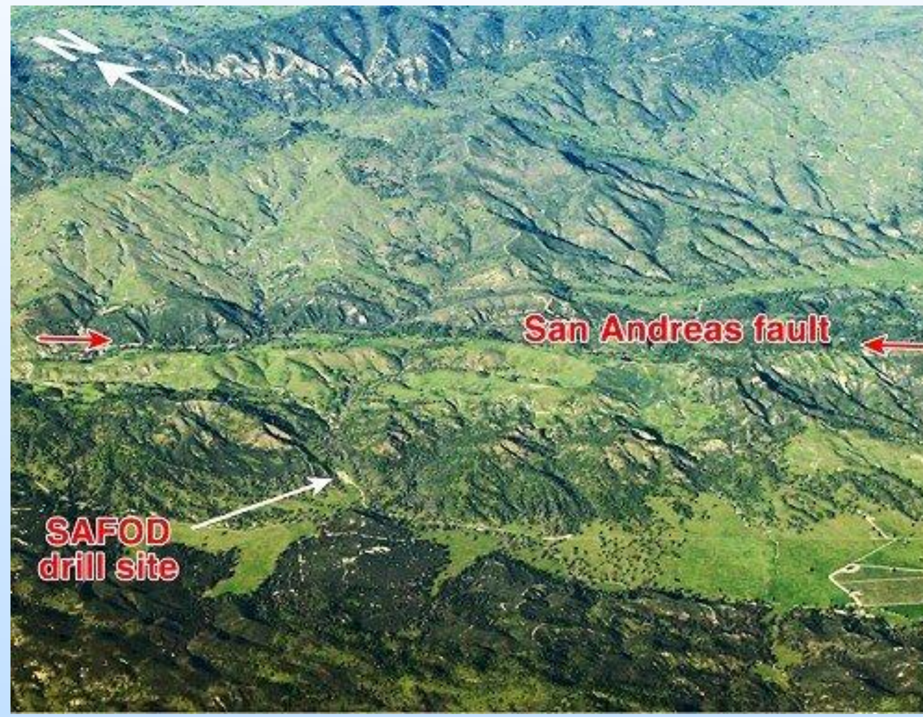
Micro Seismic – a closer look!

Examples of Fault Imaging using Borehole Seismology

SAFOD Survey Site – Parkfield, California

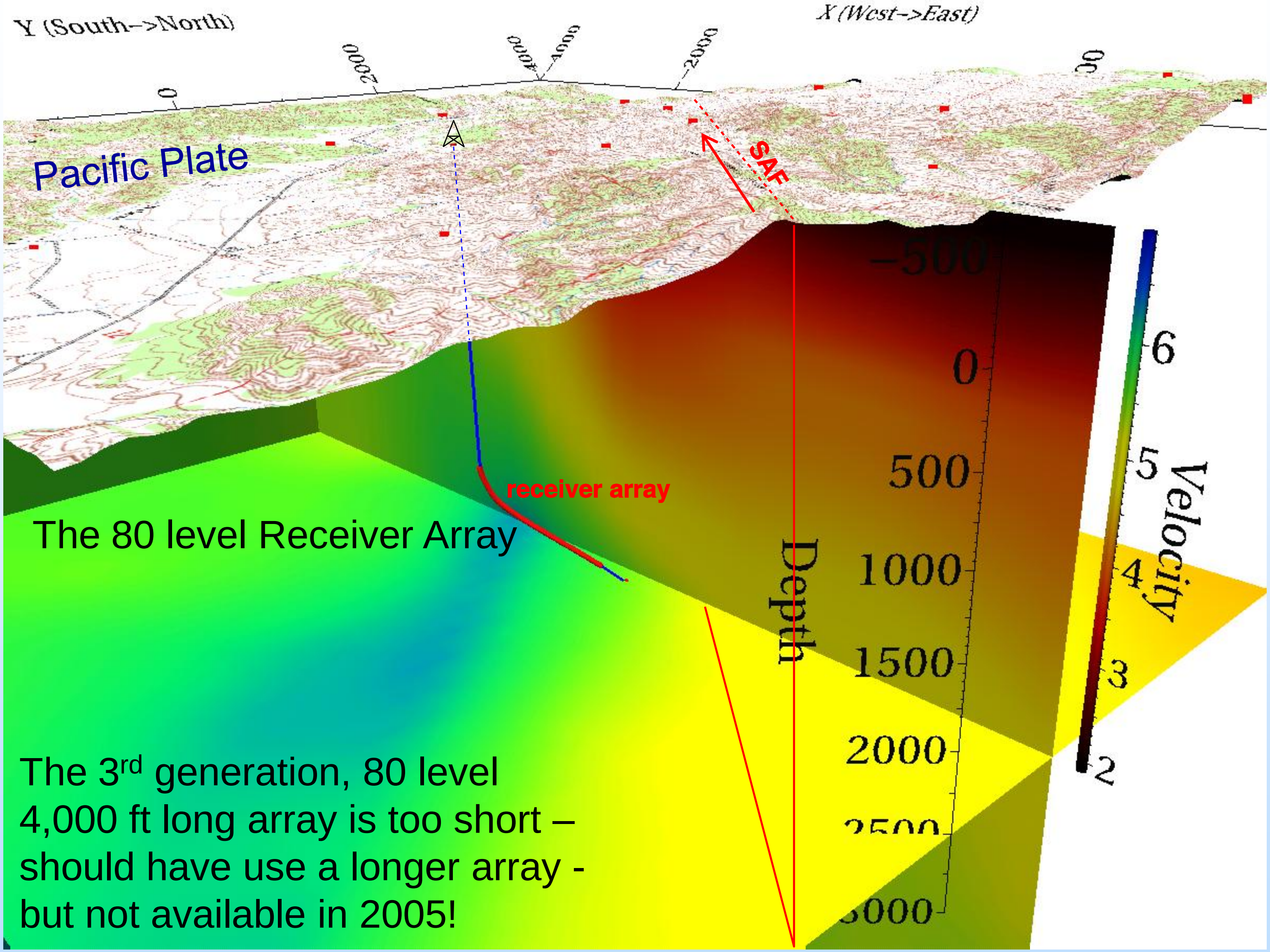


Zoback (2006)



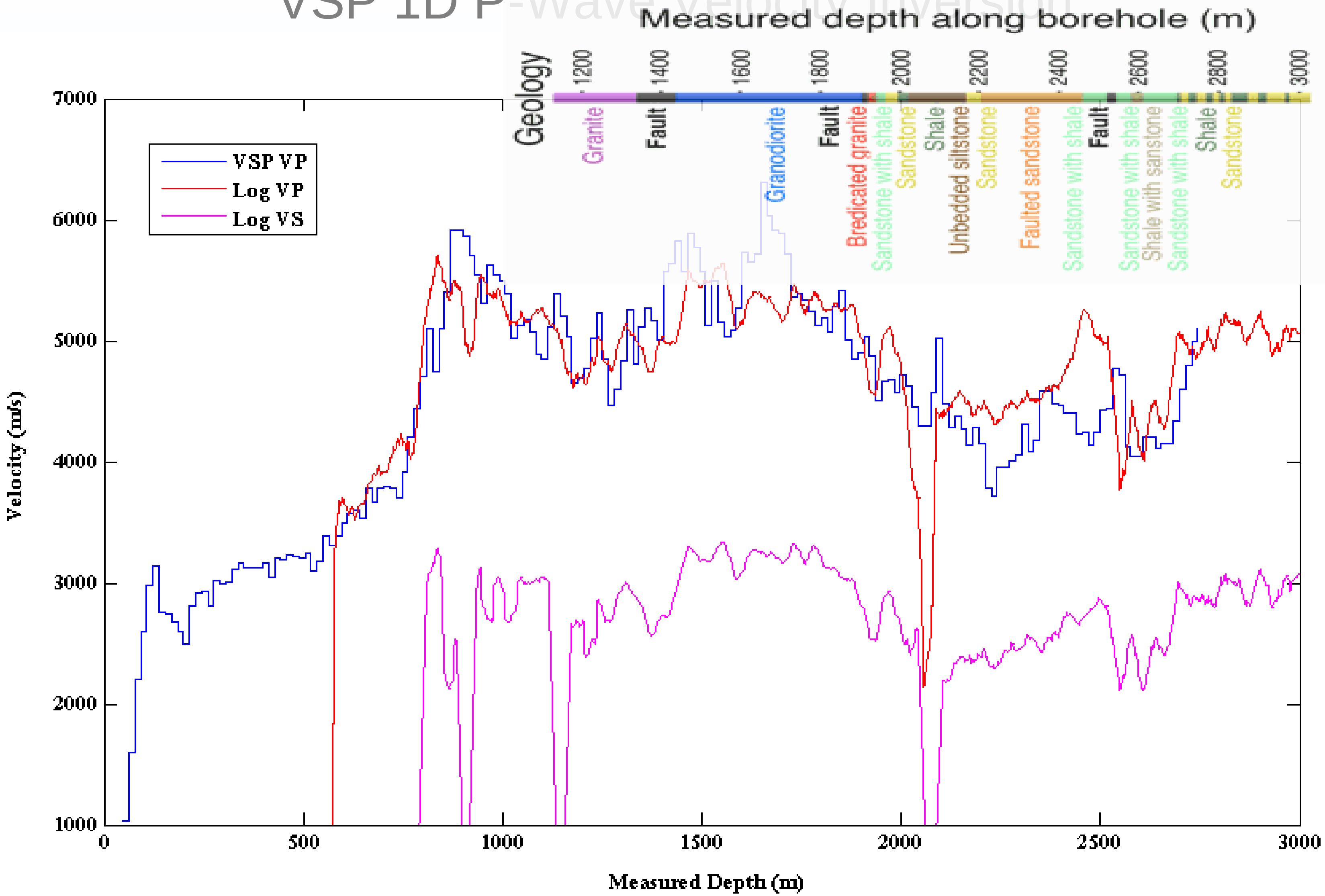
Alden (2009)

San Andreas Fault Survey Site – Parkfield, California

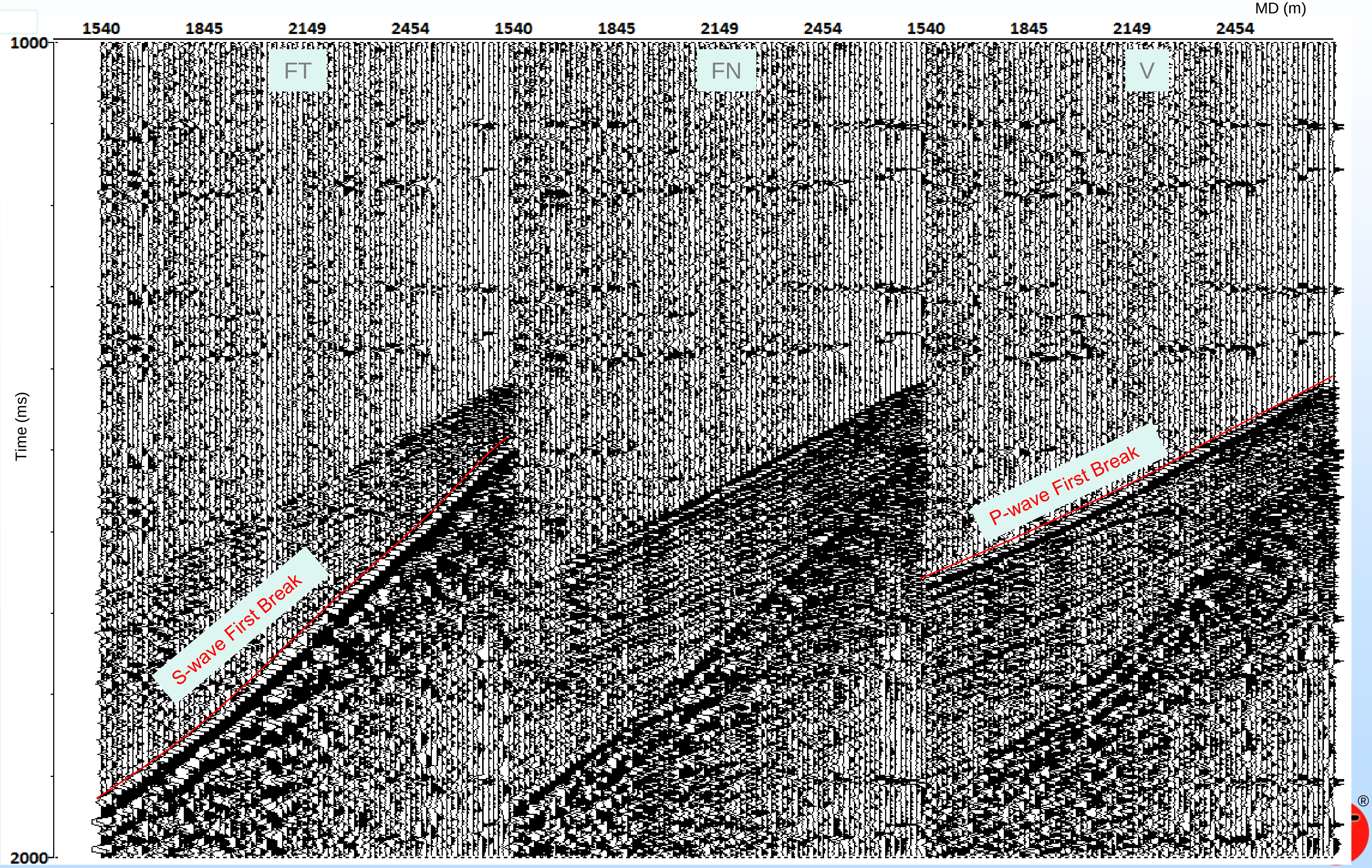


USGS 2005

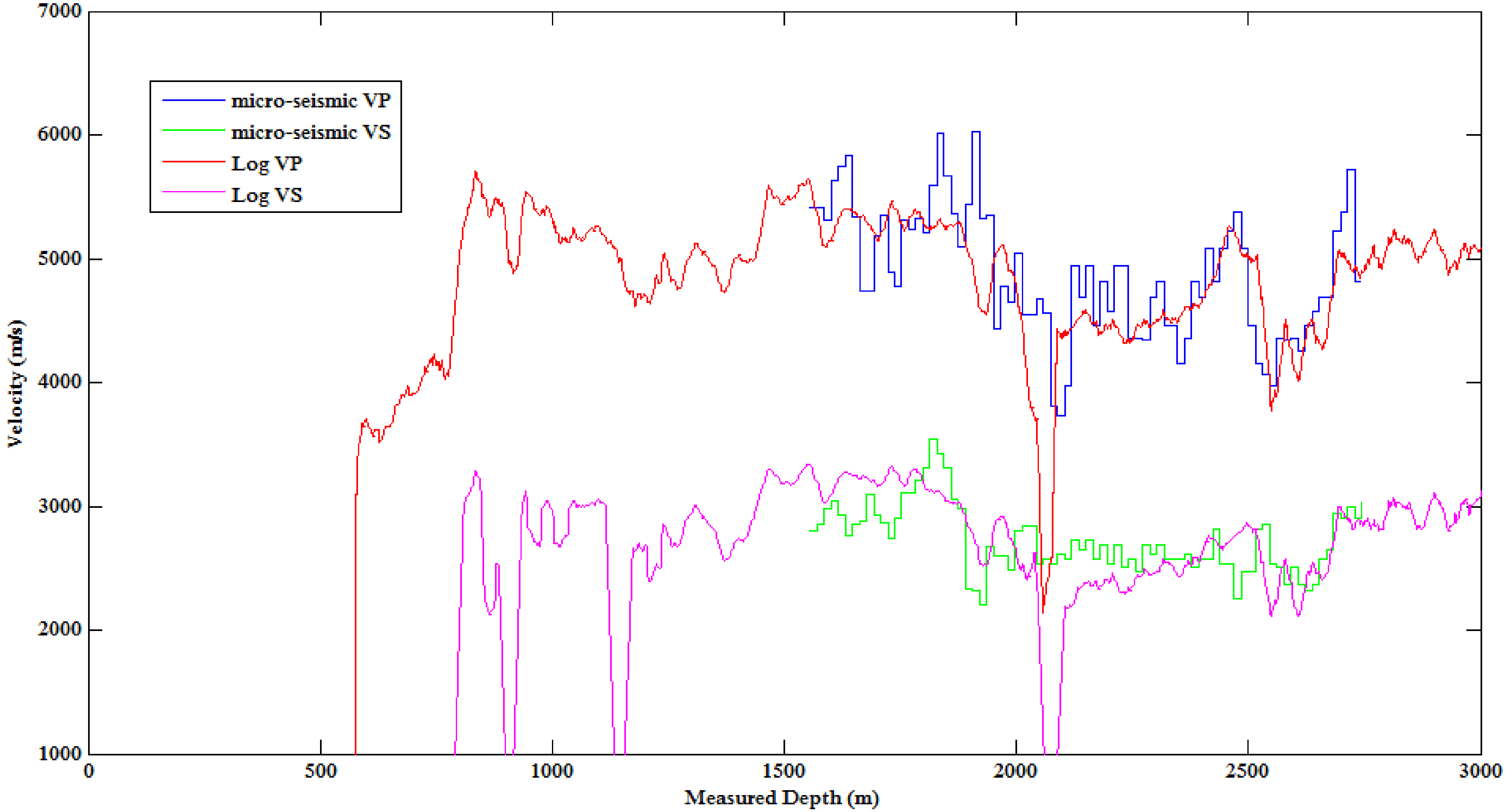
VSP 1D P-Wave Velocity Inversion



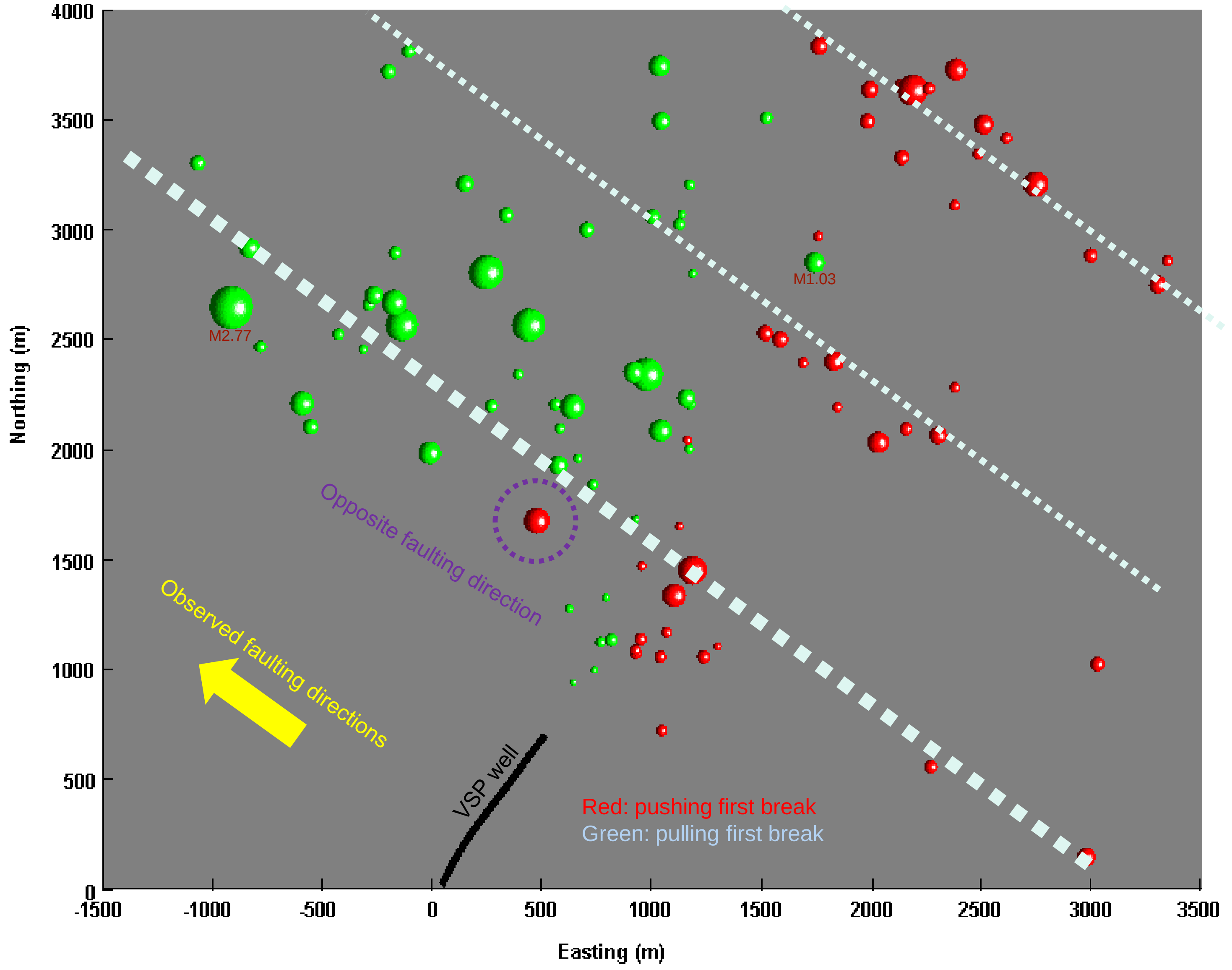
A "Zero Offset" Micro Seismic Event Recorded on a Paulsson 3rd Generation Borehole Seismic Array



•P and S Wave Velocity Inversions using Micro-seismic Data:
•This is only possible with an Ultra Long Borehole Seismic Array



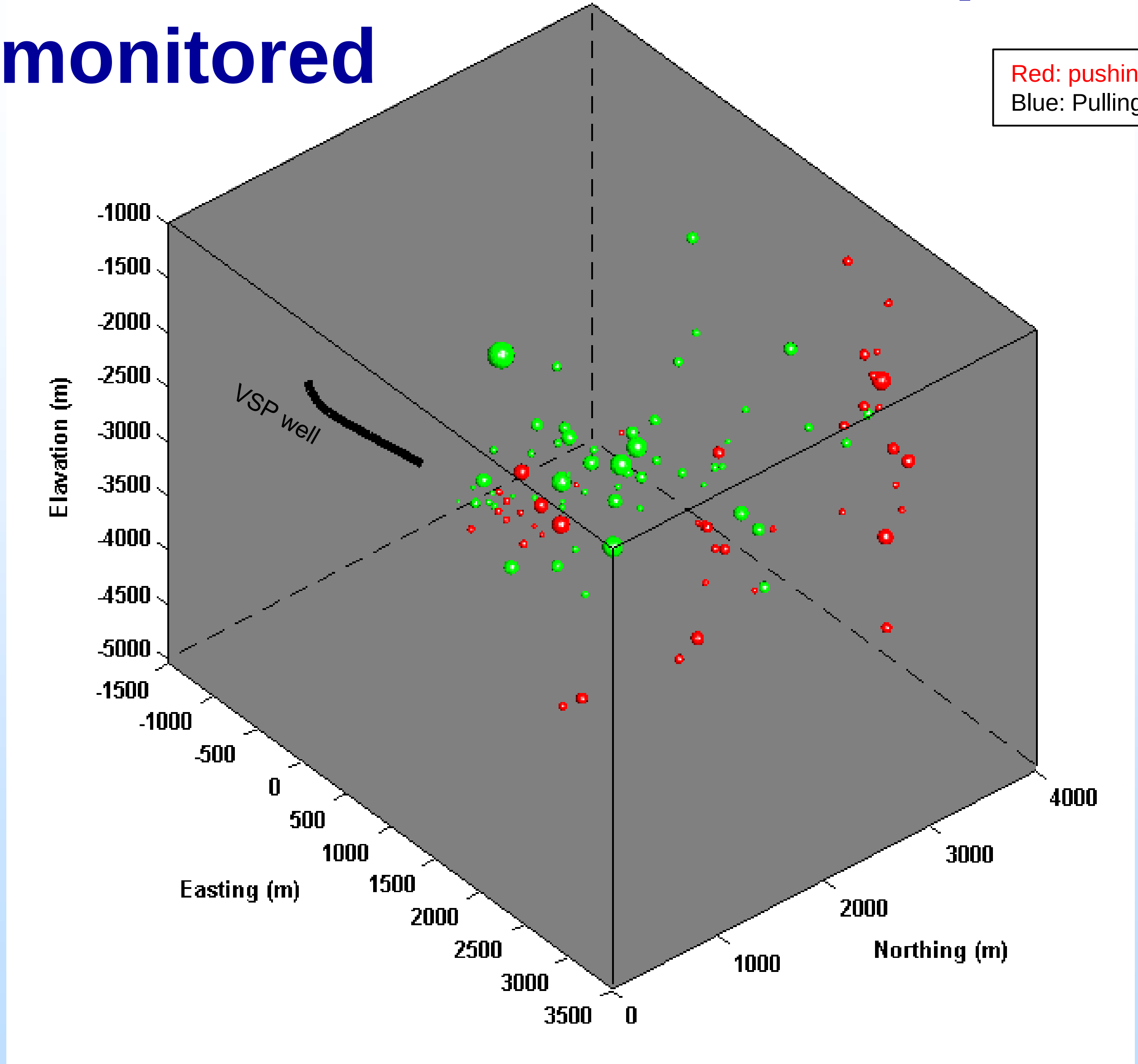
Micro-Seismic Source Locations (Top View). Data from the 3rd Gen Paulsson Borehole Seismic Array



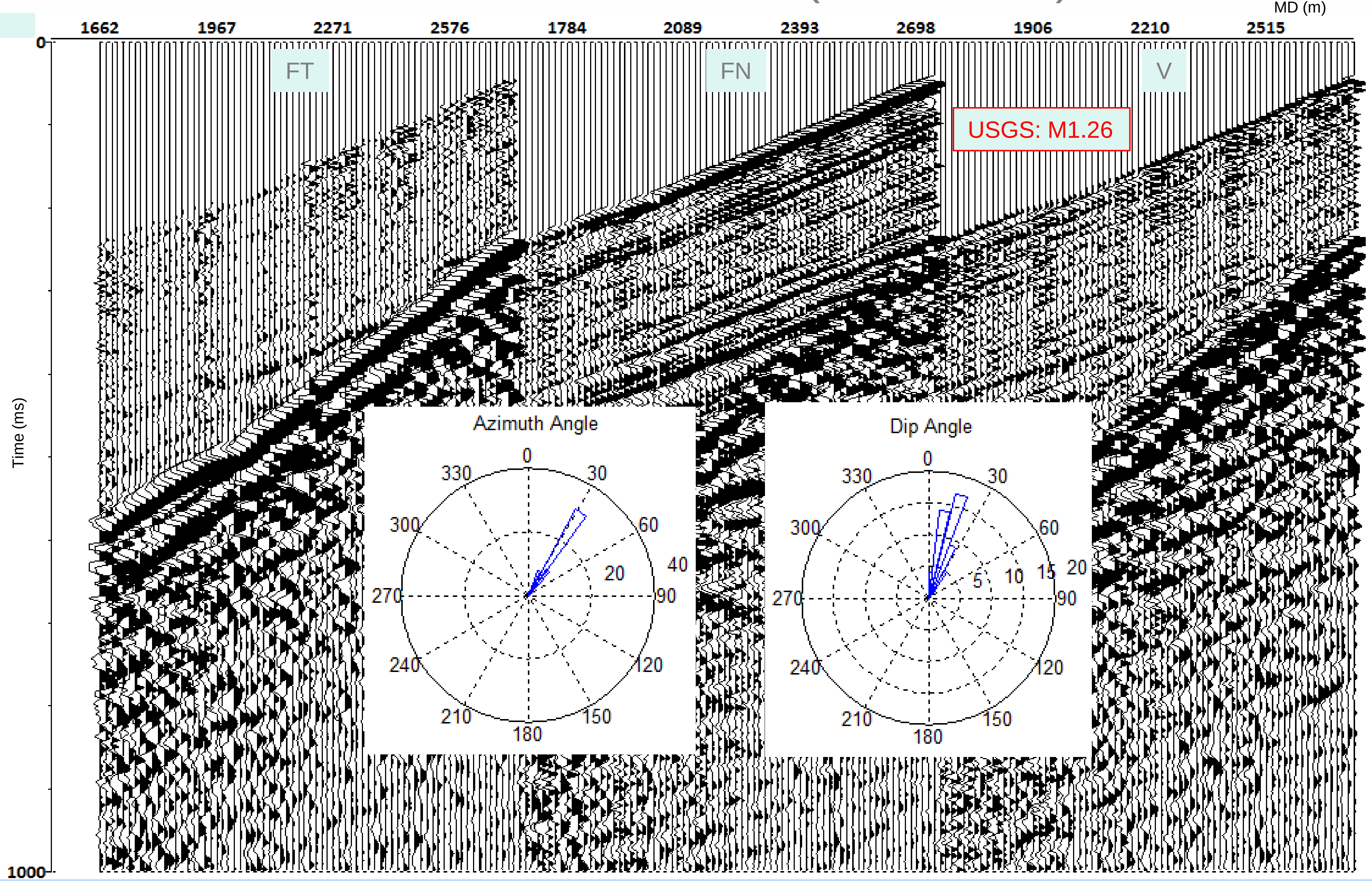
Micro-Seismic Source Locations (3D View)

80 km^3 monitored

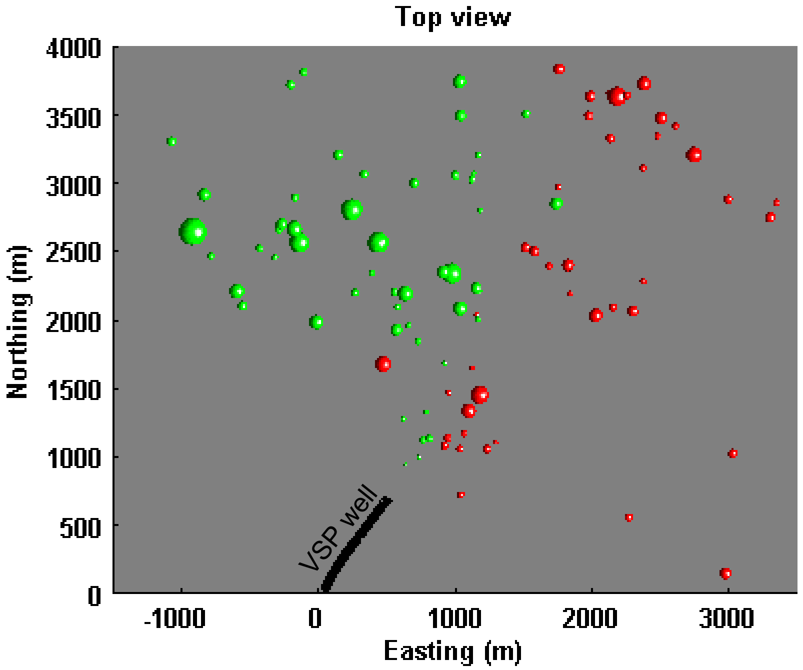
Red: pushing first break
Blue: Pulling first break

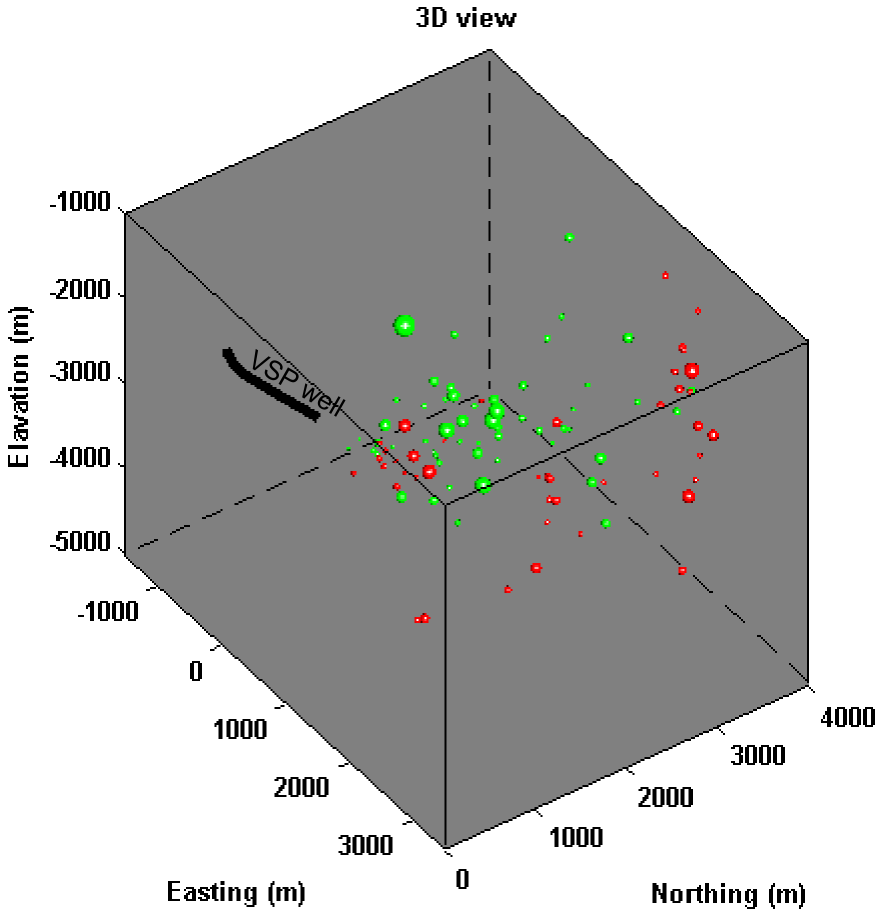


A Micro-Seismic Event (5/1/2005 19:27)

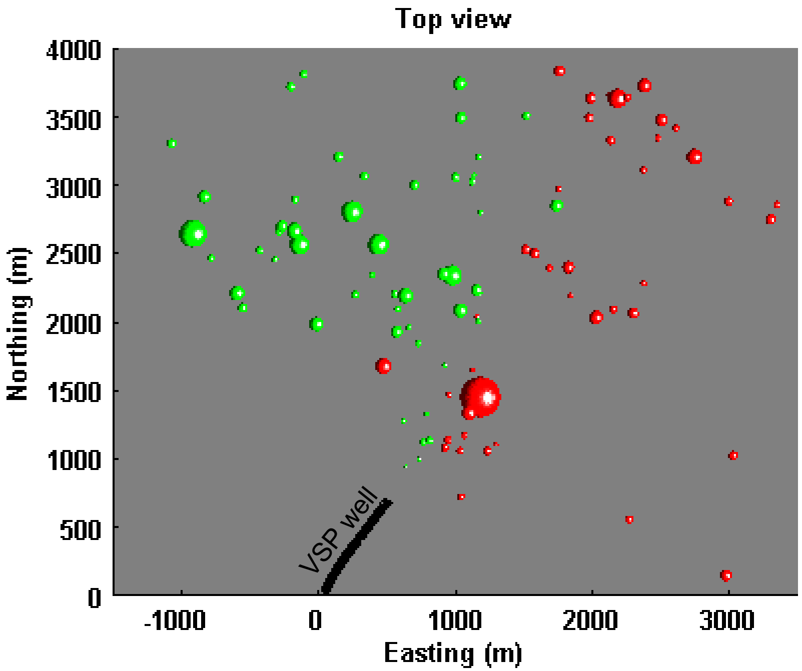


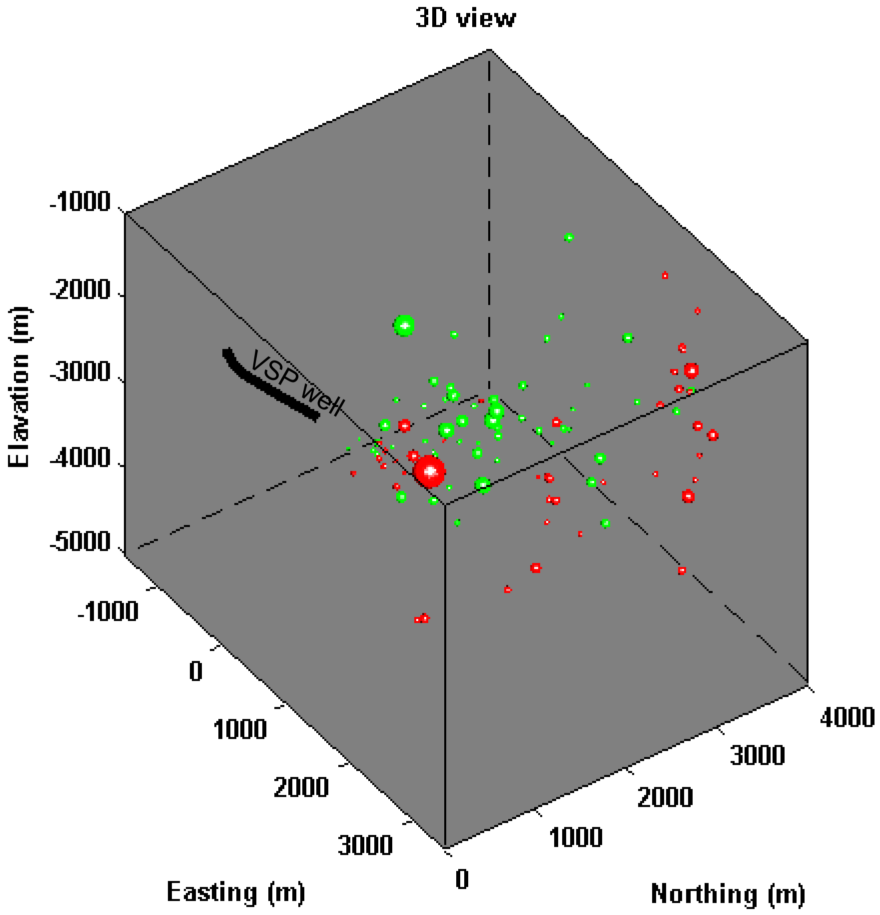
Micro-Seismic Source Locations



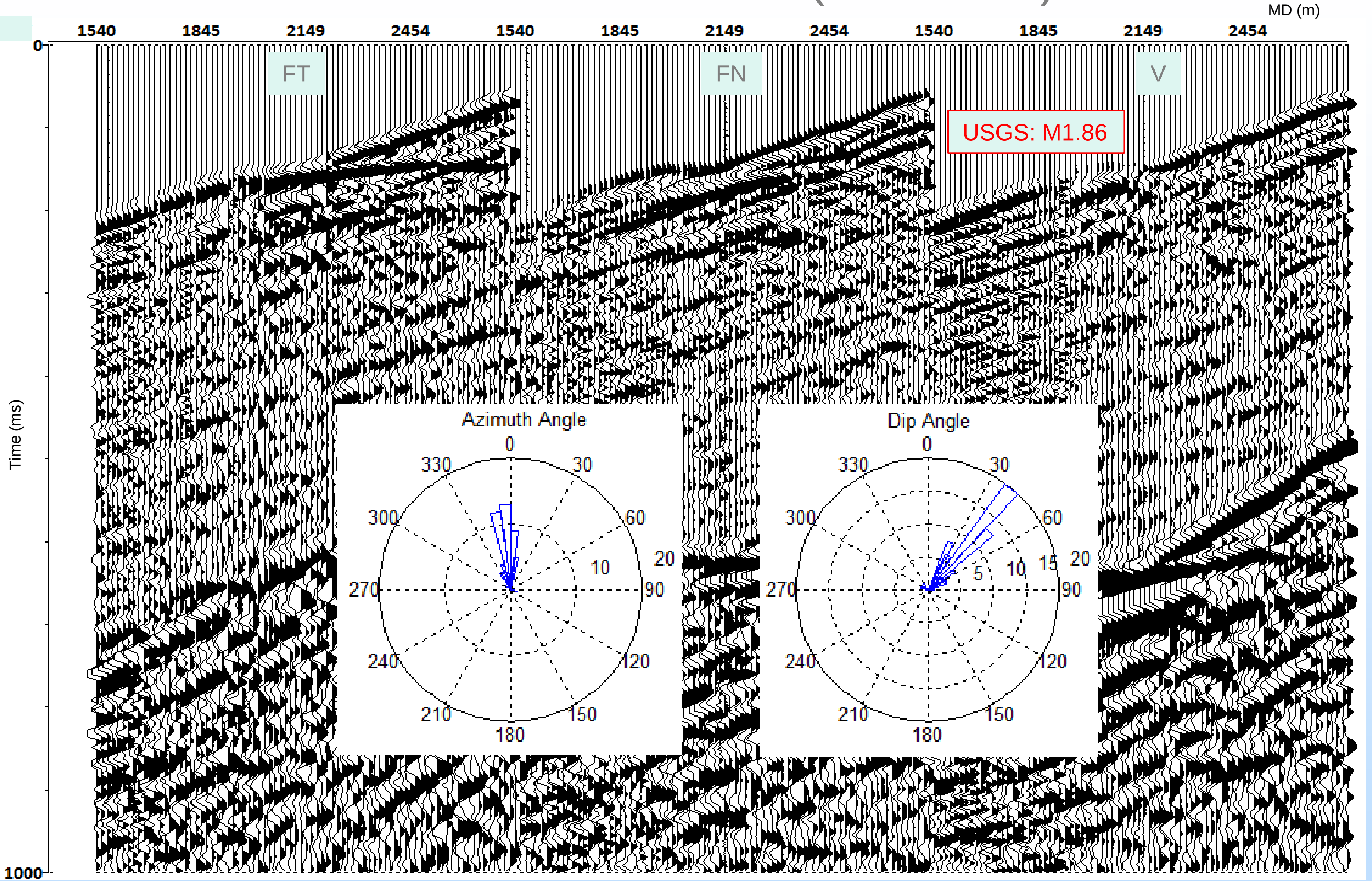


Micro-Seismic Source Locations

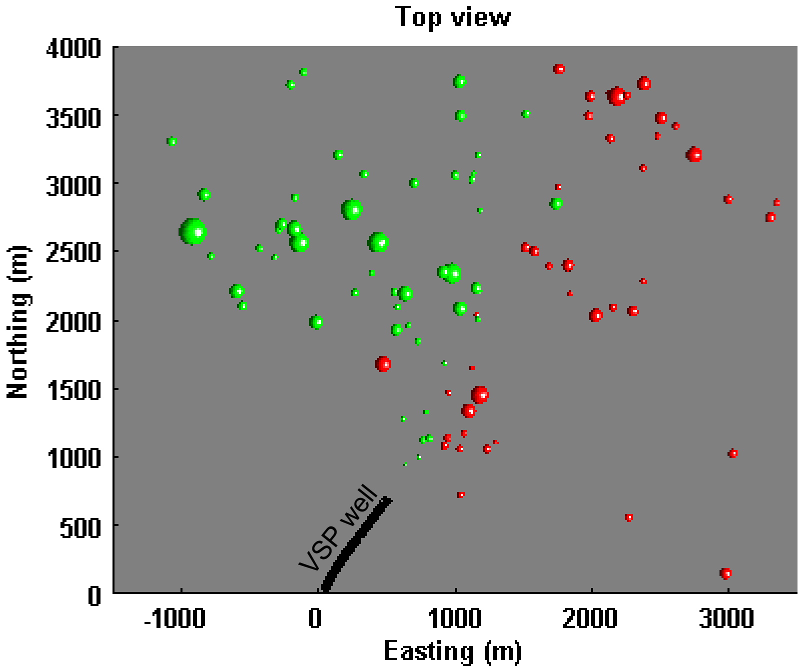


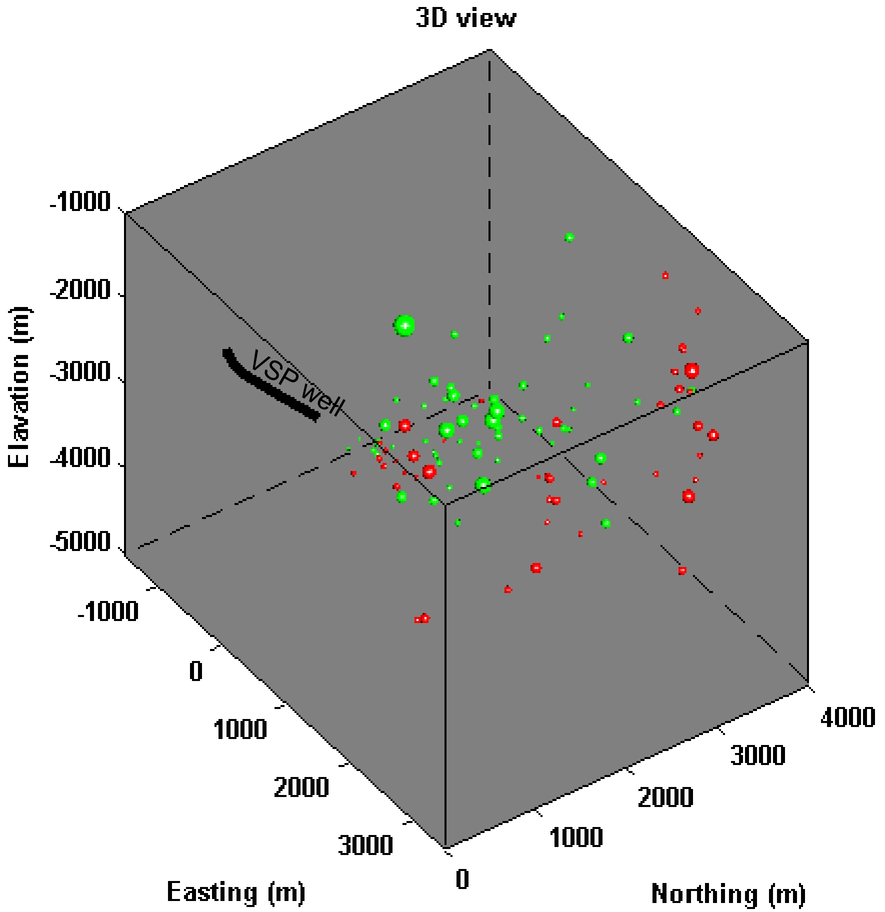


A Micro-Seismic Event (5/4/2005 9:23)

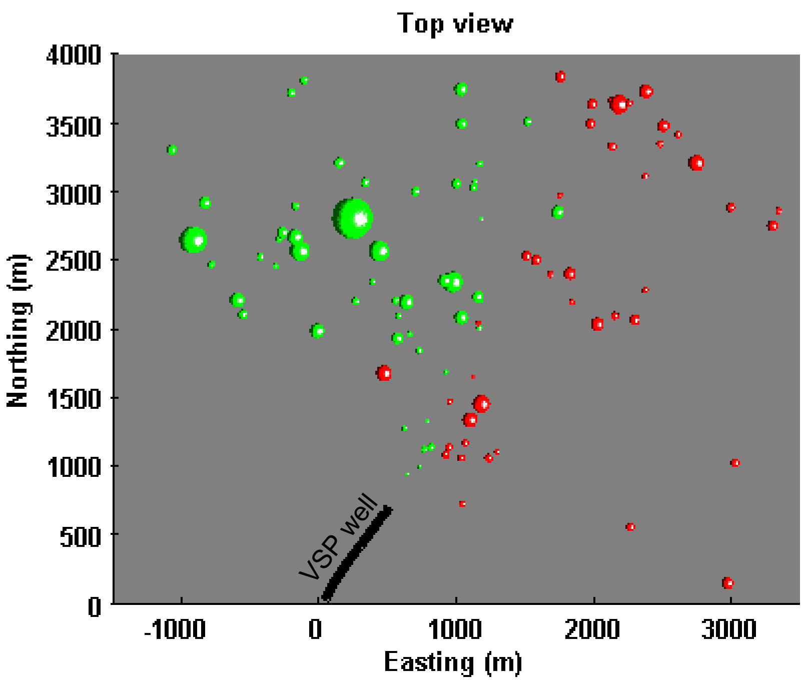


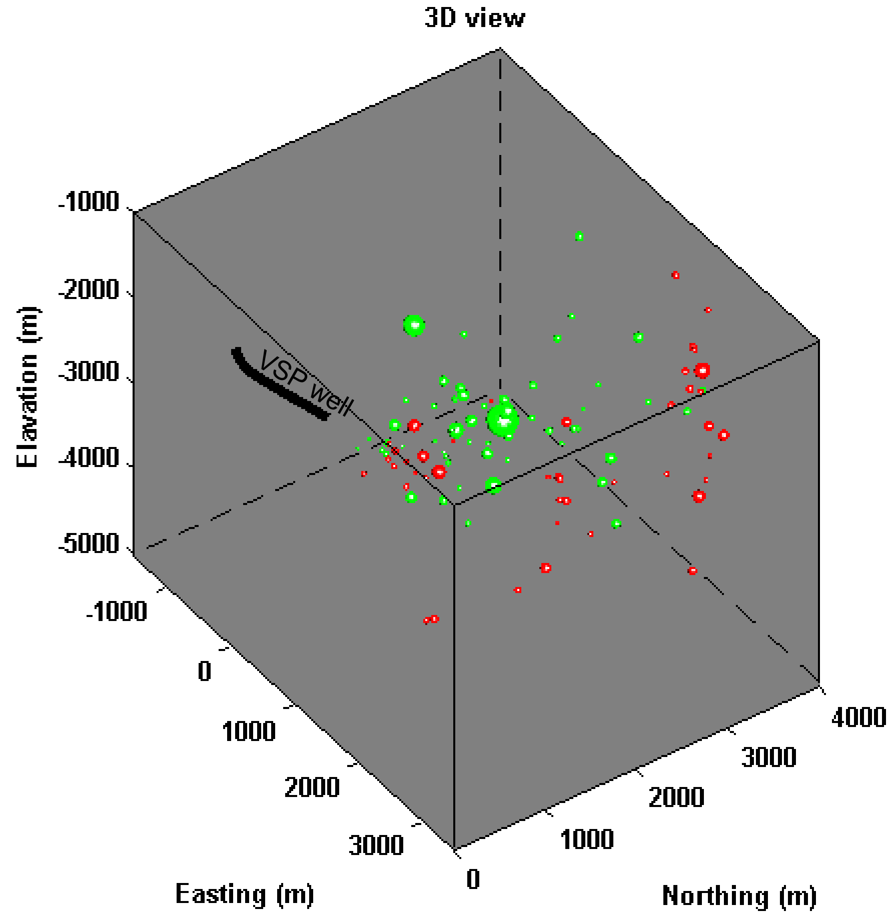
Micro-Seismic Source Locations



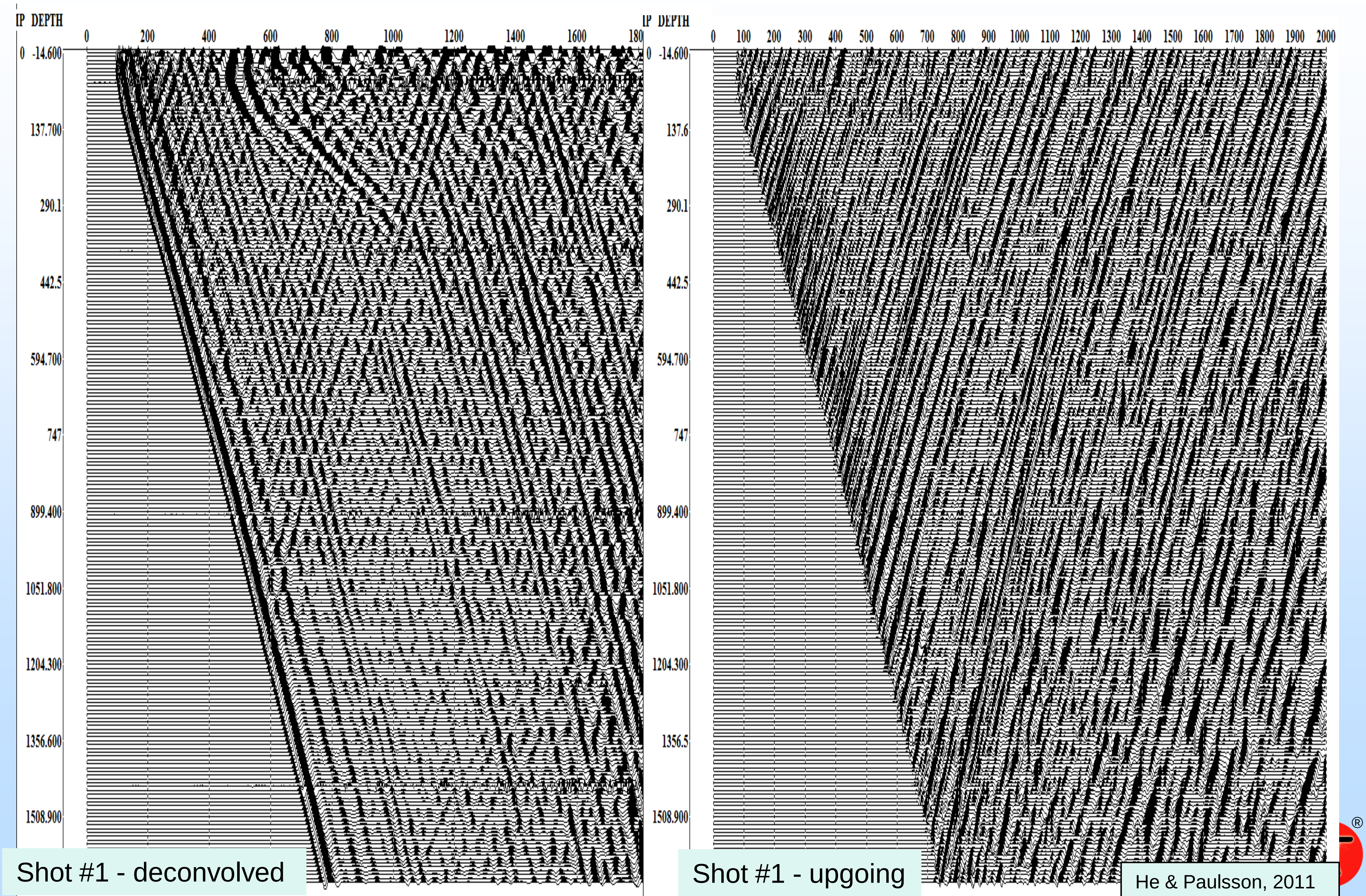


Micro-Seismic Source Locations

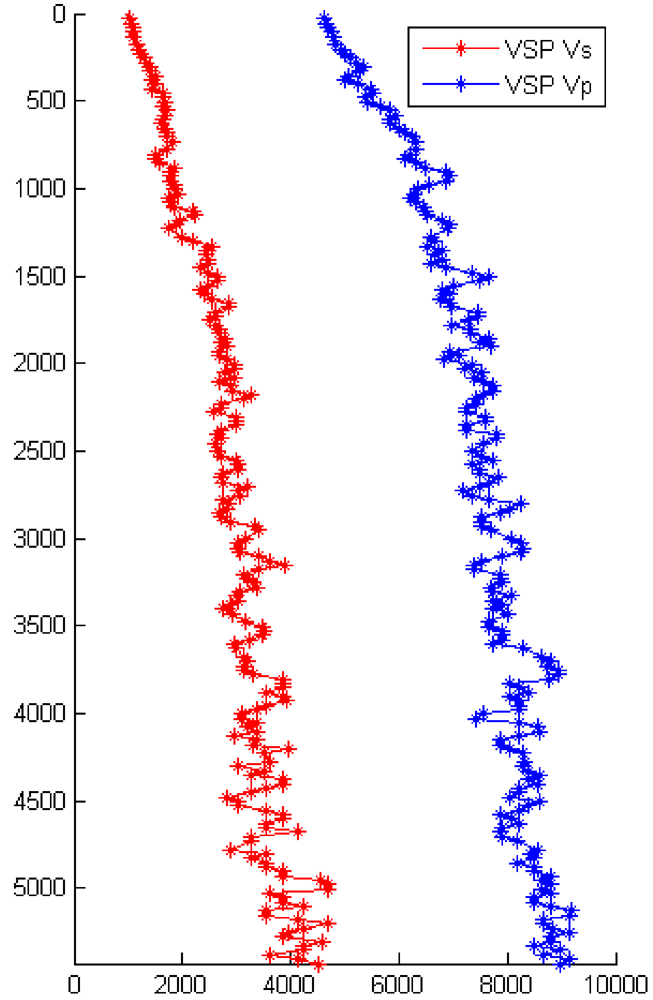


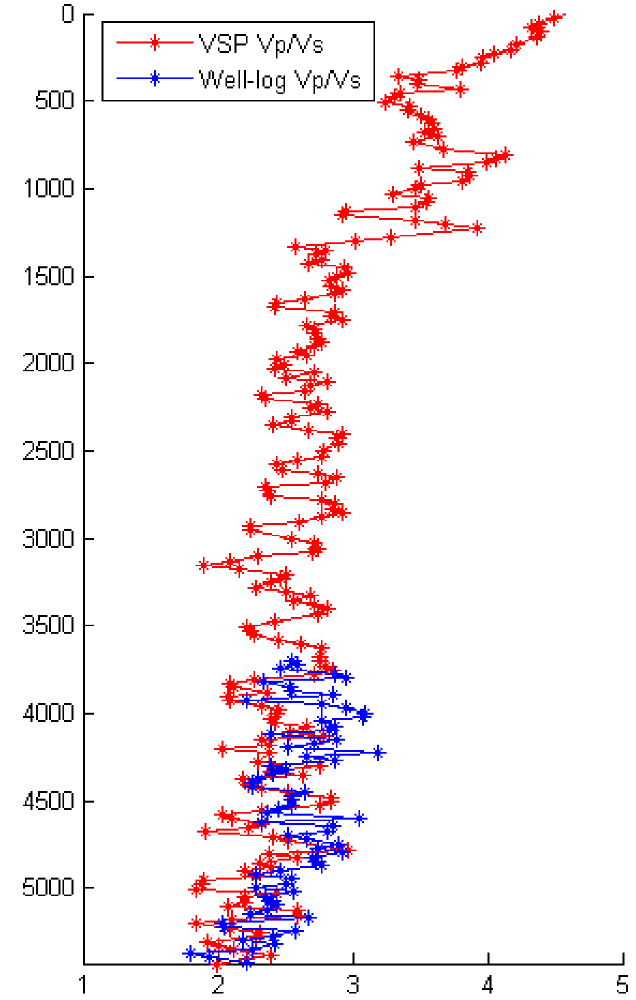


Frio CO2 Site, VSP Deconvolved + Upgoing P Waves Using Paulsson 3rd Generation Borehole Seismic Array



Frio VSP: P & S Velocity Models Using Paulsson's 3rd Generation Array

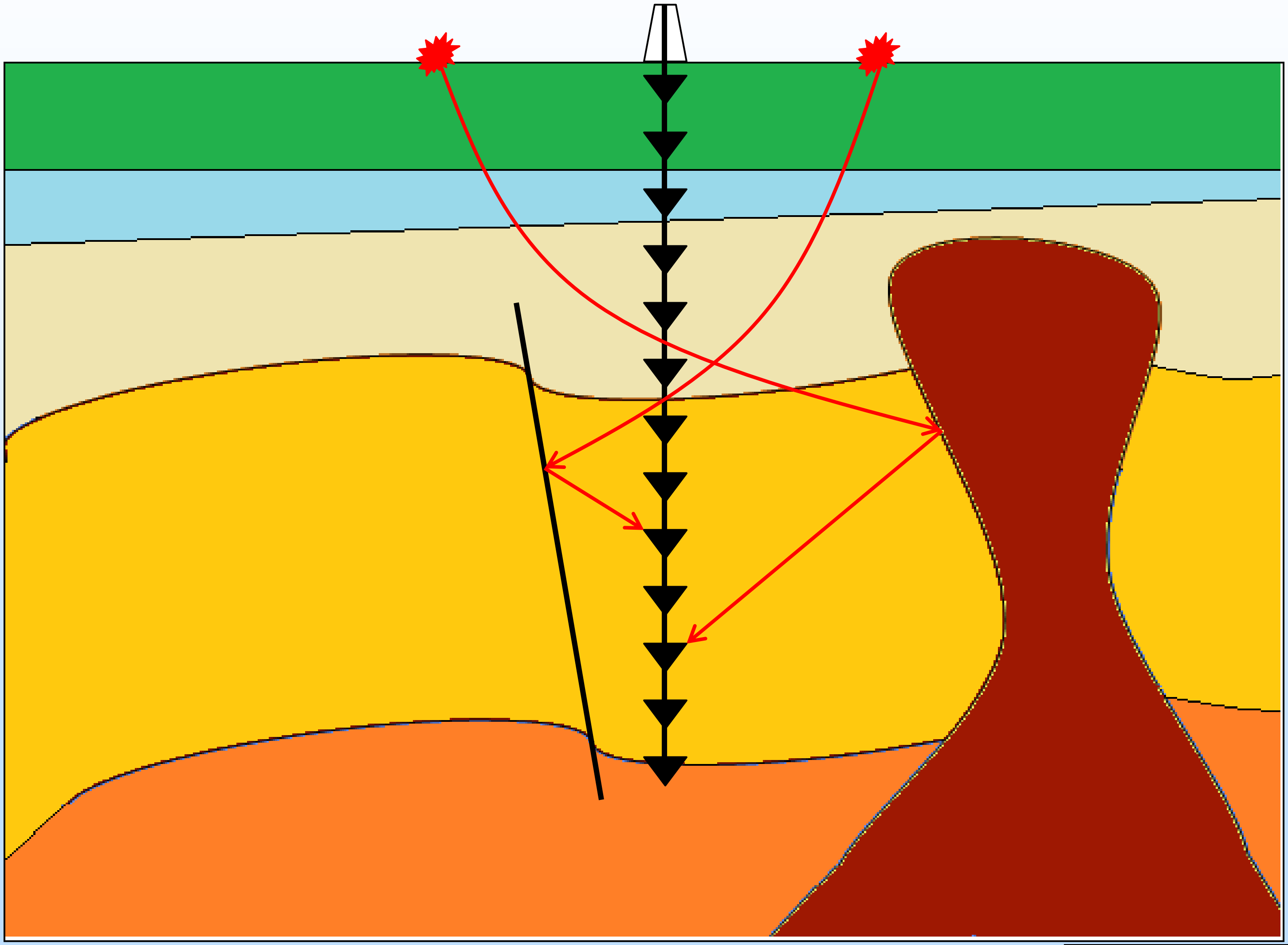




High Quality Velocity Model needed to map Micro Seismic Events

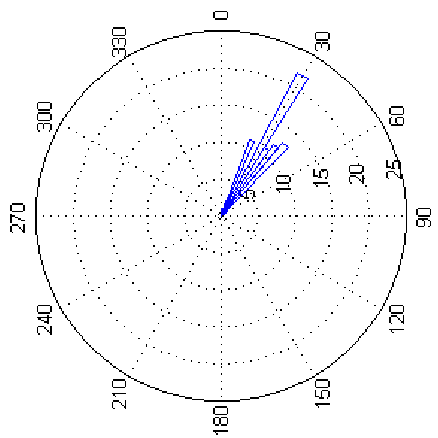
He & Paulsson, 2011

Generalized Interferometric Migration (GIM) of Side Reflections in VSP Data

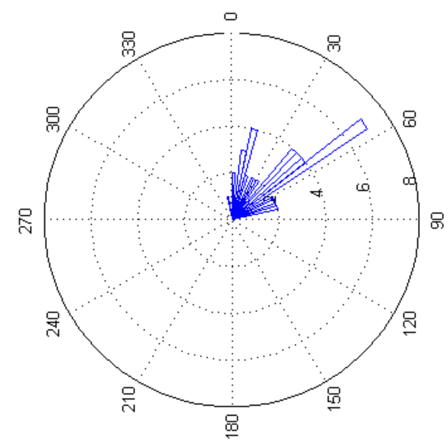


He & Paulsson, 2011

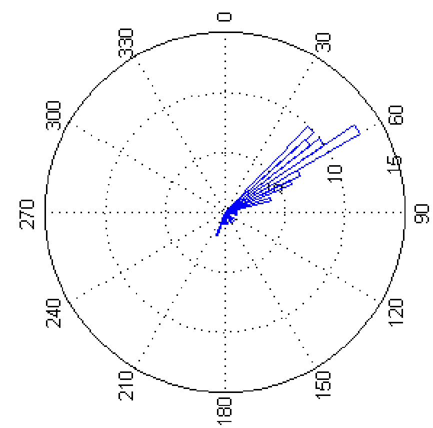
Paulsson 3rd Generation Borehole Seismic Data Hodograms to Determine Vector of Reflection



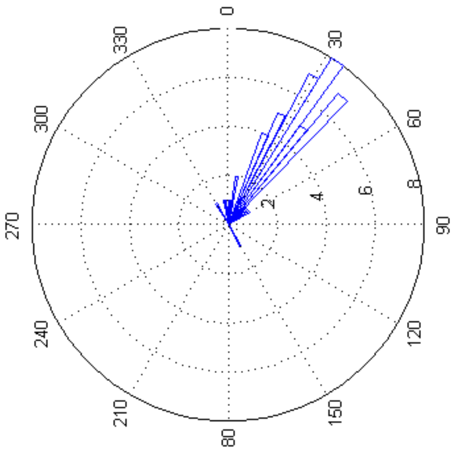
S1



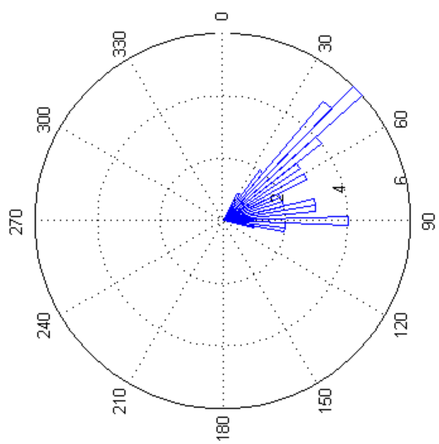
S2



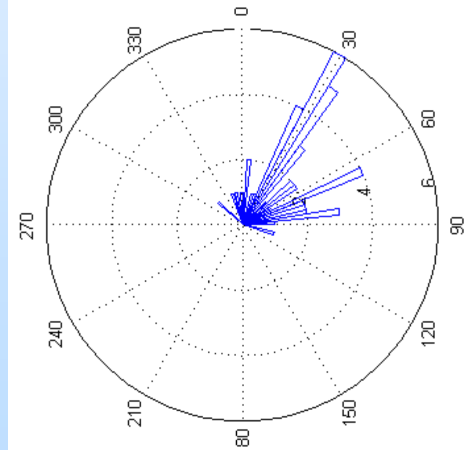
S3



S4

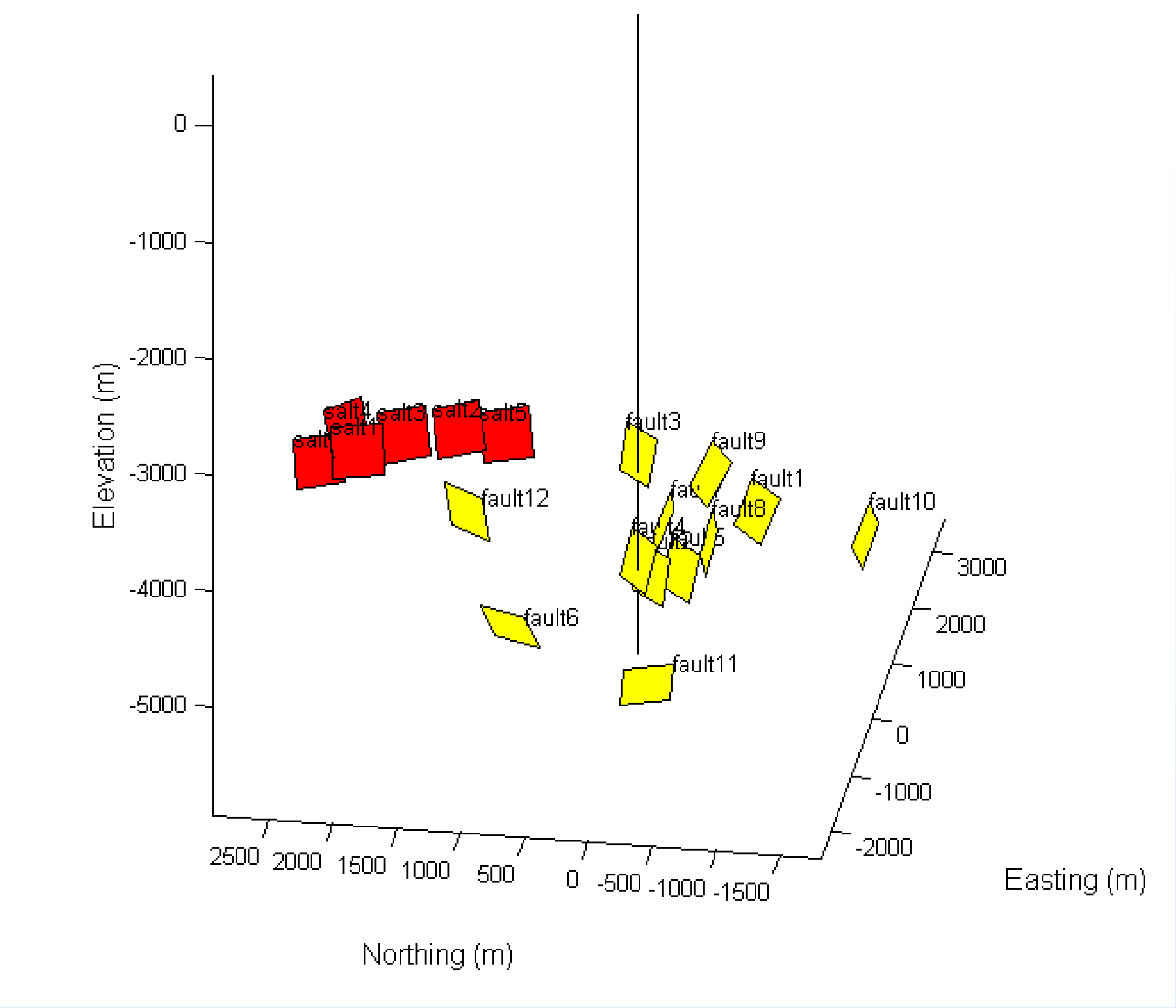


S5



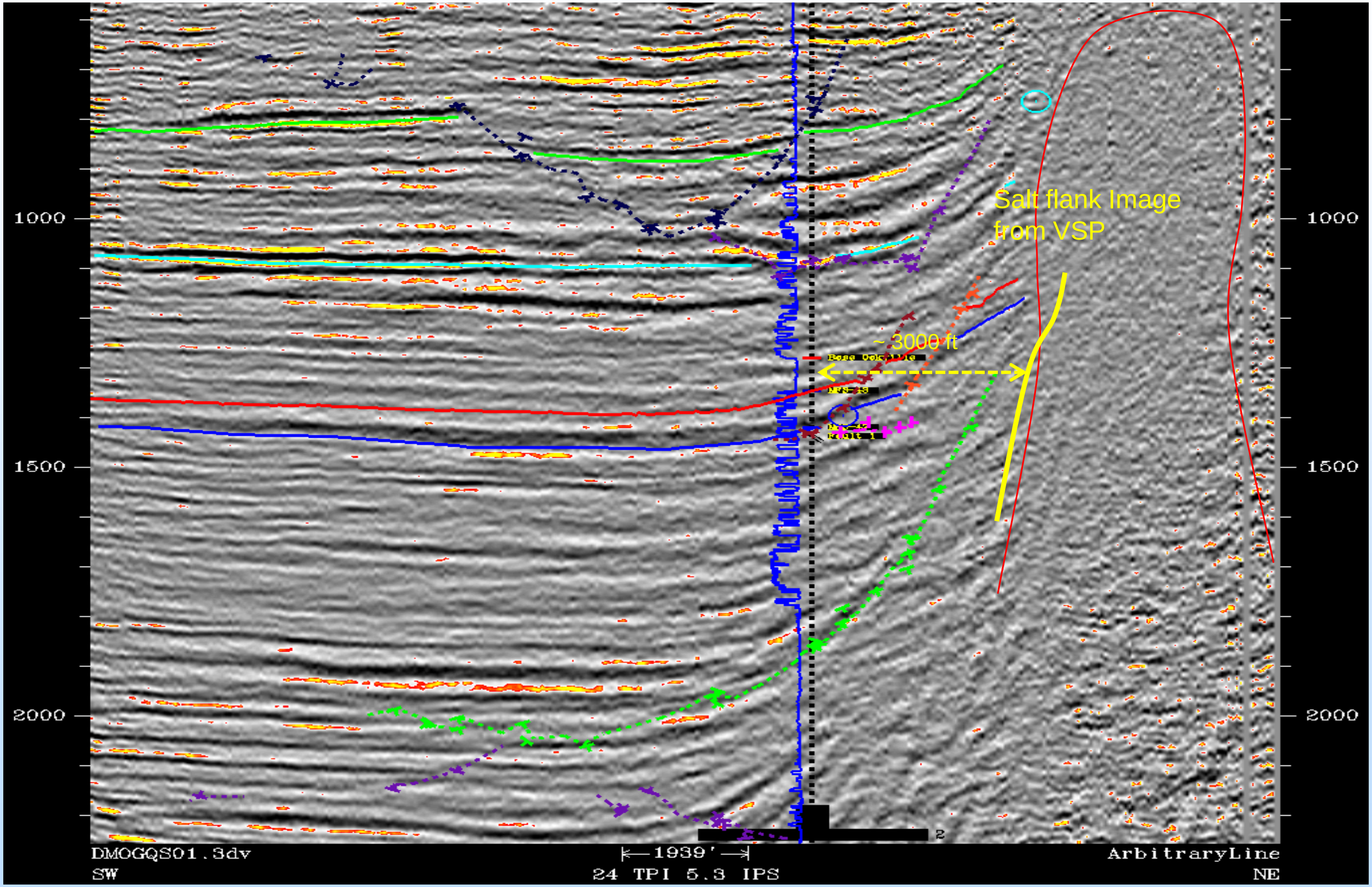
S6

VSP Generalized Interferometric Migration (MIG) of a Salt Flank (red) & Faults (yellow)



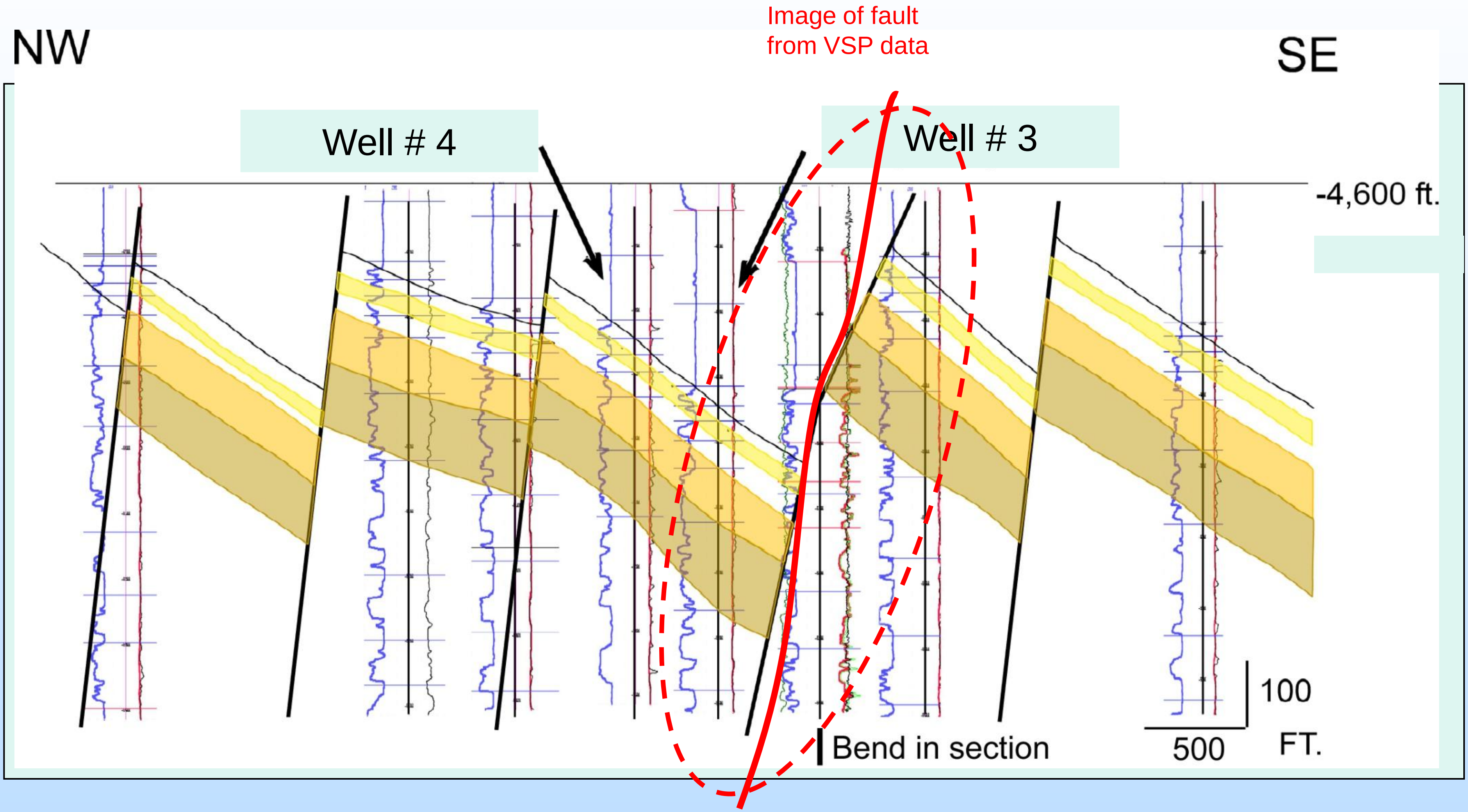
He & Paulsson, 2011

Frio CO2 Site: Surface Seismic Image with VSP mapped Salt Flank location



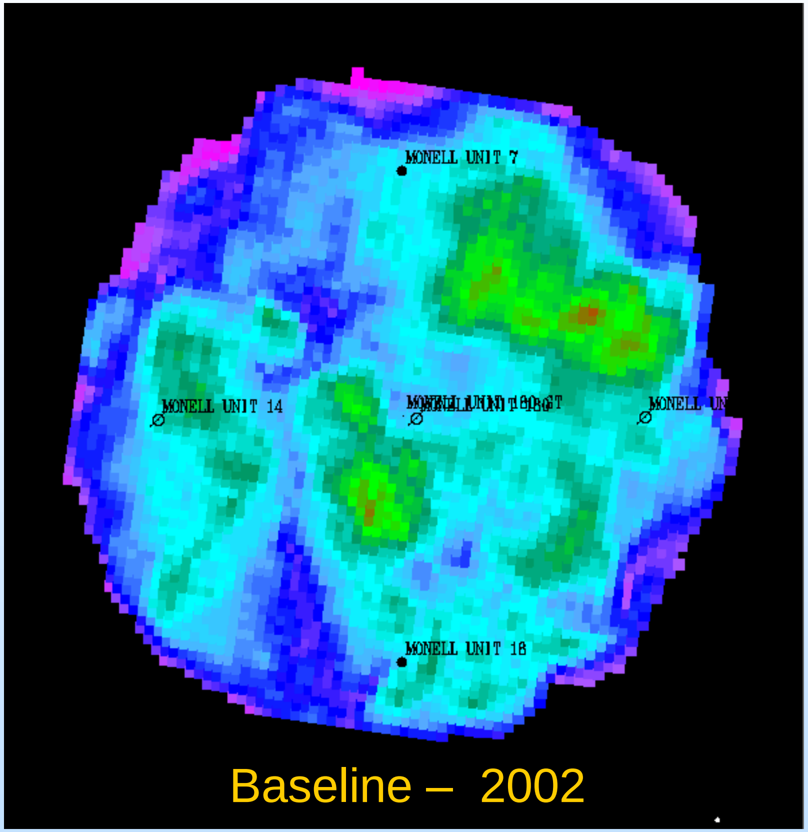
He & Paulsson, 2011

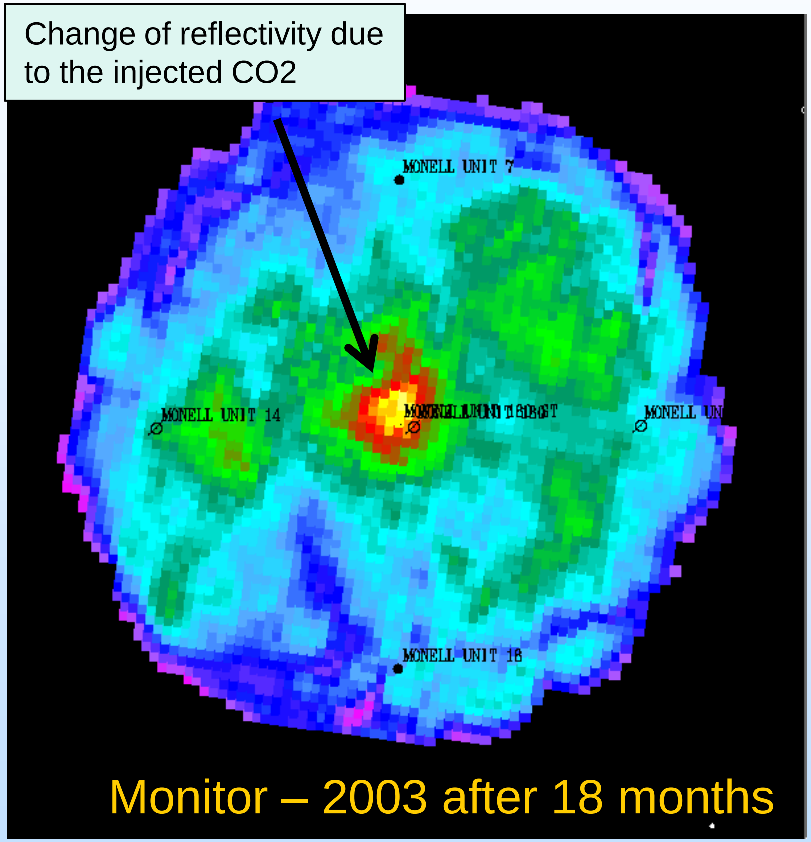
Frio Well Ties: Compare Fault image from well log geology and from VSP imaging



Paulsson 3rd Generation Borehole Seismic arrays used for CO2 Time Lapse Monitoring Surveys

Depth Amplitude Maps showing the CO_2 Injection





O'Brien et al., 2004

Accomplishments to Date

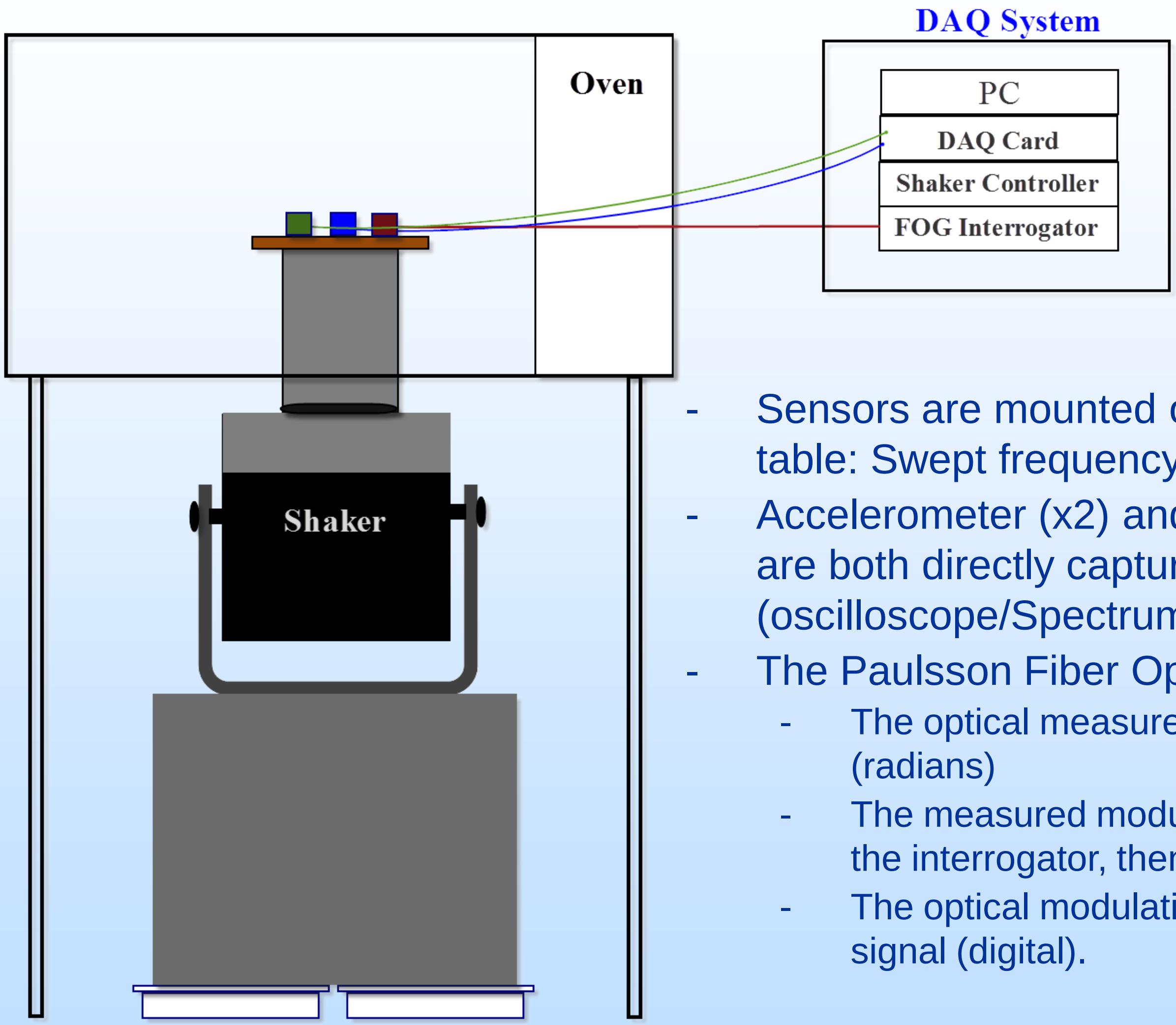
- Developed an Ultra Sensitive Fiber Optic Geophone
- Tested the Fiber Optic Geophone at High Temperature at large Range of Frequencies and Loads
- Developed a Facility to Manufacture High Performance Fiber Optic Geophone (FOG's) Arrays
- Designed and built a 30,000 psi capable 3C geophone pod for the Fiber Optic Geophones
- Developed a Deployment System strong enough to deploy a 1,000 level 3C borehole seismic arrays in vertical and horizontal boreholes.
- Manufactured components for a five level FOG array

1. **Fiber Optic Sensor Development**
2. **Deployment System Development**

The Clean Room for the Manufacturing of the 300ºC Fiber Optic Borehole Geophones

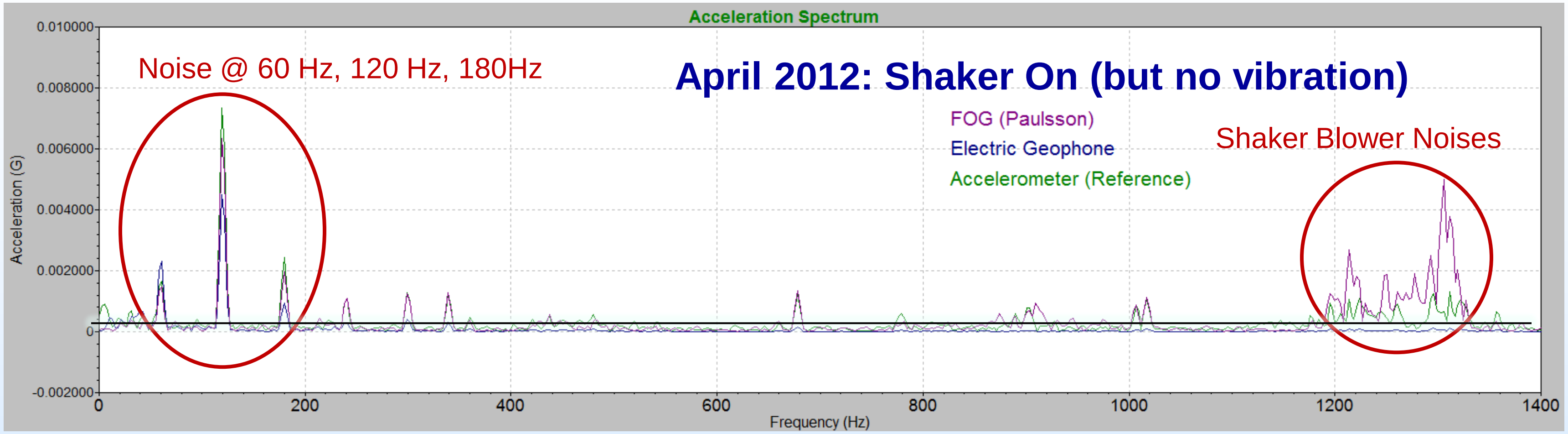
The 300ºC Dynamic Test Station for the 300ºC Fiber Optic Borehole Geophones

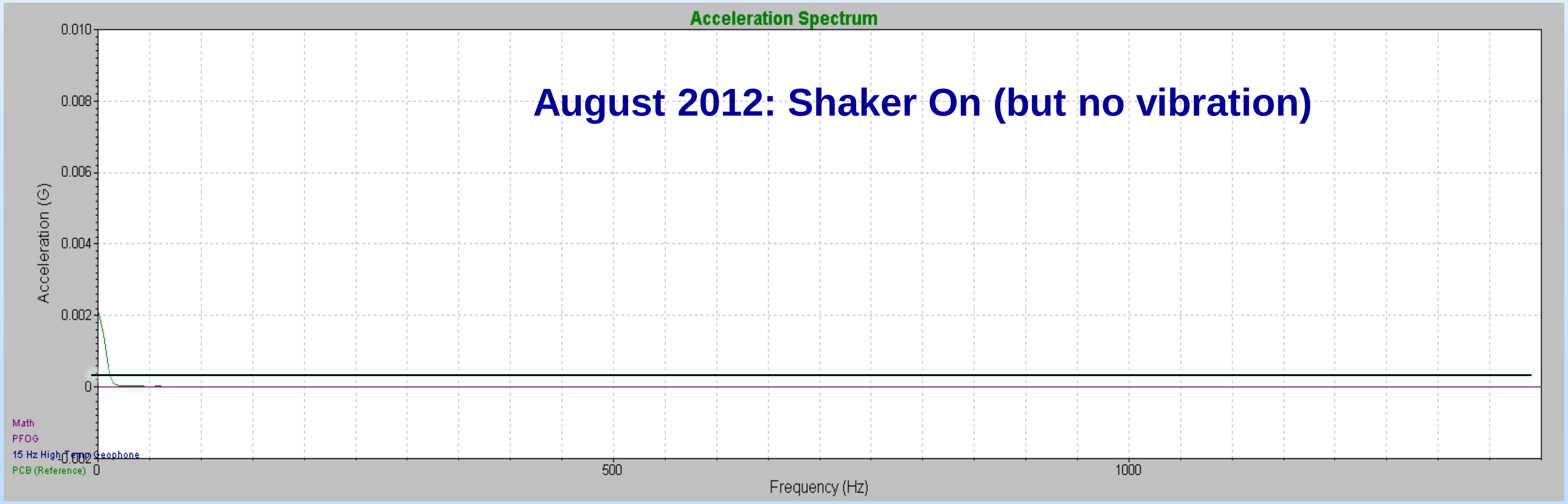
Dynamic Test Facility



- Sensors are mounted onto a plate on the shaker table: Swept frequency (0 up to 4kHz)
- Accelerometer (x2) and Electric Geophone signal are both directly captured by the DAQ system (oscilloscope/Spectrum Analyzer).
- The Paulsson Fiber Optic Geophone signal:
  - The optical measurement is the differential phase (radians)
  - The measured modulated phase is first analyzed by the interrogator, then
  - The optical modulation is then converted to electric signal (digital).

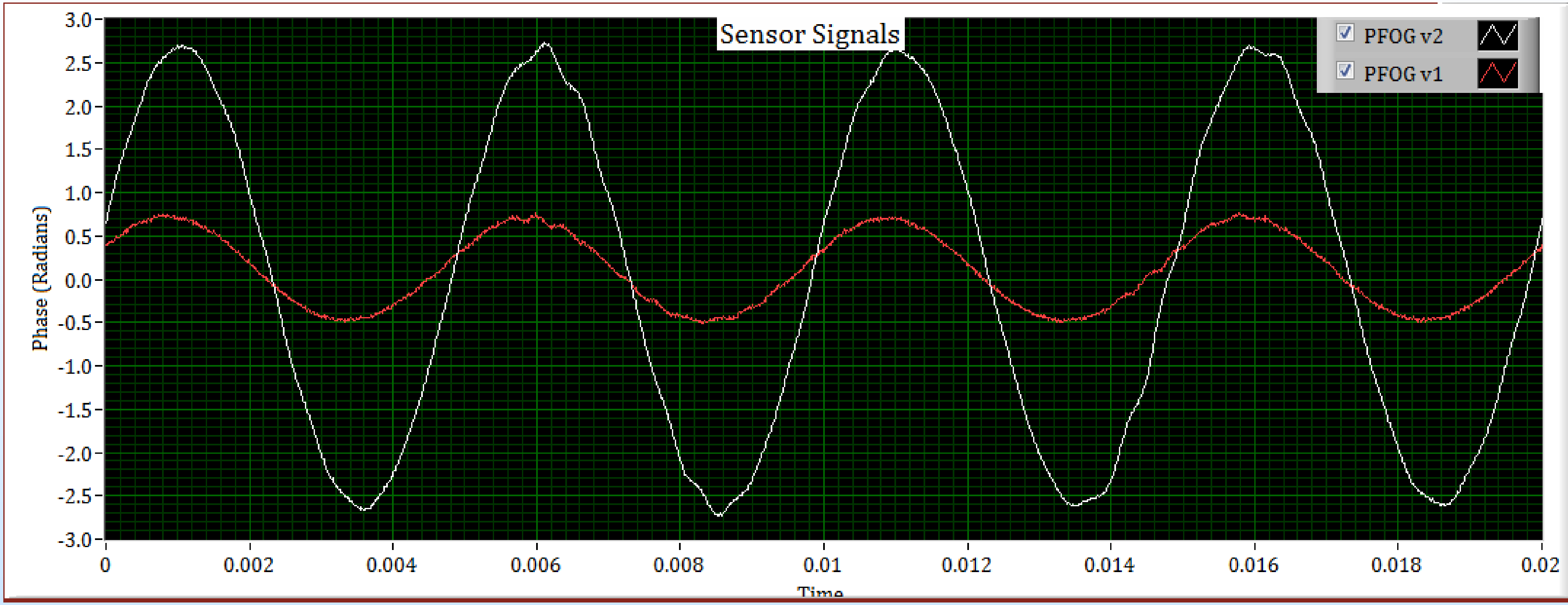
Dynamic Test Station Noise Improvements: April – August 2012





Noise Floor has been improved by a factor > 100

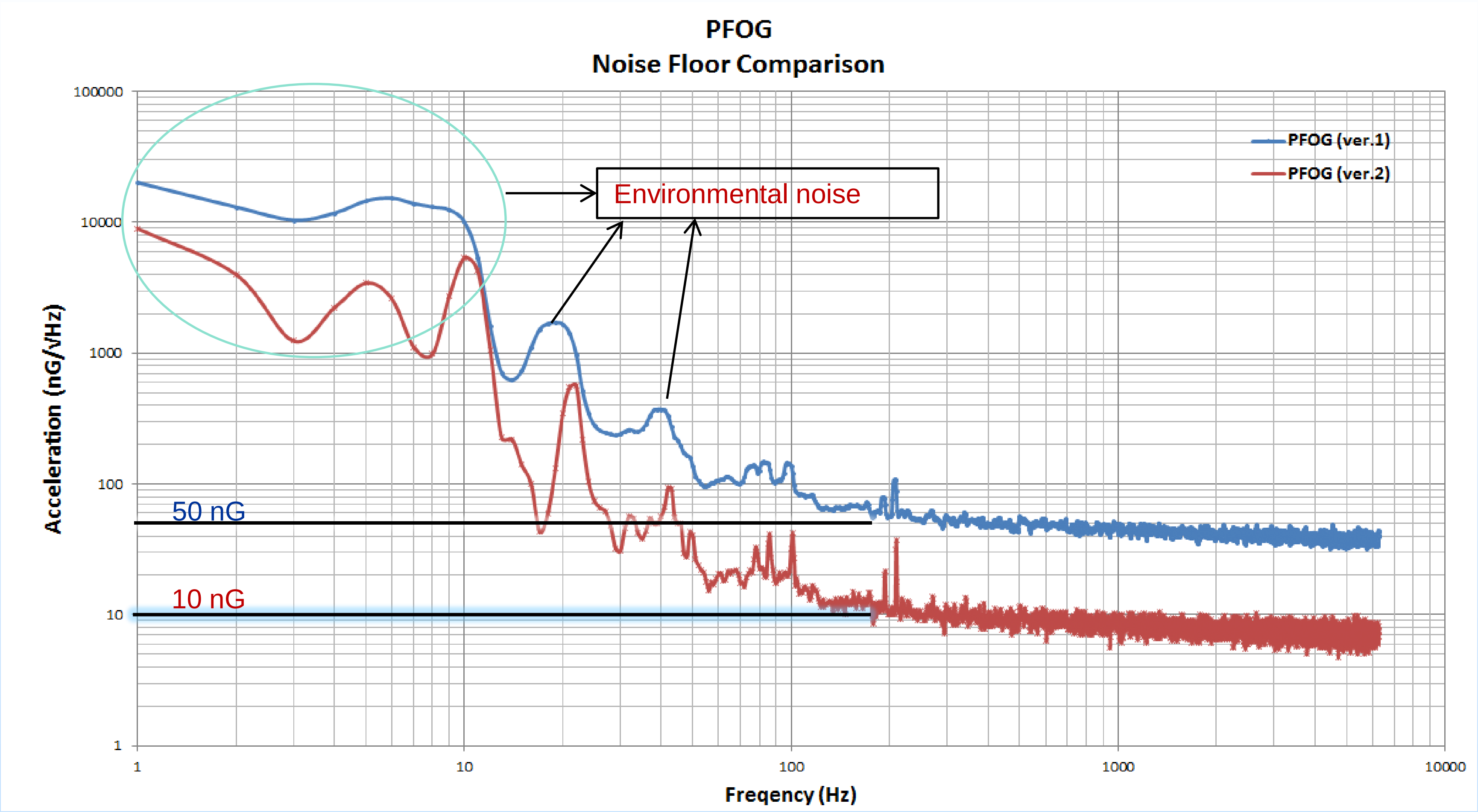
Paulsson Fiber Optic Geophone (PFOG)
Improved Sensor's Sensitivity > 4x in V2 vs. V1



Both sensors being driven @ 10mG and 200 Hz

- Great Improvements in sensitivity in V2 (> 4x Improvement!) compared with V1.
- Sensor will be better isolated in a down-hole environment where the temperature will also be stable

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

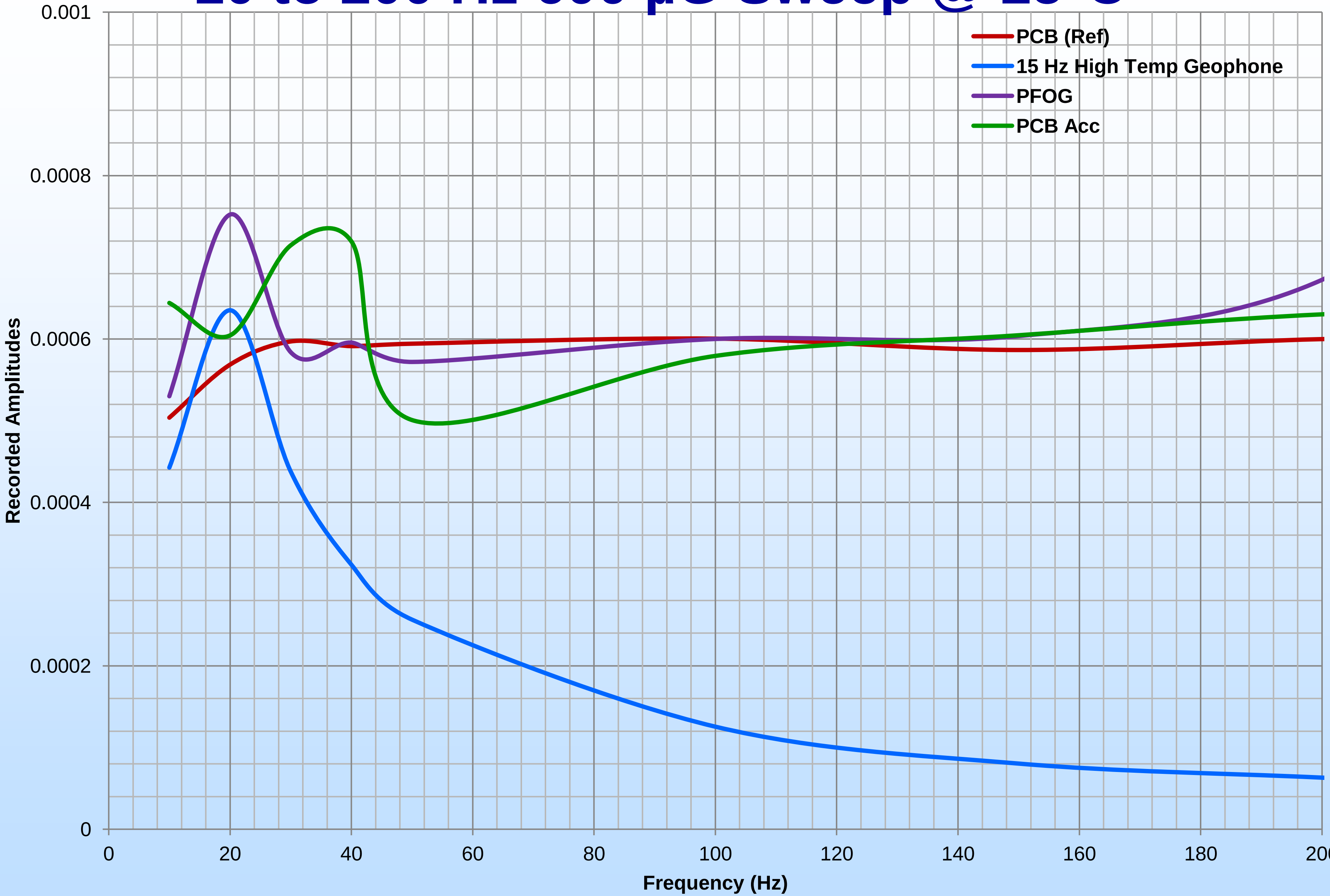


- Great Improvements in noise floor in V2 compared to V1
- As expected, we still experience higher environmental noises in our lab at low frequencies.
- Sensor will be better isolated in a down-hole environment where the temperature will also be stable
- We are confident, we can reduce the noise floor to < 10 nG for the whole band in the near future

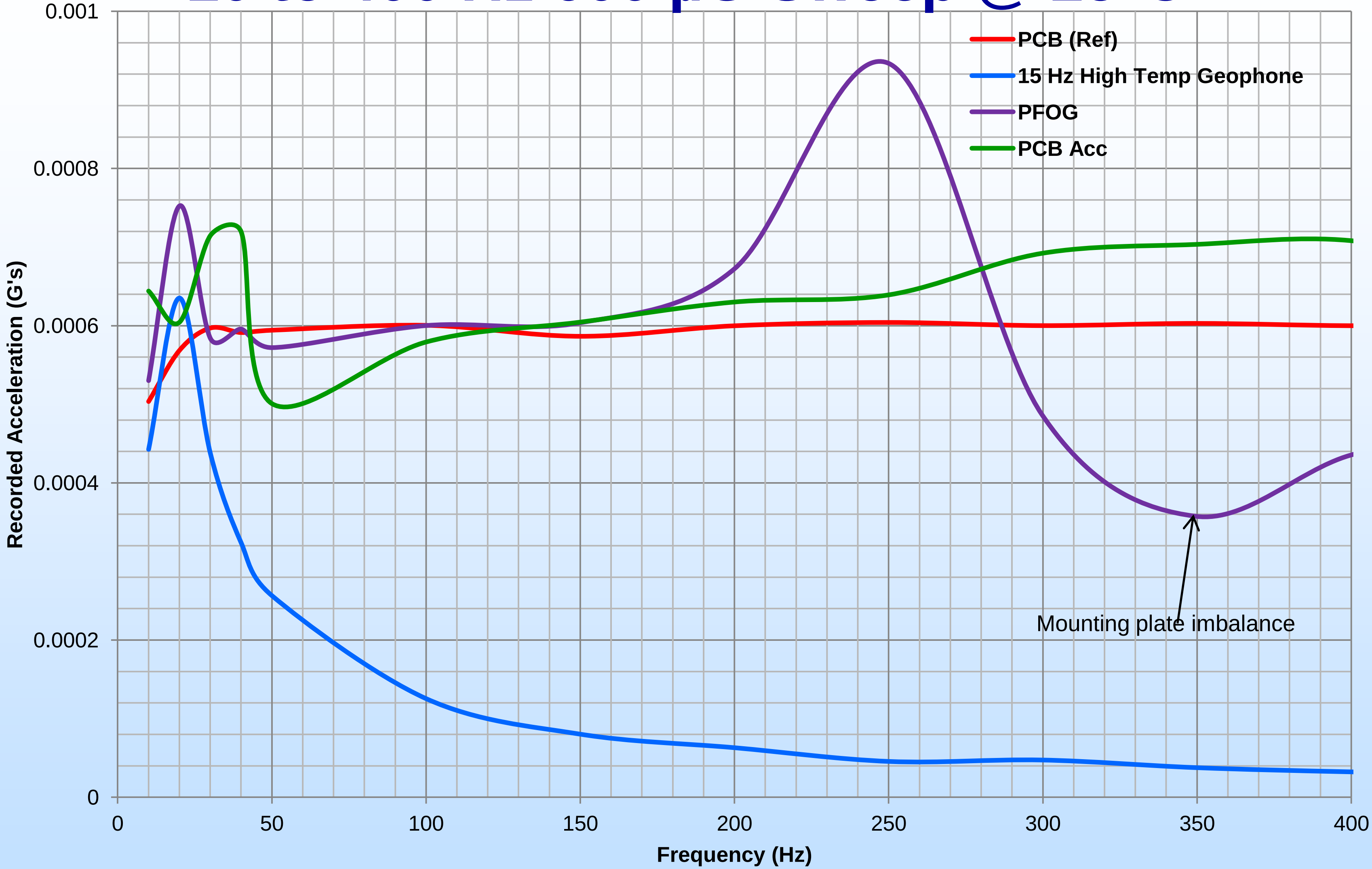
THE PAULSSON FIBER OPTIC GEOPHONE
VS.
OTHER SENSORS
@ 25°C

All Sensors - Frequency Response (10 Hz ➔ 400 Hz) using a 600 µG Acceleration @ 25°C

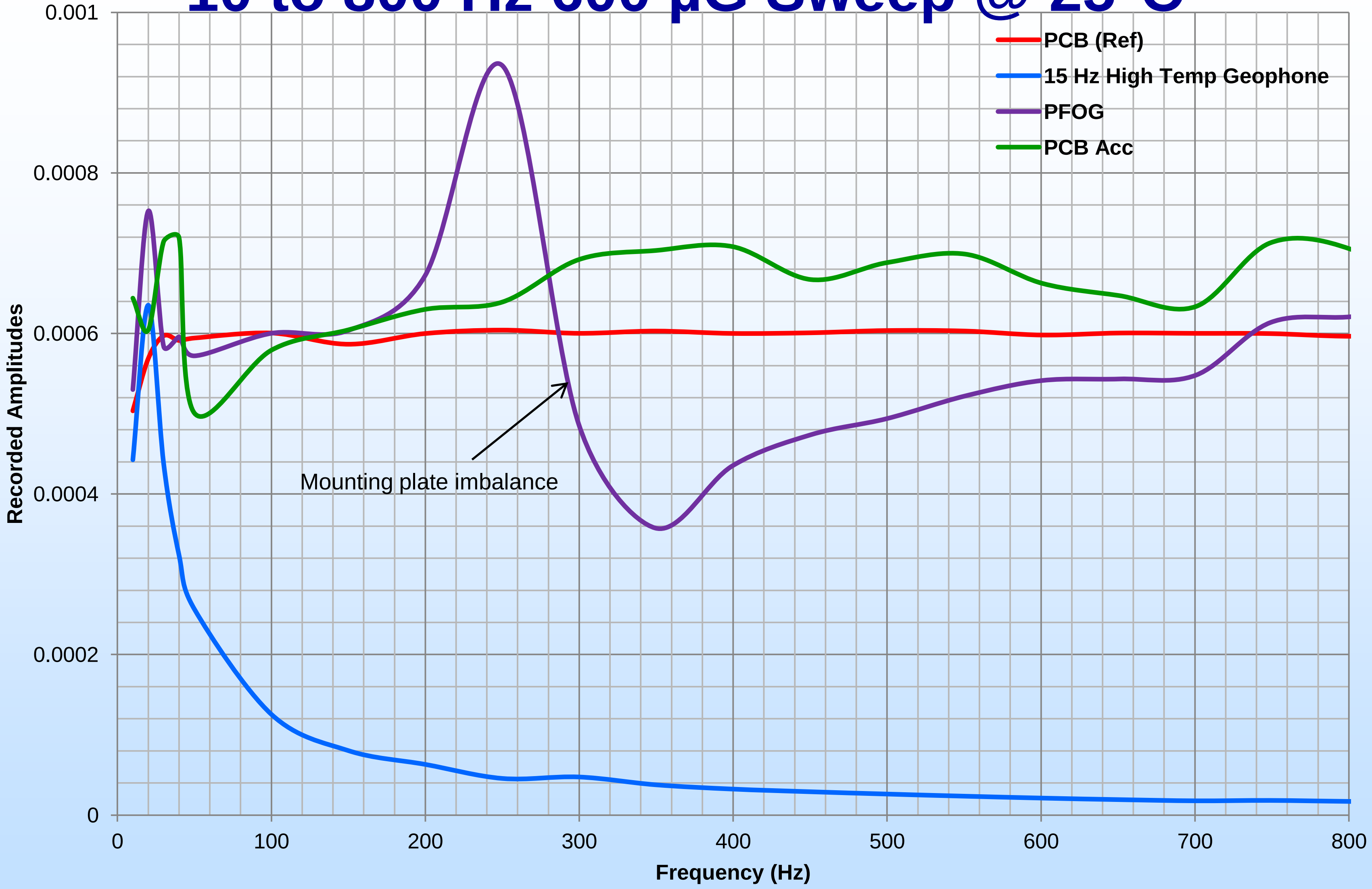
10 to 200 Hz 600 µG Sweep @ 25°C



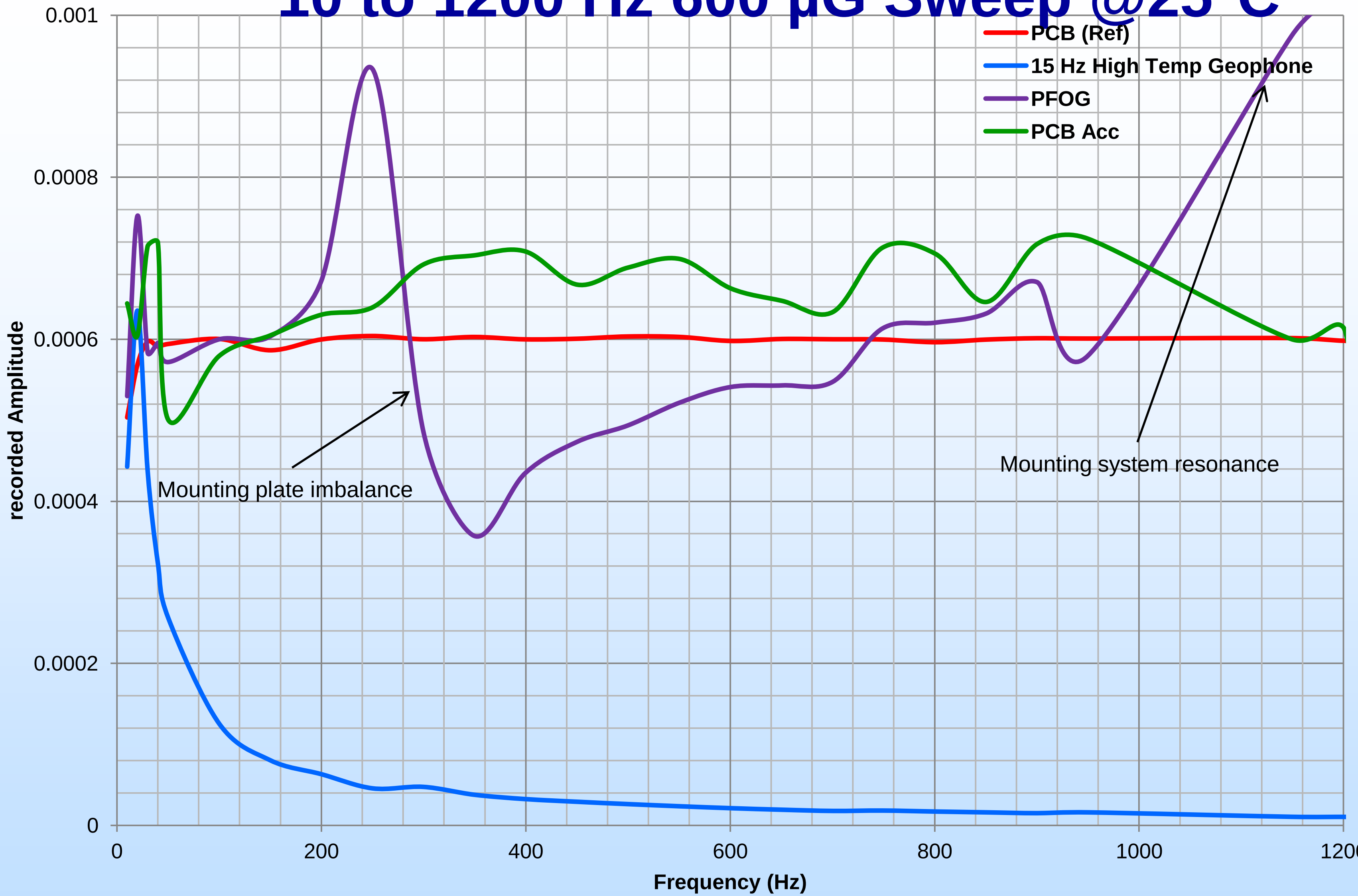
10 to 400 Hz 600 μG Sweep @ 25°C



10 to 800 Hz 600 µG Sweep @ 25°C



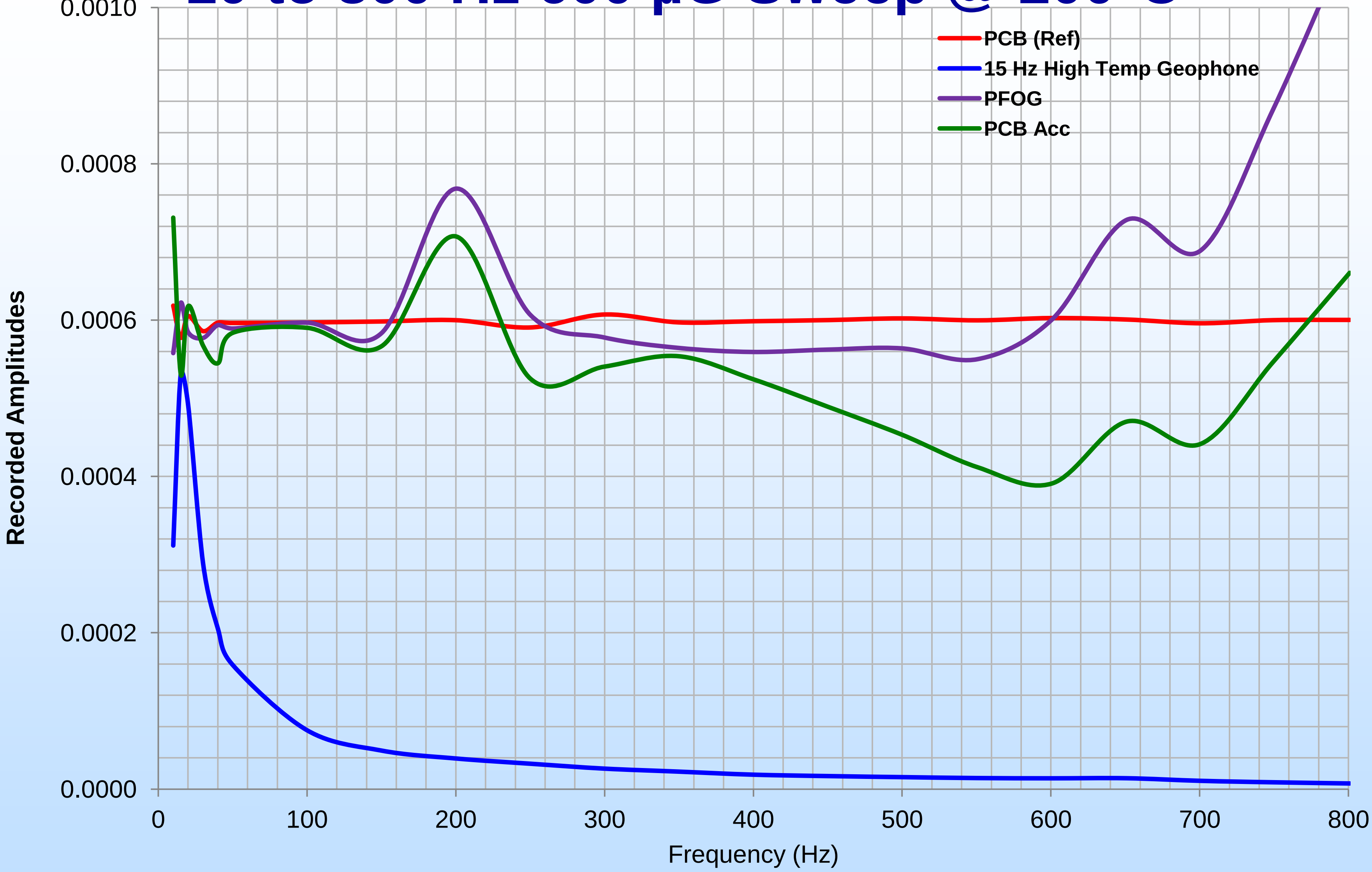
10 to 1200 Hz 600 μG Sweep @25°C



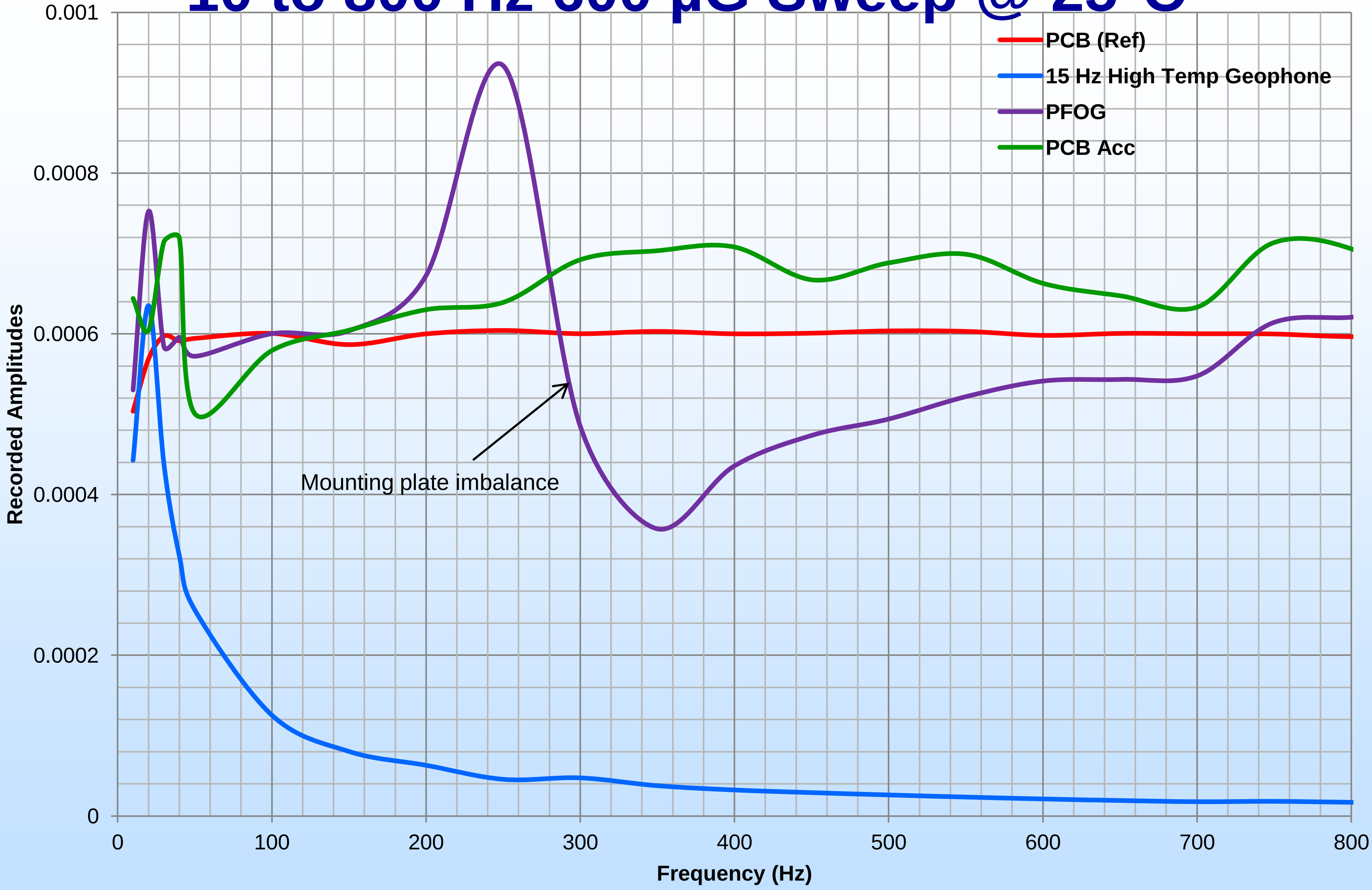
THE PAULSSON FIBER OPTIC GEOPHONE
VS.
OTHER SENSORS
@ 200°C

All Sensors - Frequency Response (10 Hz → 400 Hz) using a 600 µG Acceleration @ 200°C

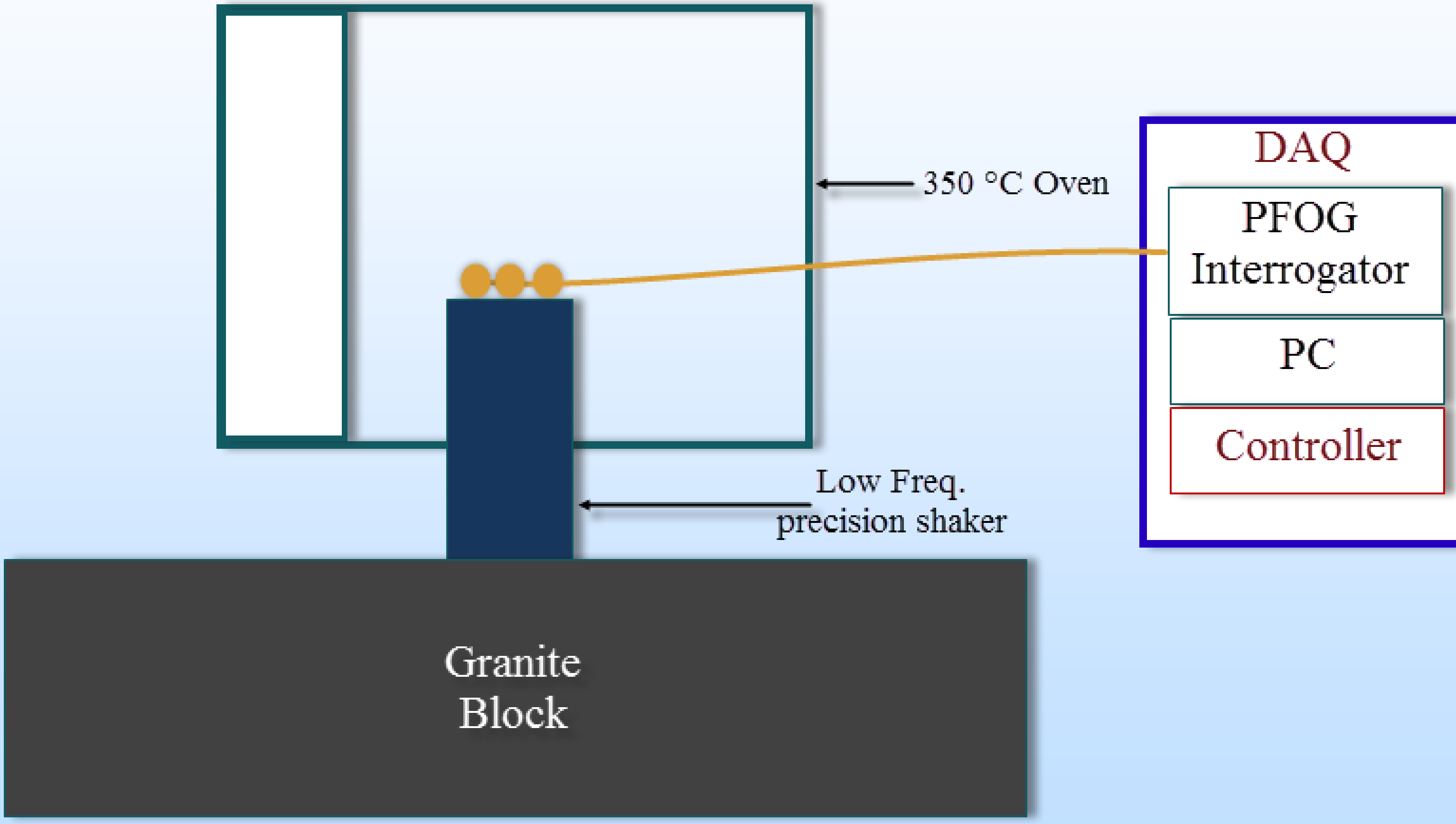
10 to 800 Hz 600 µG Sweep @ 200°C



10 to 800 Hz 600 μG Sweep @ 25°C

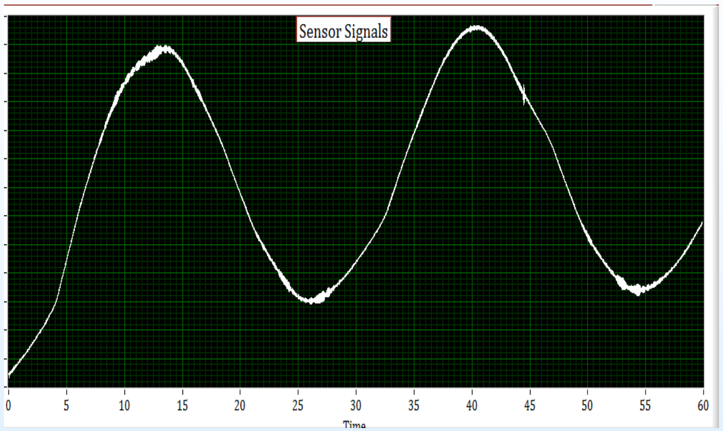


High Precision Low Frequency Vibration System @ Low Amplitude

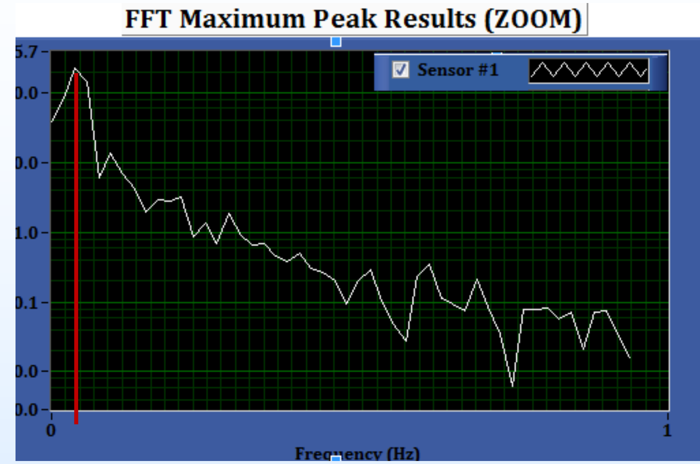


PFOG Performance Test at Frequencies < 1Hz

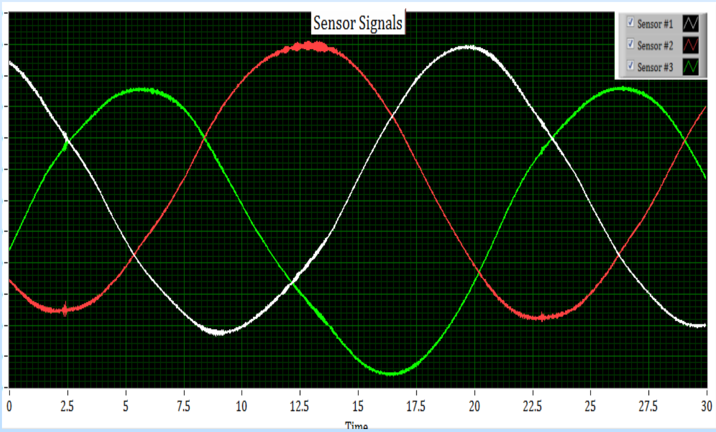
- Single PFOG sensor modulated at 0.03 Hz (33 seconds period)
- The Actuator is controlled by a PC at all frequencies (from <1 Hz to higher frequencies)



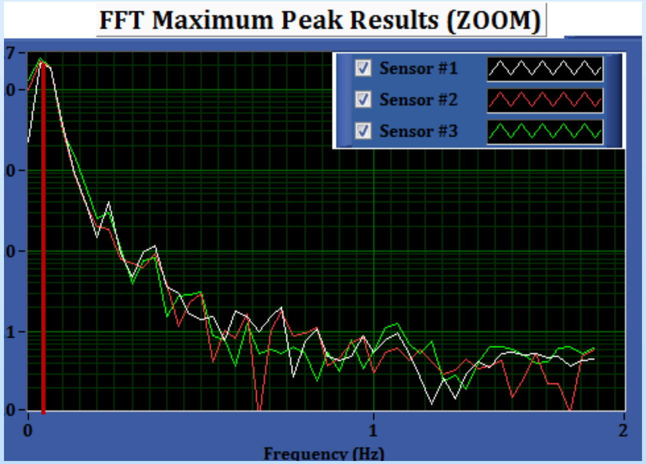
Test @ 0.03 Hz



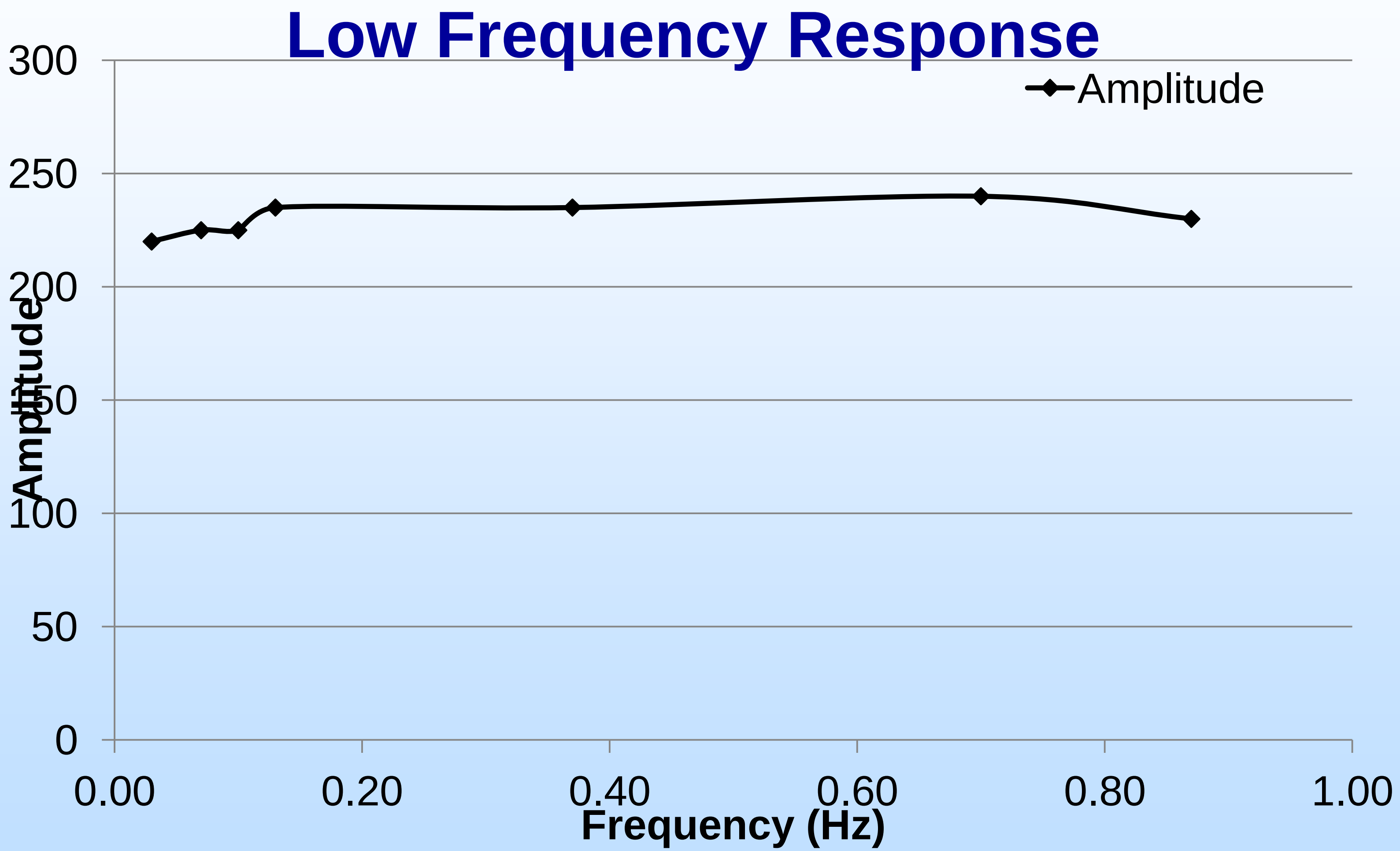
- 3 PFOGs are mounted axially to motion and modulated at 0.03 Hz
- The motion is controlled by a PC at all frequencies (from <1 Hz to higher frequencies)



Test @ 0.03 Hz

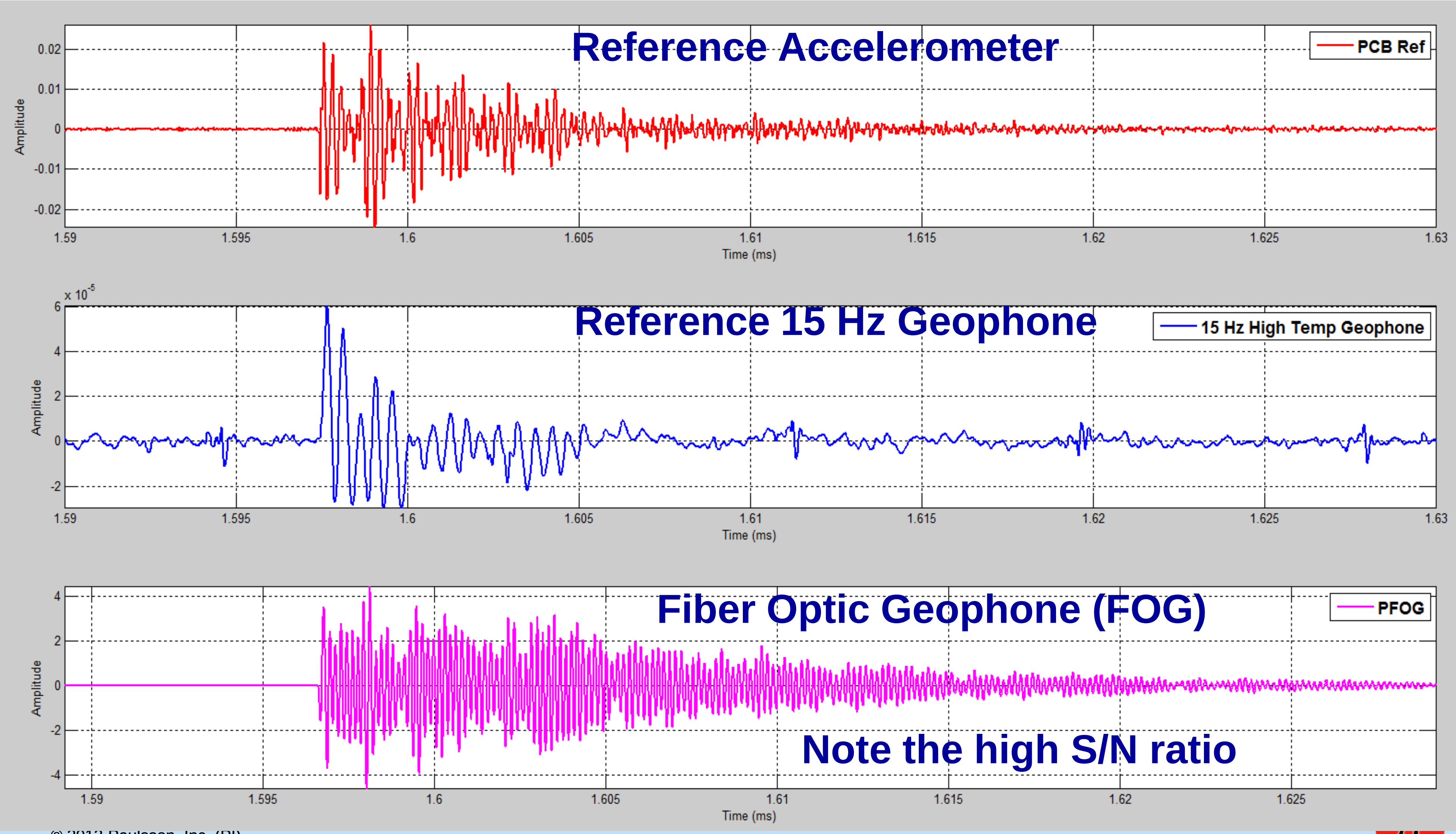


PFOG Test @ 0.03 – 1 Hz (33 – 1 sec period)



Seismic Traces from Tap Test

Simultaneous Acquisition of all sensors; Band Pass Filter: 5 – 2,500 Hz



Conclusions

1. Fiber-Optic Geophone's design is successful
   a. Flat frequency response over a large frequency range
   b. Low Frequency performance
   c. Very high sensitivity
   d. High Signal to Noise ratio

2. Outstanding Issues
   a. Resonances in the test setup
   b. Facility's environmental noise
   c. Interrogation system tuning

The OpticSeis™ 3C Pod
For The Fiber Optic Geophone

1. **Fiber Optic Sensor Development**

2. **Deployment System Development**

Drill Pipe Based Borehole Seismic Deployment System

The Borehole Seismic Deployment System

Drill Pipe Based Deployment System

Pipe Strength: 140,000 lbs (verified July 25, 2011)

Depth Capability: 30,000 ft

Pressure Rating: 30,000 psi

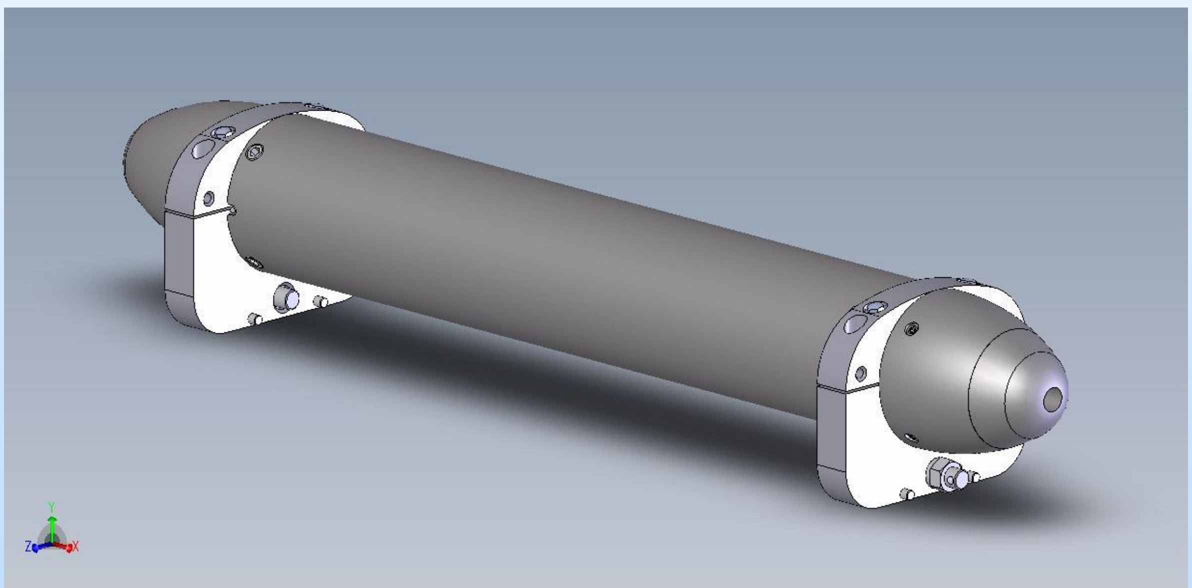
Clamping Actuators: 572ºF (300ºC)

Temperature for Optical System: 572ºF (300ºC)

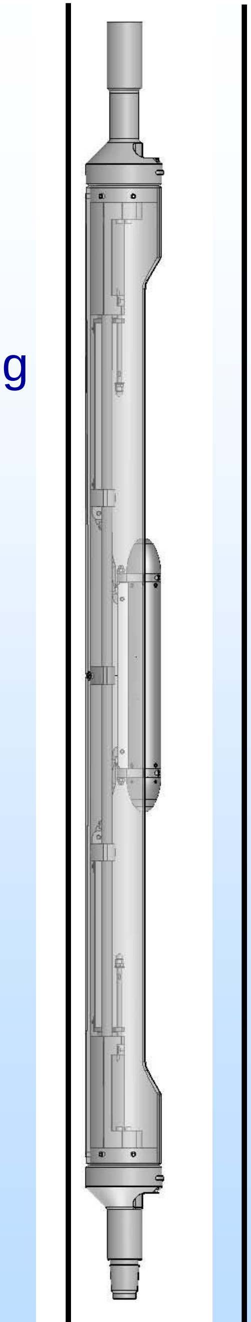
Optical 3C Levels: 1,000

Deployable in both Vertical and Horizontal wells

Geophone Pod Housing
and the Fiber Optic Pod Geophone pod

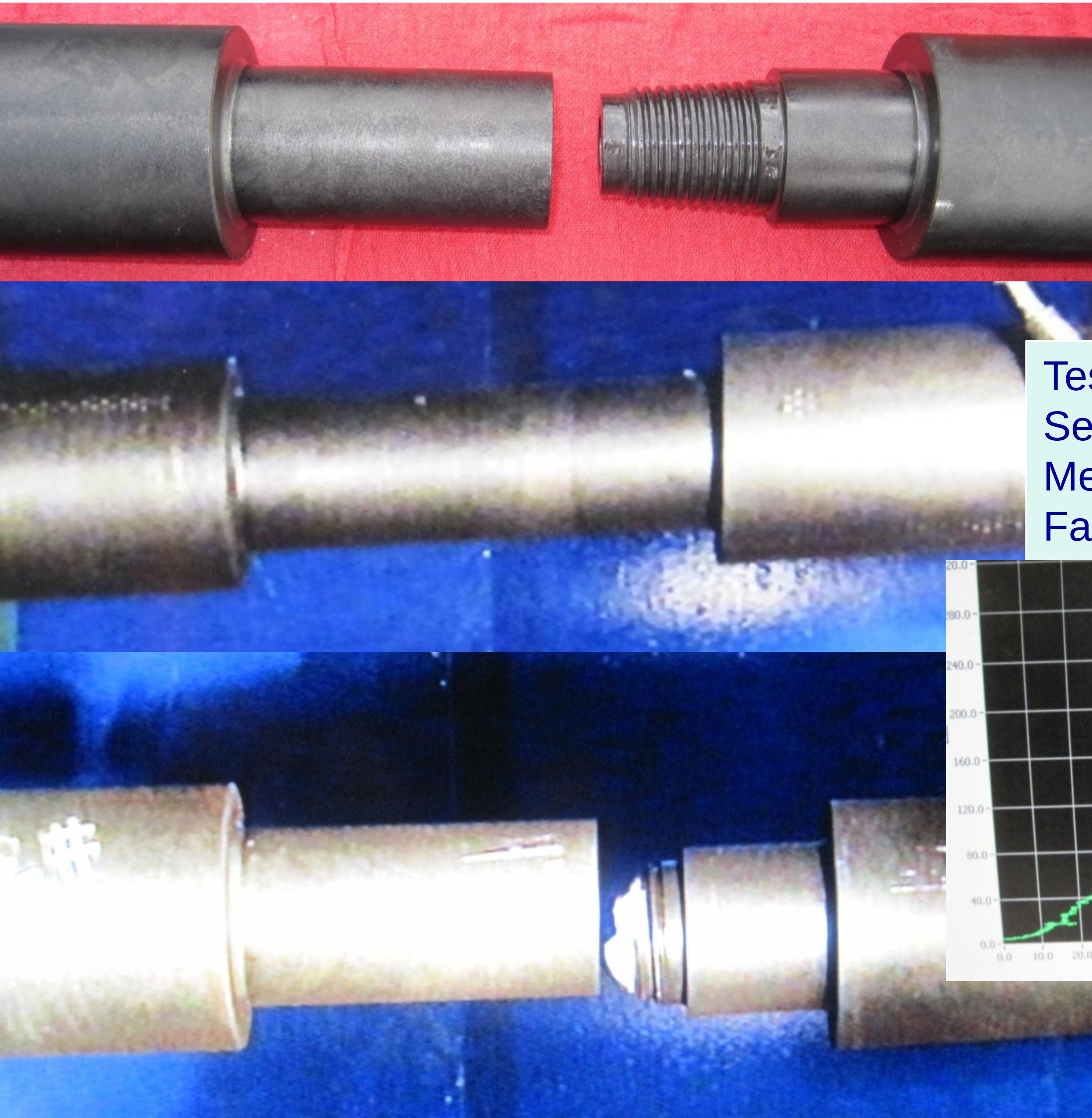


Casing

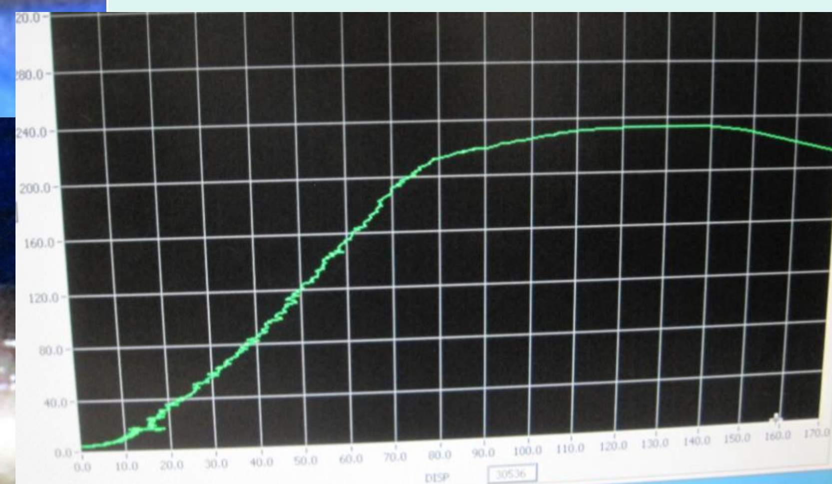


Casing

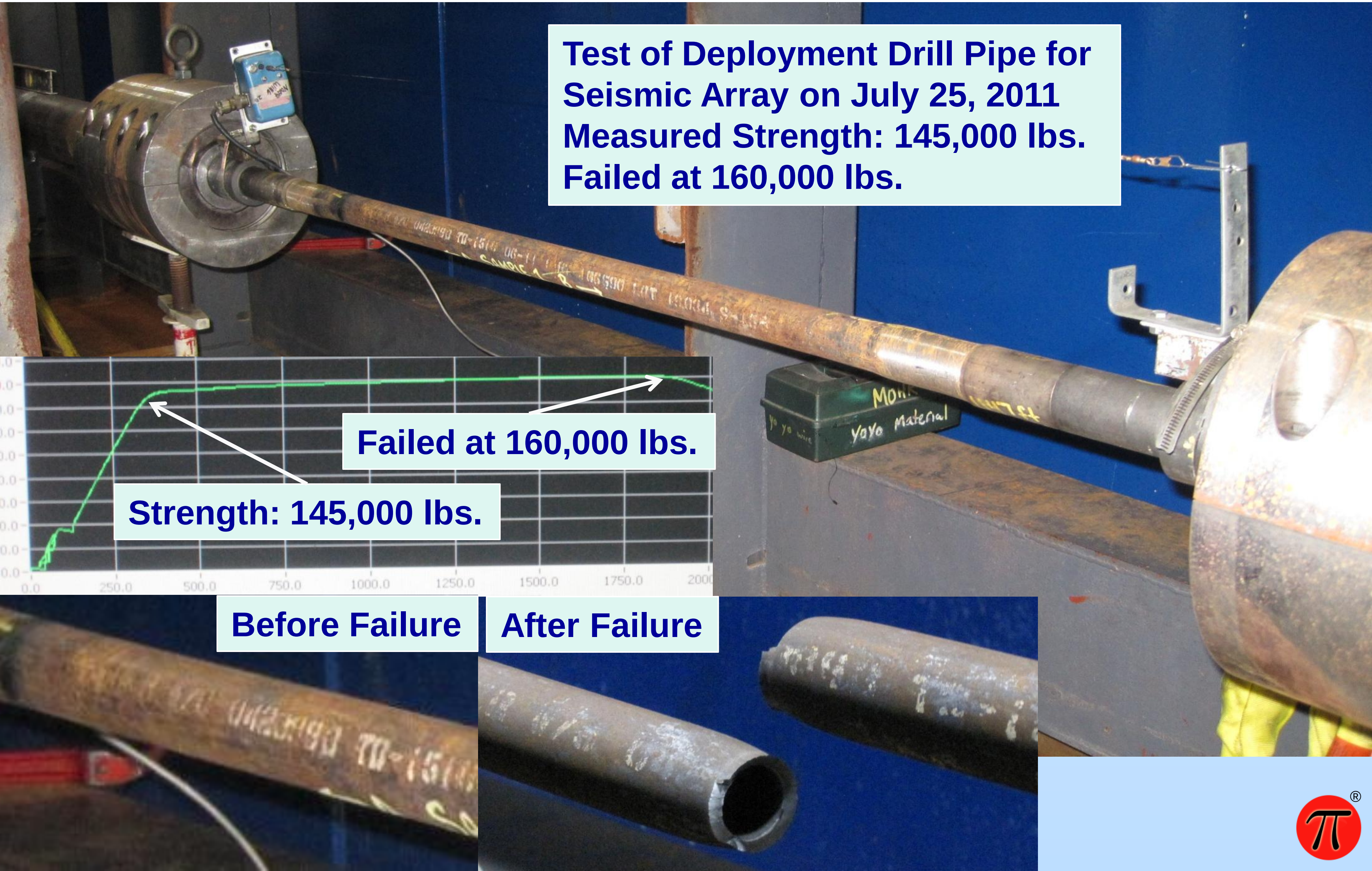
Destructive Testing of Tool Joints



Test of Tool Joints for
Seismic Array on Nov. 22, 2010
Measured Strength: 210,000 lbs.
Failed at 238,000 lbs.



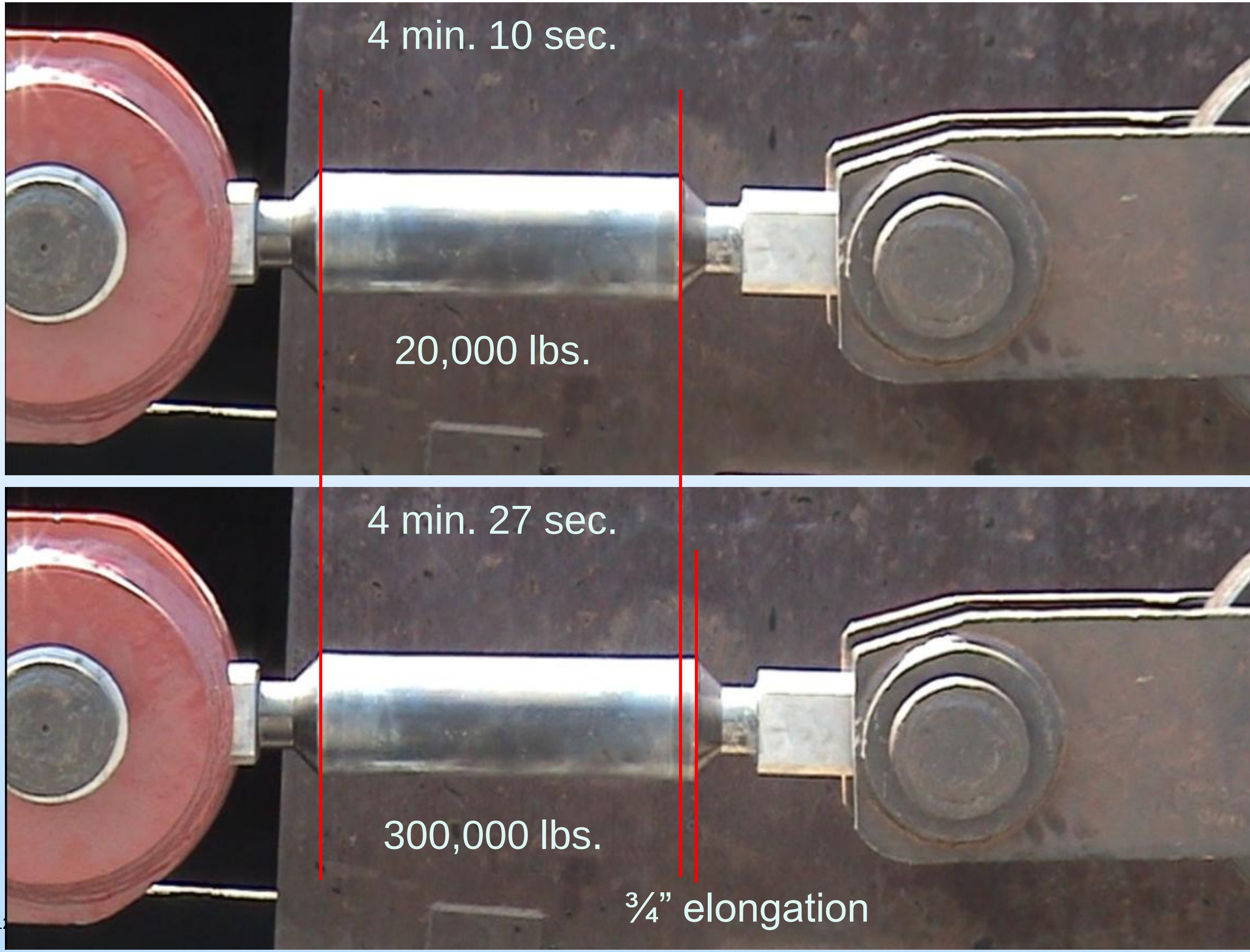
Destructive Testing of Deployment drill pipe



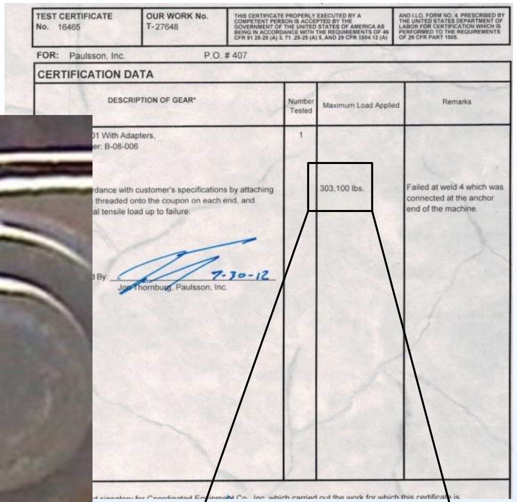
Deployment Drill Pipe During Manufacturing

15,000 ft of Deployment Drill Pipe

Destructive Test of Geophone Pod Housing



Destructive Test of Geophone Pod Housing
July 30, 2012



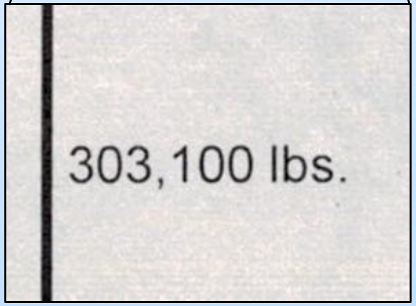
TEST CERTIFICATE No. 16465	OUR WORK No. T-27648	THIS CERTIFICATE PROPERLY EXECUTED BY A COMPETENT PERSON IS ACCEPTED BY THE GOVERNMENT OF THE UNITED STATES OF AMERICA AS BEING IN ACCORDANCE WITH THE REQUIREMENTS OF 46 CFR 91.25-25 (A) 3. 71 .25-25 (A) 5, AND 29 CFR 1504.12 (A)	AND I.L.O. FORM NO. 4, PRESCRIBED BY THE UNITED STATES DEPARTMENT OF LABOR FOR CERTIFICATION WHICH IS PERFORMED TO THE REQUIREMENTS OF 29 CFR PART 1505.

FOR: Paulsson, Inc. P.O. # 407

CERTIFICATION DATA

DESCRIPTION OF GEAR*	Number Tested	Maximum Load Applied	Remarks
01 With Adapters, er: B-08-006 ... rdance with customer's specifications by attaching ... threaded onto the coupon on each end, and ... al tensile load up to failure.	1	303,100 lbs.	Failed at weld 4 which was connected at the anchor end of the machine.

d By: 7-30-12
Jon Thornburg, Paulsson, Inc.



Paulsson Project Summary

- Fiber Optic Geophones (FOG's) are more sensitive than regular geophones
- FOG's can operate at high temperature
- FOG's have a very large band width: 0.03 Hz – 4kHz
- Lessons Learned:
  - Require a high quality measurement and calibration system
  - Manufacturing is expensive
  - Manufacturing takes a long time and must be carefully tracked
- Currently Building a Five Level 3C Array
- Plan to test Five level array in September 2012
- Complete a 150 level 3C FOG array in 2013

Thank you!

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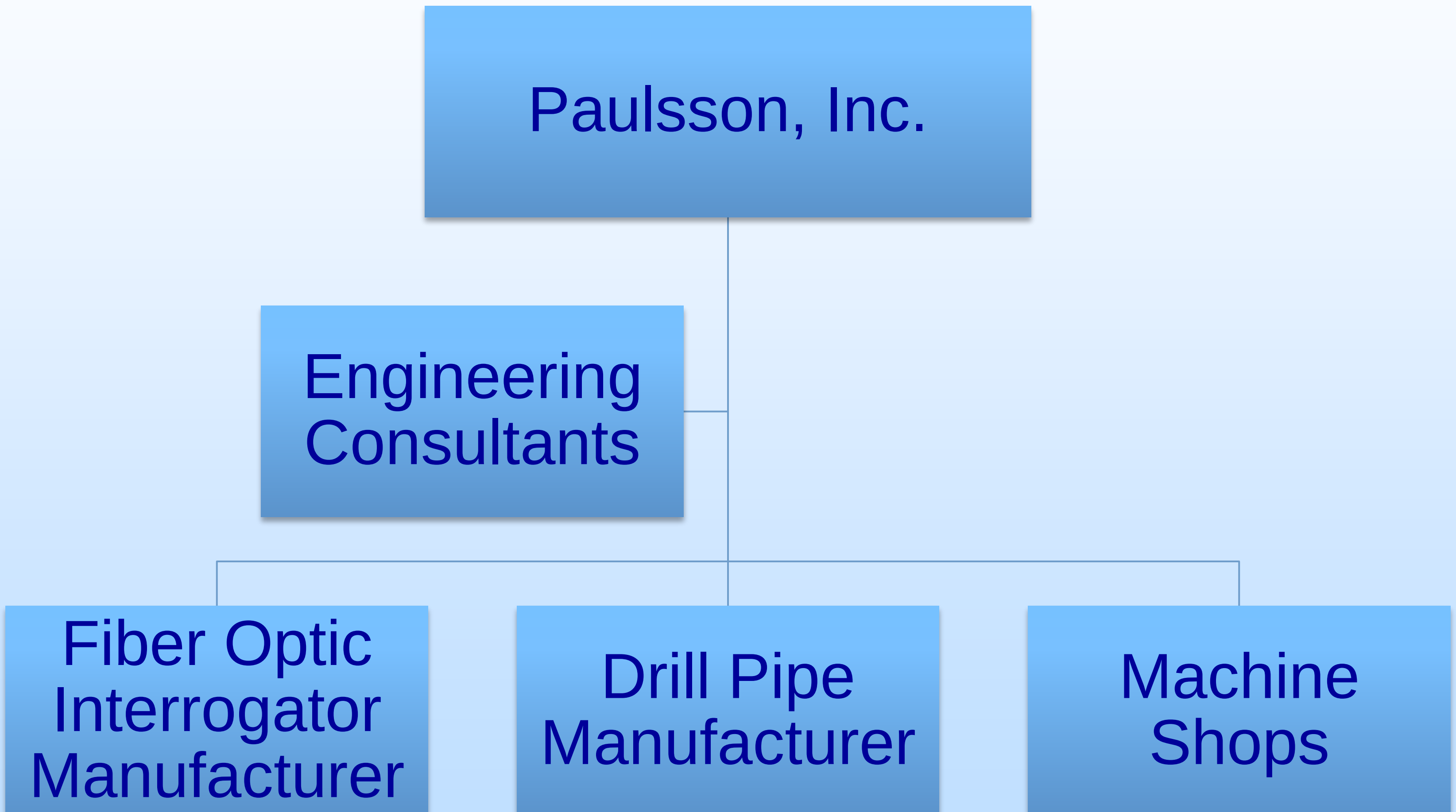
Appendix

– These slides will not be discussed during the presentation, but are mandatory

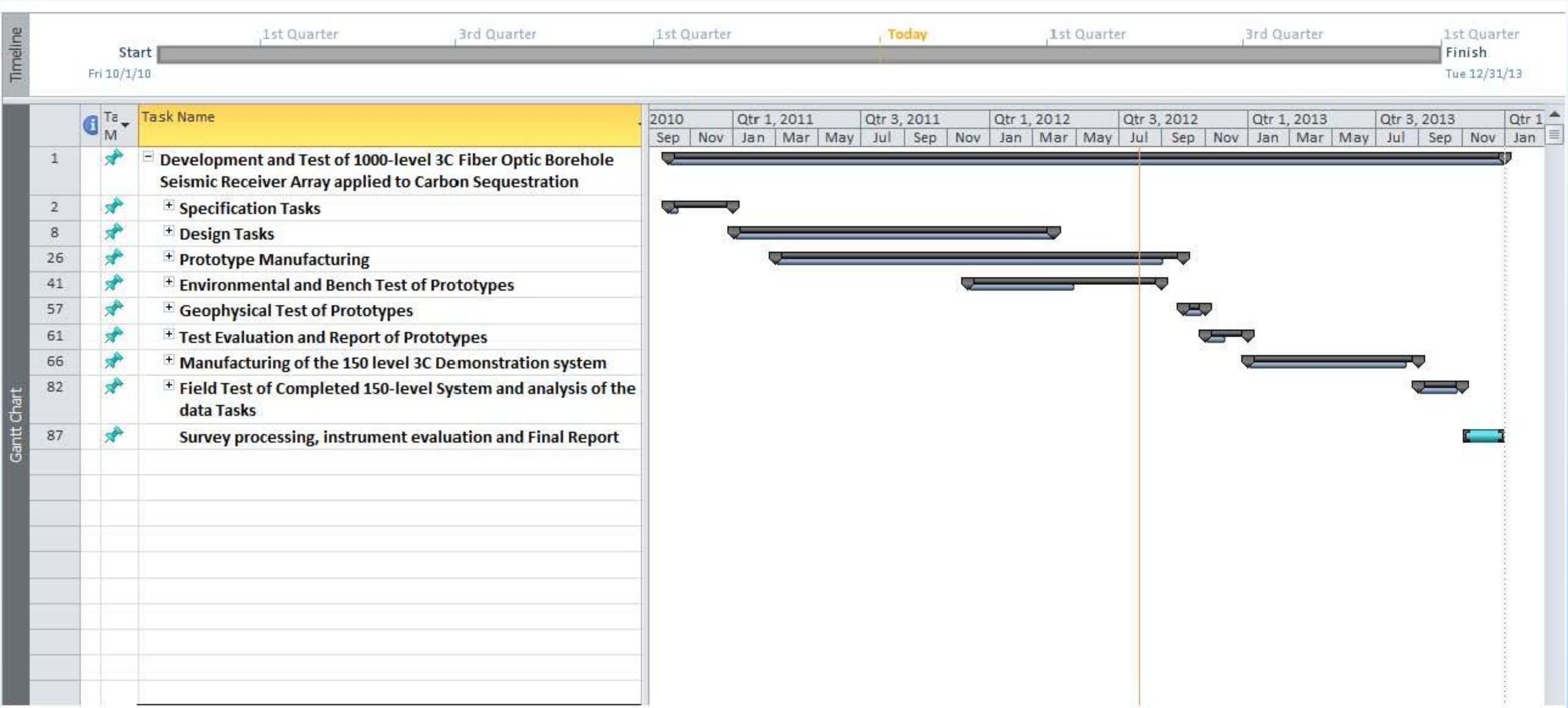
Project Team and Project Organization

- Project Team
  - Paulsson, Inc.
    - Principal Investigator, System design, Fiber Optic Sensor Design and Manufacturer, Design geophone pods
  - Fiber Optic Interrogator Manufacturer
    - System noise abatement, Interrogator design & manufac.
  - Drill Pipe Manufacturer
    - Design tool joints, manufacture drill pipe and related components
  - Machine Shops
    - Manufacture geophone pods, geophone pod housings and other components

Paulsson Organization Chart



Paulsson Fiber Optic Geophone Project Gantt Chart



Bibliography

List peer reviewed publications generated from project per the format of the examples below

- First Publication Expected in 2013