Paulsson, Inc. (PI)

Björn Paulsson, Mike Wylie, Ruiqing He

CO_2 Storage, Monitoring, Verification and Accounting

Development of an Optical Based Well Seismic System (OBWS) for CCUS, UGS+H2, EGS & ECEOR Characterization and Monitoring (Think - Much More than DAS!)

Whole Value Chain Carbon Capture, Utilization, and Storage (CCUS) September 24, 2025

We Need New and Effective Sensors to Monitor and Account for CO2 in CCUS

Technology used Today:

- Surface Geophones deployed in Noisy & Attenuating Envir.
- Surface Geophones – Far Away/Low Freq P-wave
- Surface Seismic Sources (VibSeis) – Low Freq (<100 Hz)
- Borehole Geophone Arrays – Short: 12-24 Levels

For Effective Surveying and Monitoring we Need P+S waves:

- Extreme Sensitivity & and large Bandwidth (kHz)
- Large Borehole Seismic 3C Vector Sensor Arrays
- Large Aperture Borehole Acoustic Arrays (DAS)
- High Frequency Borehole Seismic Sources (1,000 Hz)
- Real Time True Depth Processing and Imaging

Survey and Monitoring Markets (>$2 Trillion)

- Underground Gas Storage (UGS: NG, NG+H2, H2)
  - Today 15,000 wells @ 412 sites. 3,000 wells (20%) at risk. >$750 Billion USA Market by 2026.
  - Carbon Capture Utilization and Storage (CCUS)

    >14,000 wells to be drilled before 2050 ~ $750 Billion
- Enhanced Geothermal Systems (EGS) – Super Hot (500°C)
  - EGS Potential: 2.3TW = 2X Current US Electric Produc.
- Cleaner Enhanced Oil & Gas Recovery (CEOGR)
  - We currently leave 65% of oil behind in known locations
- Nuclear Energy – generate and store Green H2
- Wind Energy Installations (WEI – OWCal) – store Green H2

Fiber Optic Seismic Vector Sensors (FOSVS) Funded by DOE

Attributes

- **Long term stability:** 30-year MTBF by the Navy
- **Very large bandwidth:** 5 Hz - 14,000 Hz
- **Extremely sensitive:** 1,000 X a geophone
- **Outstanding Vector Fidelity:** 80 dB, Geo~55dB
- **Very High Temperature Tolerant:** >320°C (700°C)

- **Intrinsically Safe and Very Robust**

High Resolution is Critical for Effective CCUS. The Subsurface is VERY COMPLEX! Below is Simple.

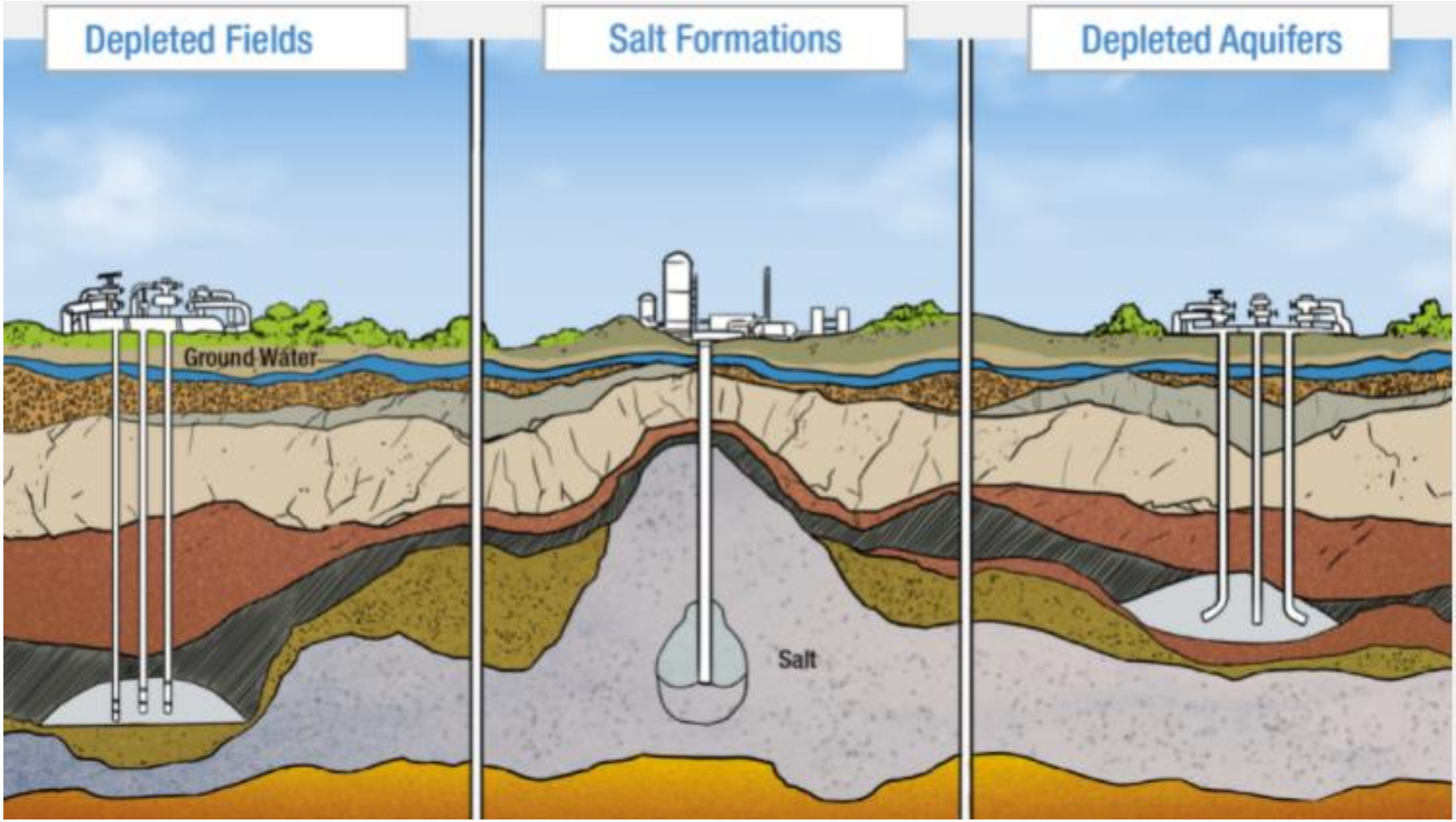


Figure from API showing three applications for improved imaging and monitoring for CCUS/CCS and UGS applications. From https://energyinfrastructure.org/energy-101/natural-gas-storage.

High Resolution is Critical for Effective CCUS. The Subsurface is VERY COMPLEX!

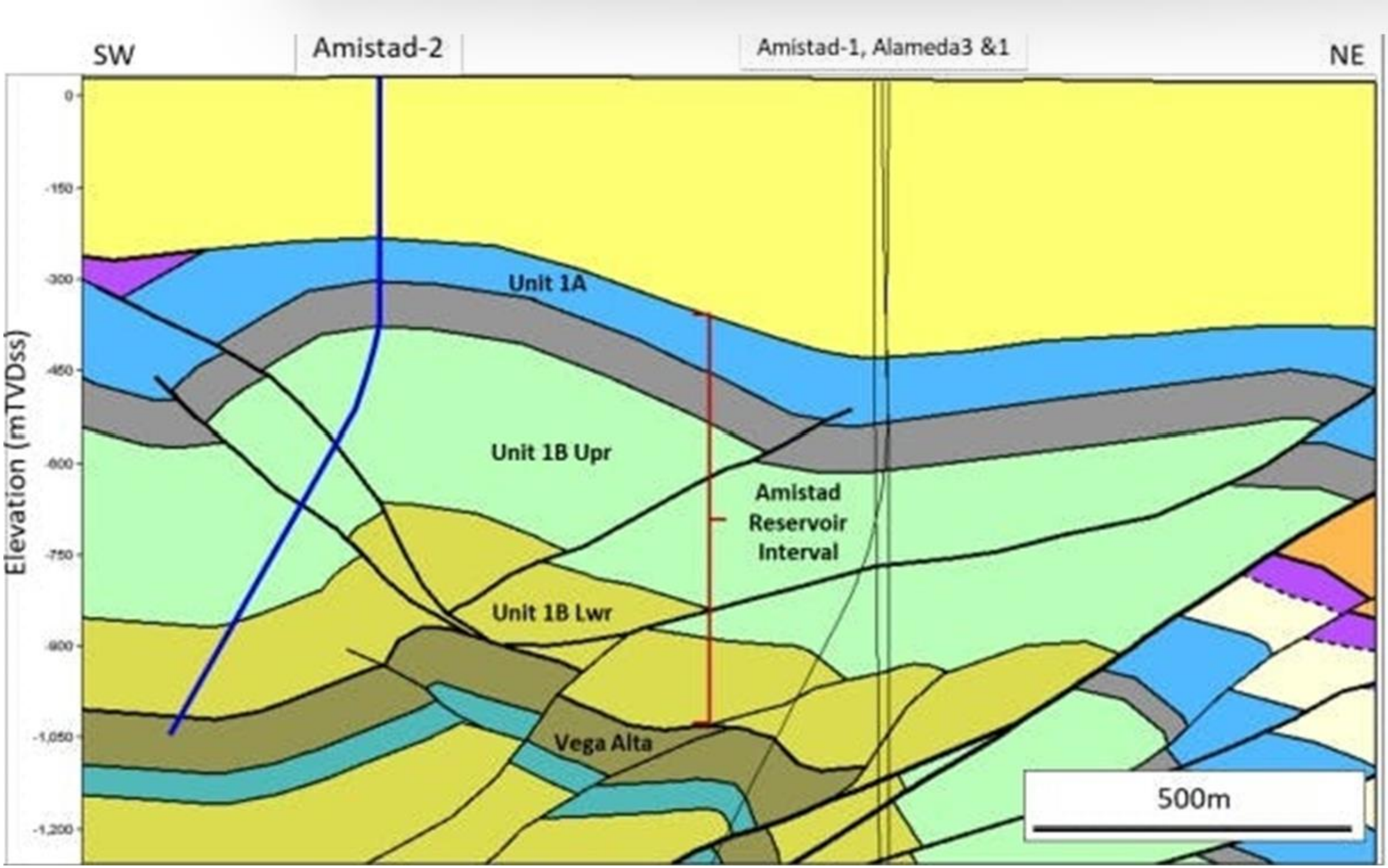


Figure from Oil & Gas Journal ogj@news.ogj.com September 23, 2025.

Presentation Outline

- Laboratory Tests of FO Sensors
- CCUS project with Battelle
- UGS project with PG&E
- Pipeline Monitoring (if time)

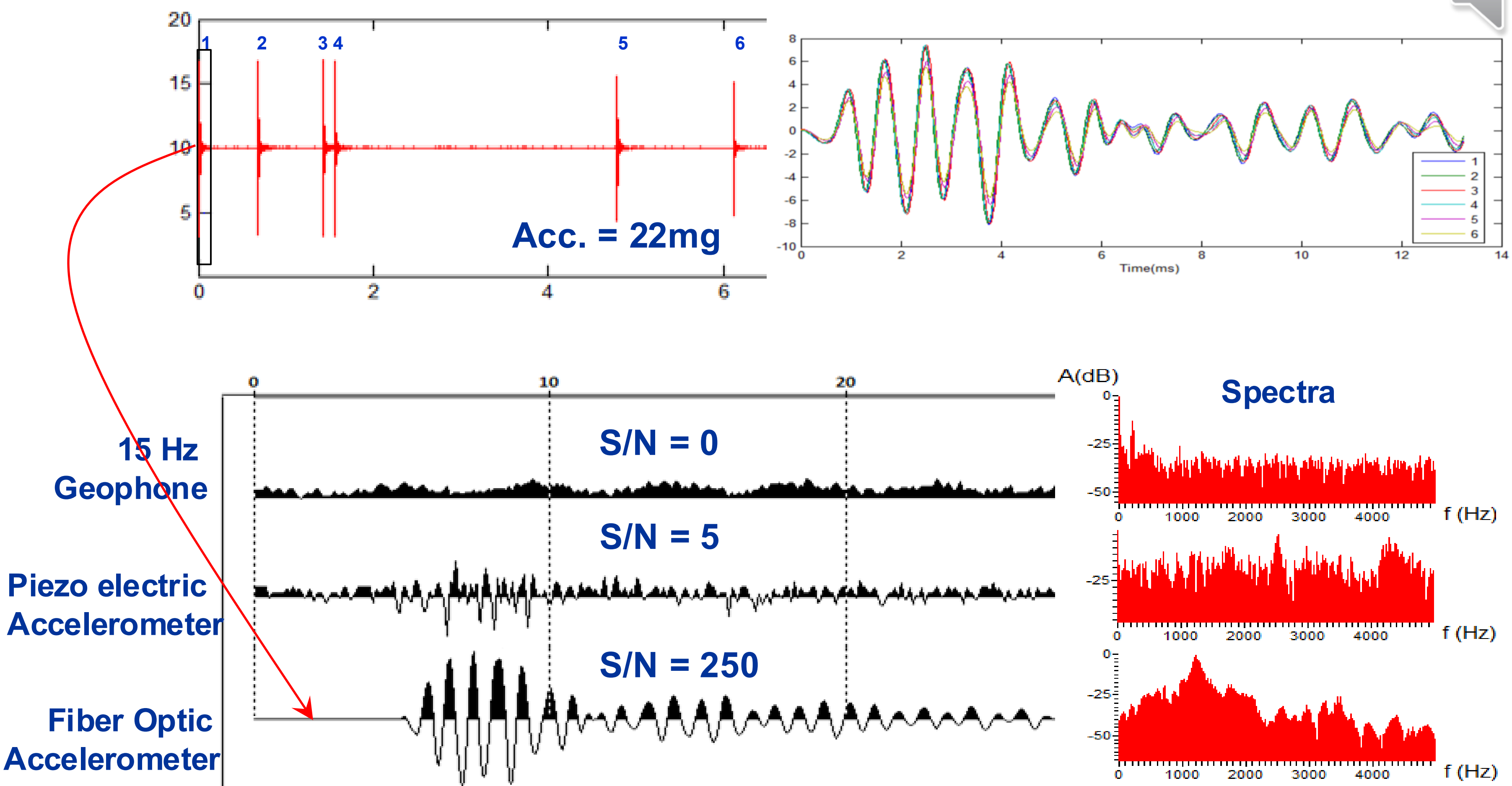
Presentation Outline

- Laboratory Tests of FO Sensors
- CCUS project with Battelle
- UGS project with PG&E
- Pipeline Monitoring (if time)

Test of Fiber Optic Seismic Vector Sensors (FOSVS.3) & IAME

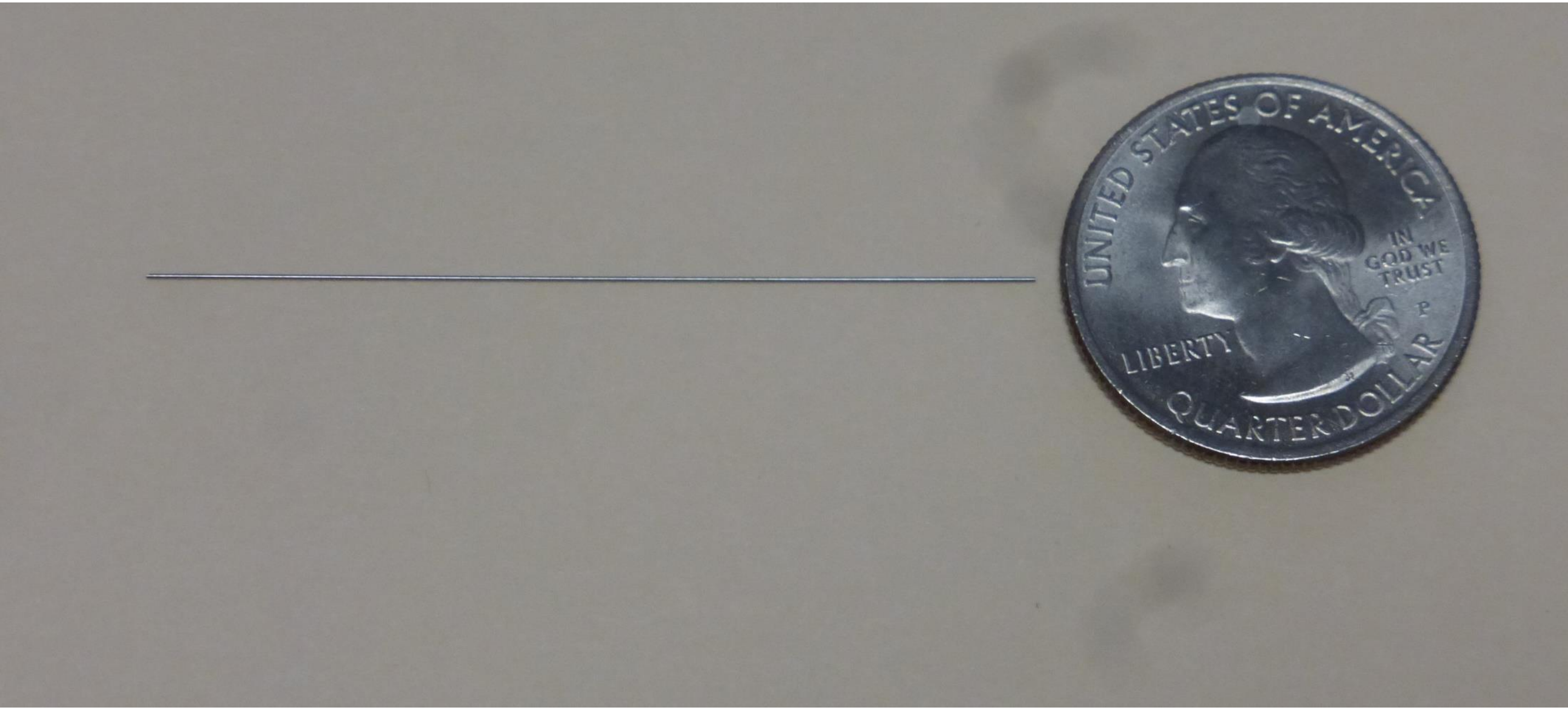
Pressure cell and sensor plate placed on a metal plate sitting on a foam mat on a metal table. Fiber sensor, geophone and accelerometer are placed approximately 20 cm (8 inches) from the pressure vessel with IAMEs

Repeatability Test: 6 Injectable Acoustic Micro Emitters (IAME's) recorded on FOSVS: Outstanding Repeatability. Allow extraction of arrivals in high noise environment. IAME Energy Released: ~0.3 J = M-3.5



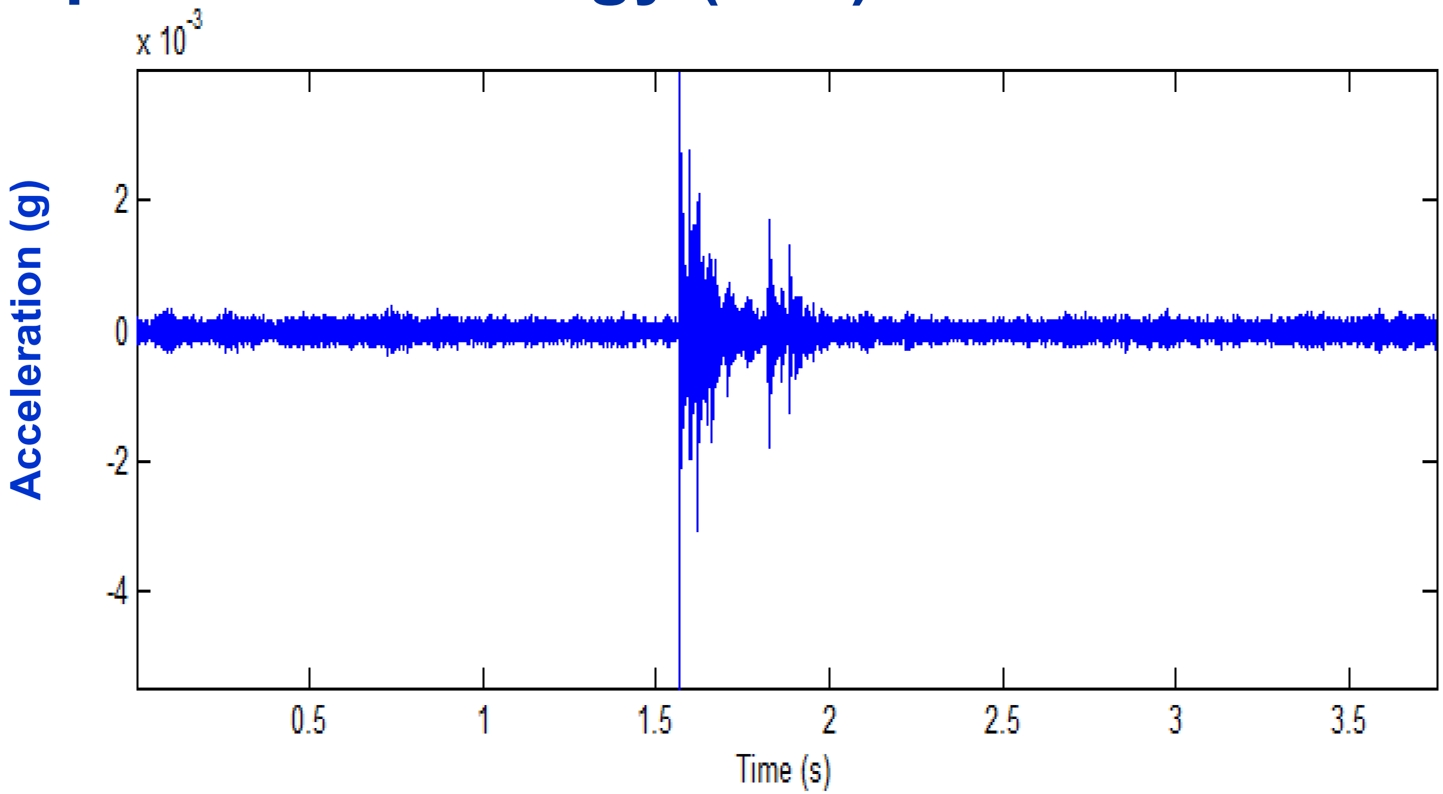
 Proprietary Material – Paulsson, Inc (PI).

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



FOSVS.3 Test: OD: 0.011”, 24.8 mg Pin Drop 10 mm:

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

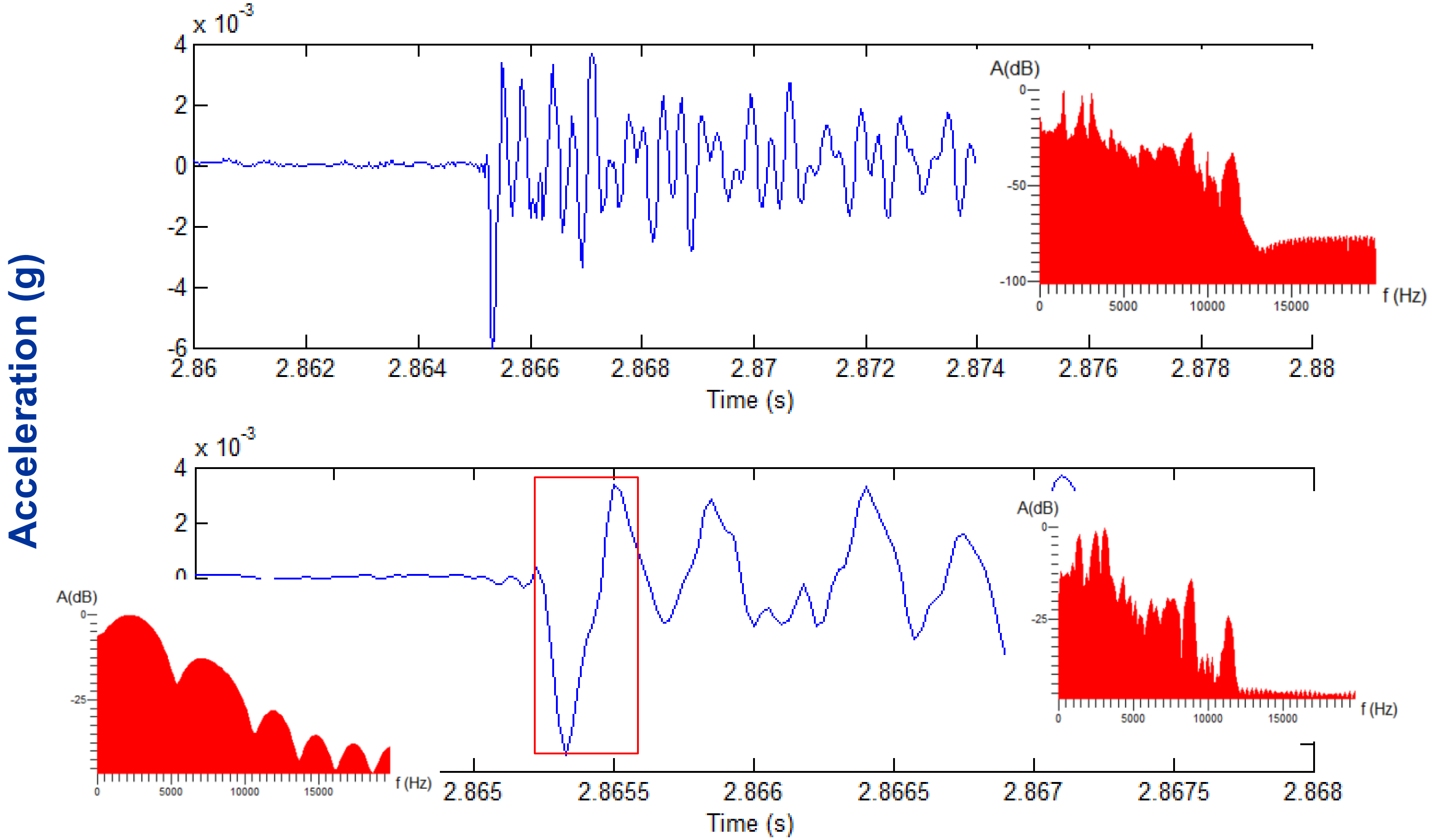


The FOSVS recorded ~17 bounces of the pin = <<M-7

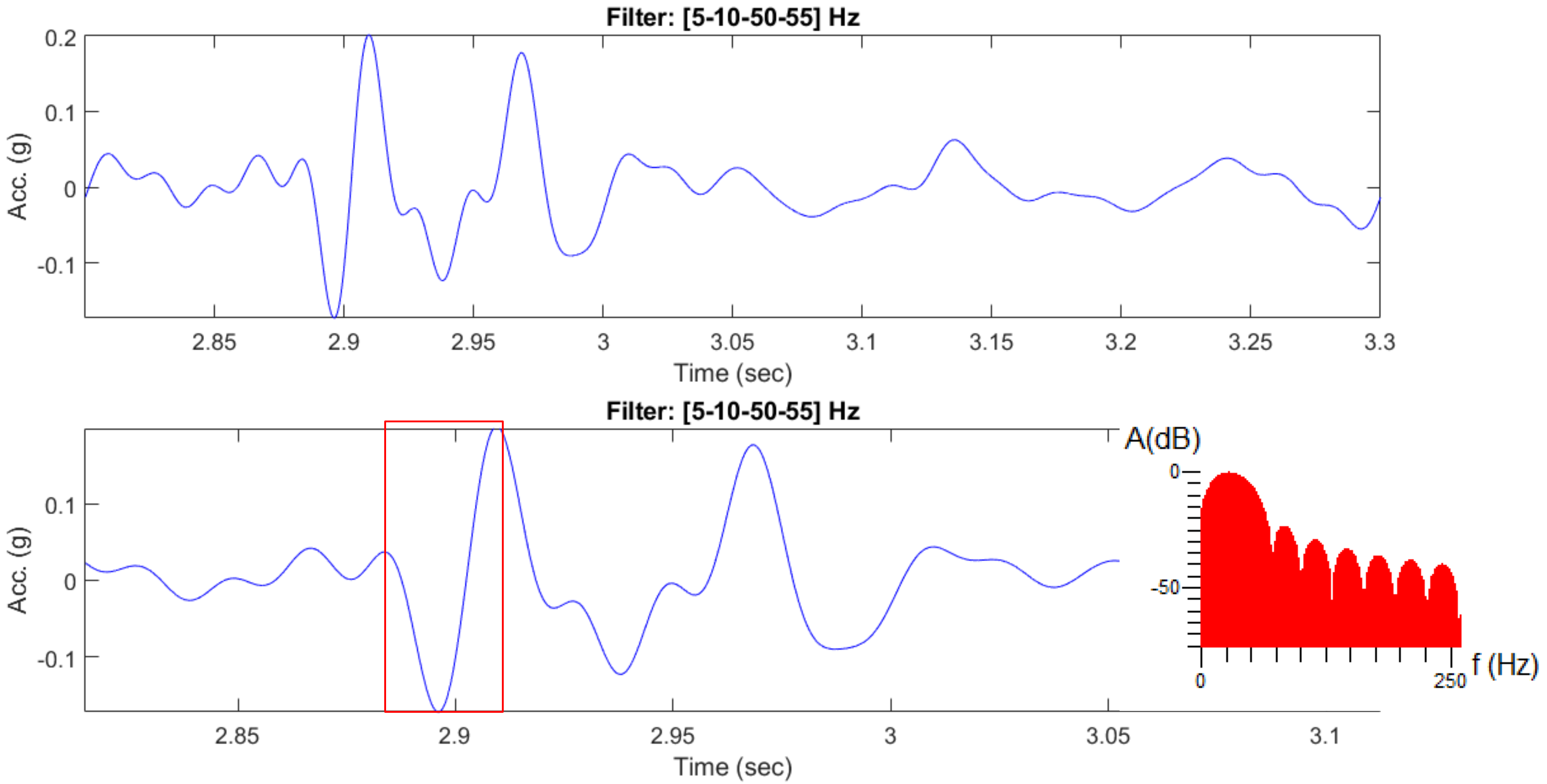
 Proprietary Material – Paulsson, Inc (PI).

FOSVS.3 Test: OD: 0.011”, 24.8 mg Pin Drop 1 cm:

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

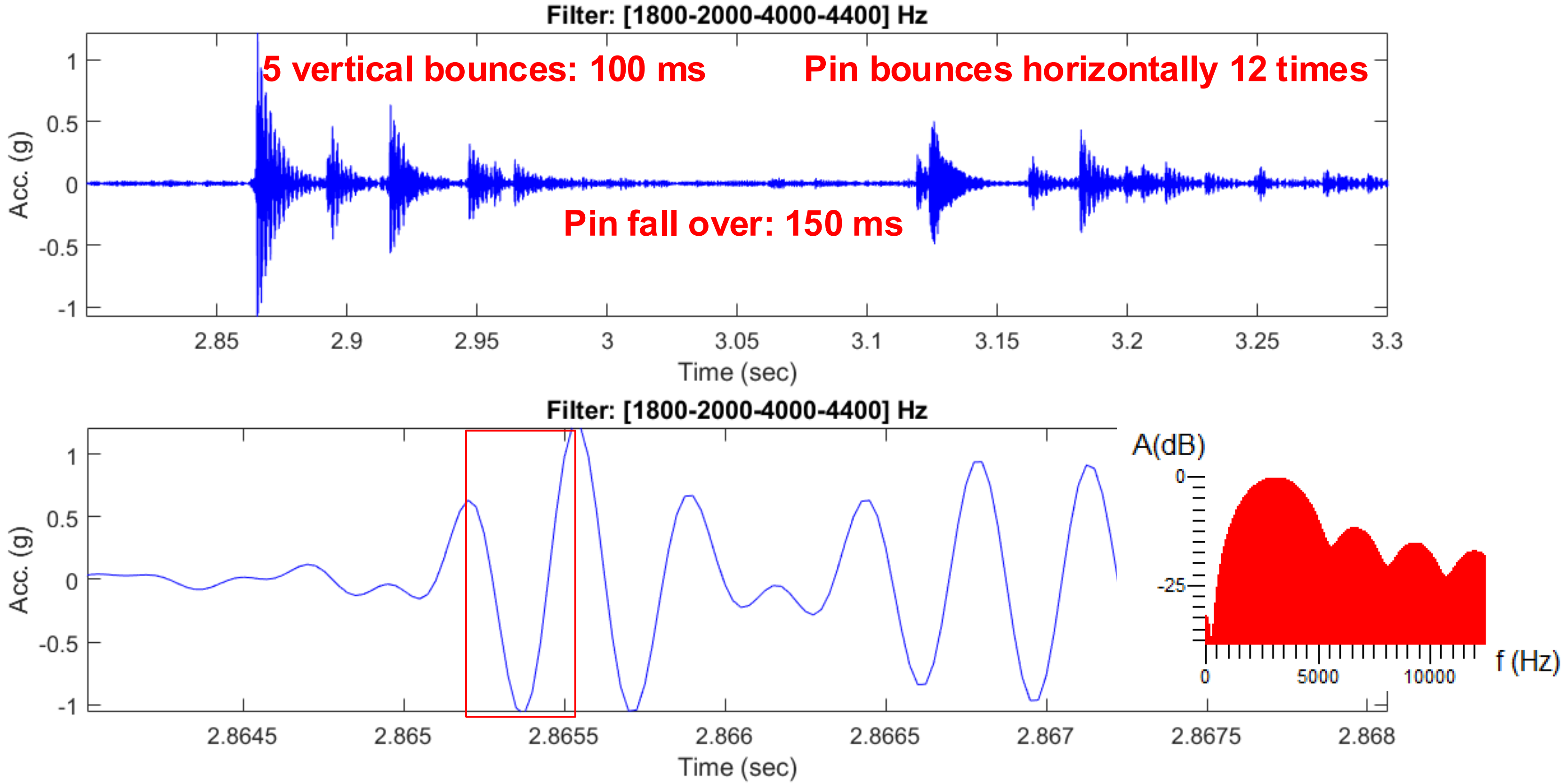


FOSVS.3 Test: OD: 0.011", 24.8 mg Pin Drop 1 cm: 2.5 µJ kinetic energy (M-7) on primary drop Ormsby Filter: 5-10-50-55 Hz (LOW FREQUENCY)



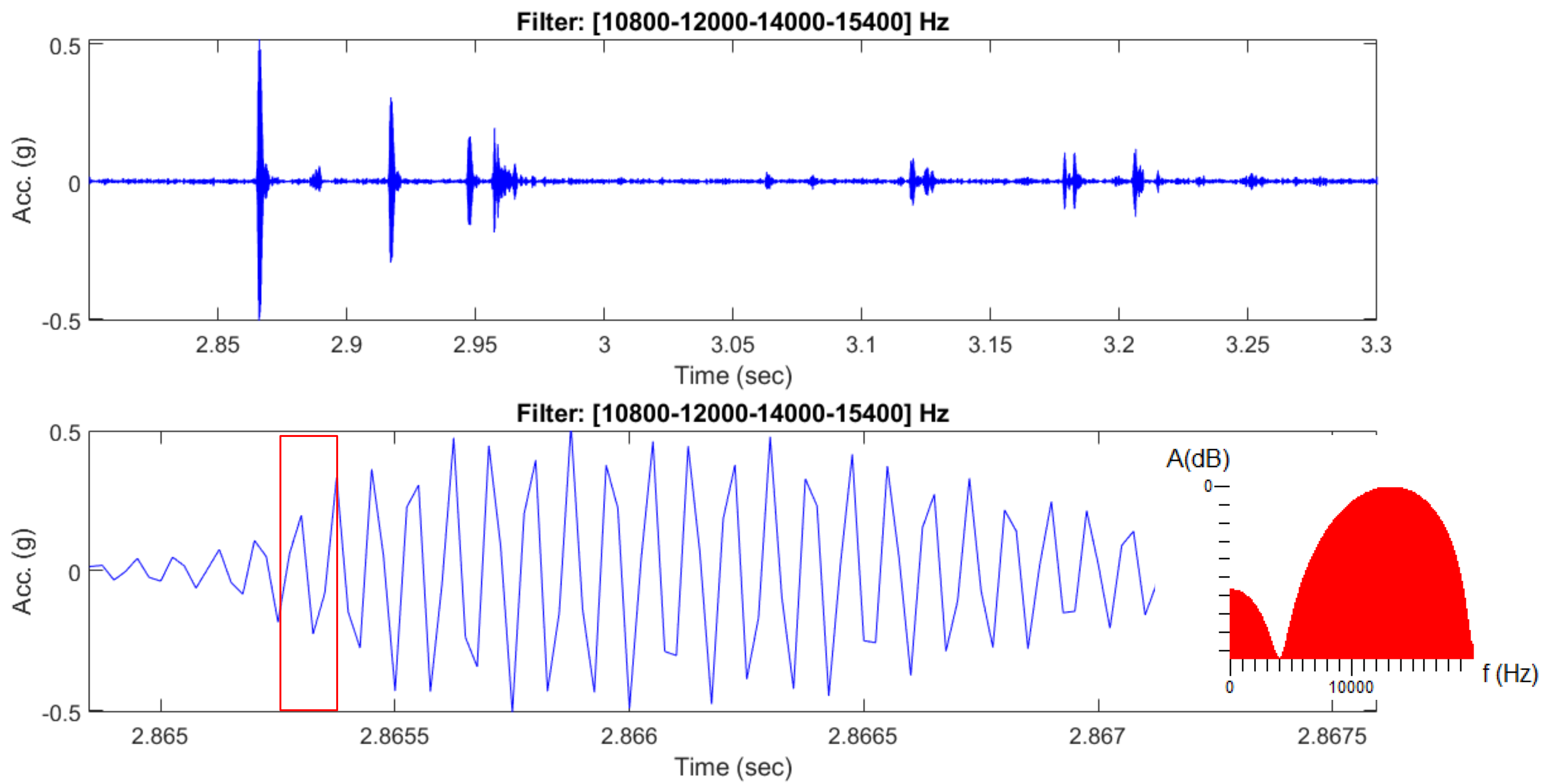
 Proprietary Material – Paulsson, Inc (PI).

FOSVS.3 Test: OD: 0.011”, 24.8 mg Pin Drop 1 cm: 2.5 µJ kinetic energy (Primary: M-7, Bounces: M-8) Ormsby Filter: 1,800-2,000-4,000-4,400 Hz



 Proprietary Material – Paulsson, Inc (PI).

FOSVS.3 Test: OD: 0.011”, 24.8 mg Pin Drop 1 cm: 2.5 µJ kinetic energy (Primary: M-7, Bounces: M-8) Ormsby Filter: 10.8-12-14-15.4 kHz (HIGH FREQ.)



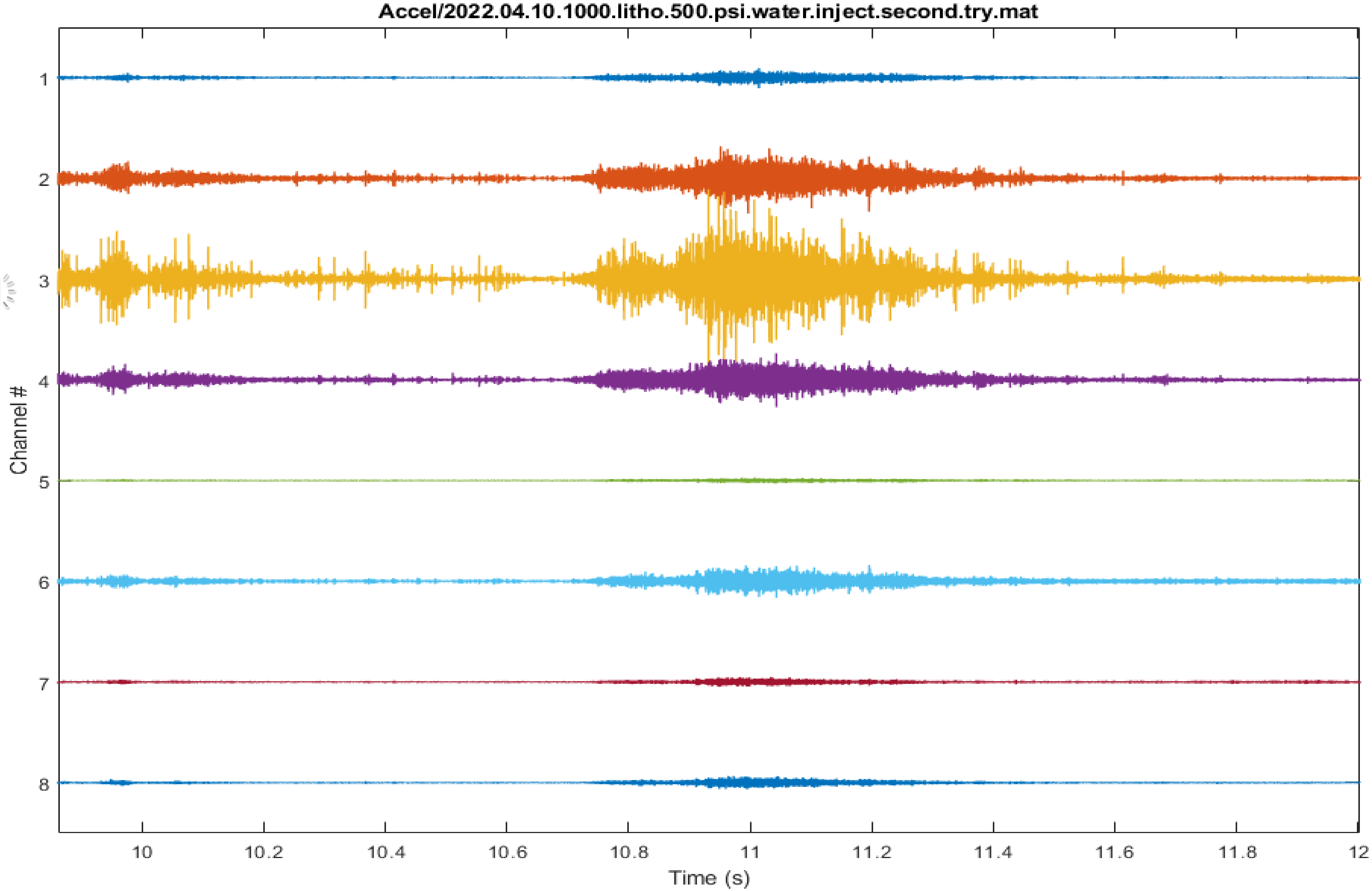
Lab Setup (Side View) of Fracture Fluid Flow MS Test

 Proprietary Material – Paulsson, Inc (PI).

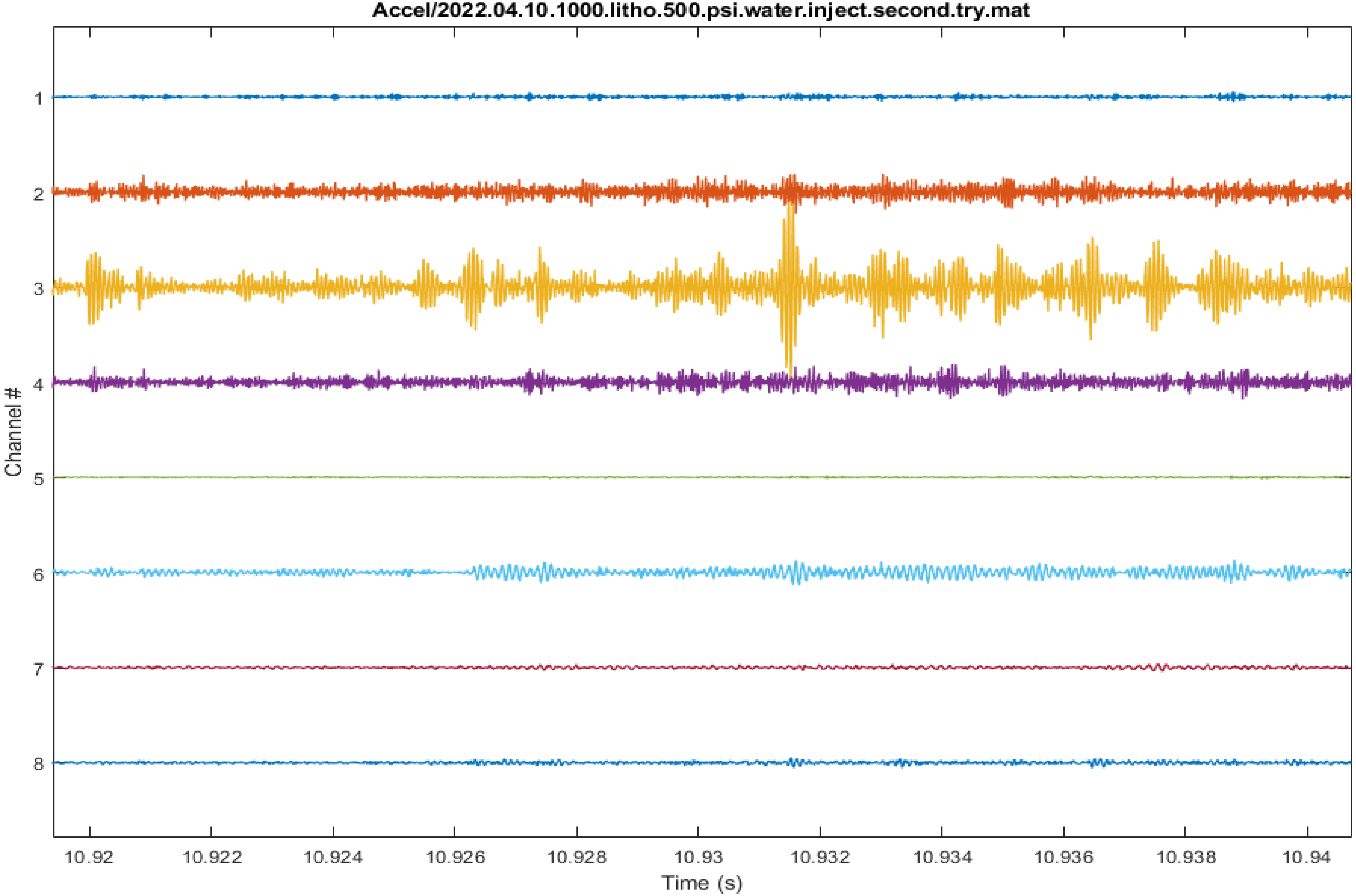
Pressures:

- 1,000 psi Lithostatic (288 tons)
- 500 psi H2O Injection

Accelerometer Data 2 seconds



Accelerometer Data 20ms



Downhole Seismic Source for Single Well Seismic Tool

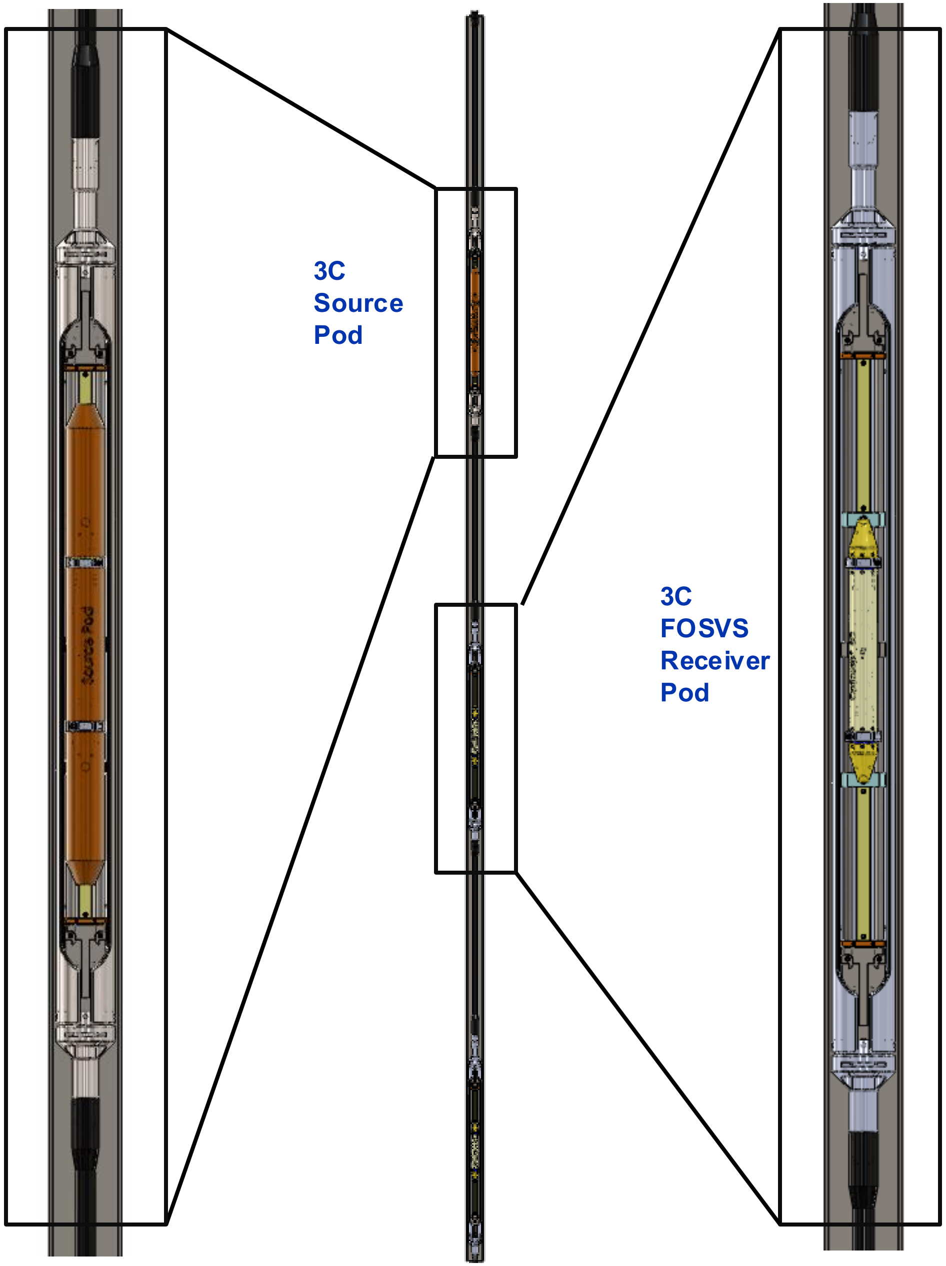
- By placing the Receivers in the borehole, we record 10X the frequency and get 10X the resolution compared with surface seismic!

- By placing both the source and the receivers we get much better than 10 X (i.e. 20-30 X) the frequency and resolution!

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

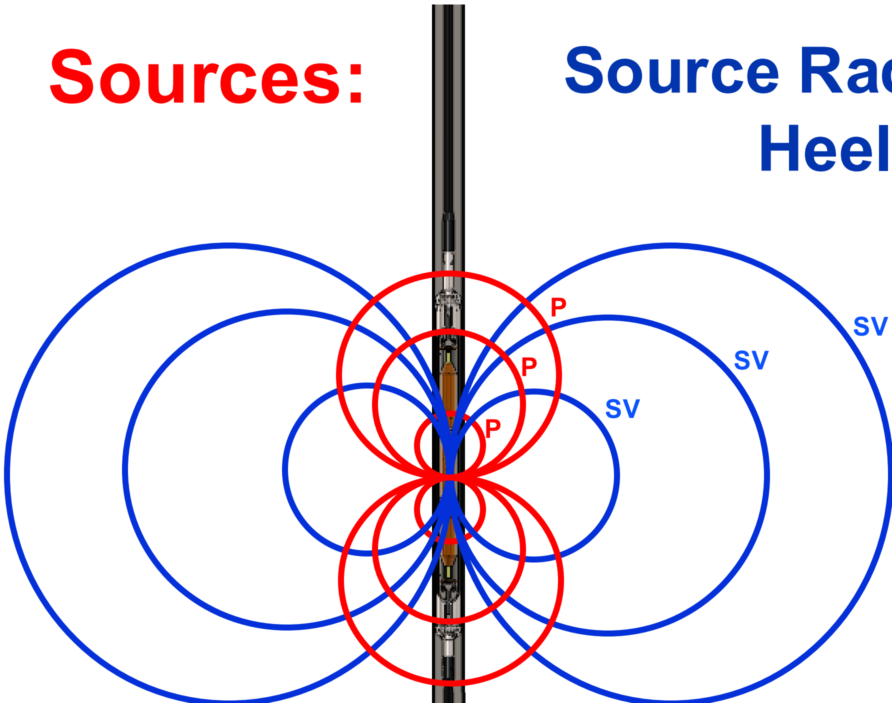
This is NOT a well Logging System – this is a Seismic System with a 10 – 3,200 Hz Operating Frequency.

This system will be able to image to a radius of >1,000 m (3,000 ft) – Q dependent of course.



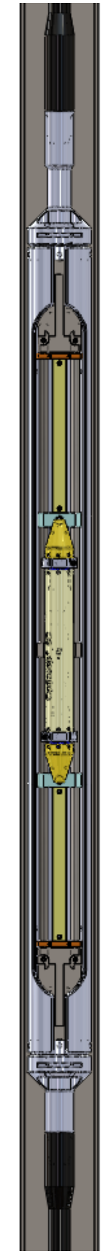
Sources:

Source Radiation Patterns
Heelan (1953)



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

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



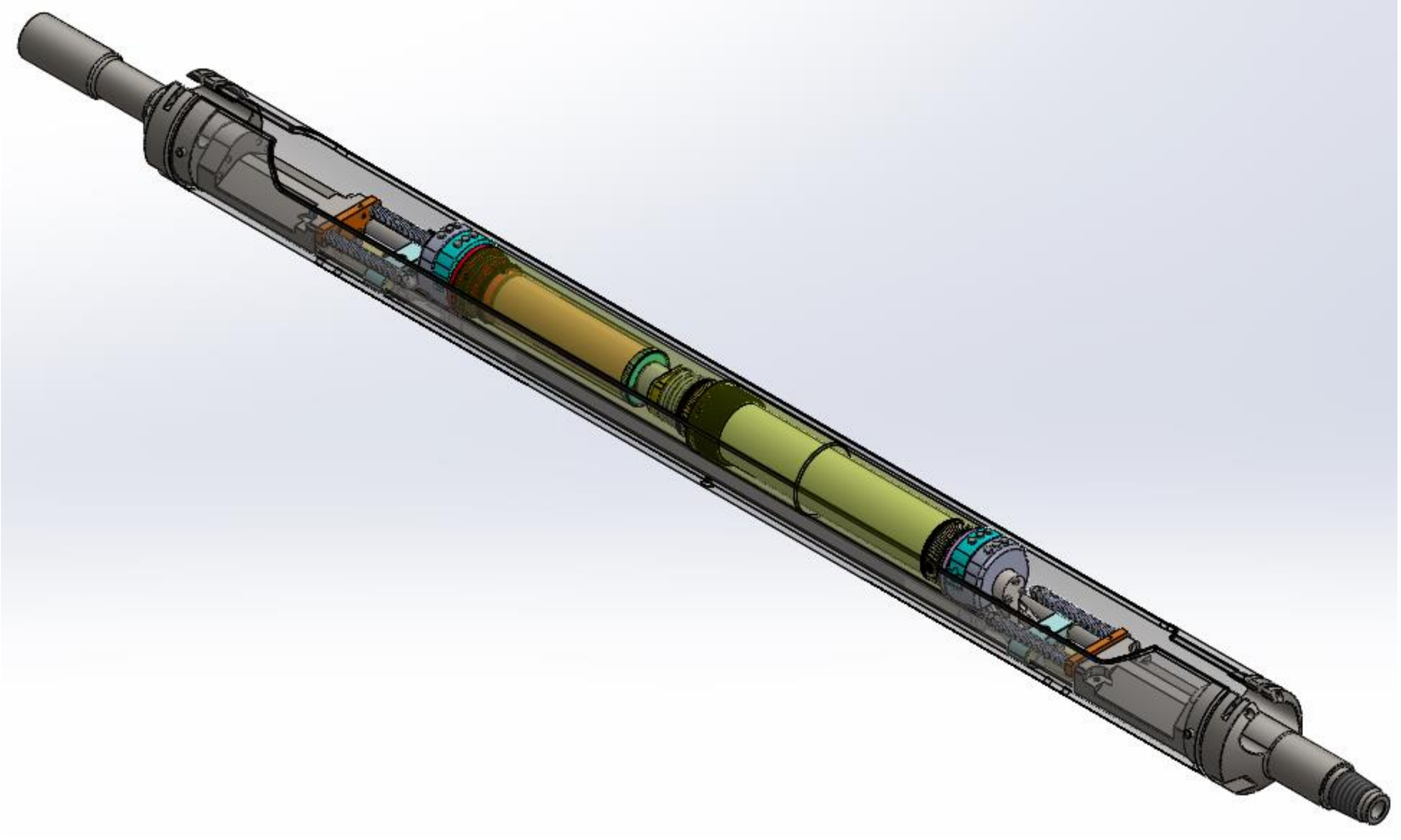
FOSVS Receiver Pod

 Proprietary Material – Paulsson, Inc (PI).

Task 4: Design Updates & Detailed Drawings as of March 16th, 2021

SAME SENSOR POD HOUSING AND PIPE AS USED FOR FOSVS RECEIVERS

Isometric - Resting Position



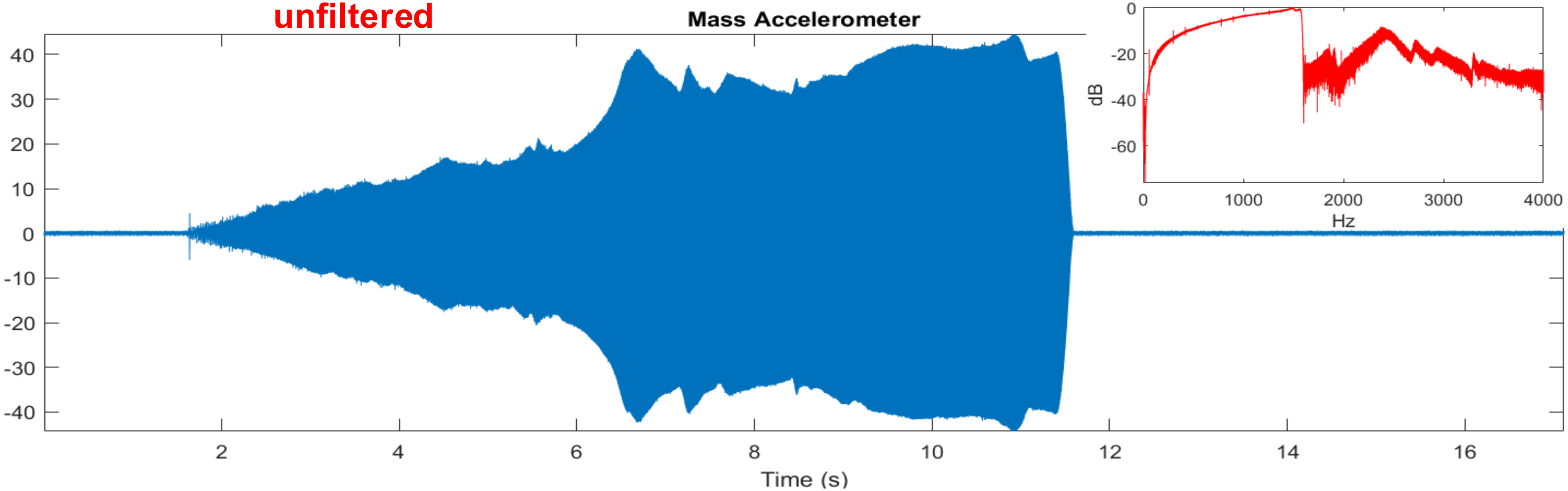
Laboratory and Small Scale Field Tests of Axial Vibrator Unit Developed under a US DOE Grant

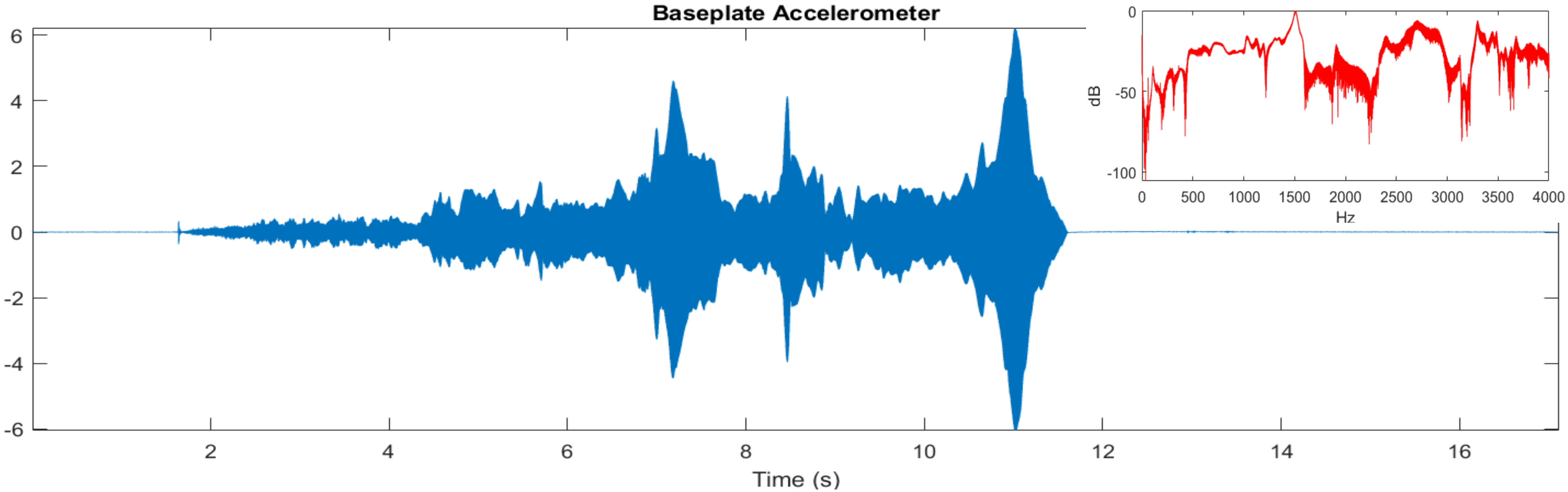
Test Fixture for a Downhole Seismic Vibrator: Actuator is the size of two soda cans

10-410hz, 10sec, 10vpp (200Vpp), 3.2kg, F=40 lbs.
Custom Sweep w/ $A=e^{x/8}$
Weight drop: 50 kg @ 60g

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

unfiltered

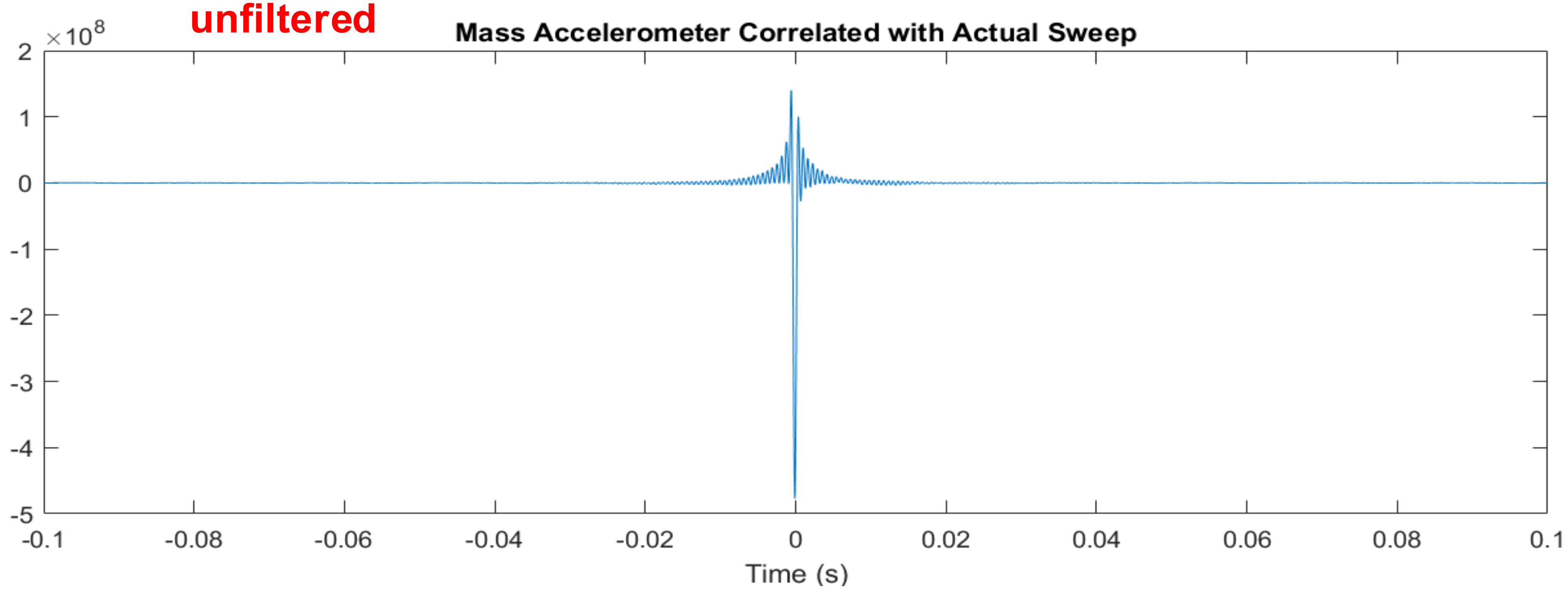


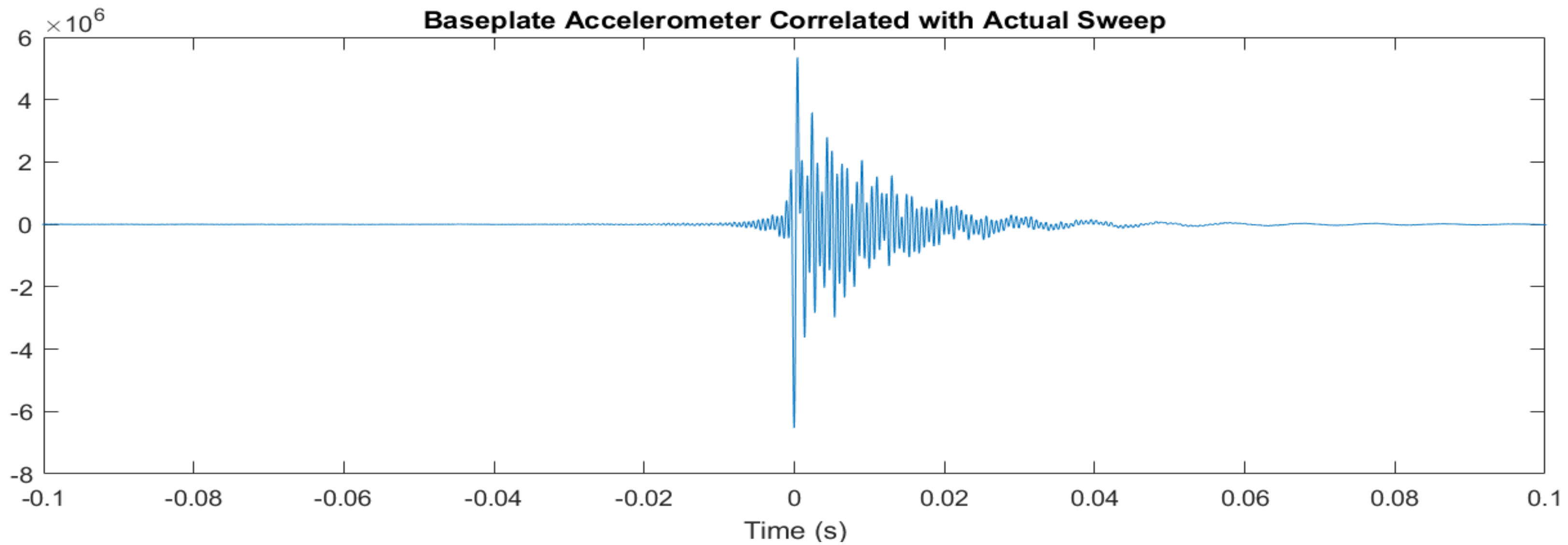


 Proprietary Material – Paulsson, Inc (PI).

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

unfiltered





Drops of a Steel Pin, Sugar Grains & Styrofoam balls Test Data Recorded on a FOSVS.3 accelerometer

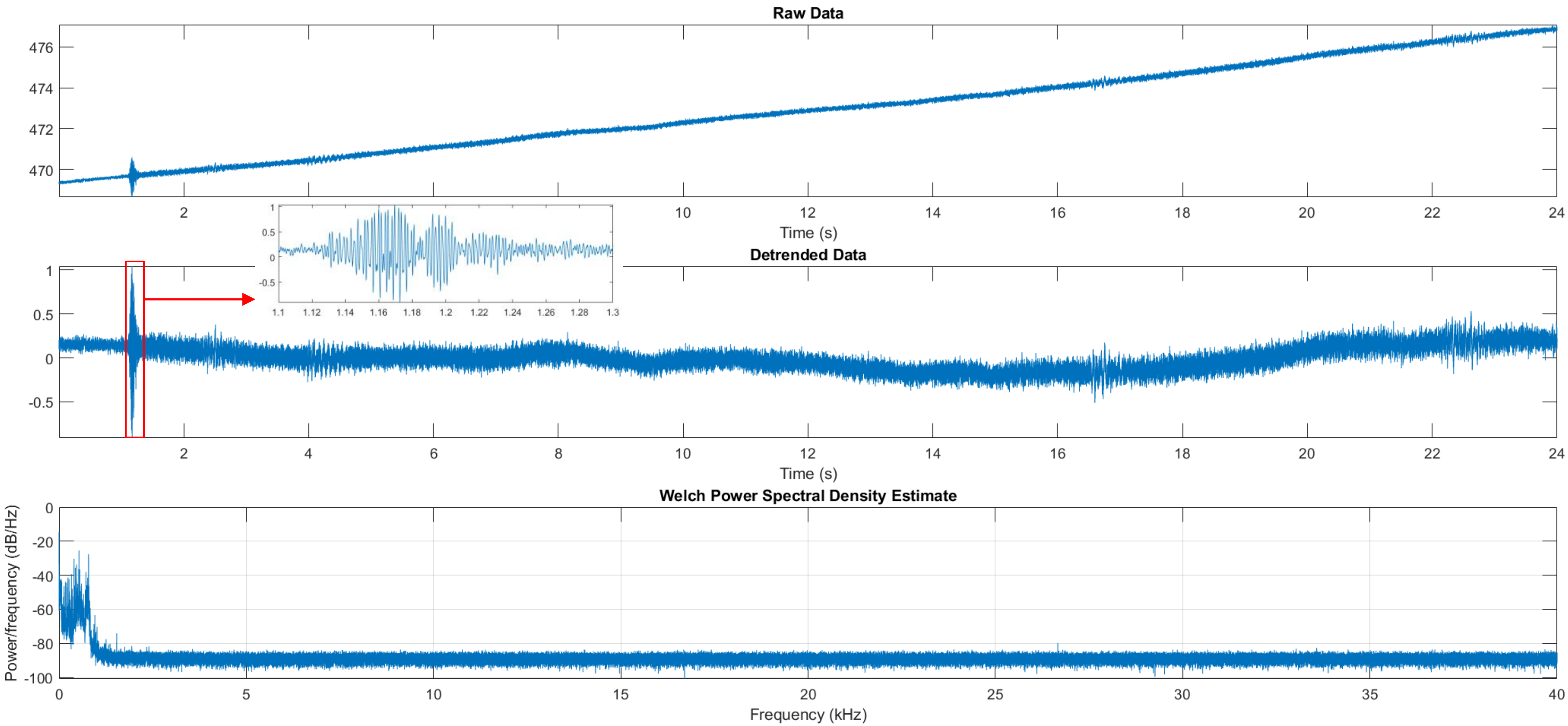
Paulsson, Inc. (PI)
March 21, 2025

Drop Test Photo. The FOSVS.3 Sensor is under the steel cap

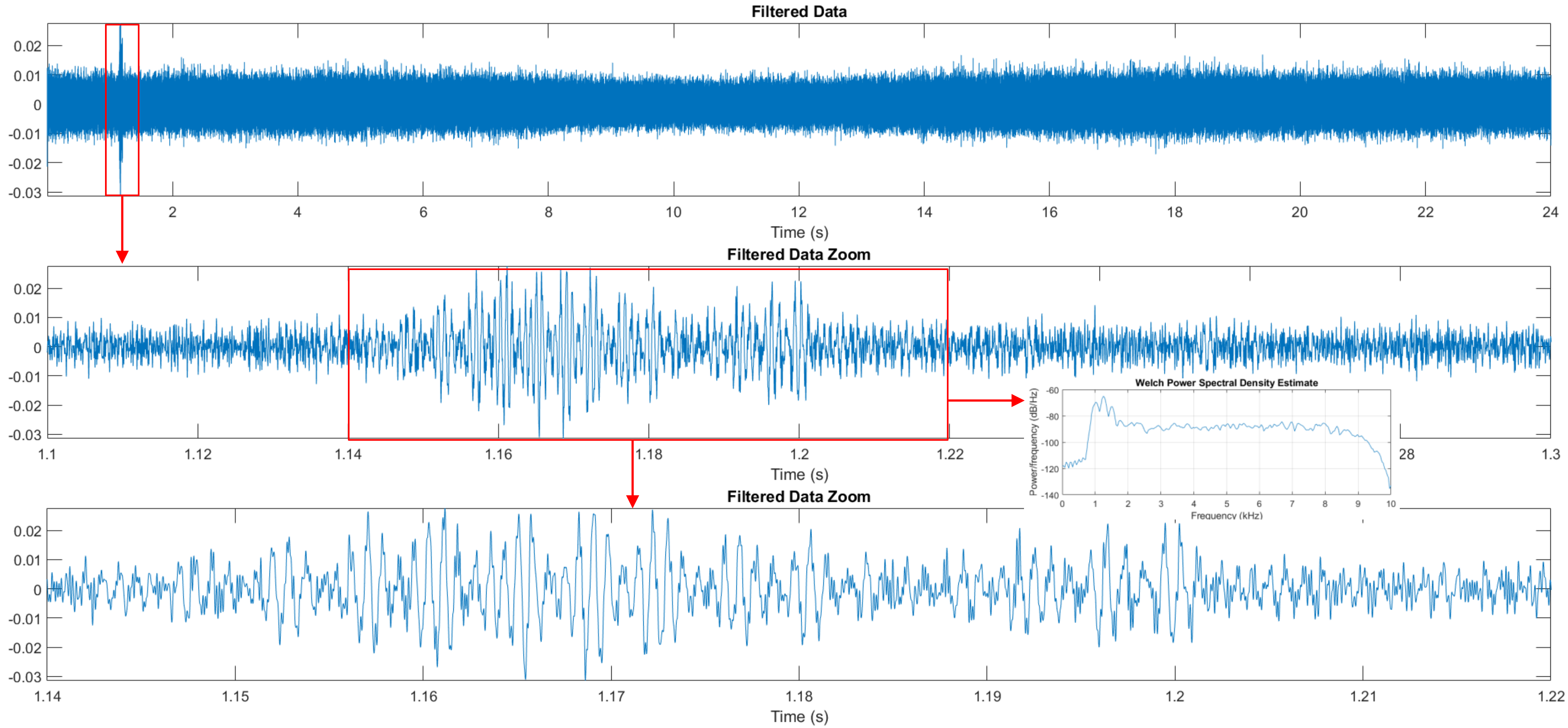
Recordings of FOSVS.3 Sensor Data

- Pin (25 mg) 10 mm Drops = 2.5 µJ
- Sugar Grain (0.2 mg) 25 mm Drops = 50 nJ
- Styrofoam Ball (0.5 mg) 10 mm Drops = 50 nJ

Background Noise:

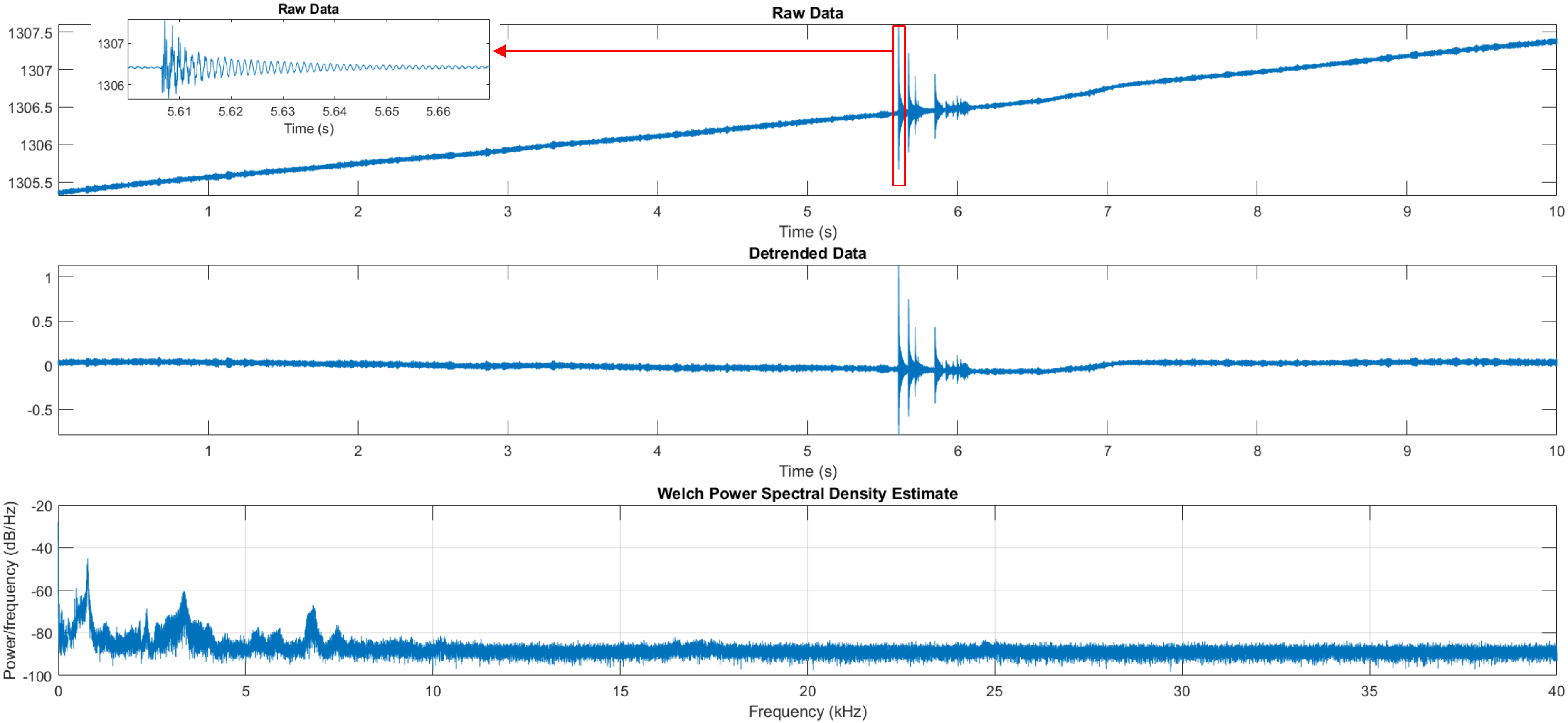


Background Filtered: 800-1000-8000-10000 Hz



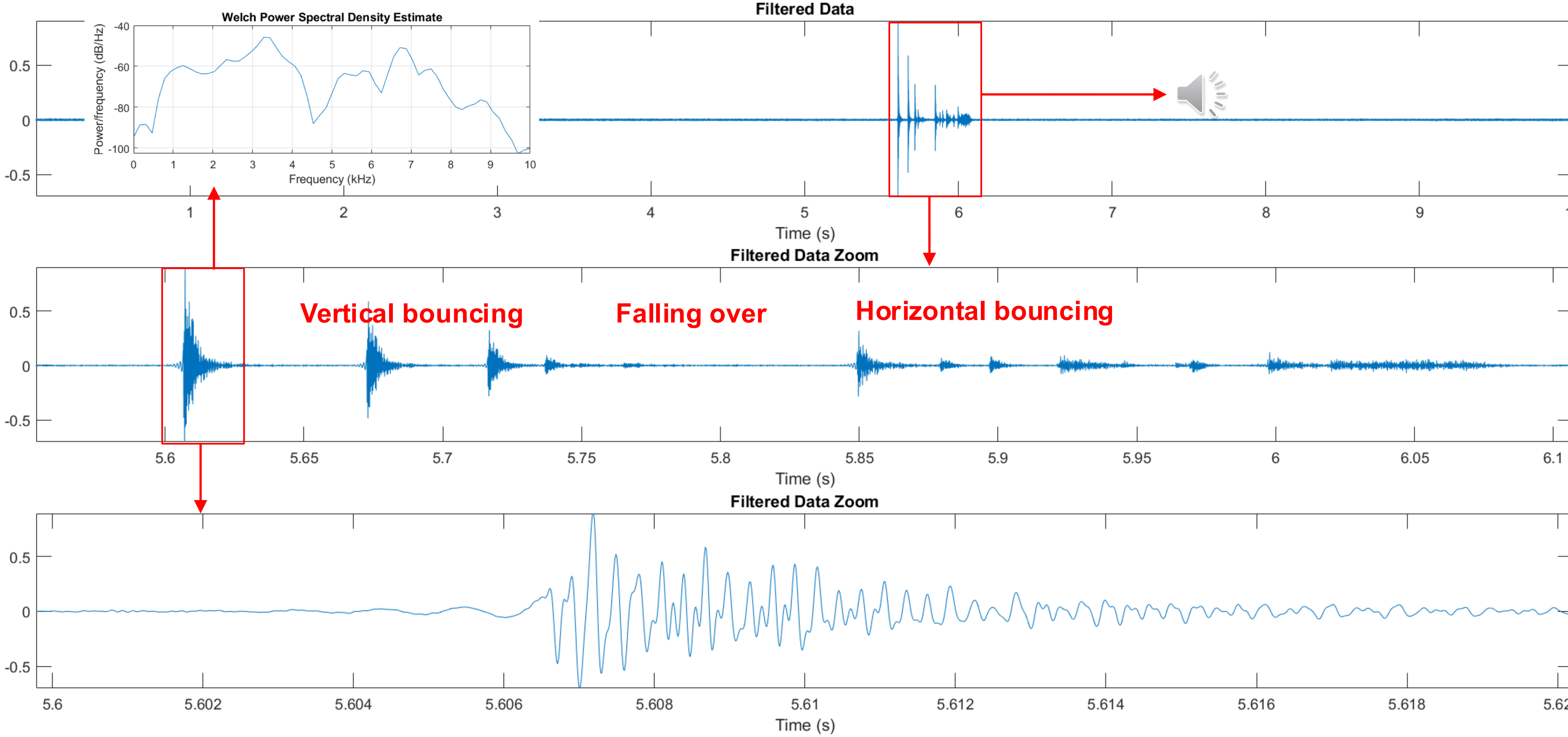
 Proprietary Material – Paulsson, Inc (PI).

1st Pin Test, 25 mg, 10 mm Drop Test: = 2.5 µJ
Raw - No Filter

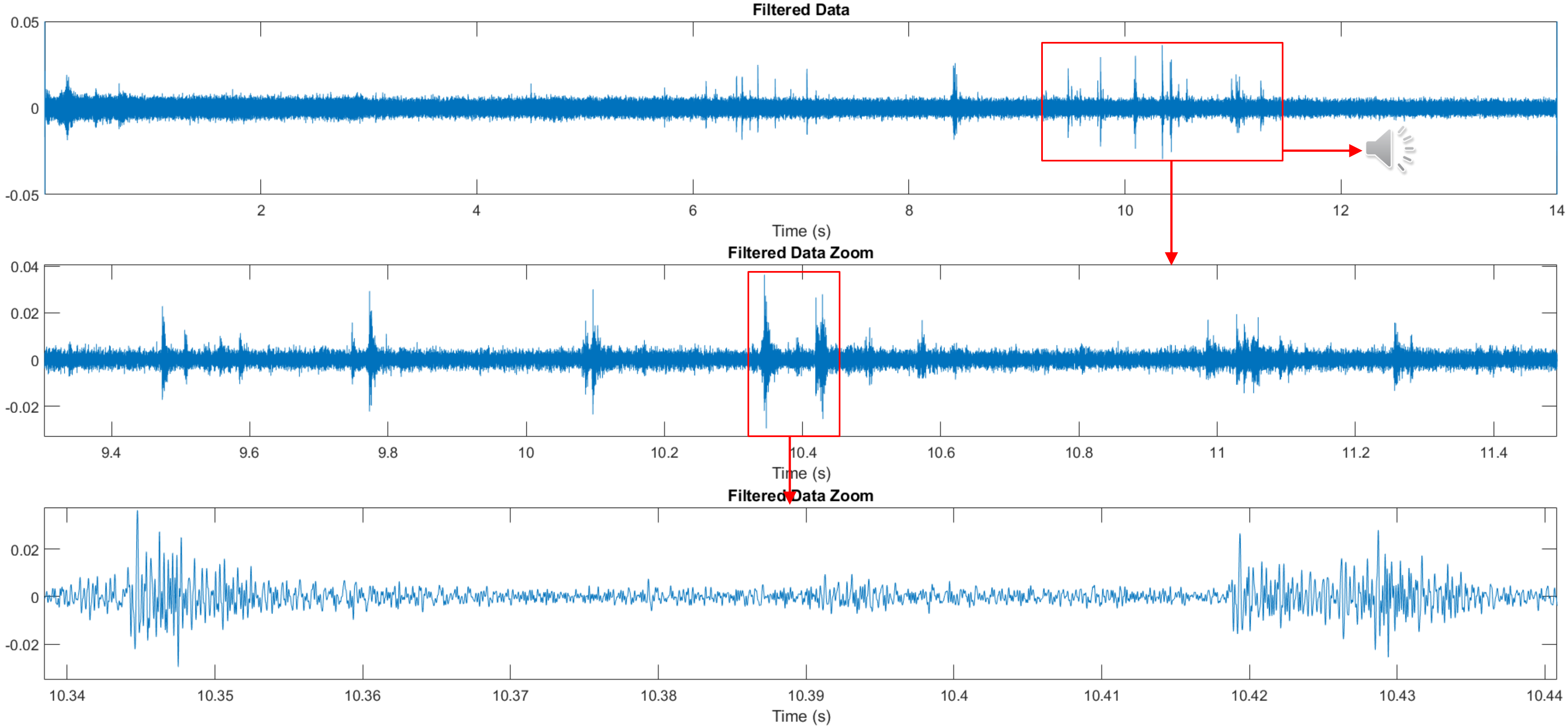


Pin Drop Test 1

1^{st} Pin Drop Test, m=25 mg, h=10 mm: = 2.5 µJ
Ormsby Filtered: 800-1000-8000-10000 Hz

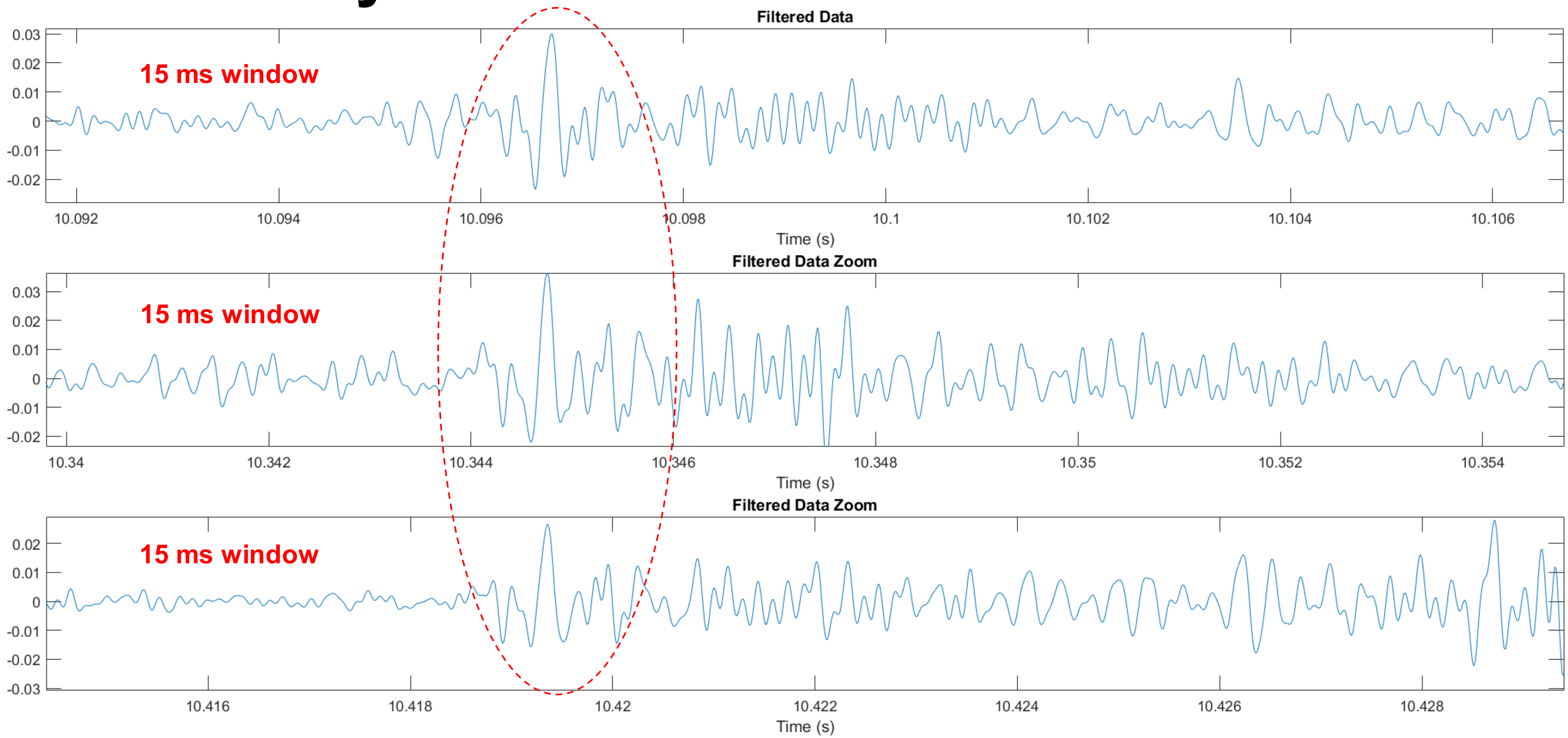


Sugar Grains (0.2 mg) 25 mm Drop Test: = 50 nJ
Ormsby Filtered: 800-1000-8000-10000 Hz



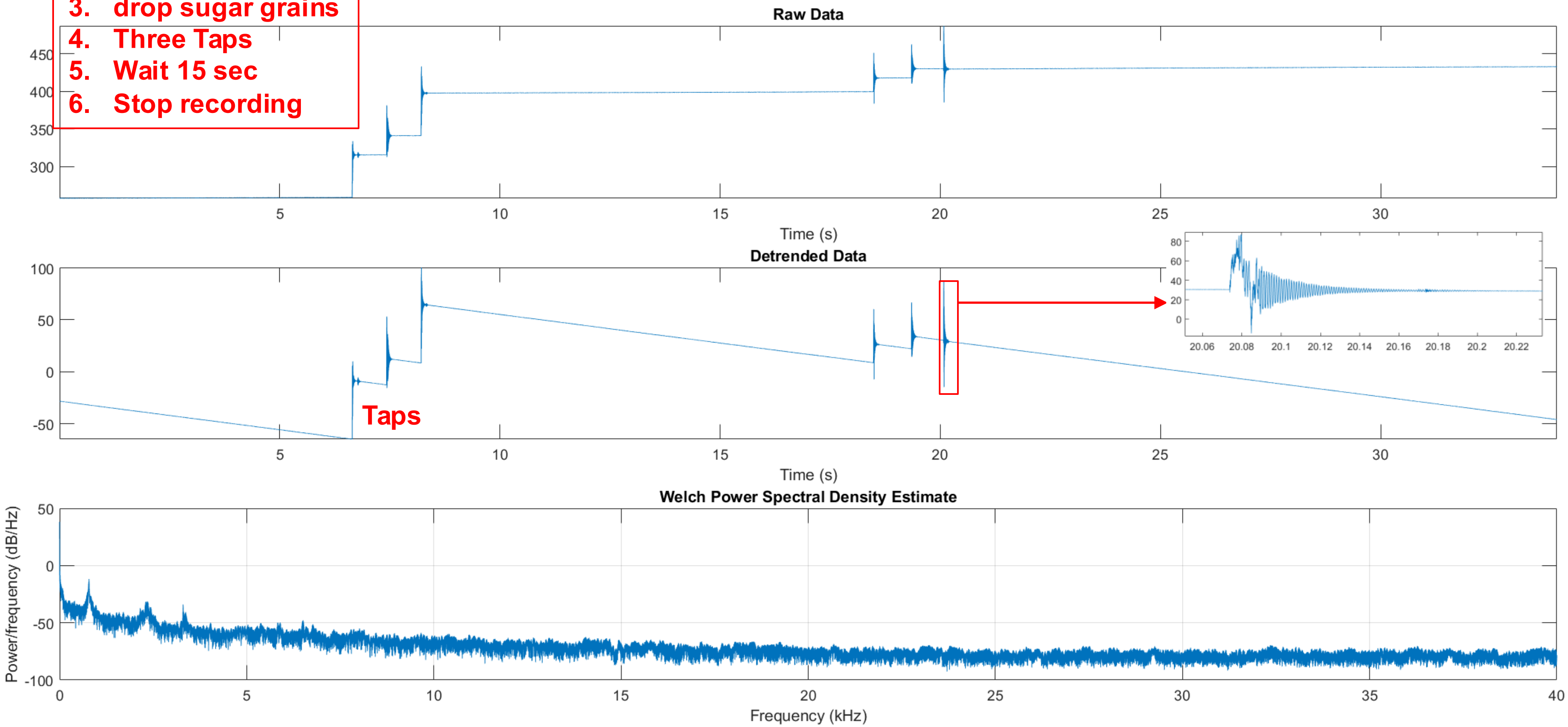
 Proprietary Material – Paulsson, Inc (PI).

Sugar Grains (0.2 mg) 25 mm Drop Test: = 50 nJ
Ormsby Filtered: 800-1000-8000-10000 Hz



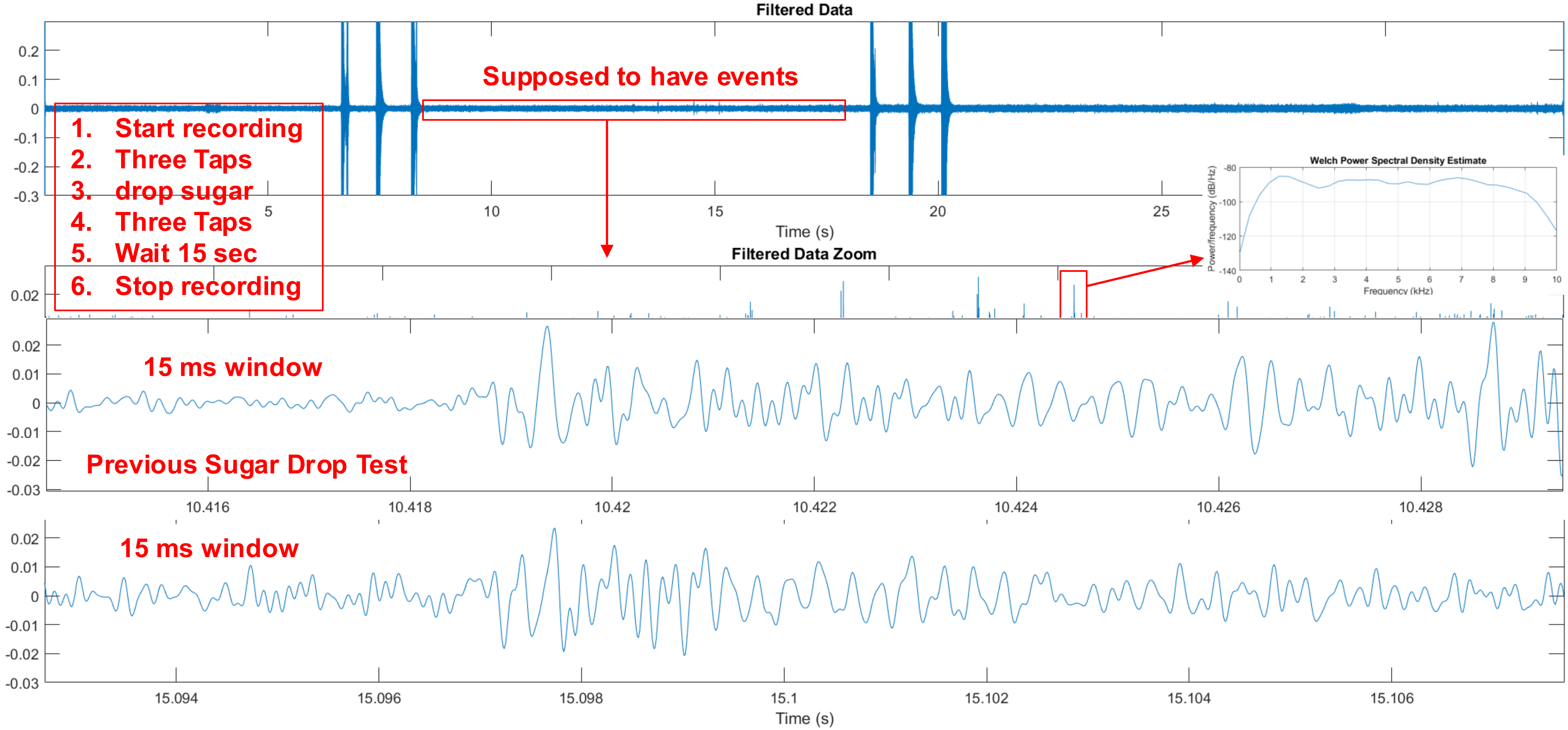
2nd Sugar Grains: 0.2 mg: 25 mm Drop: = 50 nJ
Raw - No Filter

1. Start recording
2. Three Taps
3. drop sugar grains
4. Three Taps
5. Wait 15 sec
6. Stop recording



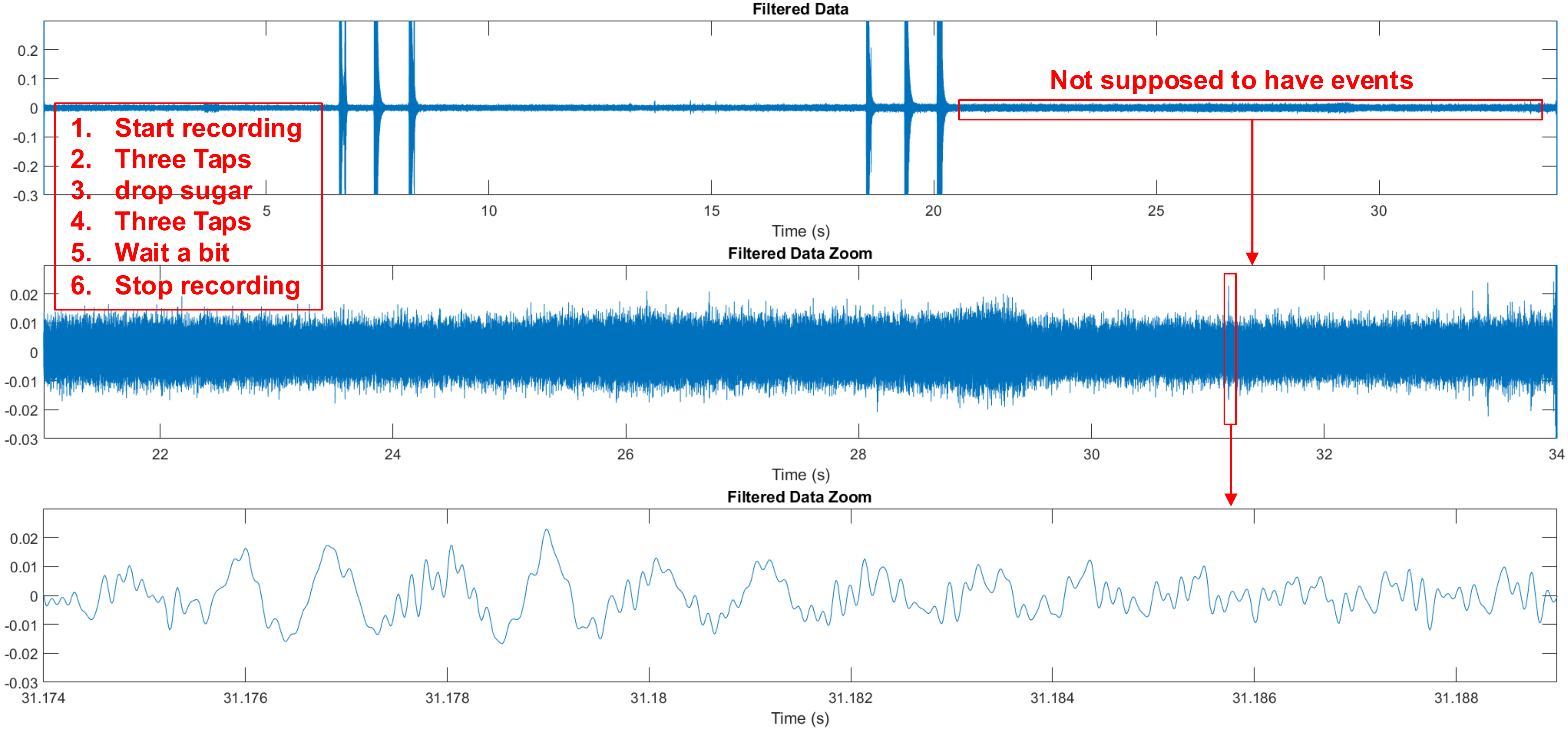
 Proprietary Material – Paulsson, Inc (PI).

2nd Sugar Grains: 0.2 mg: 25 mm Drop: = 50 nJ
Ormsby Filtered: 800-1000-8000-10000 Hz

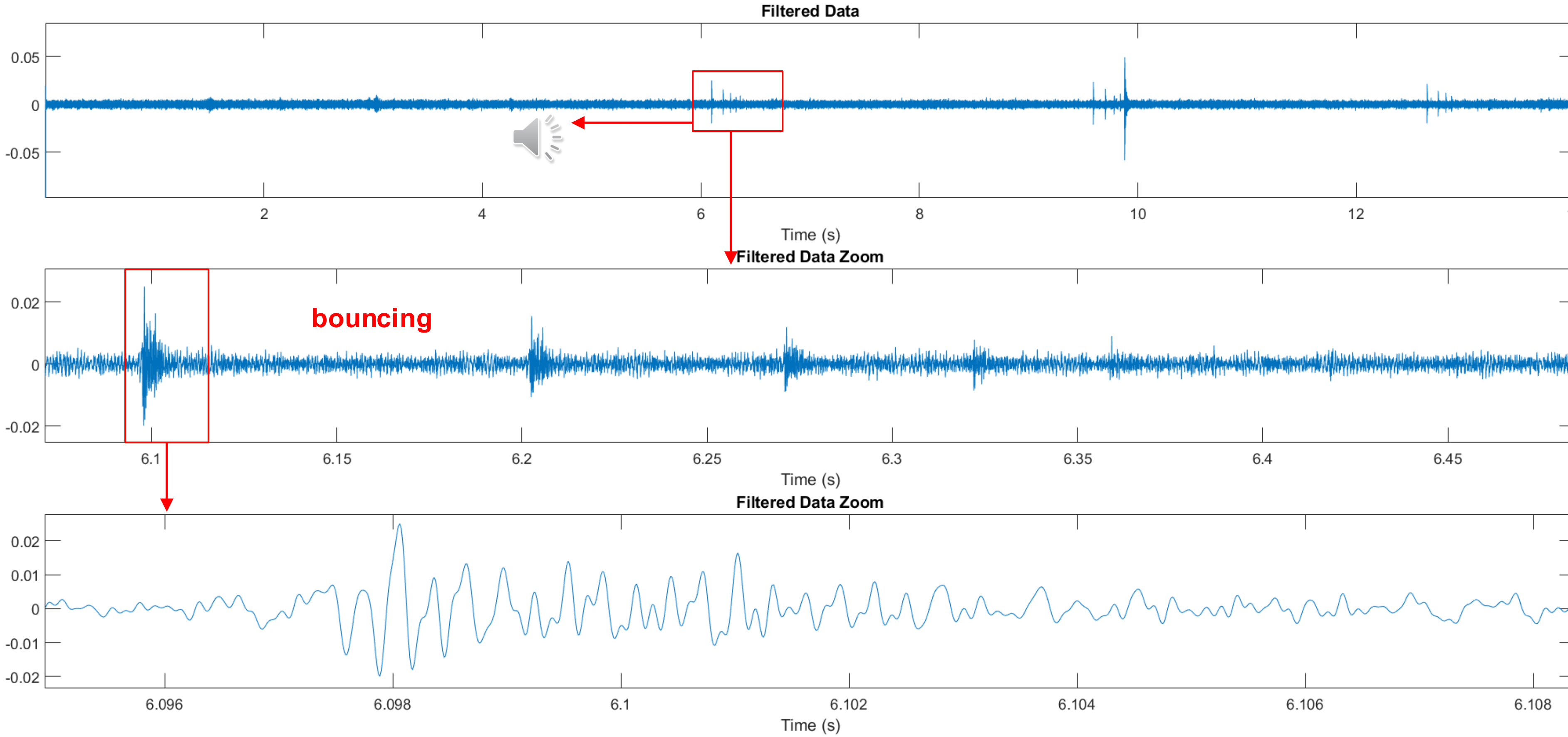


 Proprietary Material – Paulsson, Inc (PI).

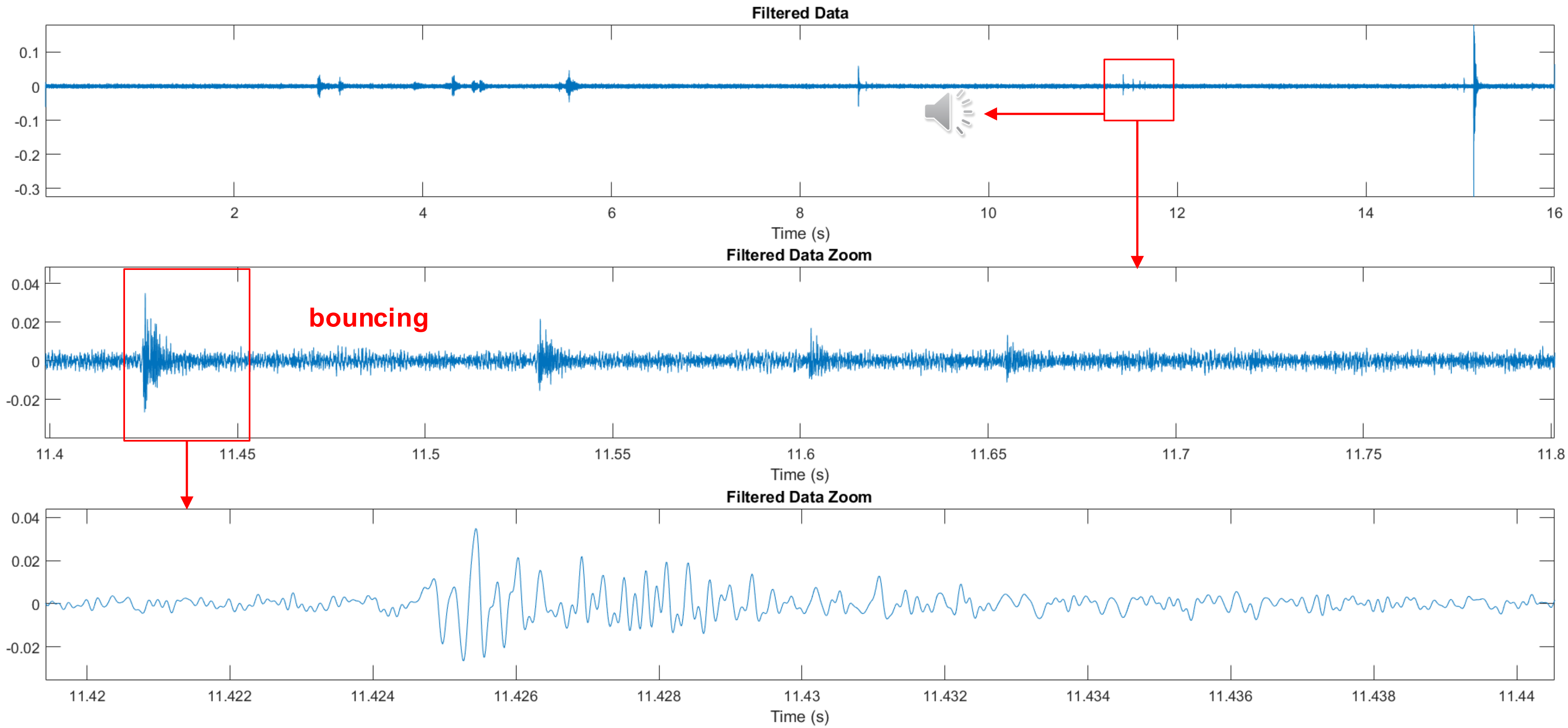
2^{nd} Sugar Grains: 0.2 mg: 25 mm Drop: = 50 nJ
Ormsby Filtered: 800-1000-8000-10000 Hz



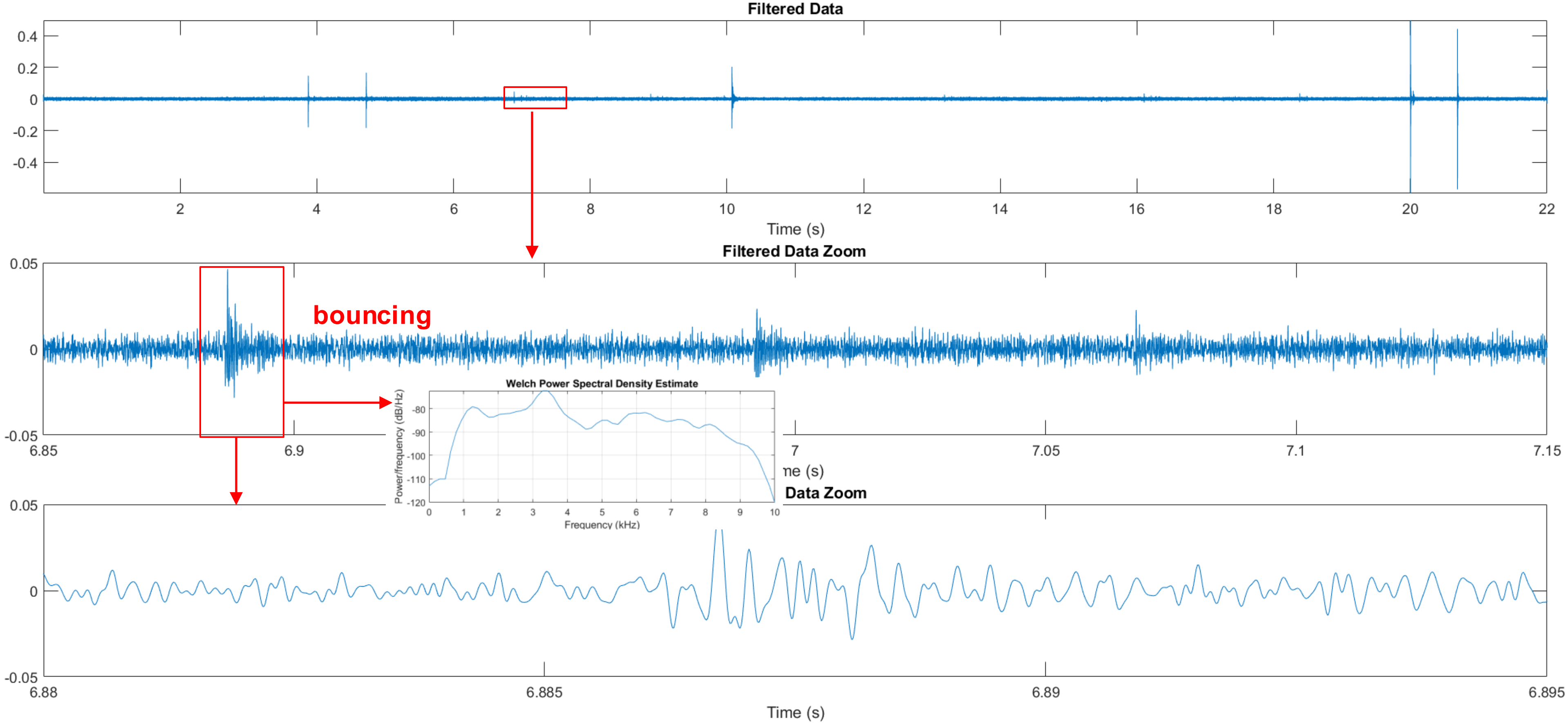
First Drop Test of a Styrofoam Ball (0.5 mg) at 10 mm = 50 nJ
Ormsby Filtered: 800-1000-8000-10000 Hz



Second Drop Test: Styrofoam Ball (0.5 mg) at 10 mm = 50 nJ
Ormsby Filtered: 800-1000-8000-10000 Hz

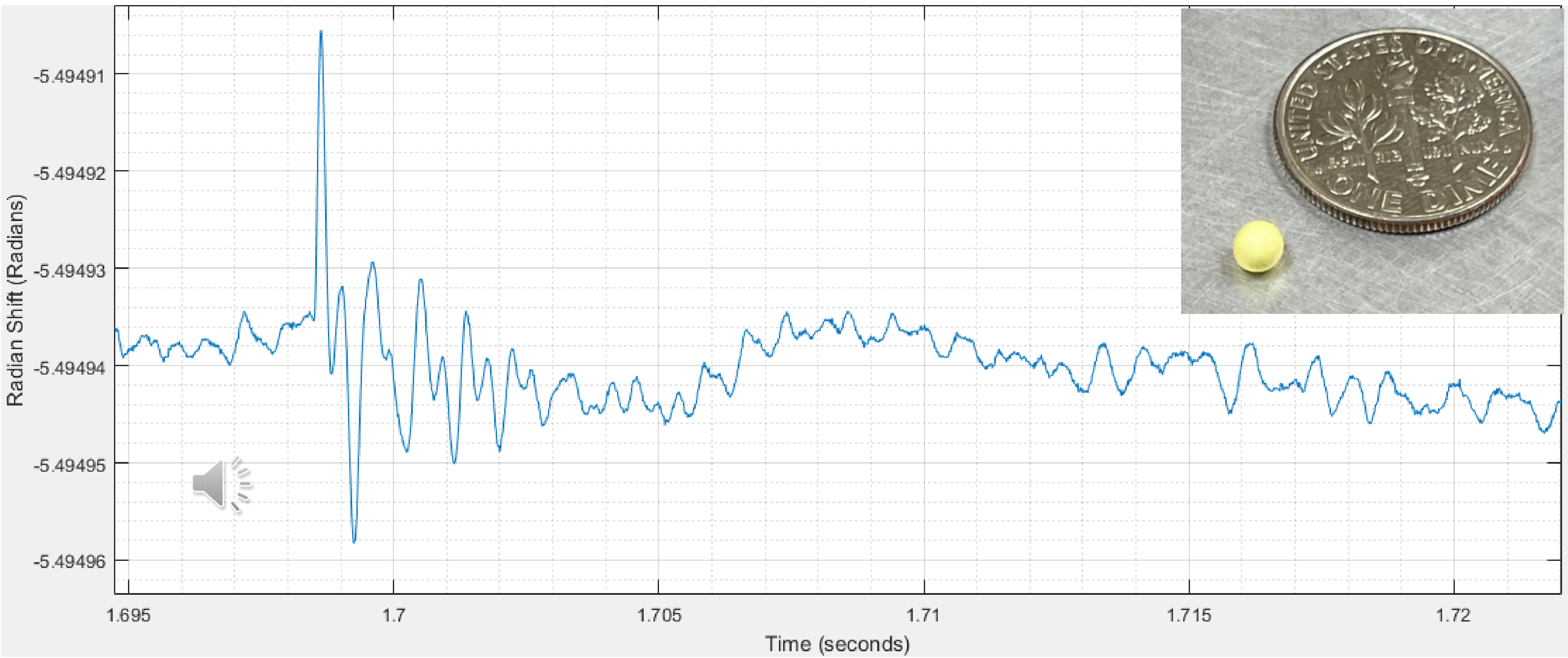


Third Drop Test of a Styrofoam Ball (0.5 mg) at 10 mm = 50 nJ
Ormsby Filtered: 800-1000-8000-10000 Hz



Fiber Optic Seismic Vector Sensors (FOSVS.4)
Accelerometer – MOD4

Drop a 0.5 mg Styrofoam Ball 10 mm, Estimated Energy: 50 nano Joules (nJ) 20×10^{-9} for the first of five bounces. Two orders of Magnitude more sensitive than previous sensor



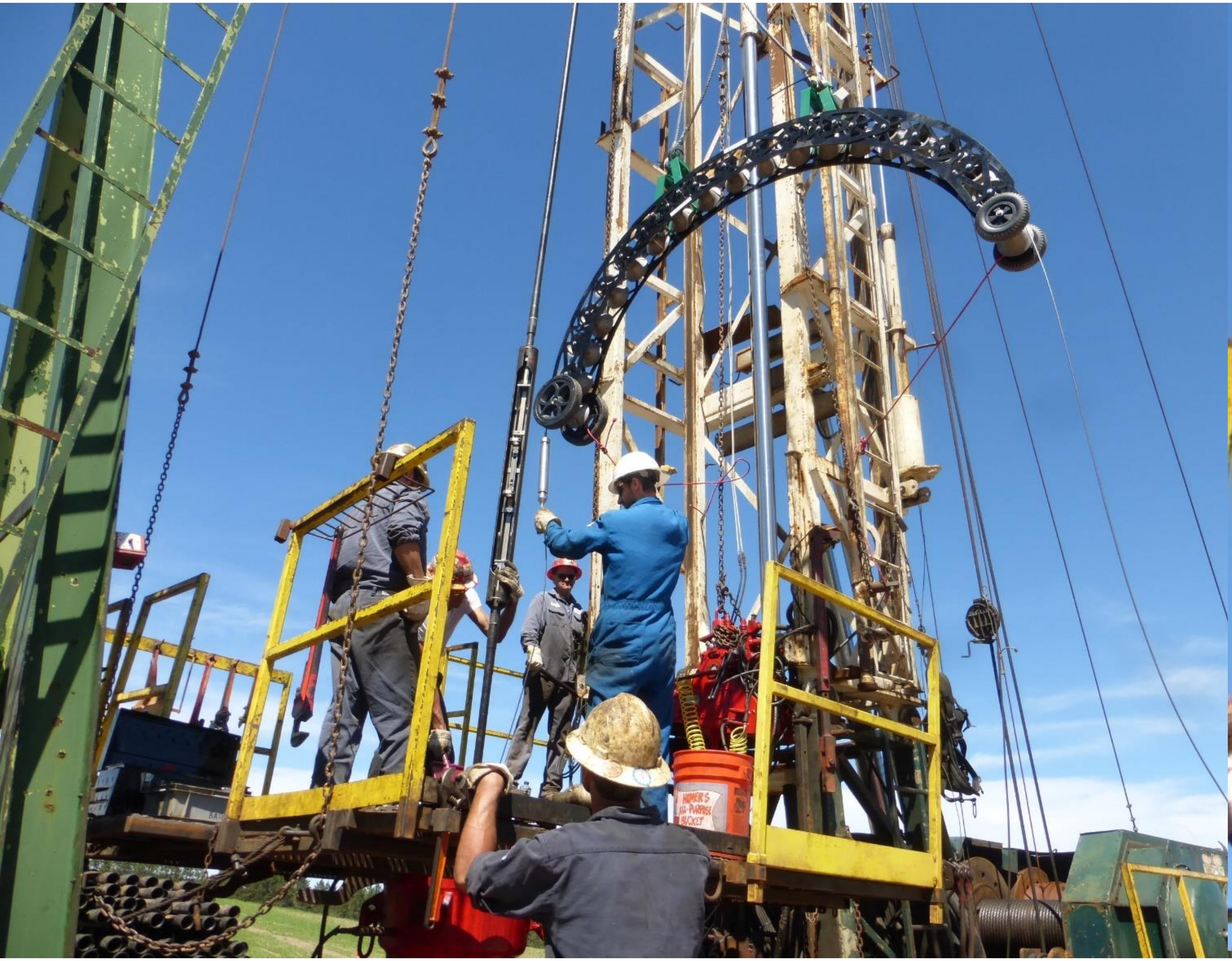
4th Gen Fiber Optic Seismic Vector Sensors FOSVS.4

 Proprietary Material – Paulsson, Inc (PI).

Presentation Outline

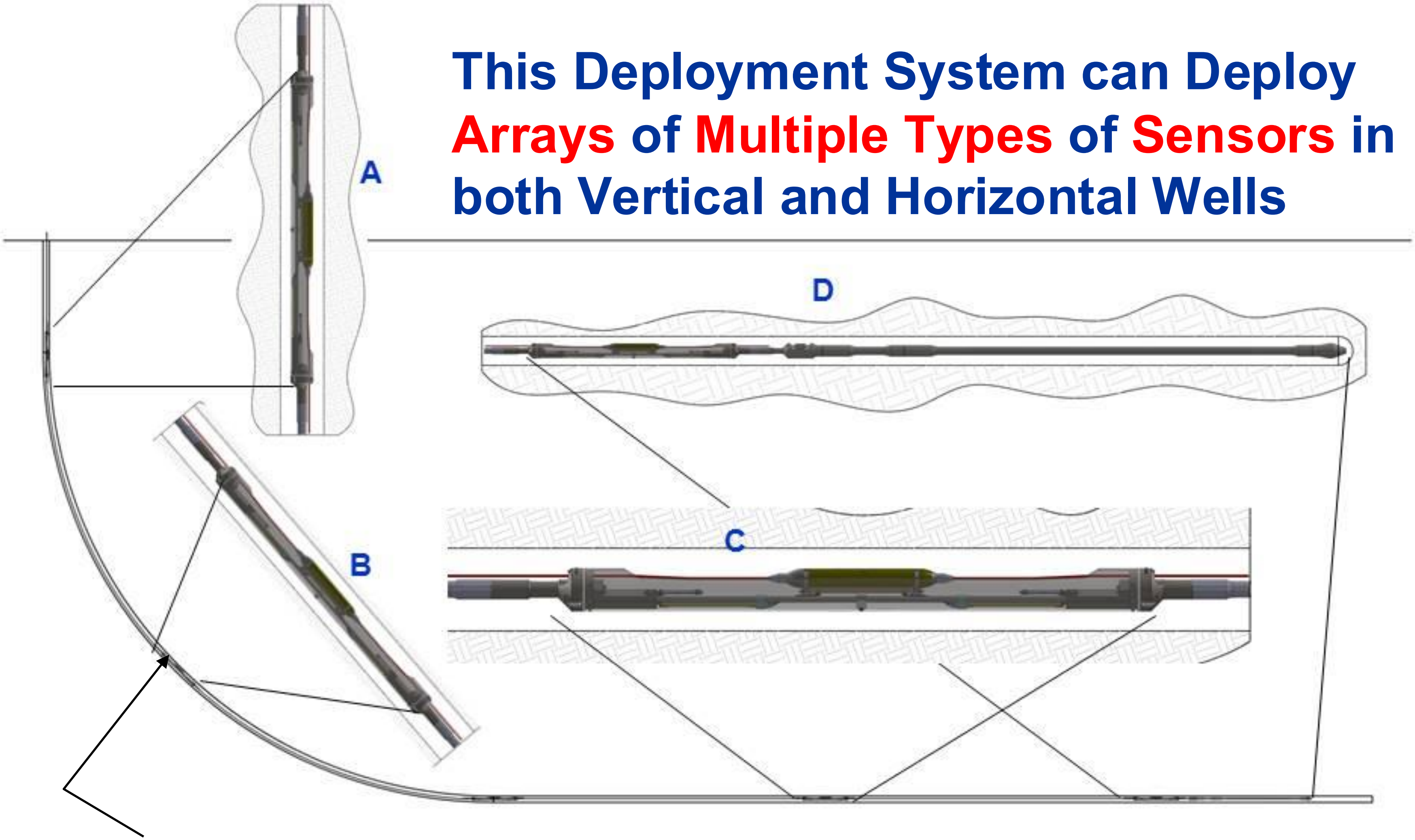
- Laboratory Tests of Sensors
- CCUS project with Battelle
- UGS project with PG&E
- Pipeline Monitoring (if time)

Fiber Optic Seismic Sensor System Deployment Battelle, MI June 2016 – using FOSVS.3 sensor



Drill Pipe Deployed System – Housing and Clamping

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

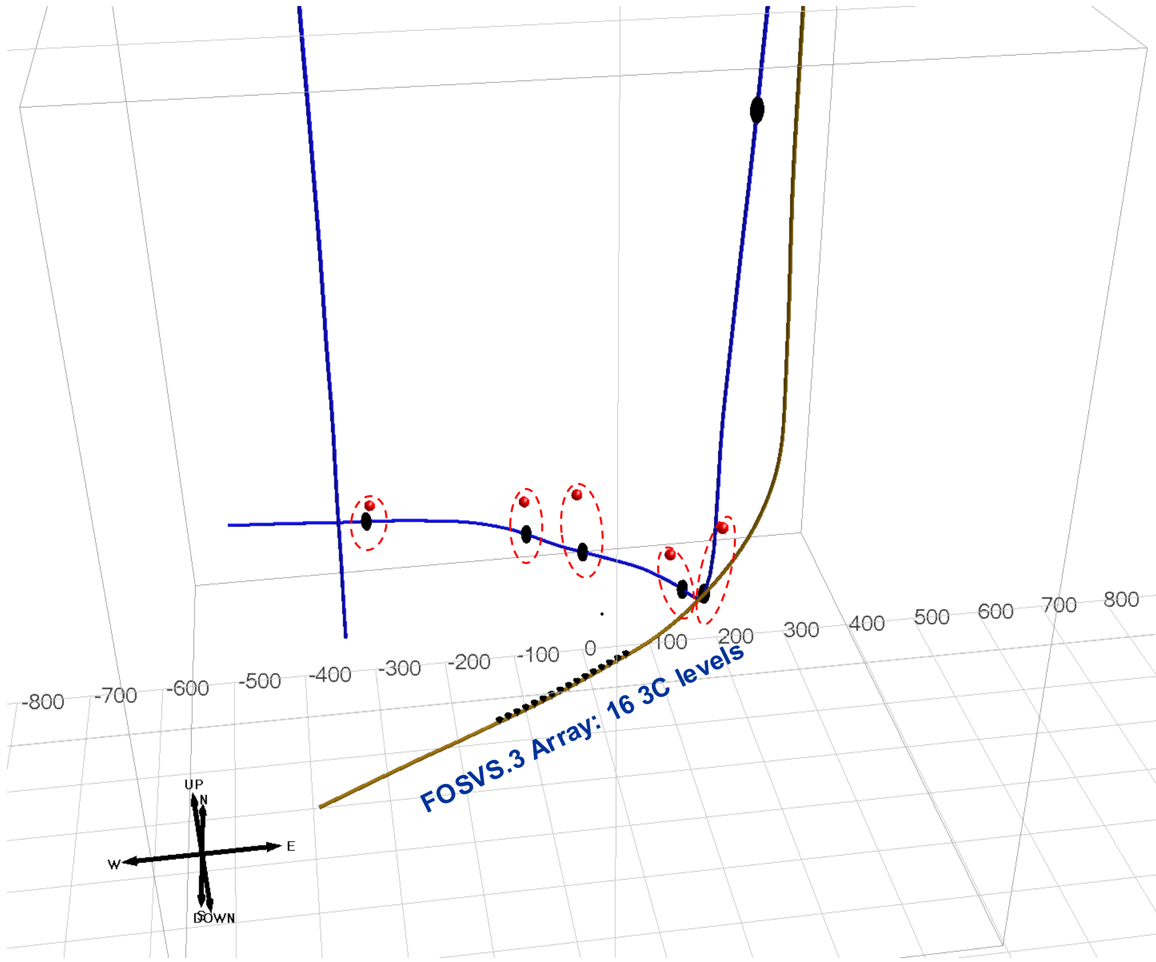


Clamping system operates by increasing the pressure inside the drill pipe and manifolds using the borehole fluid as the pressurized medium

Monitor Fluid (CO_2) Injection:

Field 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



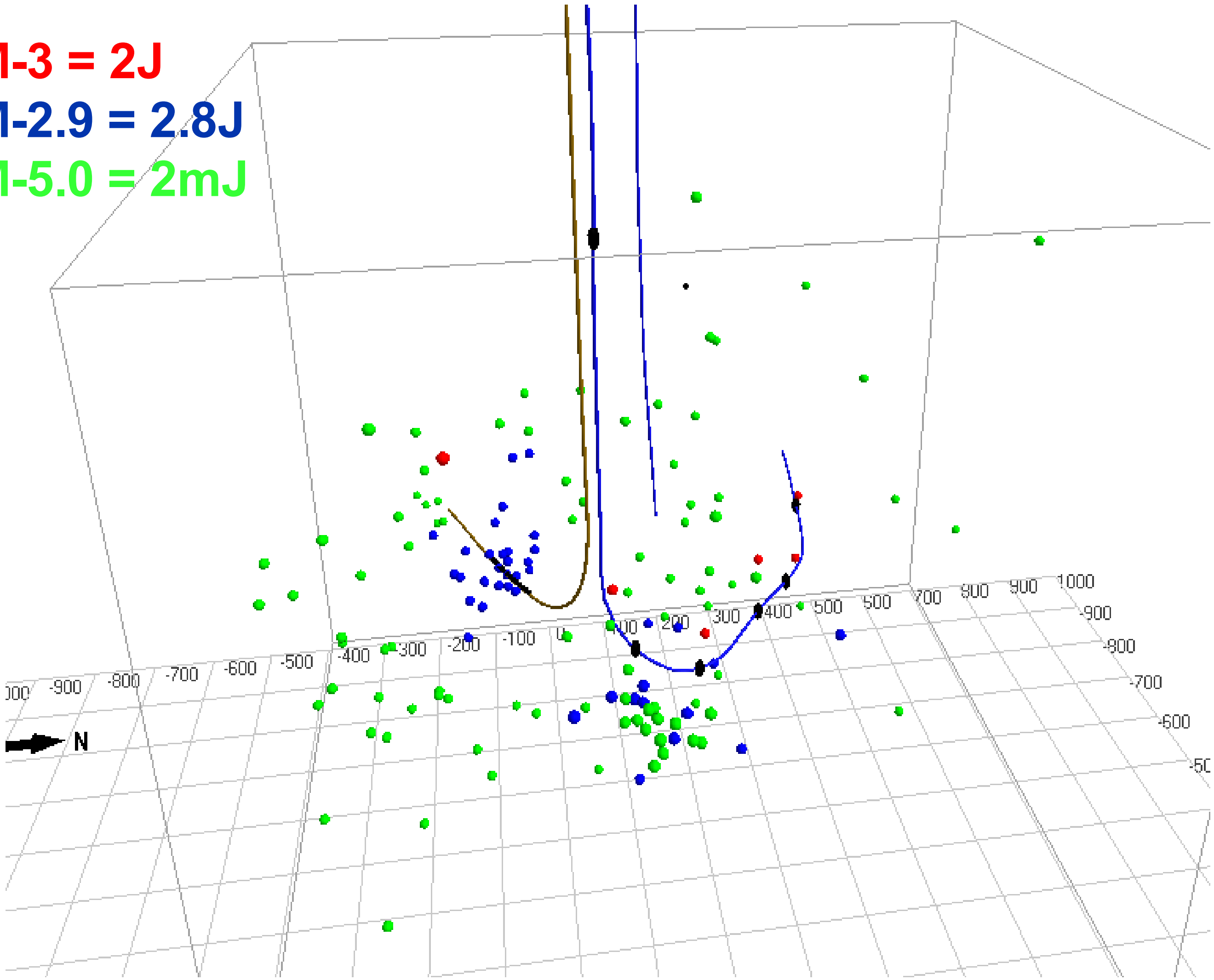
Survey for Battelle - Locating String Shots and Micro Seismic Events
Recorded >500,000 events in four weeks. Displayed here are 130 events.

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

Magnitude < M-3 = 2J

Magnitude < M-2.9 = 2.8J

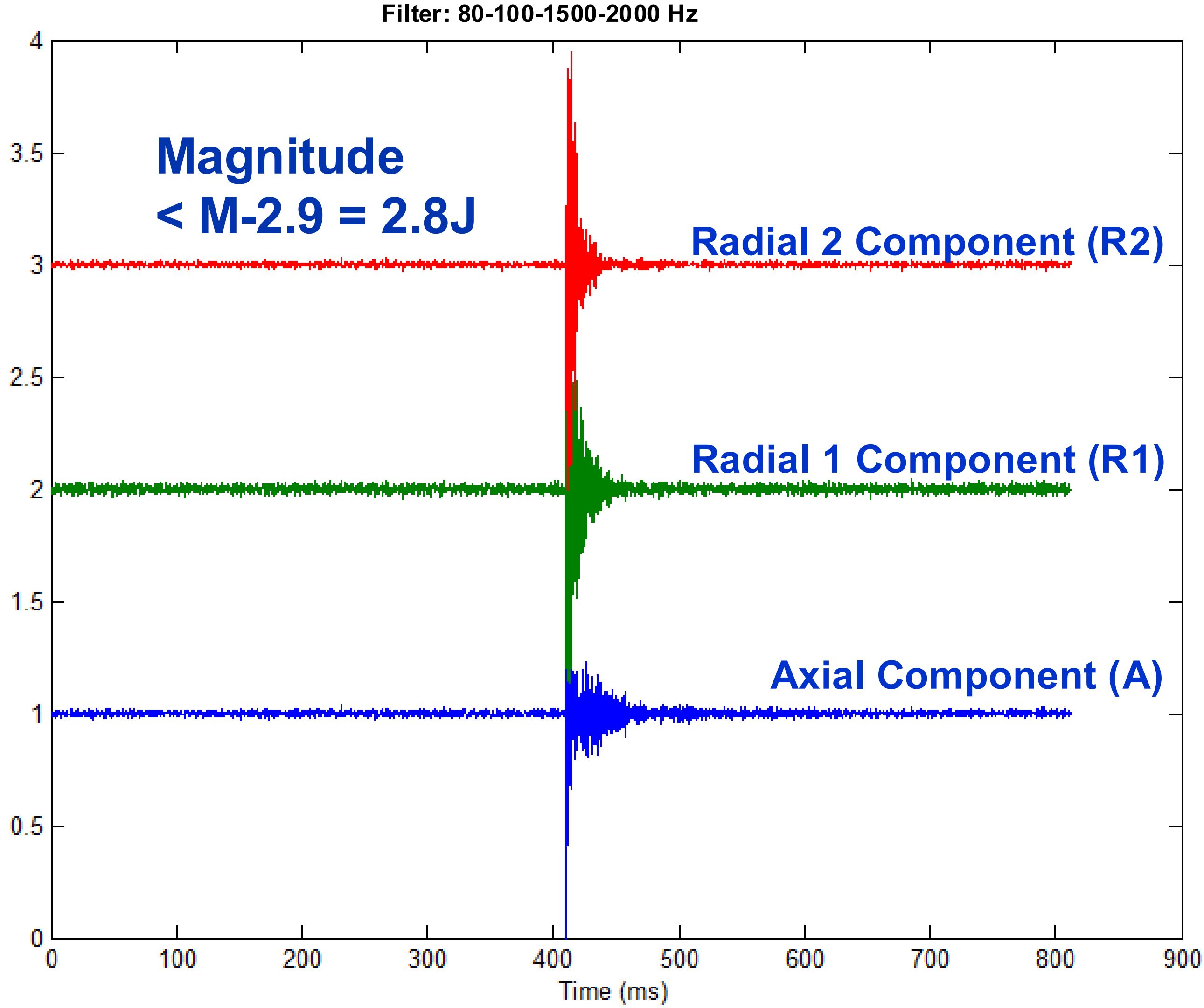
Magnitude < M-5.0 = 2mJ



 Proprietary Material – Paulsson, Inc (PI).

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

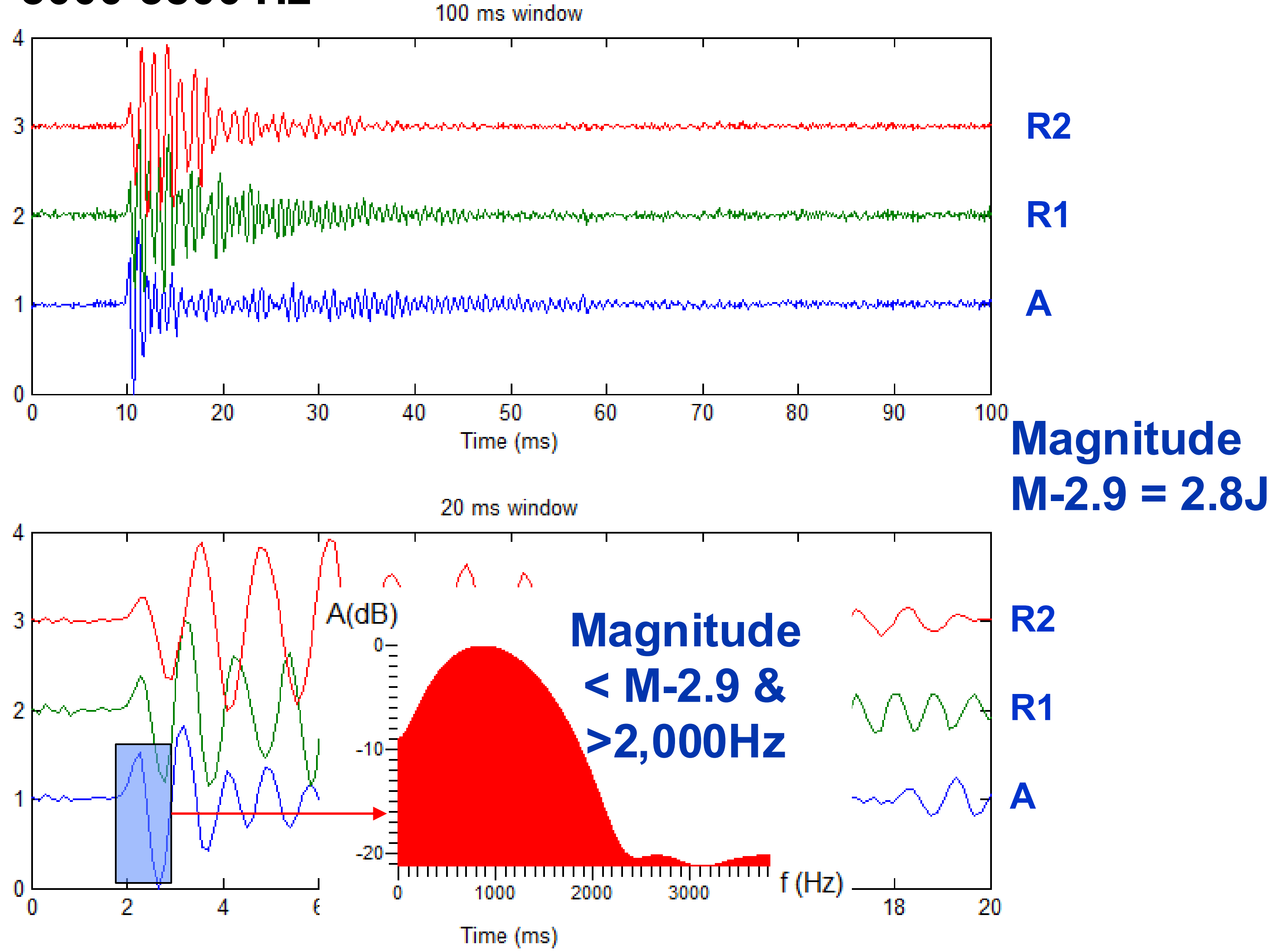
FOSVS.3



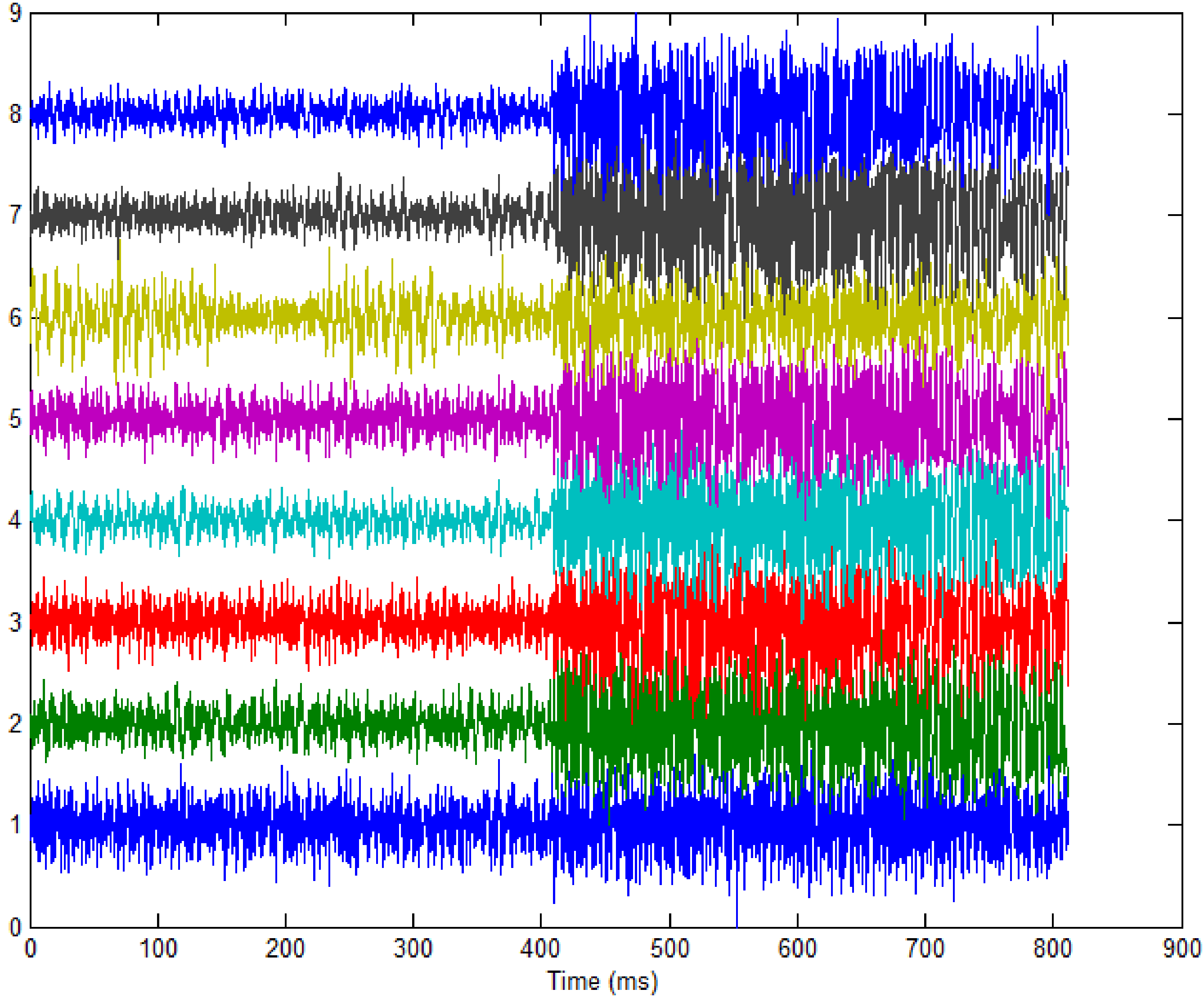
 Proprietary Material – Paulsson, Inc (PI).

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

Filter: 2-4-3000-3800 Hz

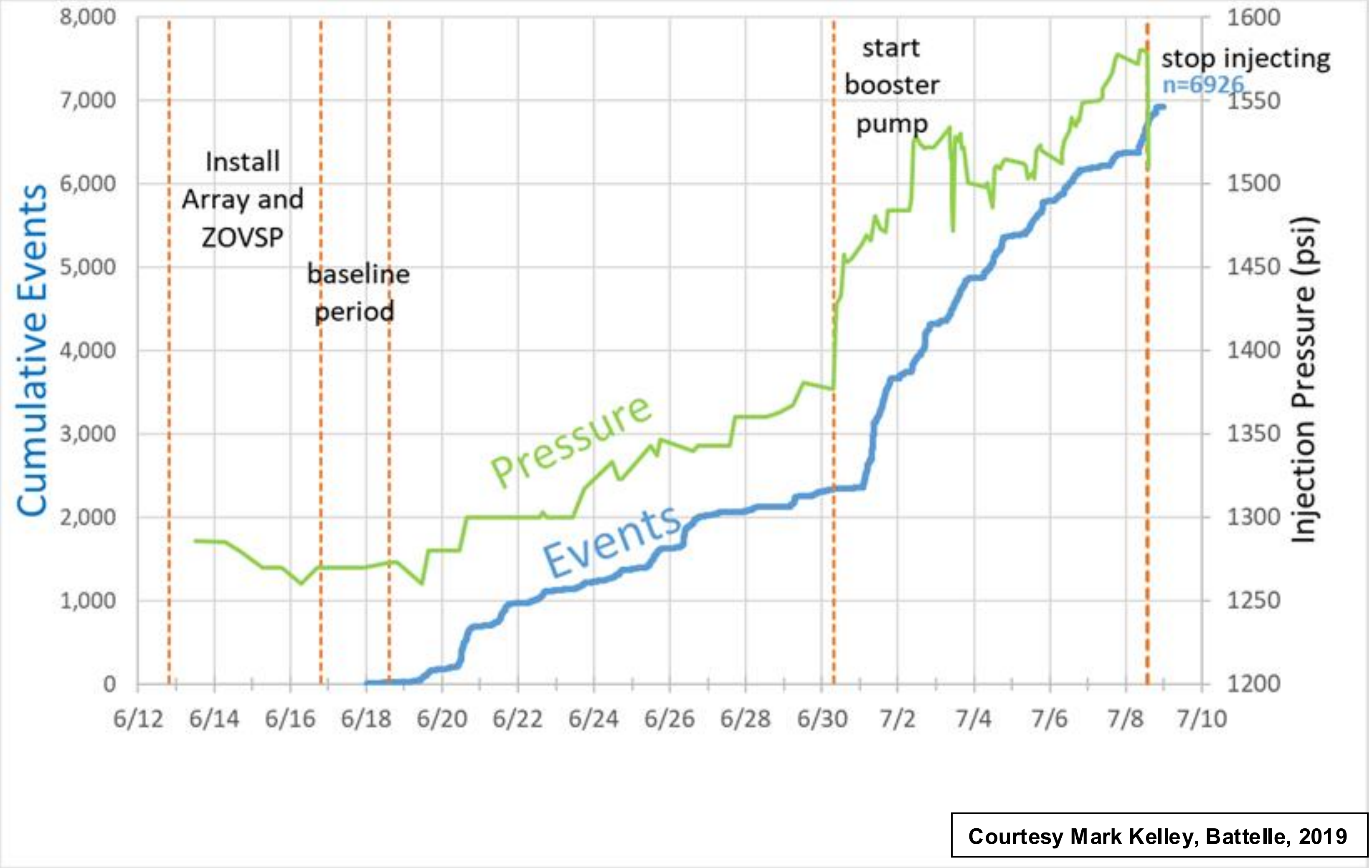


Sound of A Long Duration Event (~M-5.0) –Fluid Flow in fractures >500,000 events in four weeks



Magnitude
M-5.0 = 2mJ

Magnitude M-5.0 = 2mJ Micro Seismic Events as Function of The Pressure of the Injected CO_2

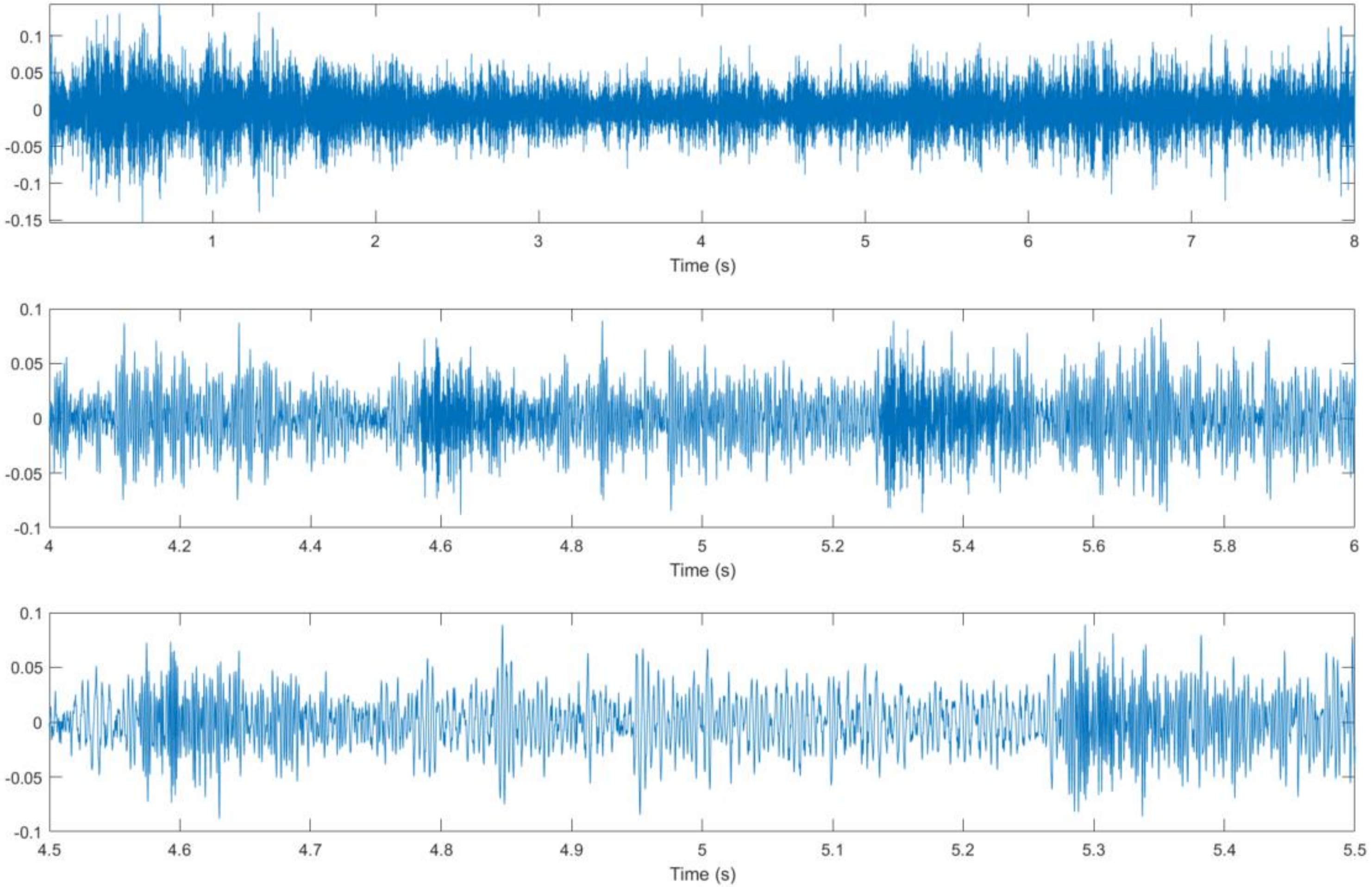


We looked for Analogs: Cardiac Blood Flow

8 seconds

Zoomed in 2 seconds

Zoomed in 1 second

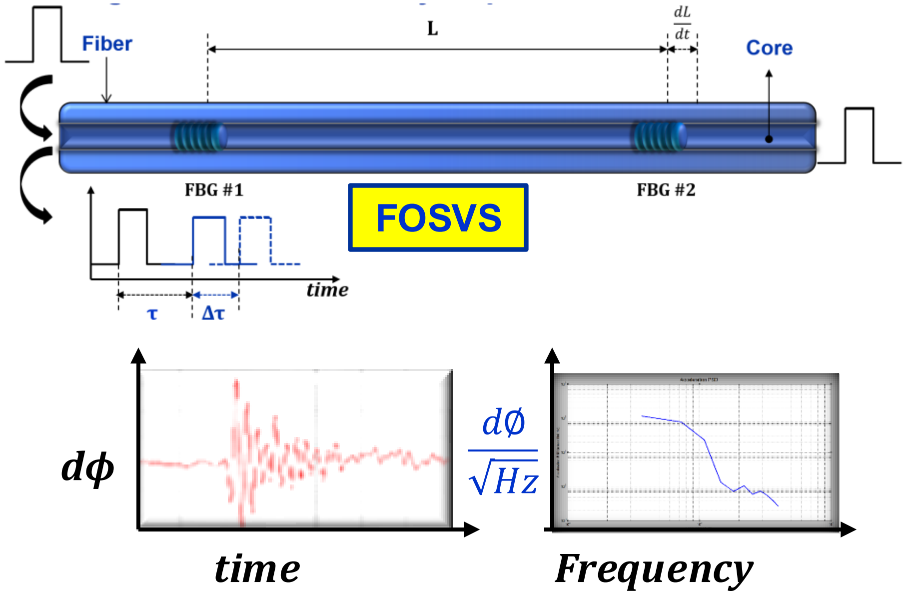


Presentation Outline

- Laboratory Tests of Sensors
- CCUS project with Battelle
- UGS project with PG&E
- Pipeline Monitoring (if time)

Several All-Optical Sensors are Part of Our Borehole System

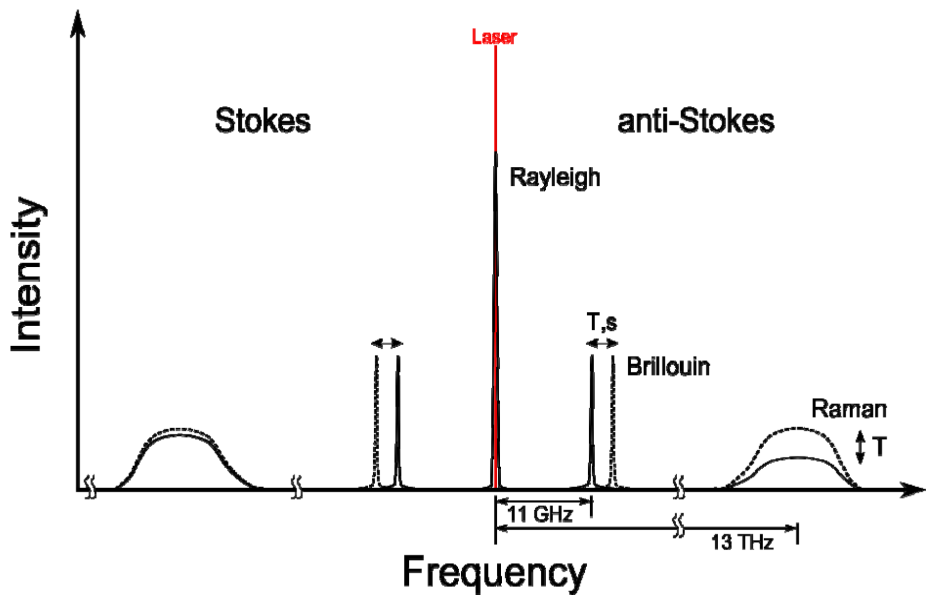
DOE supported Paulsson Point Sensors include: Accelerometers, Hydrophones & Pressure Sensors.



Interferometric Sensing

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

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



Rayleigh (DAS)

- Rayleigh Scattering
- **Acoustic**

Raman (DTS)

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

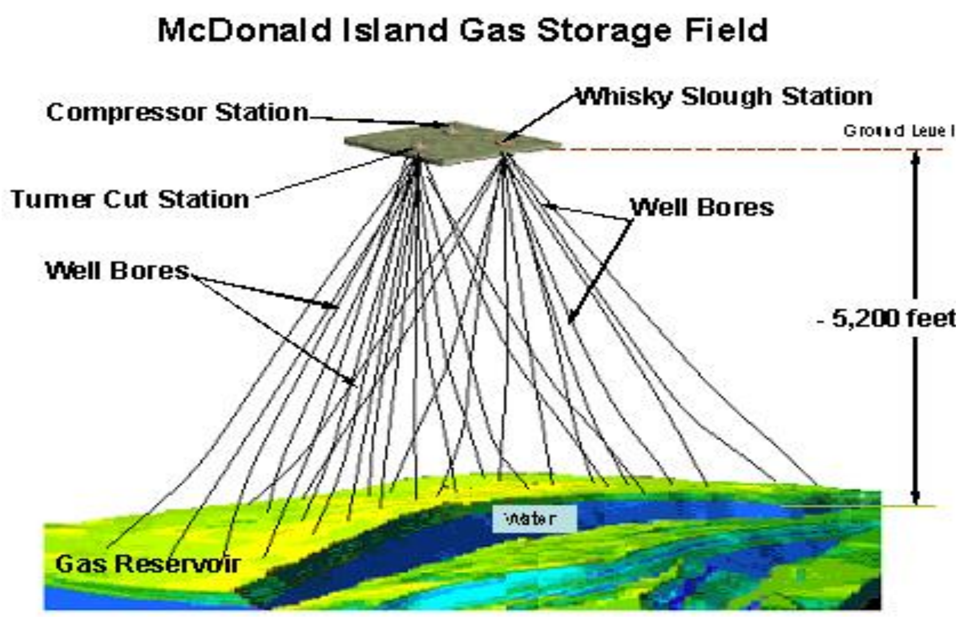
Brillouin (DSS)

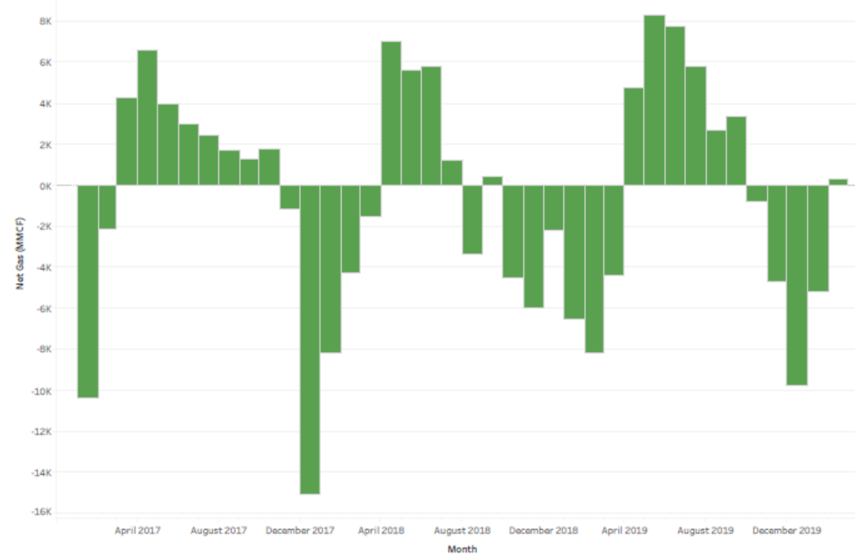
- Frequency of Brillouin peak
- **Strain** and temperature

Why and when do we store gas?

PURPOSE OF UNDERGROUND STORAGE

- **Enables large volumes of natural gas to be stored and later withdrawn during high-demand periods**
- **Provides the ability to purchase natural gas and inject into storage, taking advantage of seasonal gas pricing as well as market fluctuations**

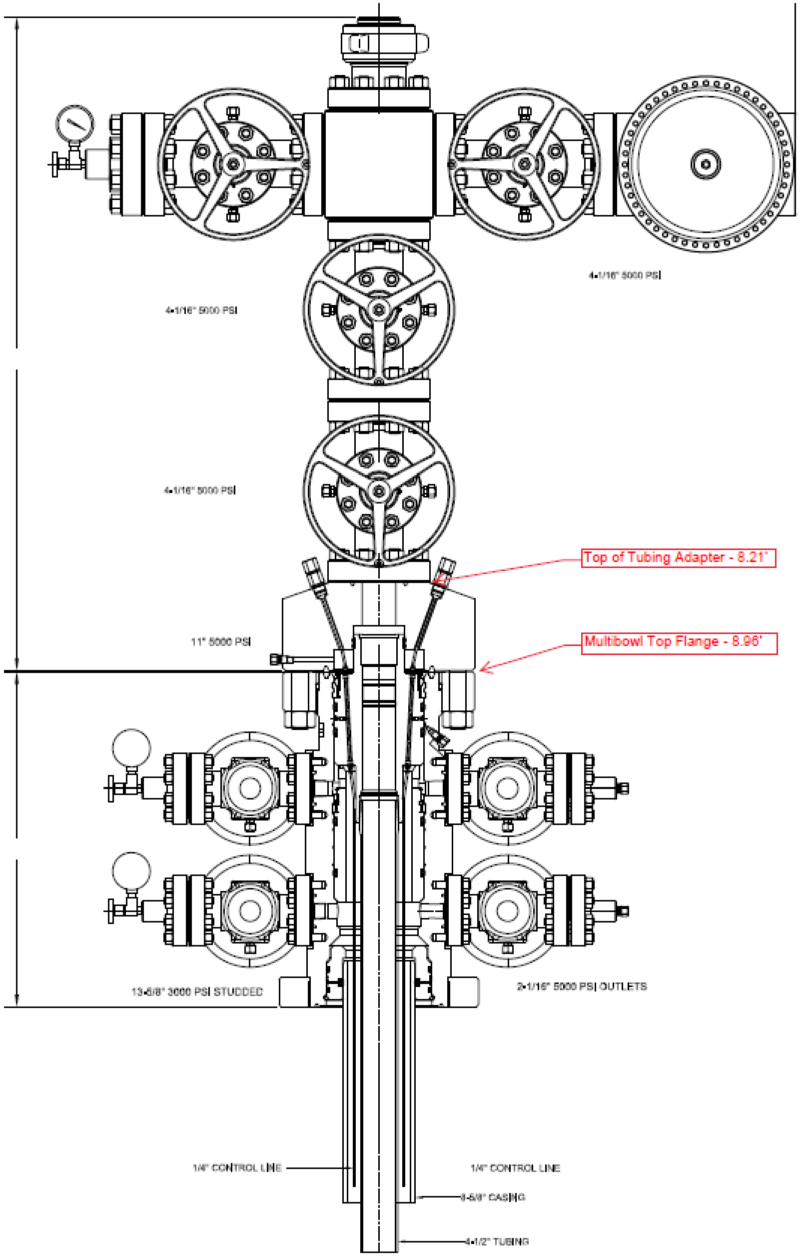




The McDonald Island UGS – The Survey Site: 84 wells

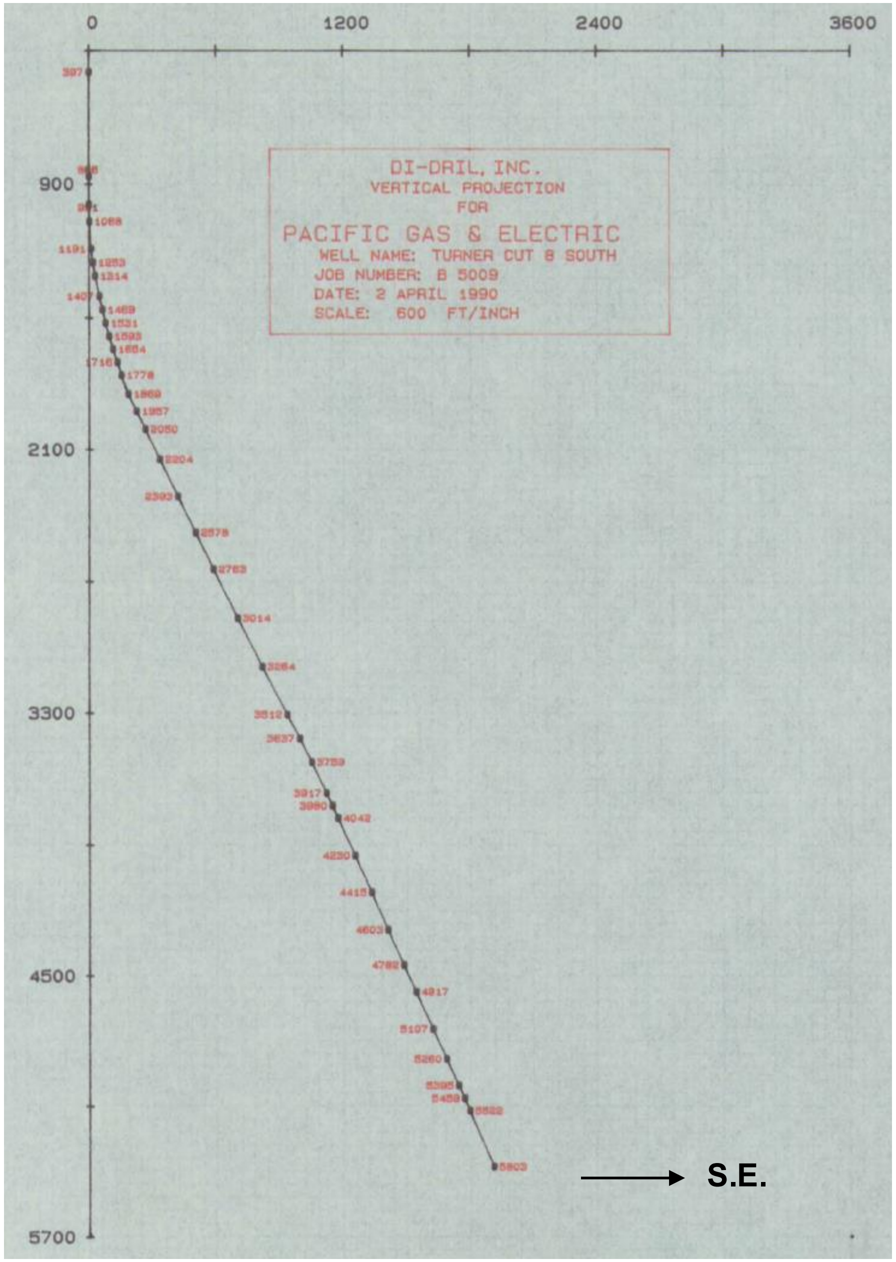
McDonald Island – The Survey Site during Sensor Installation

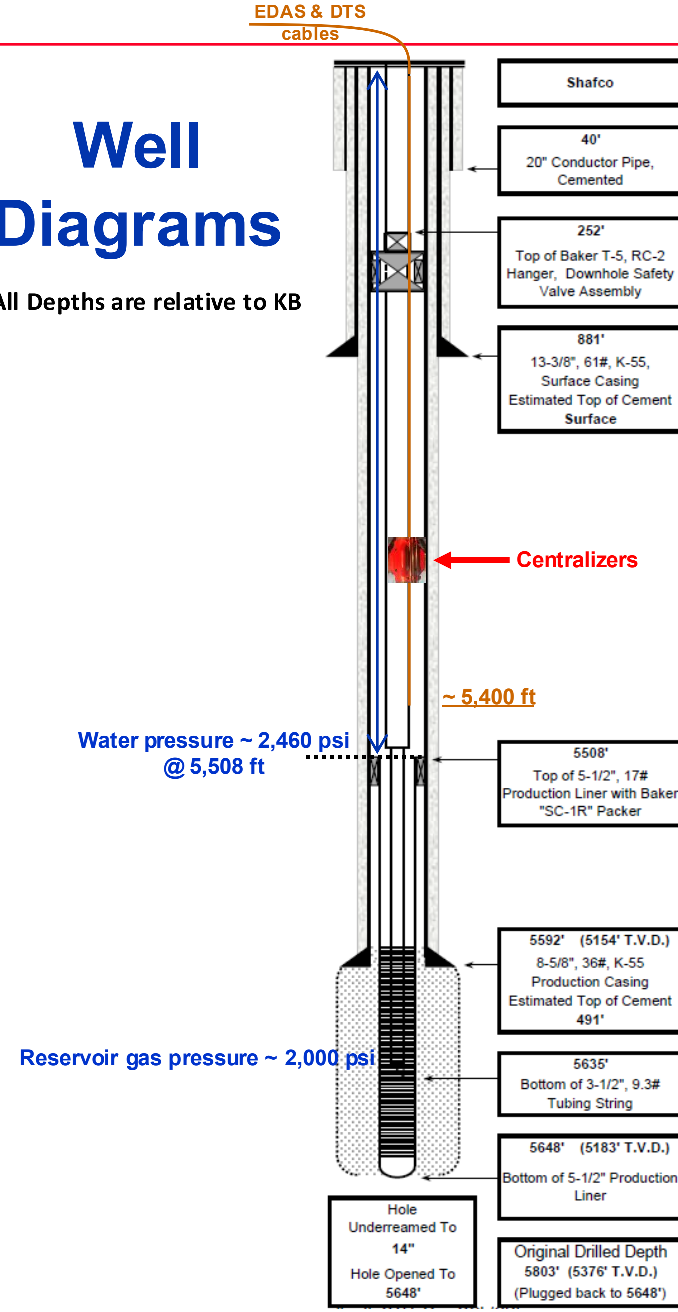
Wellhead of the TC 8S well



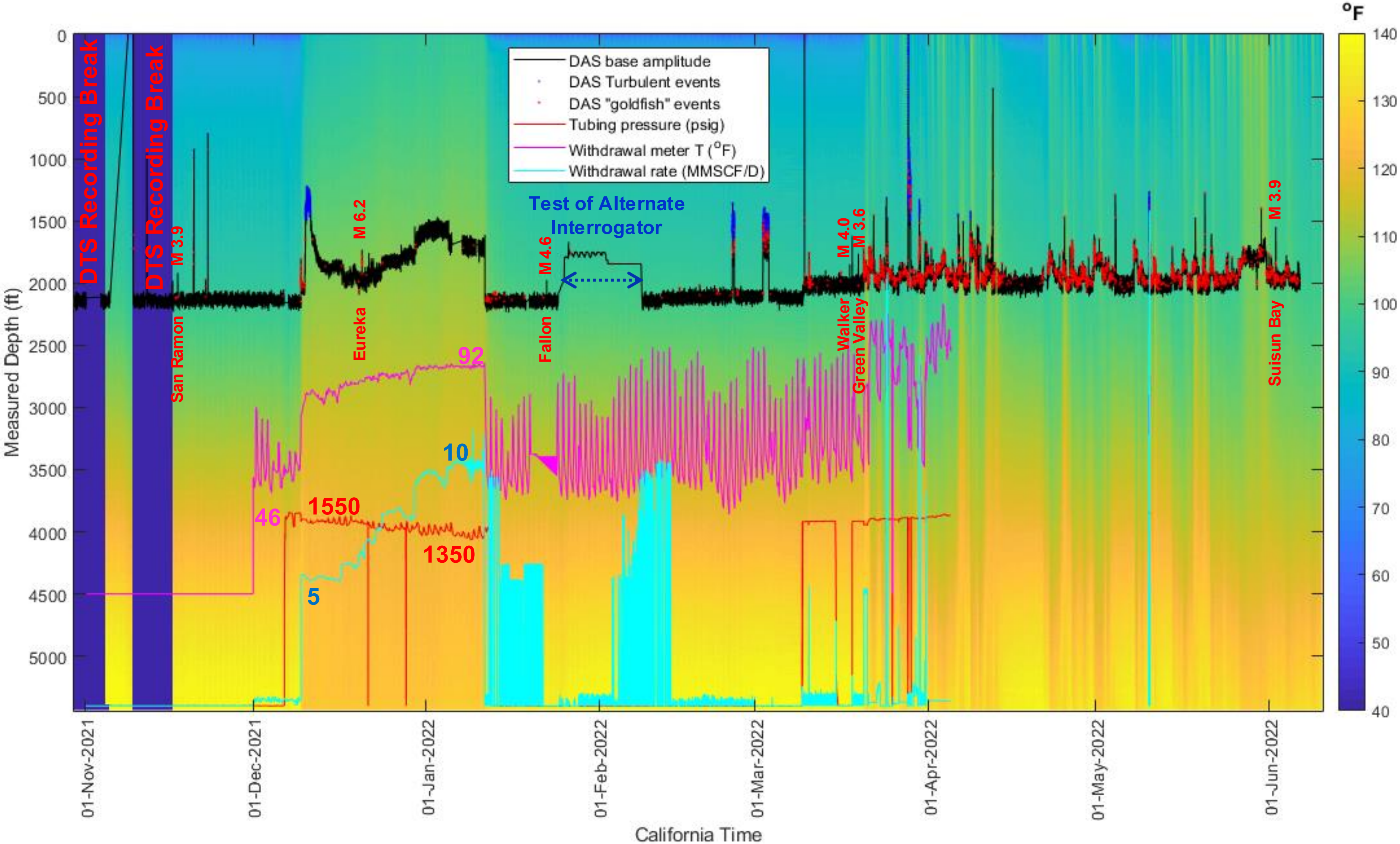
Well Diagrams

All Depths are relative to KB



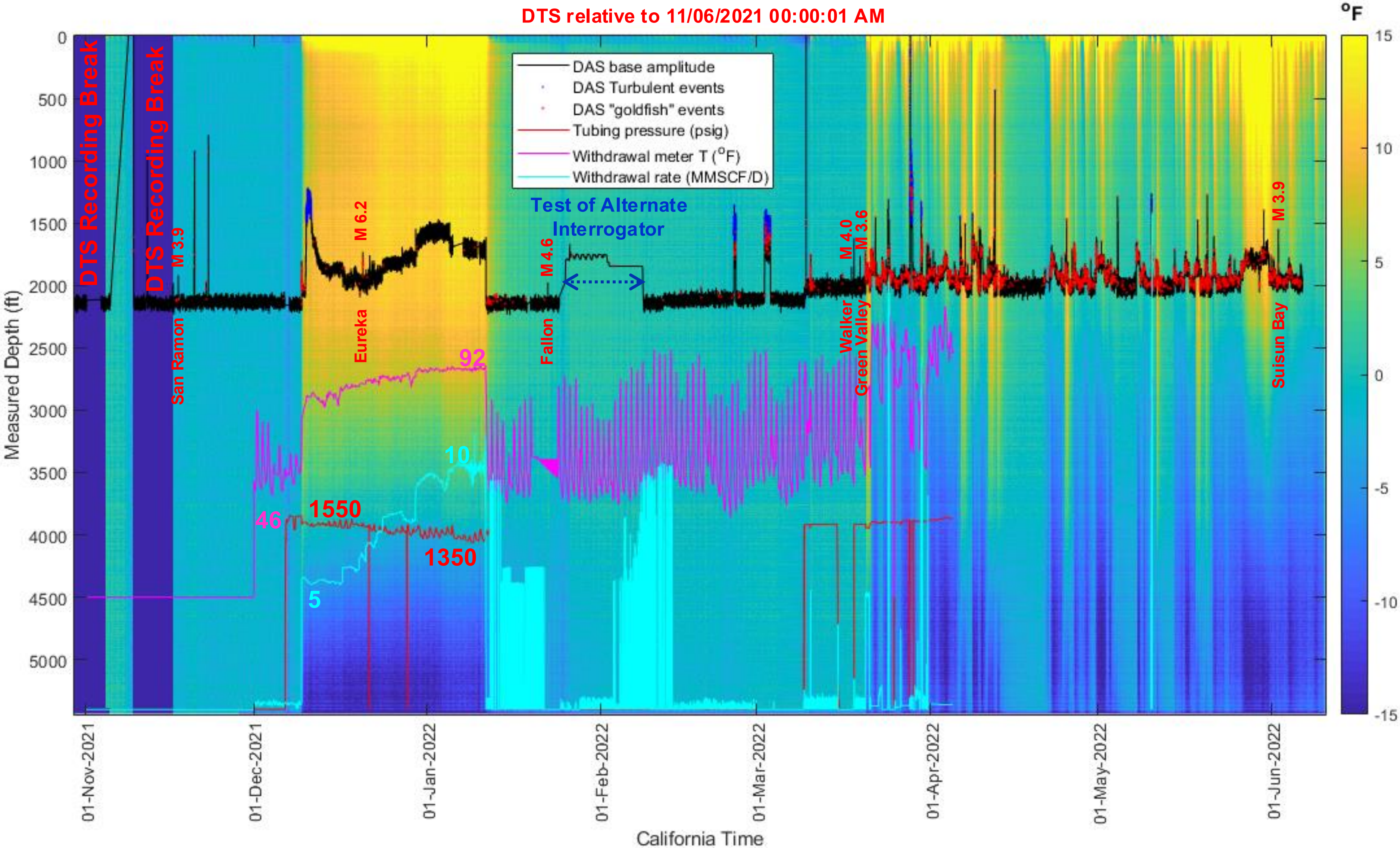


EDAS and DTS Data: Overall ~7 Months (out of ~8 months)



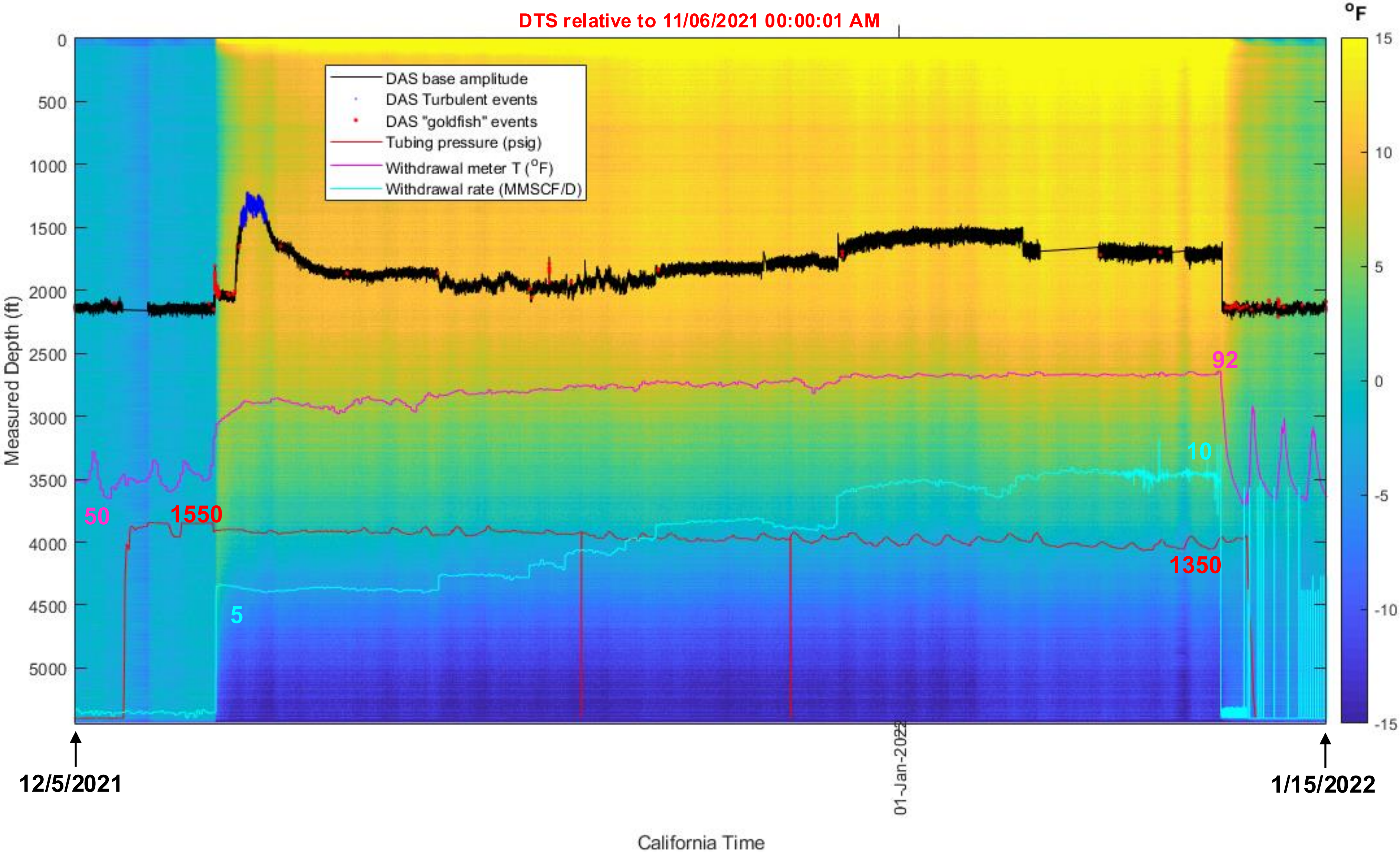
 Proprietary Material – Paulsson, Inc (PI).

EDAS and Relative DTS Data: Overall ~7 Months (out of ~8)



 Proprietary Material – Paulsson, Inc (PI).

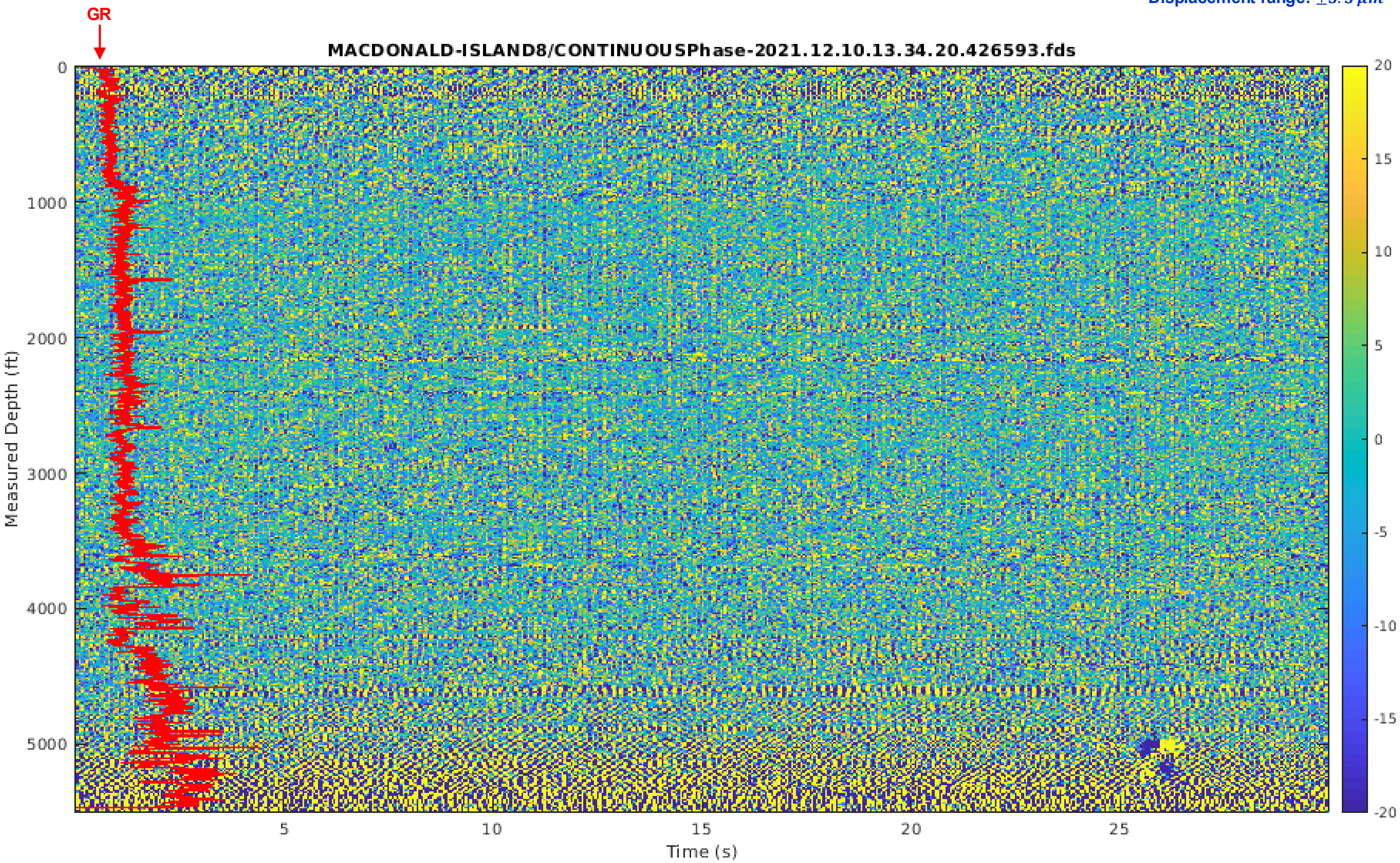
EDAS and Relative DTS Data: 12/5/2021 – 1/15/2022



 Proprietary Material – Paulsson, Inc (PI).

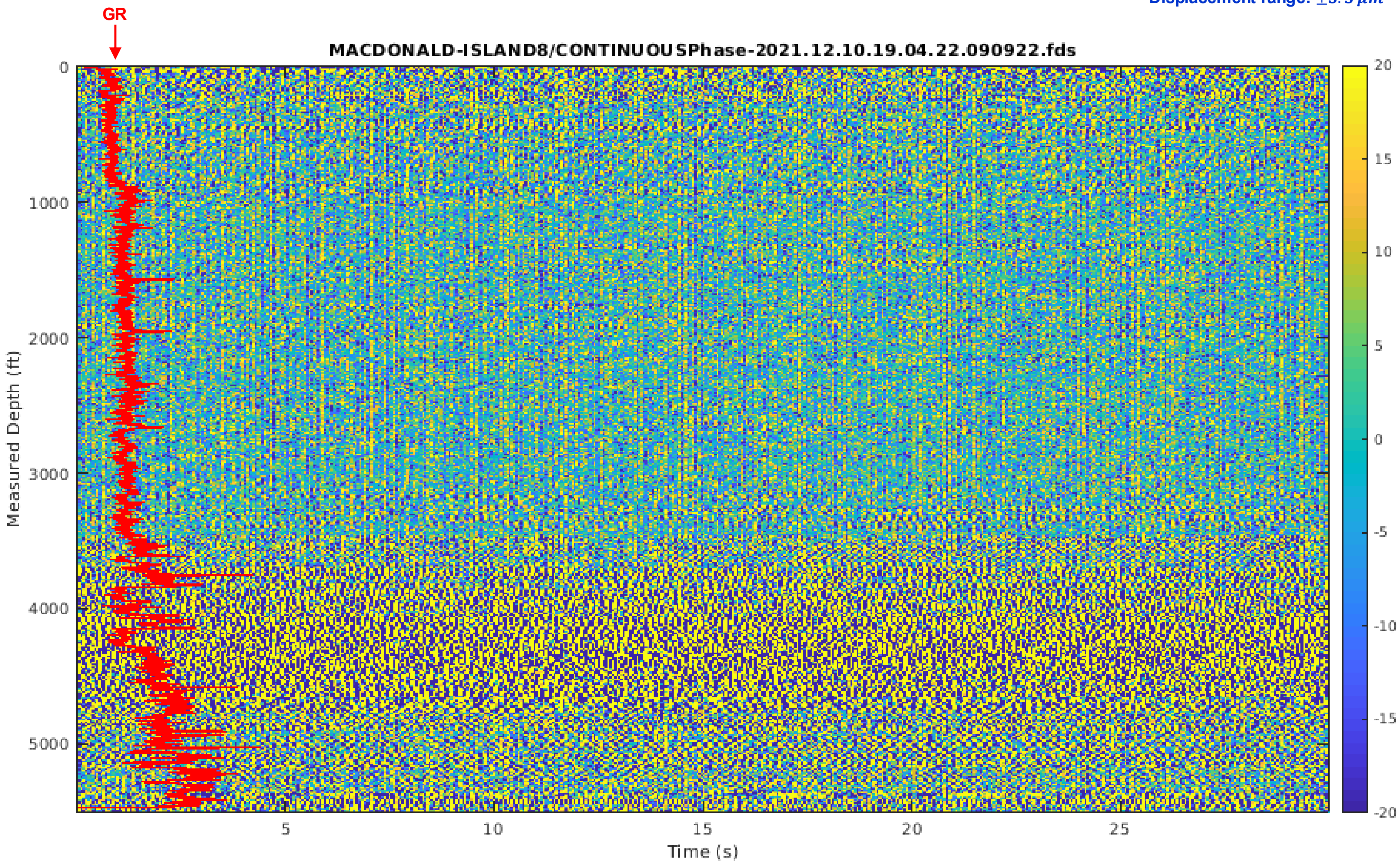
30 Minutes after Start of Fluid Flow Acoustic Events (Degas.)

Displacement range: $\pm 3.5\ \mu m$



6 Hours after Start of Fluid Flow Acoustic Events (Degassing)

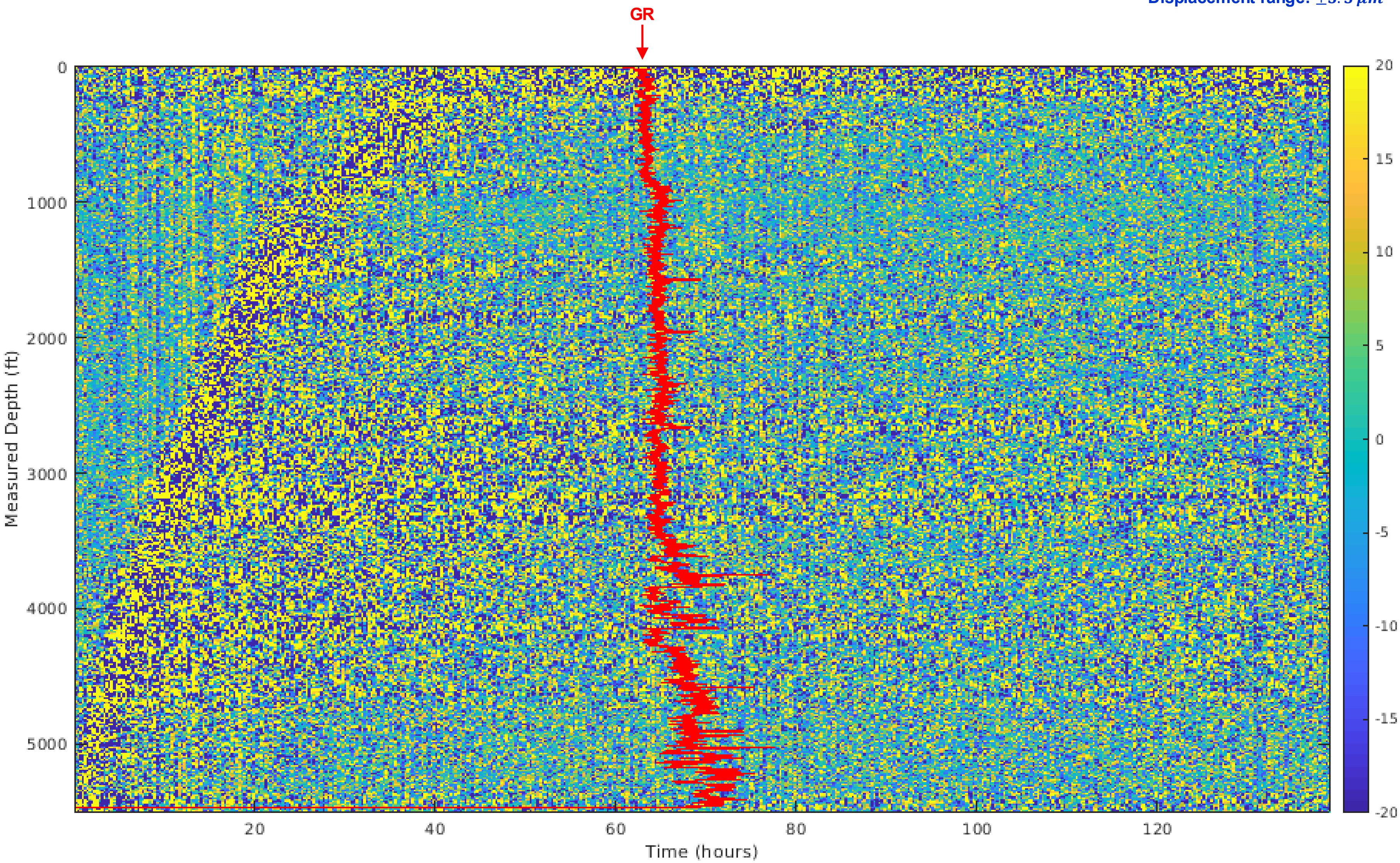
Displacement range: $\pm 3.5\ \mu m$



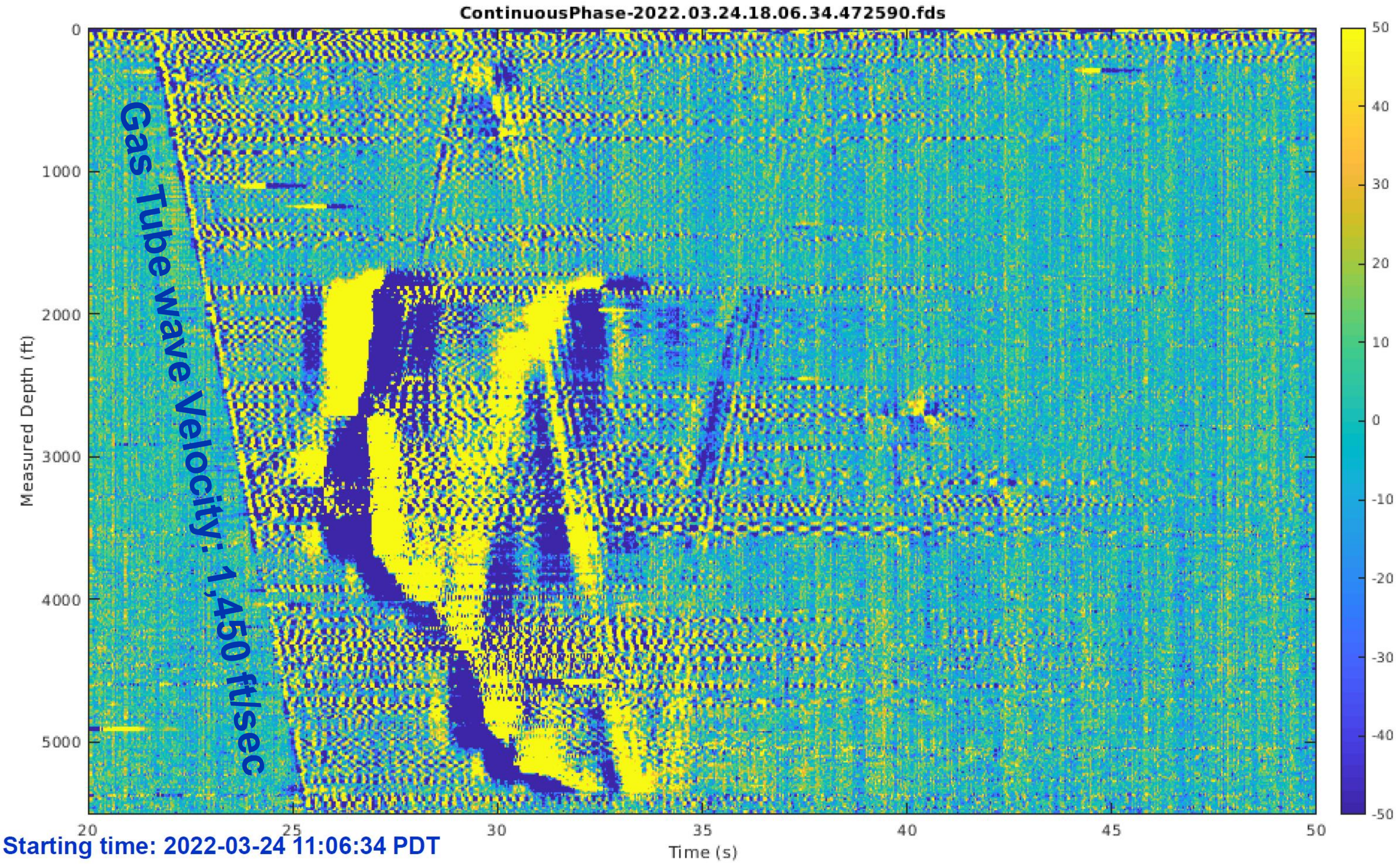
 Proprietary Material – Paulsson, Inc (PI).

Fluid Flow Acoustic Events for 6 Days (Degassing)

Displacement range: $\pm 3.5\ \mu m$

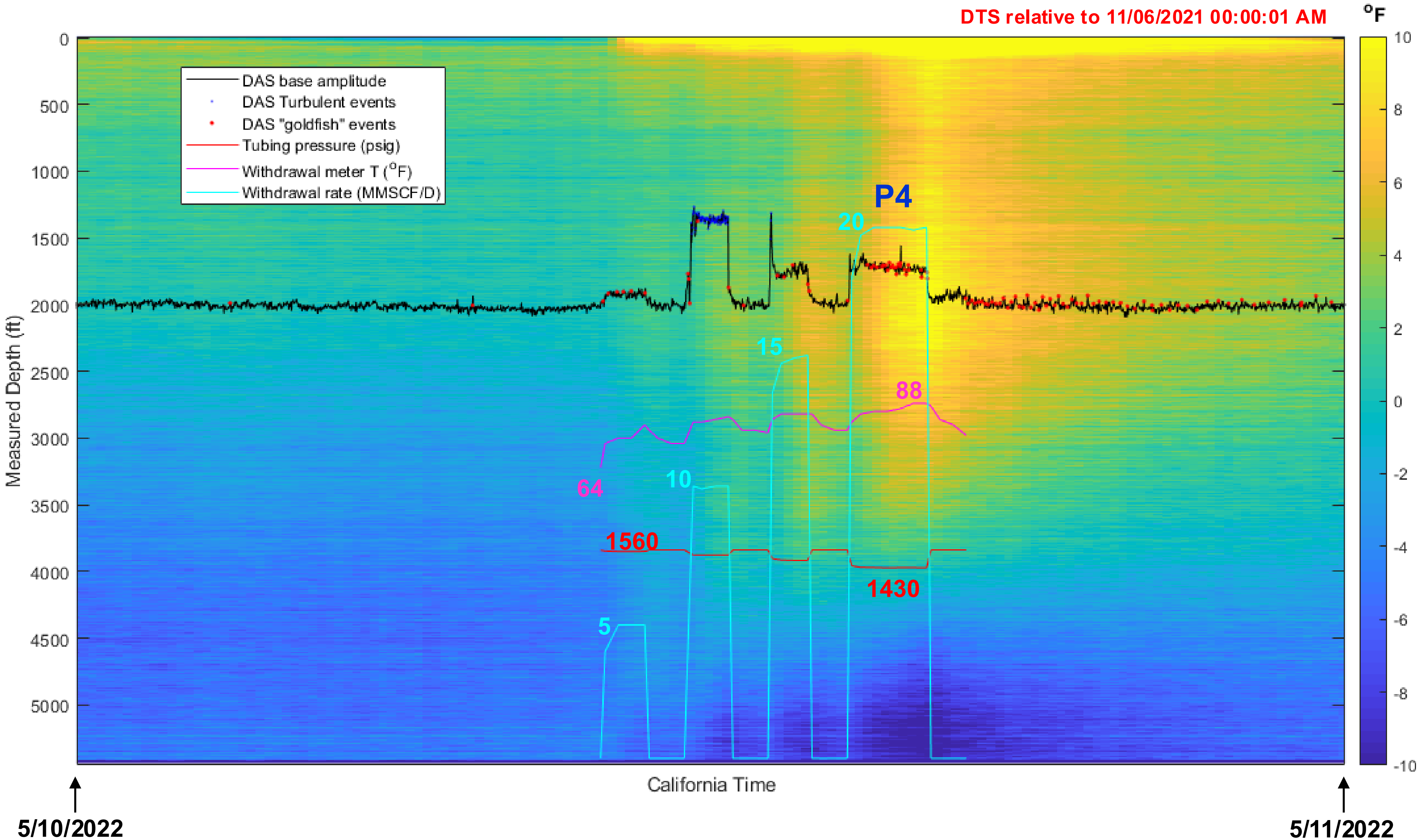


Start of P1: 2022-03-24 11:06:56 PDT



Starting time: 2022-03-24 11:06:34 PDT

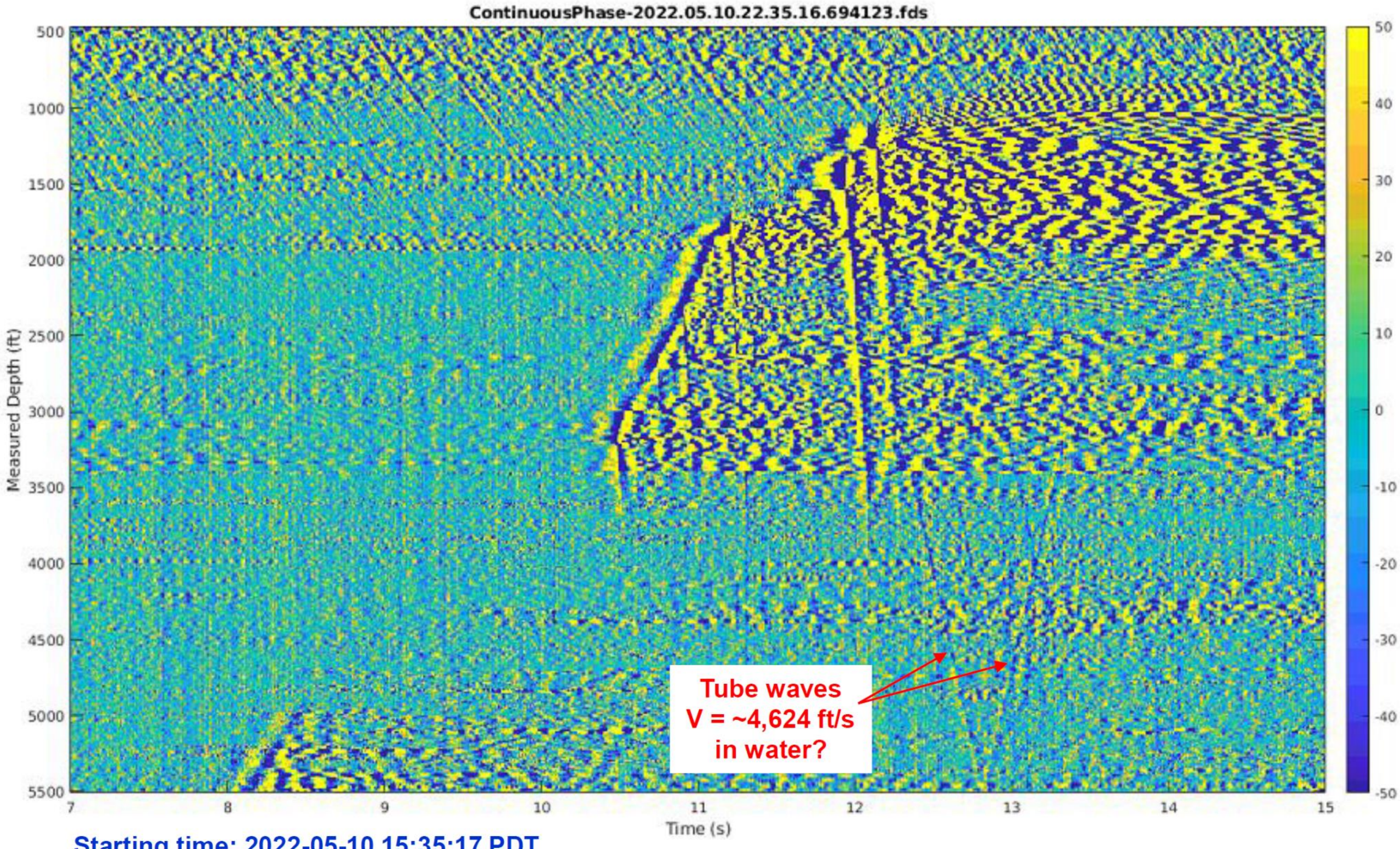
EDAS and DTS Data: 5/10/2022: Test Withdrawal Rates



 Proprietary Material – Paulsson, Inc (PI).

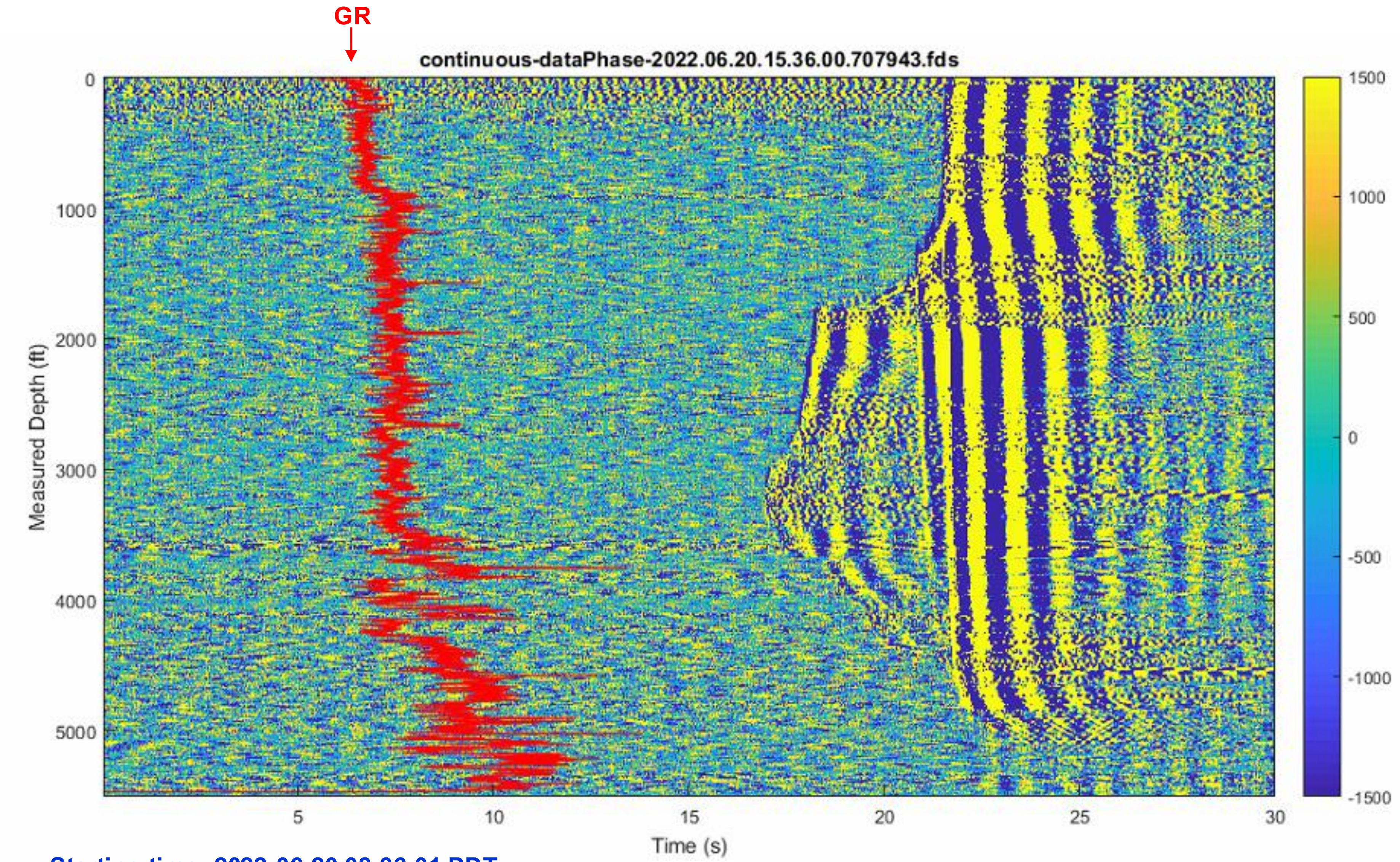
60 Minutes after P4: 2022-05-10 15:35:17 PDT

Zoomed in and applied filter: 3-5-200-250 Hz



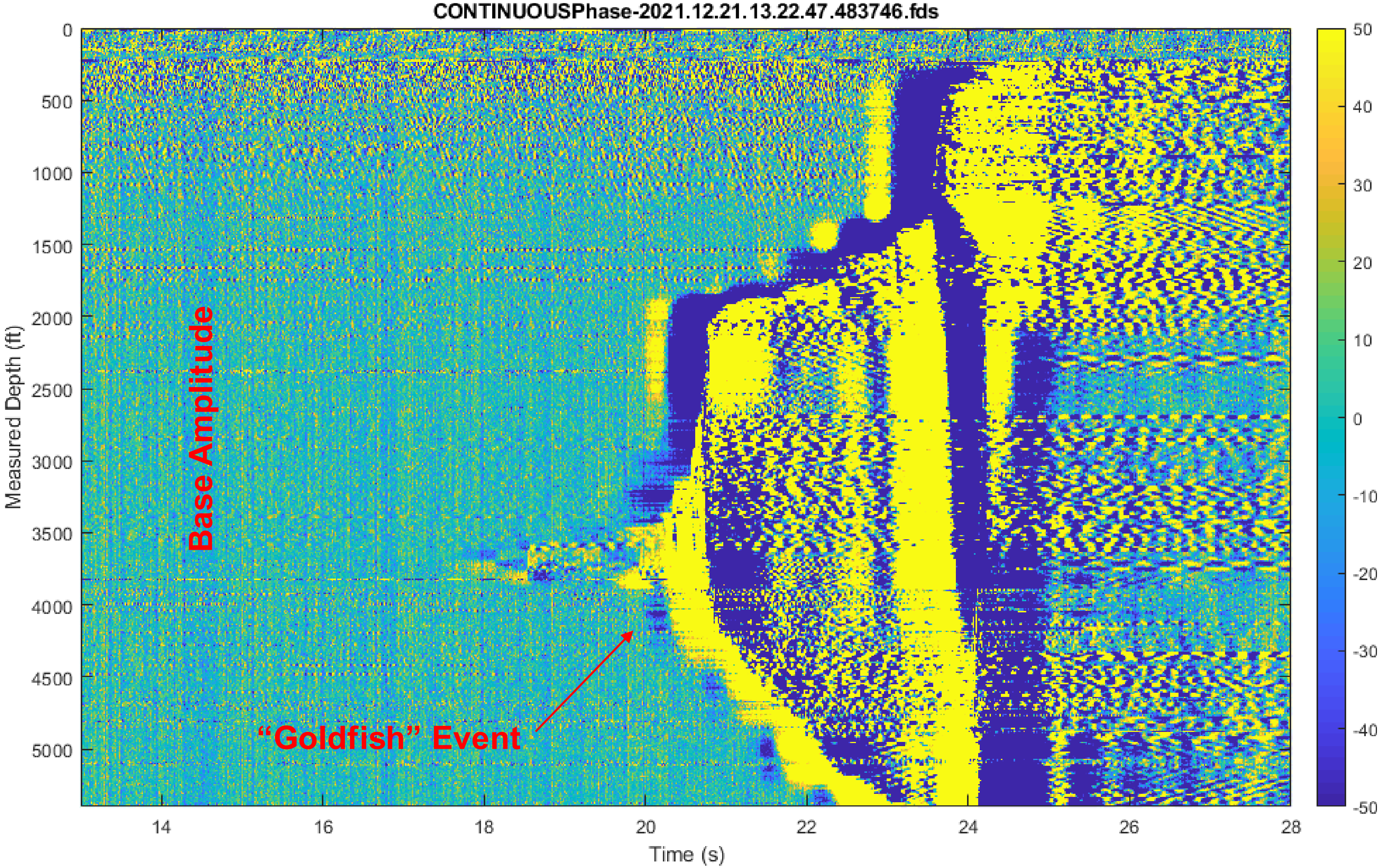
Starting time: 2022-05-10 15:35:17 PDT

Event: 2022-06-20 08:36:17 PDT



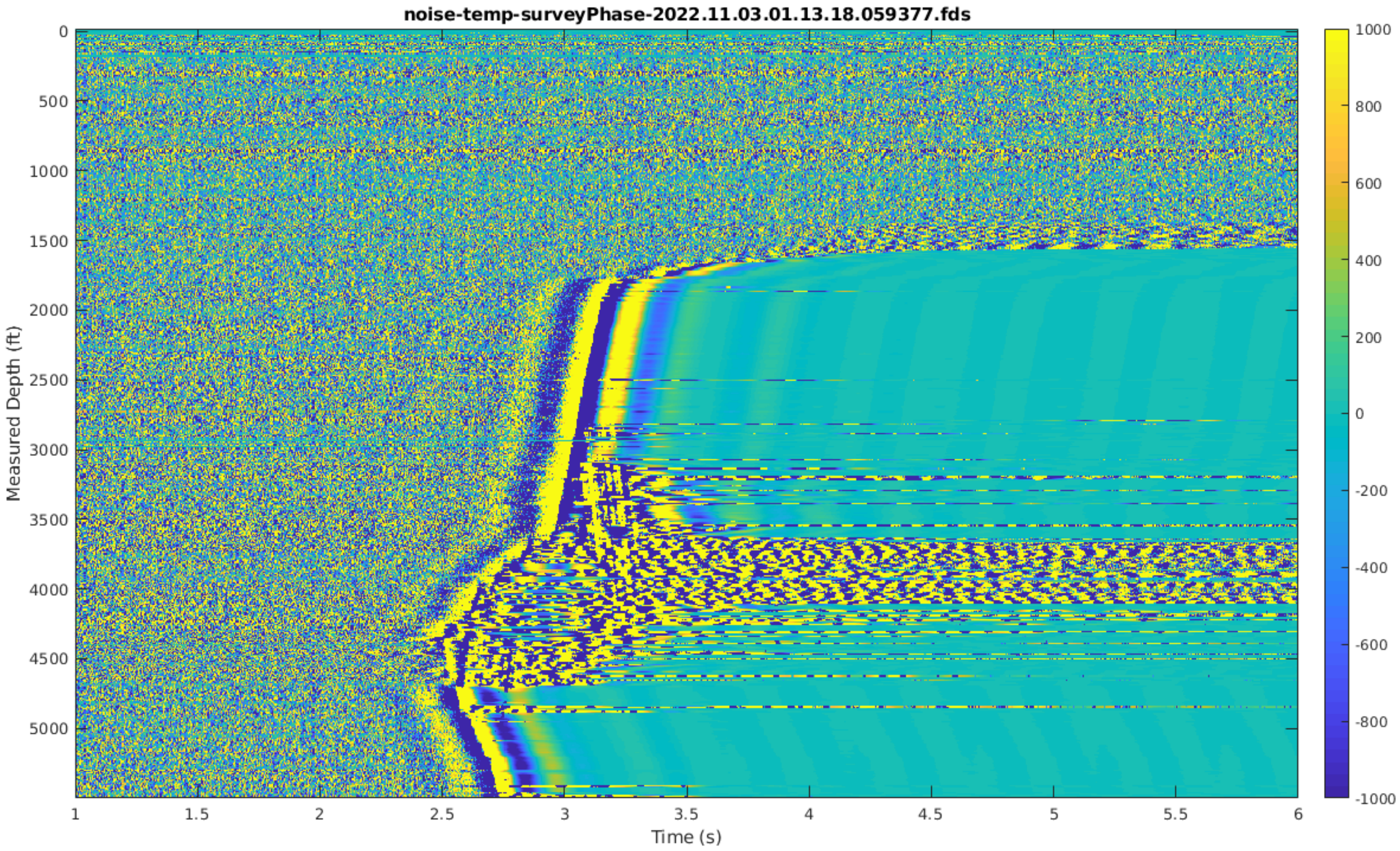
Starting time: 2022-06-20 08:36:01 PDT

EDAS Oscillating Gas Bubble Event.

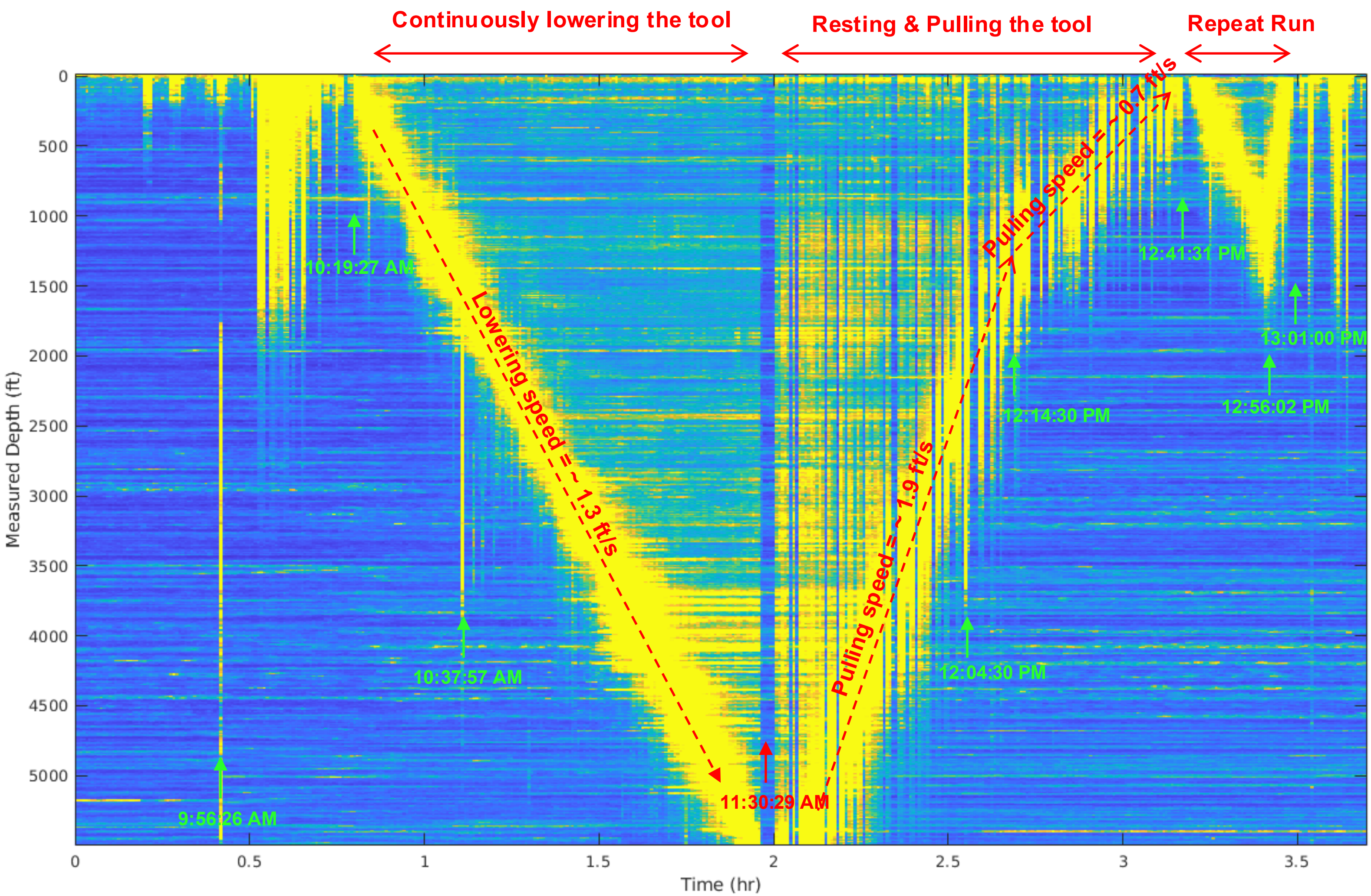


PG&E McDonald Island Noise Logging EDAS Data

An Event 40 Hours before the Survey



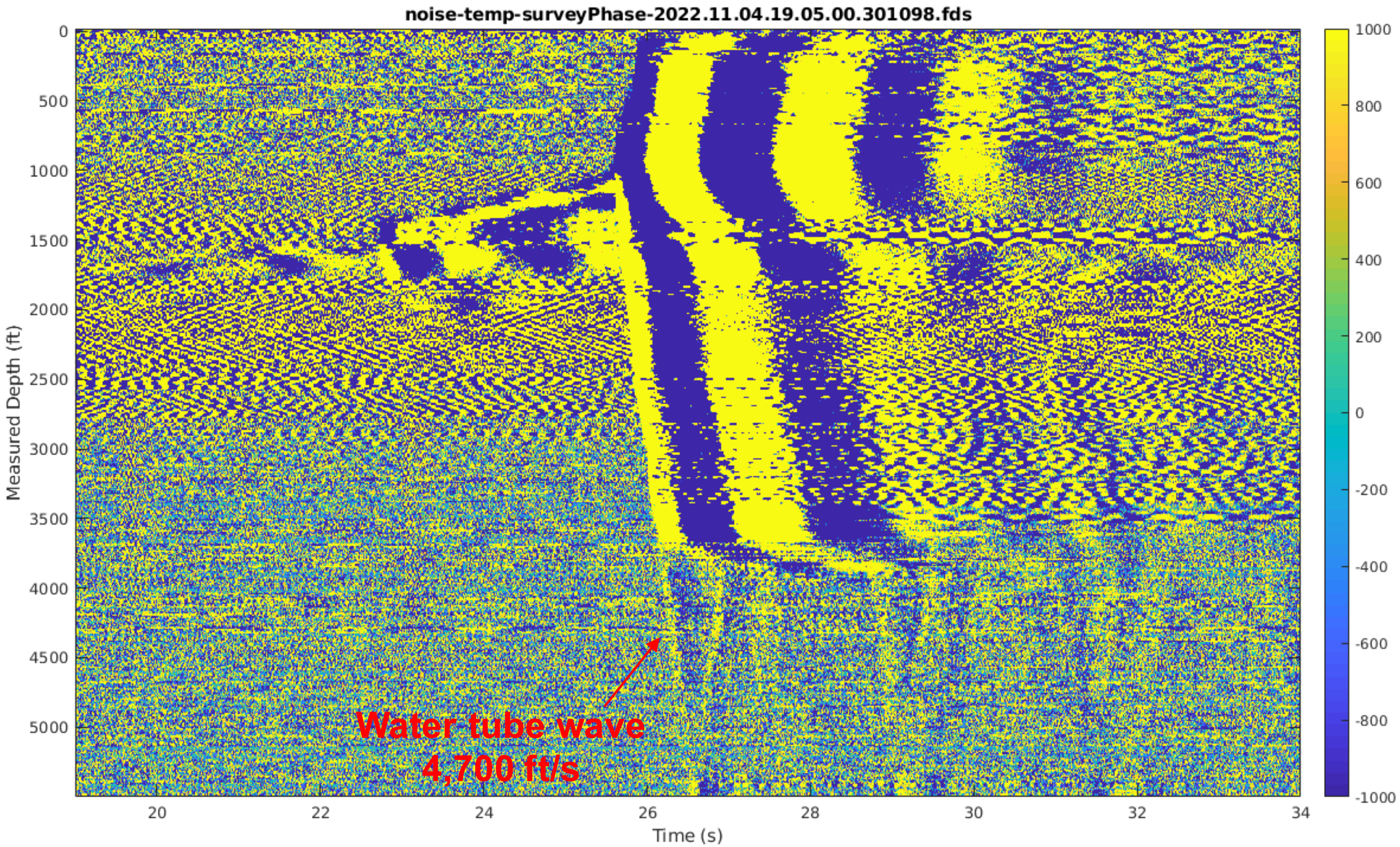
Overall EDAS Noise Level During Logging – 3.7 hour Run



Logging Date: 11/04/2022

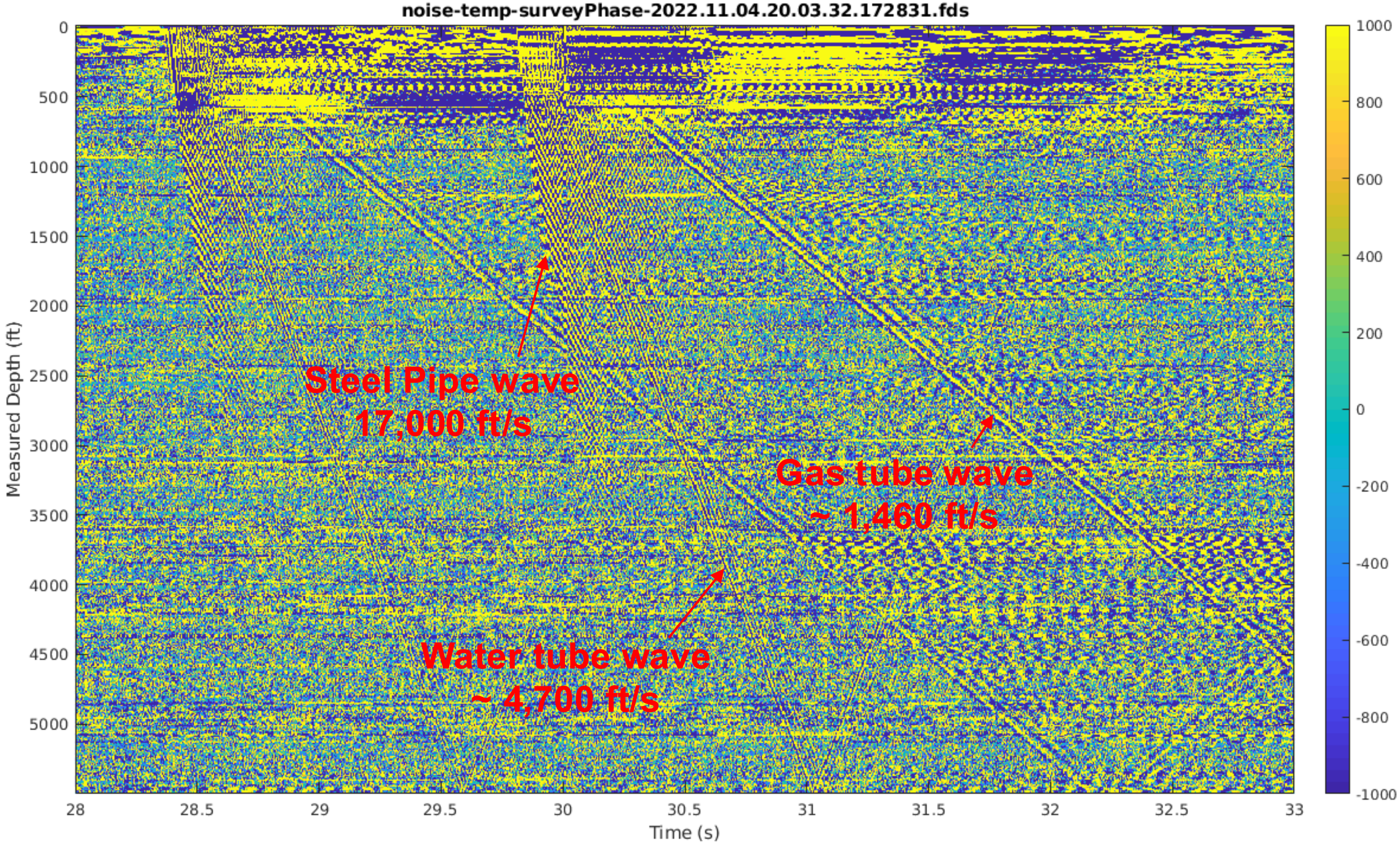
 Proprietary Material – Paulsson, Inc (PI).

Zoom In of Event @ 12:05:20 PM



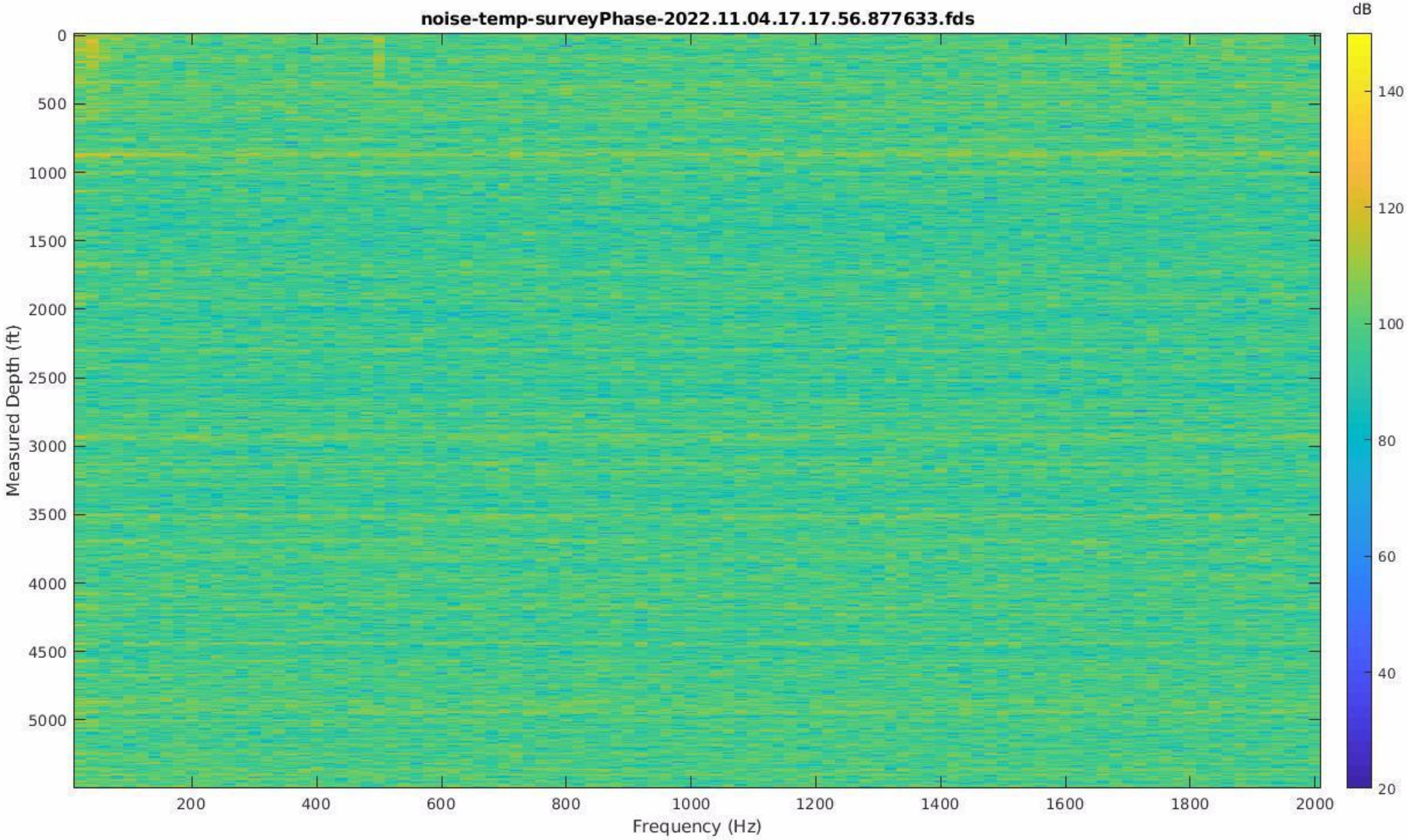
 Proprietary Material – Paulsson, Inc (PI).

After-Survey Event @ 13:04:00 PM
Three Different Tube & Pipe Waves – A Complex System!



The tubing is filled with gas, and the annulus (between tubing and casing) is filled with water.

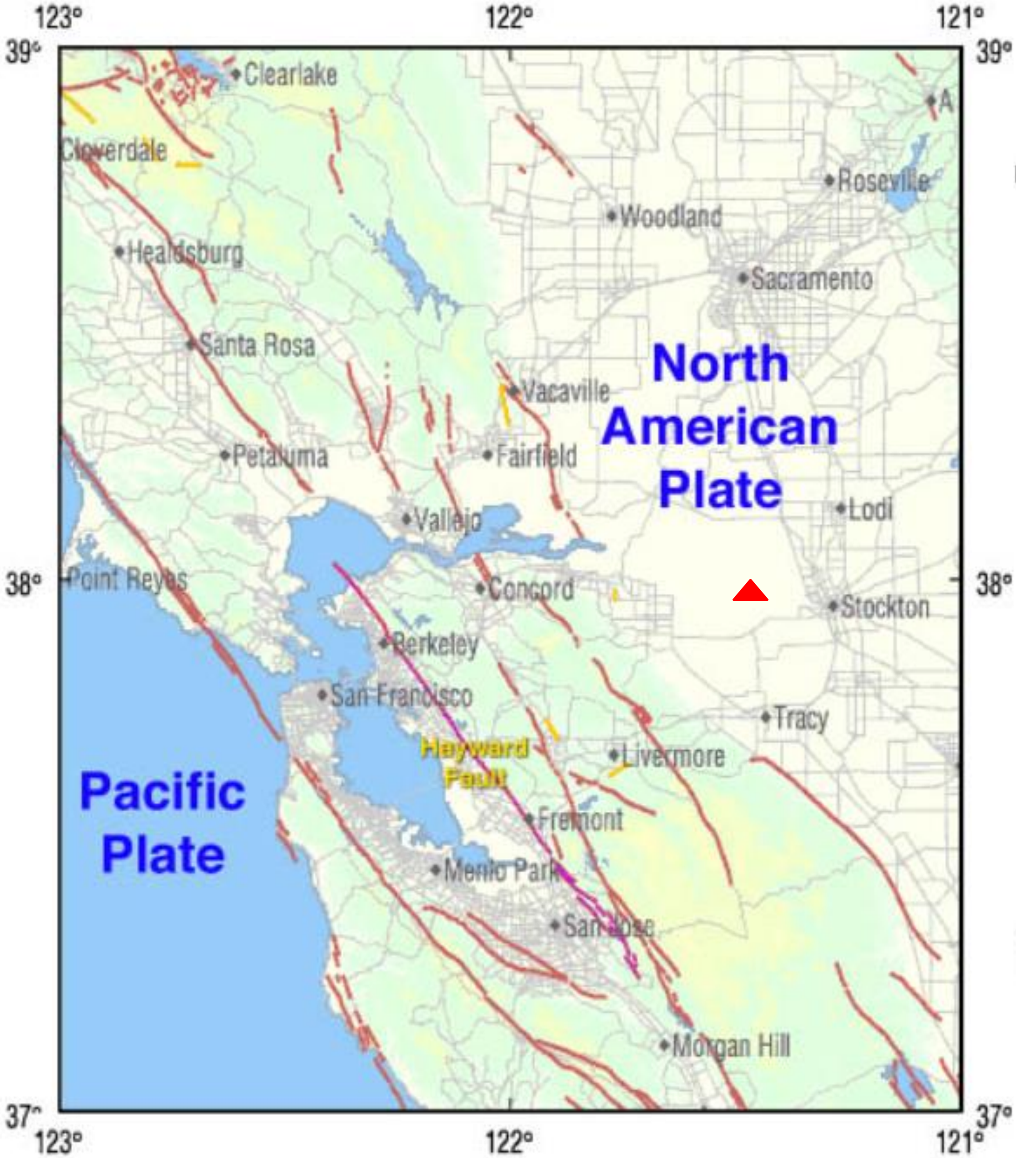
EDAS Spectrum Movie During Noise and Temperature Log

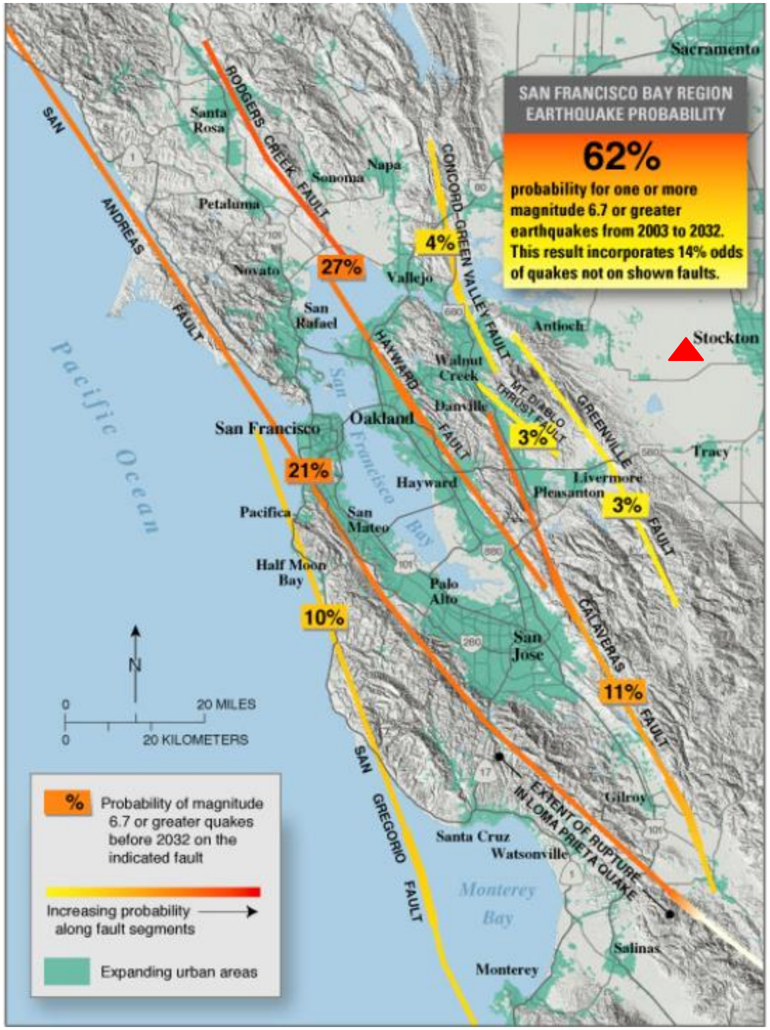


 Proprietary Material – Paulsson, Inc (PI).

PG&E McDonald Island EDAS Earthquake Data

Fault Line Maps: We Monitor the Hayward Fault with a DAS Installation





 Proprietary Material – Paulsson, Inc (PI).

USGS Surface Station & Well Site for Paulsson Borehole Seismic Array

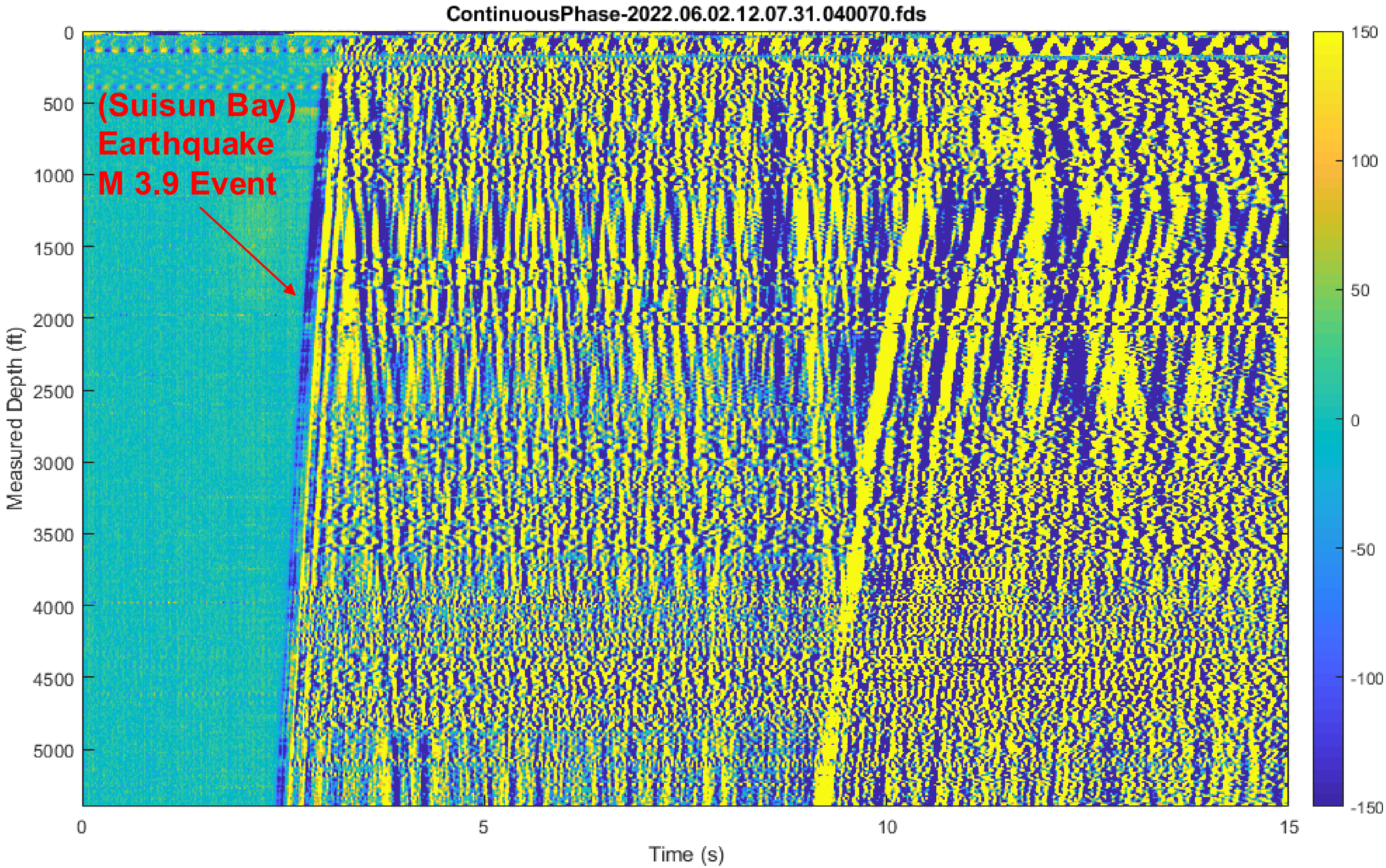
Network	Station Code	Latitude	Longitude	Elevation
BK	TWIT	38.10°	-121.68°	-3 m

USGS BK-TWIT:
Sampling Rate: 40 Hz

00: **MBB-2,Velocity Sensor,EQMET**
Depth: 2.8 m
Channels: BHE, BHN, BHZ

 Proprietary Material – Paulsson, Inc (PI).

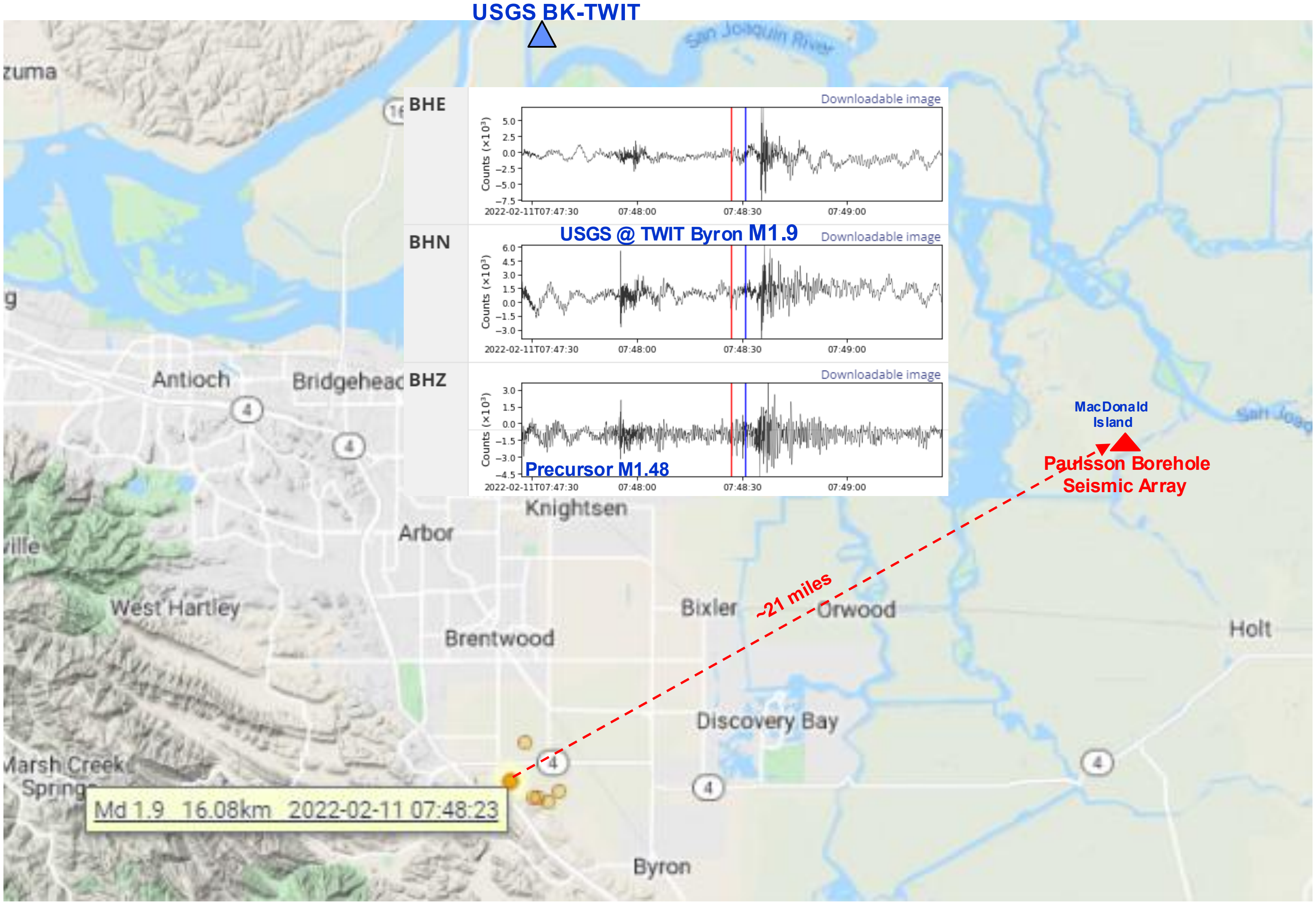
A Suisun Bay M3.9 Earthquake Event = 44×10^9 J = 44 GJ



 Proprietary Material – Paulsson, Inc (PI).

M1 – M2 Earthquakes: Byron M1.9 = 0.4 GJ Earthquake

UTC 2022-02-11 07:48:23 Depth 16.08 km

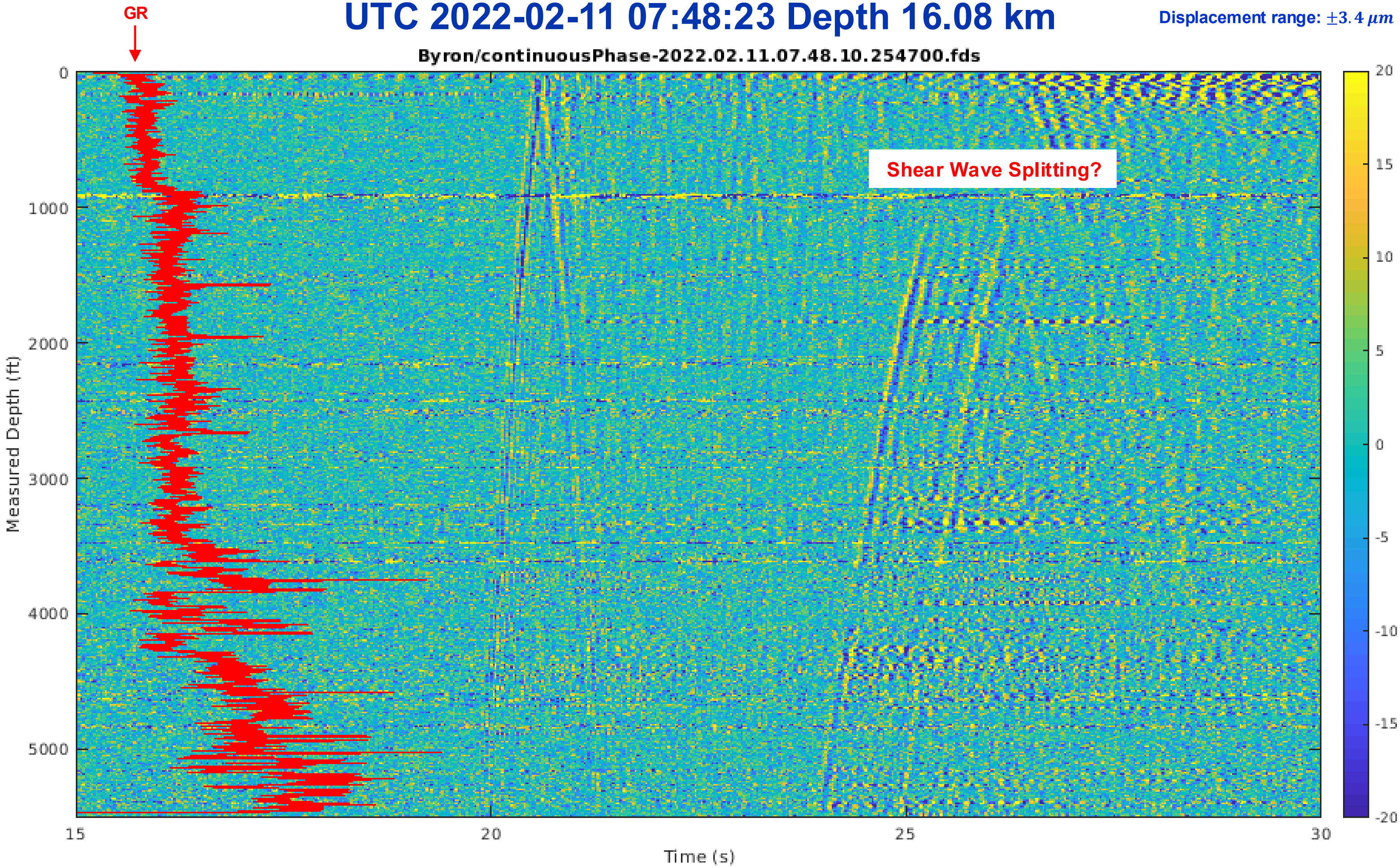


 Proprietary Material – Paulsson, Inc (PI).

M1 – M2 Earthquakes: Byron M1.9 = 0.4 GJ Earthquake

UTC 2022-02-11 07:48:23 Depth 16.08 km

Displacement range: $\pm 3.4\ \mu m$

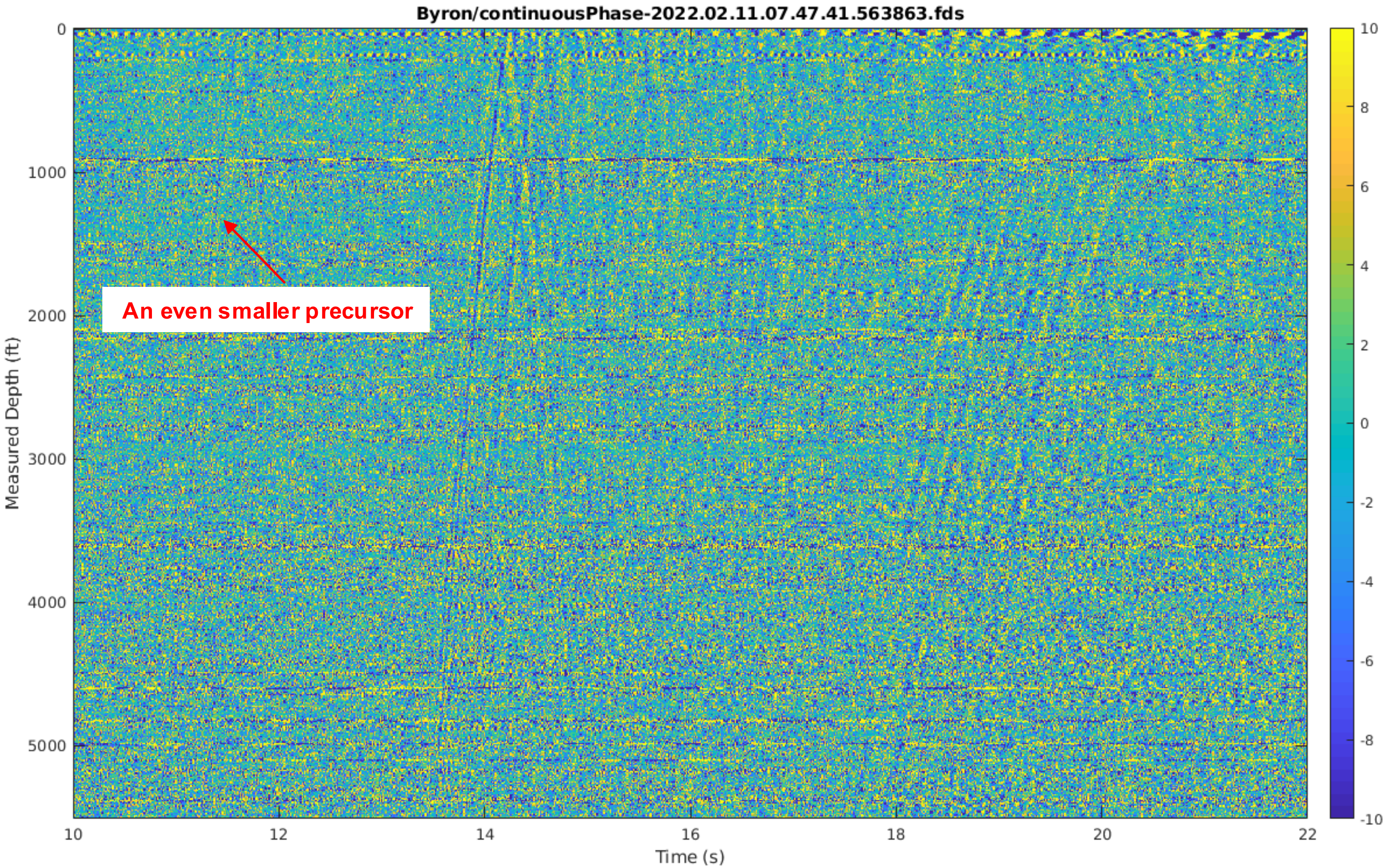


 Proprietary Material – Paulsson, Inc (PI).

M1 – M2 Earthquakes: Byron Earthquake Precursor M1.48

UTC 2022-02-11 07:47:45 Depth 10.12 km

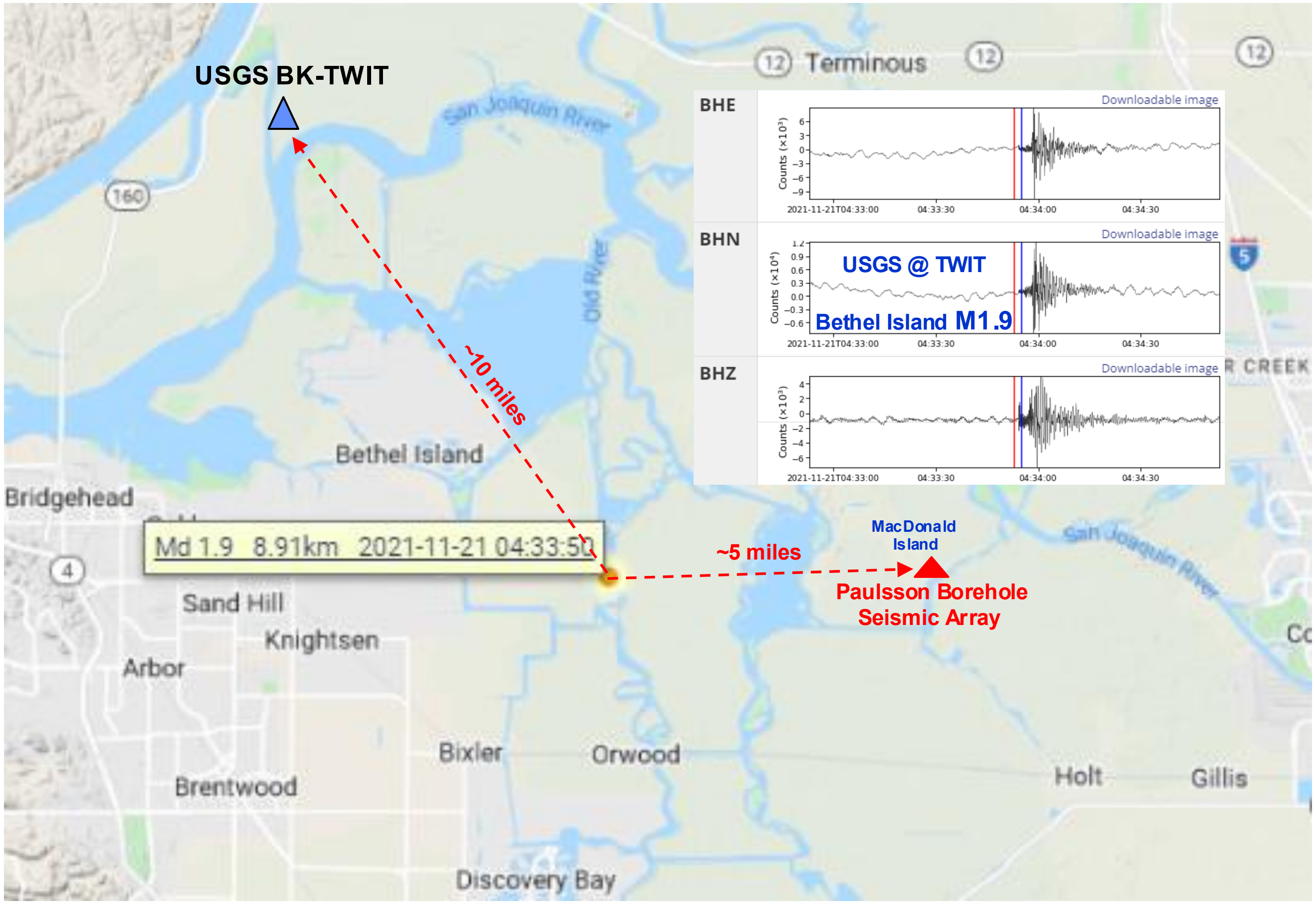
Displacement range: $\pm 1.7\ \mu m$



Precursor M1.48 = 0.1 GJ. To heat 1 m^3 $H_2$0 100°C = 0.4 GJ

<u>M1 – M2 Earthquakes:</u> Bethel Island M1.9 = 0.4 GJ Earthquake

UTC 2021-11-21 04:33:50 Depth 8.91 km

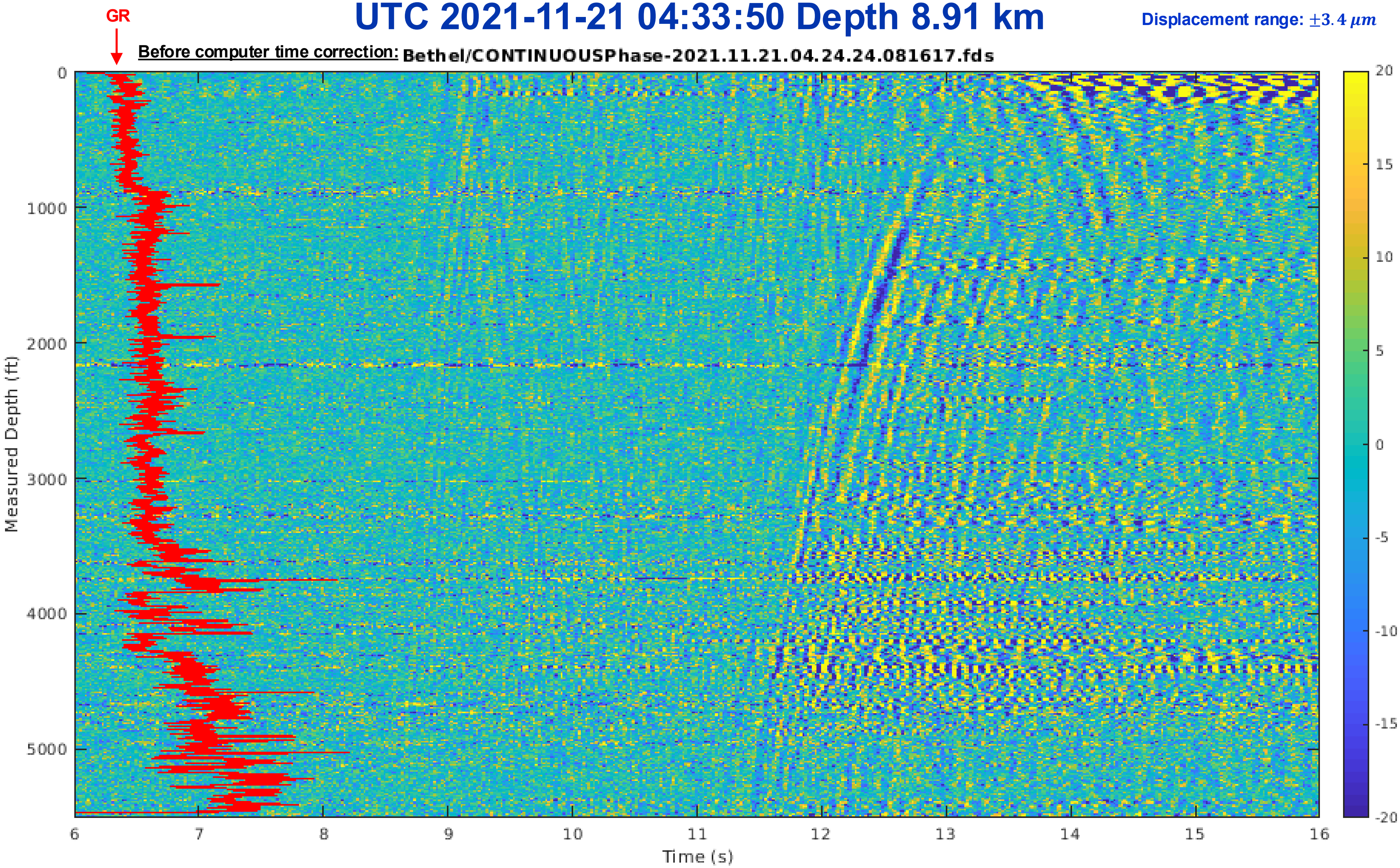


 Proprietary Material – Paulsson, Inc (PI).

M1 – M2 Earthquakes: Bethel Island M1.9= 0.4 GJ Earthquake

UTC 2021-11-21 04:33:50 Depth 8.91 km

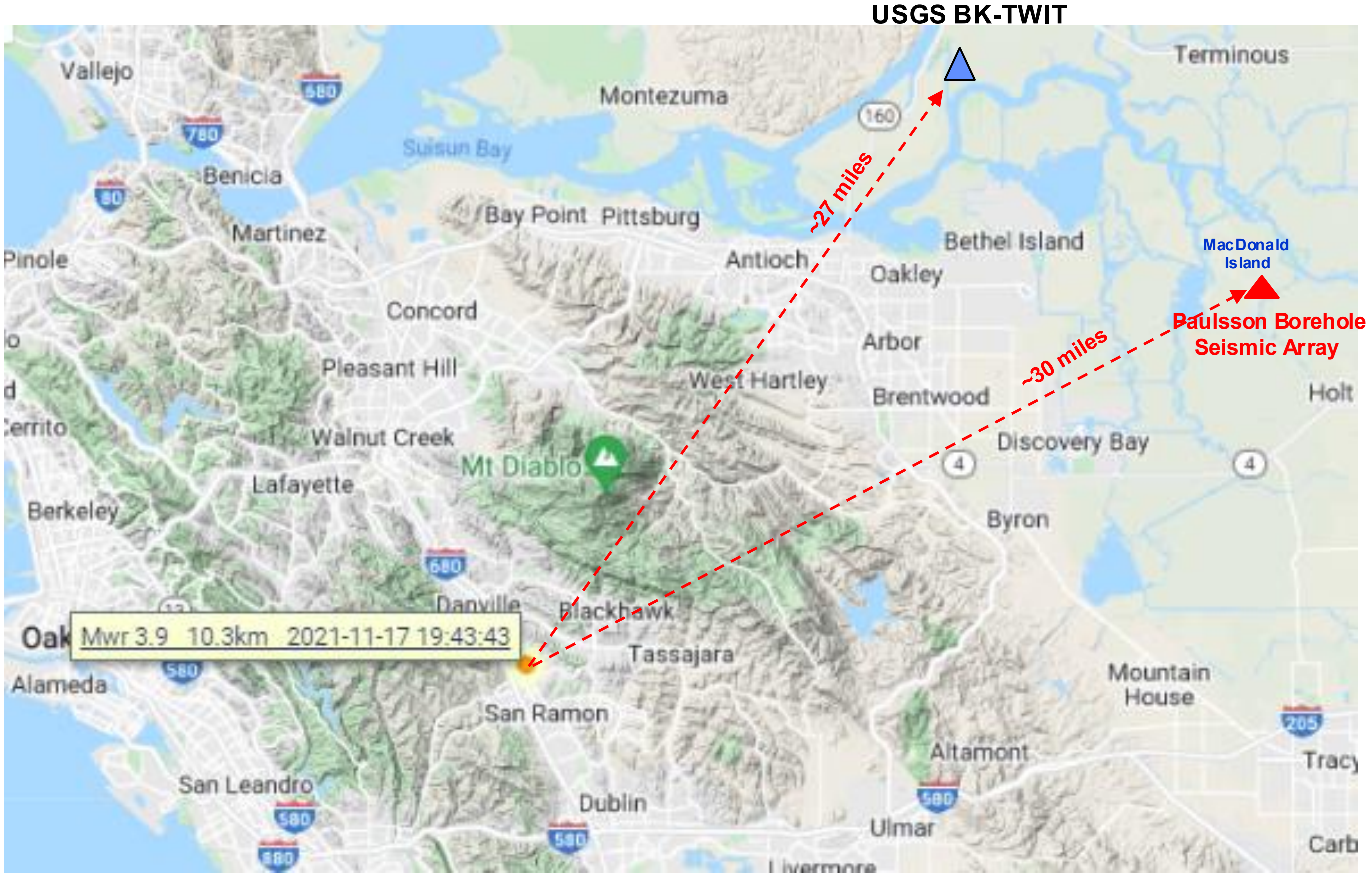
Displacement range: ±3.4 μm



 Proprietary Material – Paulsson, Inc (PI).

M3 – M4 Earthquakes: San Ramon M3.9 Earthquake

UTC 2021-11-17 19:43:43 Depth 10.3 km

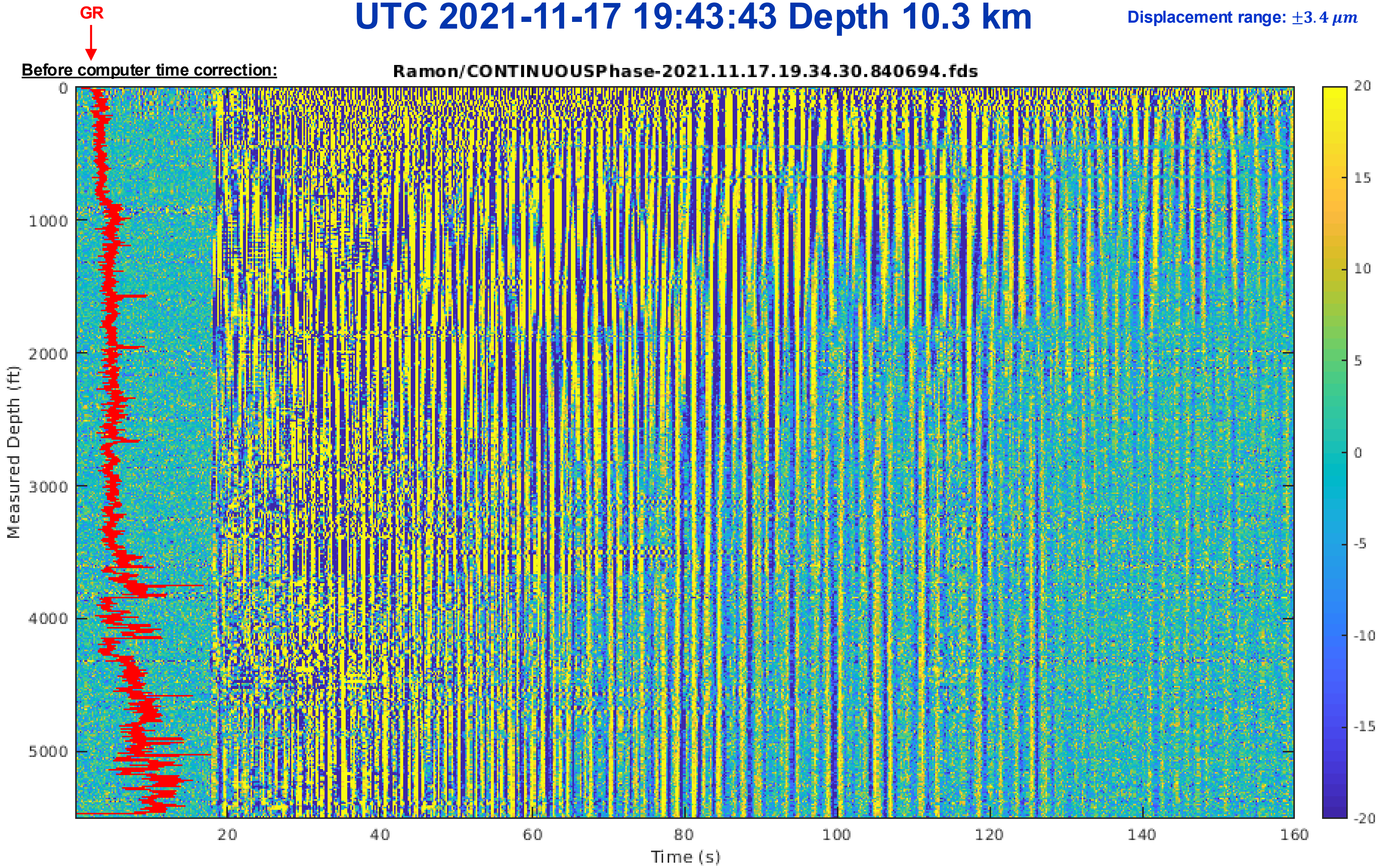


 Proprietary Material – Paulsson, Inc (PI).

M3 – M4 Earthquakes: San Ramon M3.9 Earthquake

UTC 2021-11-17 19:43:43 Depth 10.3 km

Displacement range: $\pm 3.4\ \mu m$

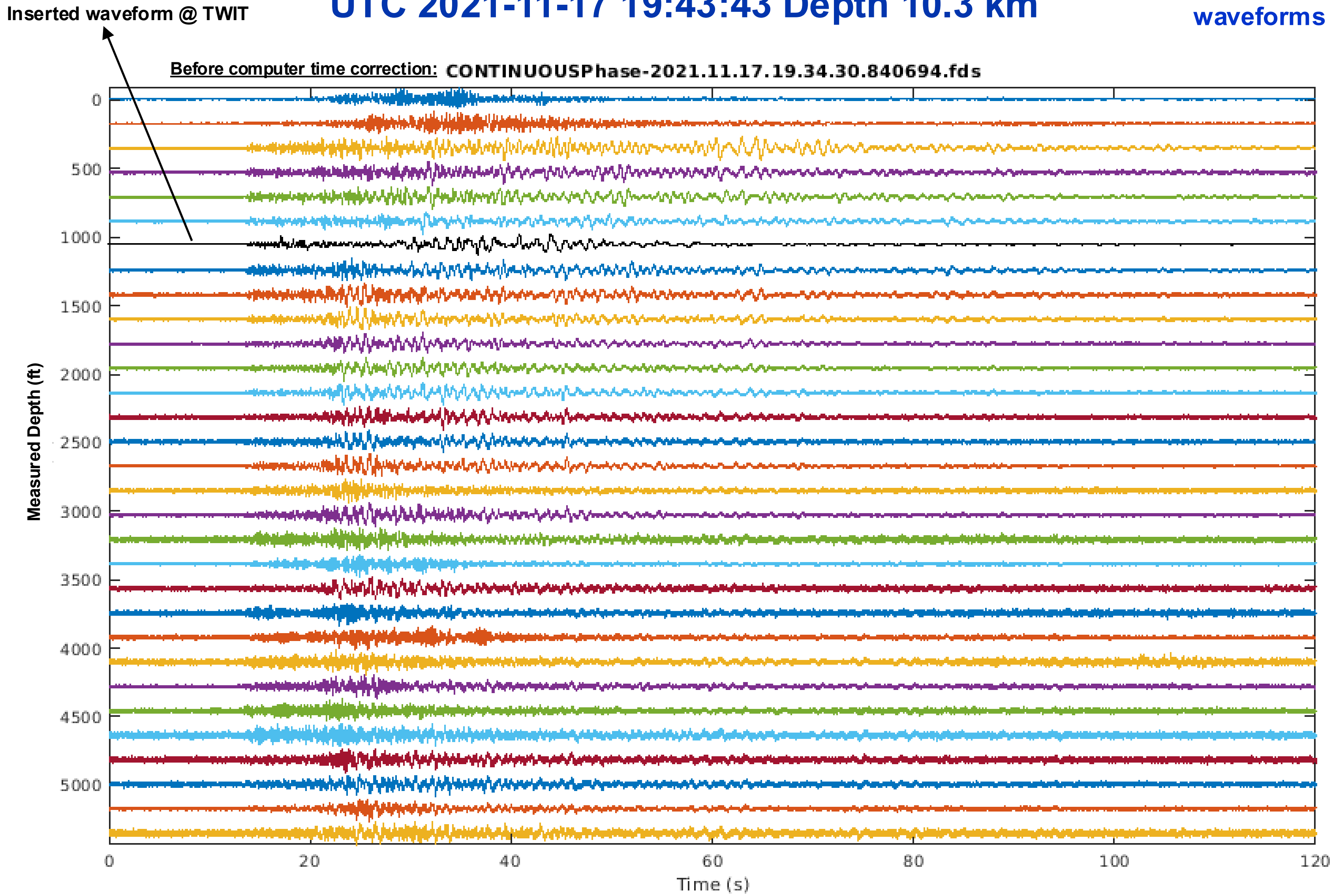


 Proprietary Material – Paulsson, Inc (PI).

M3 – M4 Earthquakes: San Ramon M3.9 Earthquake

UTC 2021-11-17 19:43:43 Depth 10.3 km

waveforms

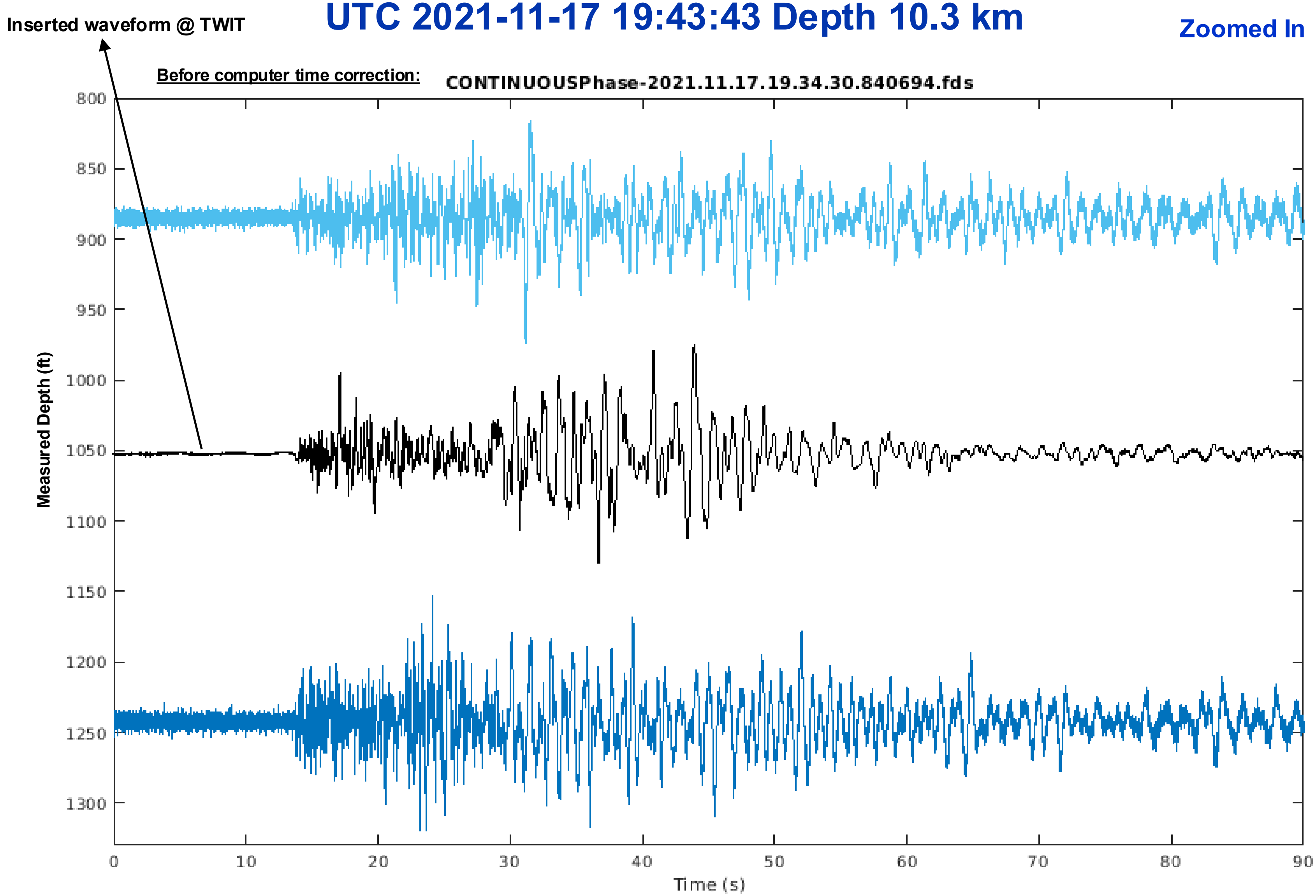


 Proprietary Material – Paulsson, Inc (PI).

M3 – M4 Earthquakes: San Ramon M3.9 Earthquake

UTC 2021-11-17 19:43:43 Depth 10.3 km

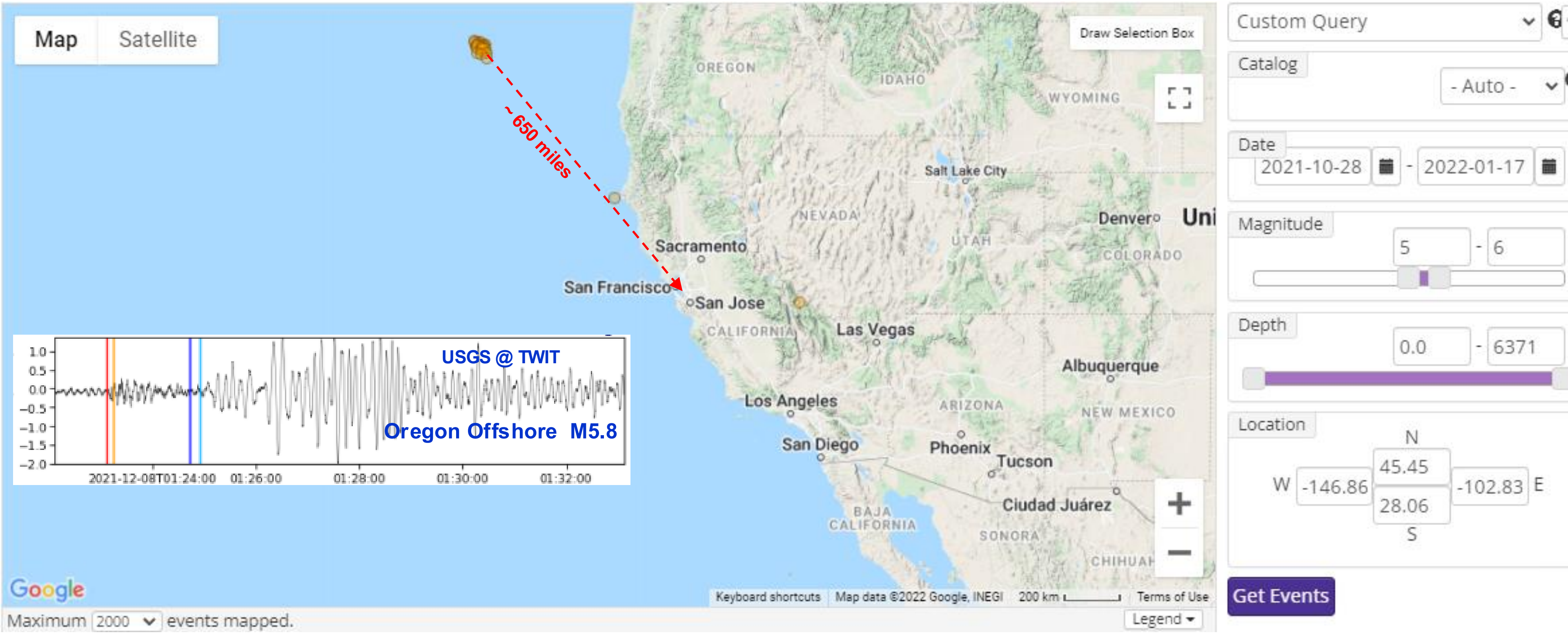
Zoomed In

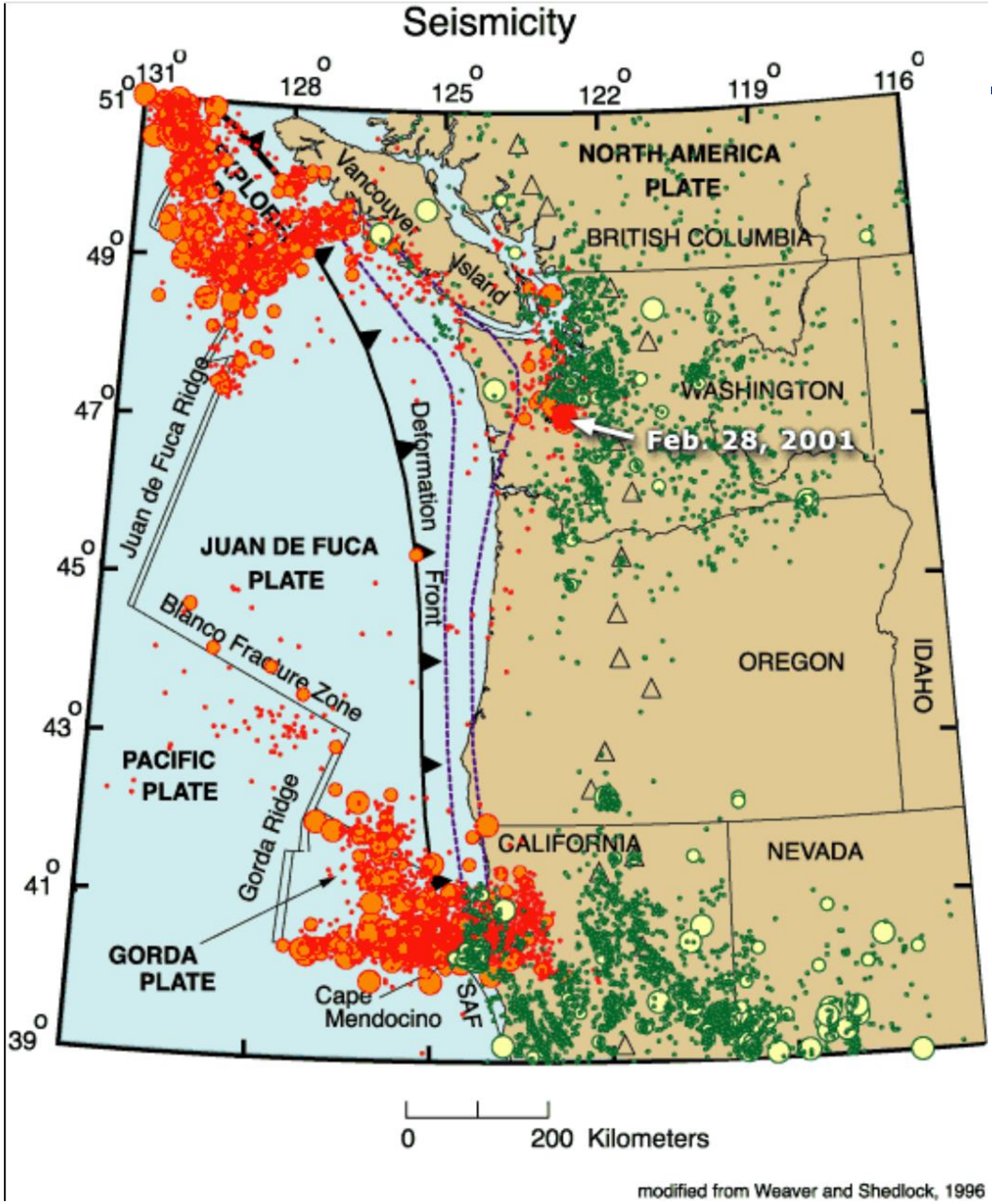


M5 – M6 Earthquakes: Oregon Offshore

M5.8 Earthquake = $30x10^{12}$ J = 30 TJ

UTC 2021-12-08 01:21:05 Depth 10 km



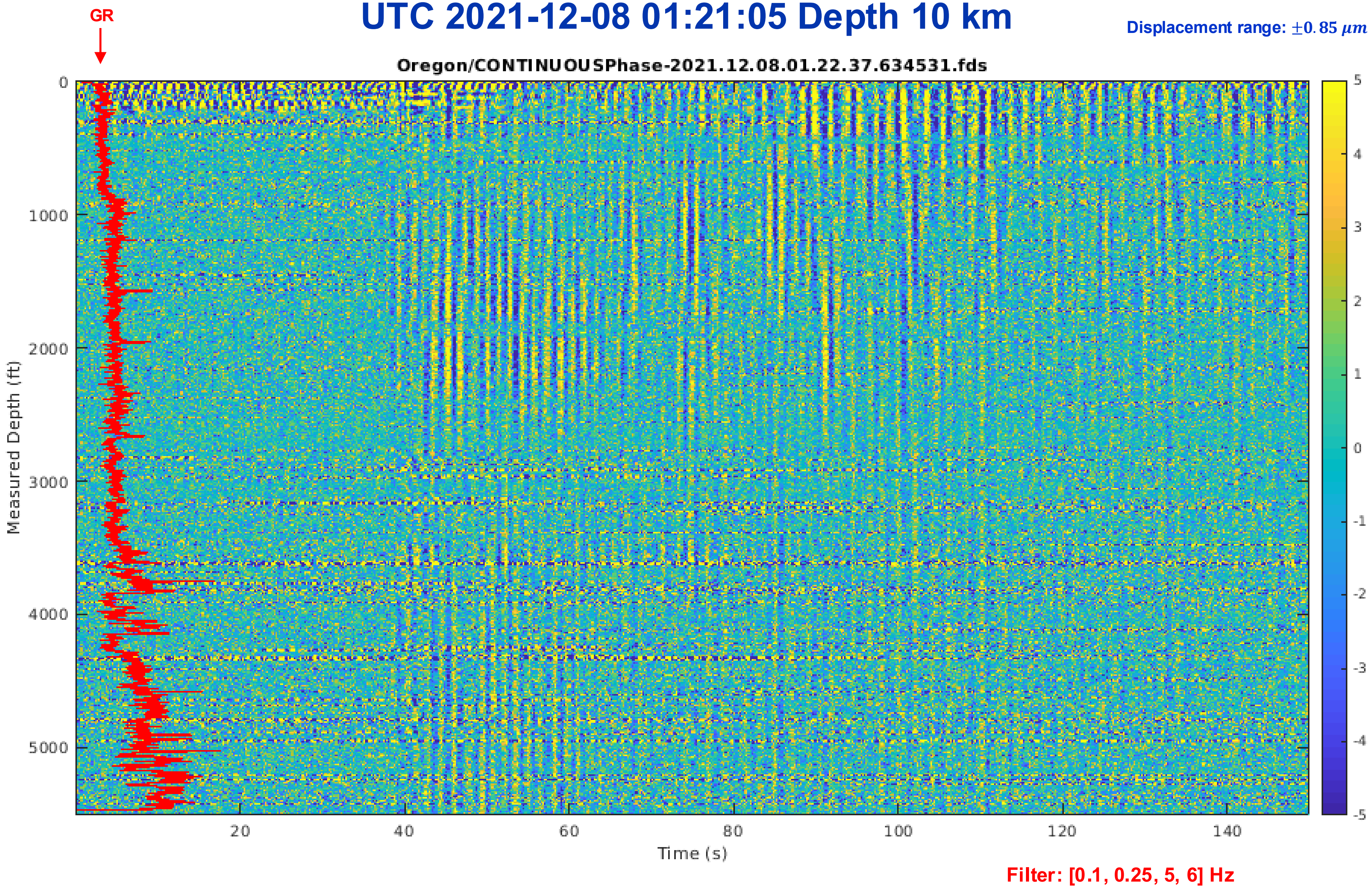


M5-M6 Earthquakes: Oregon Offshore

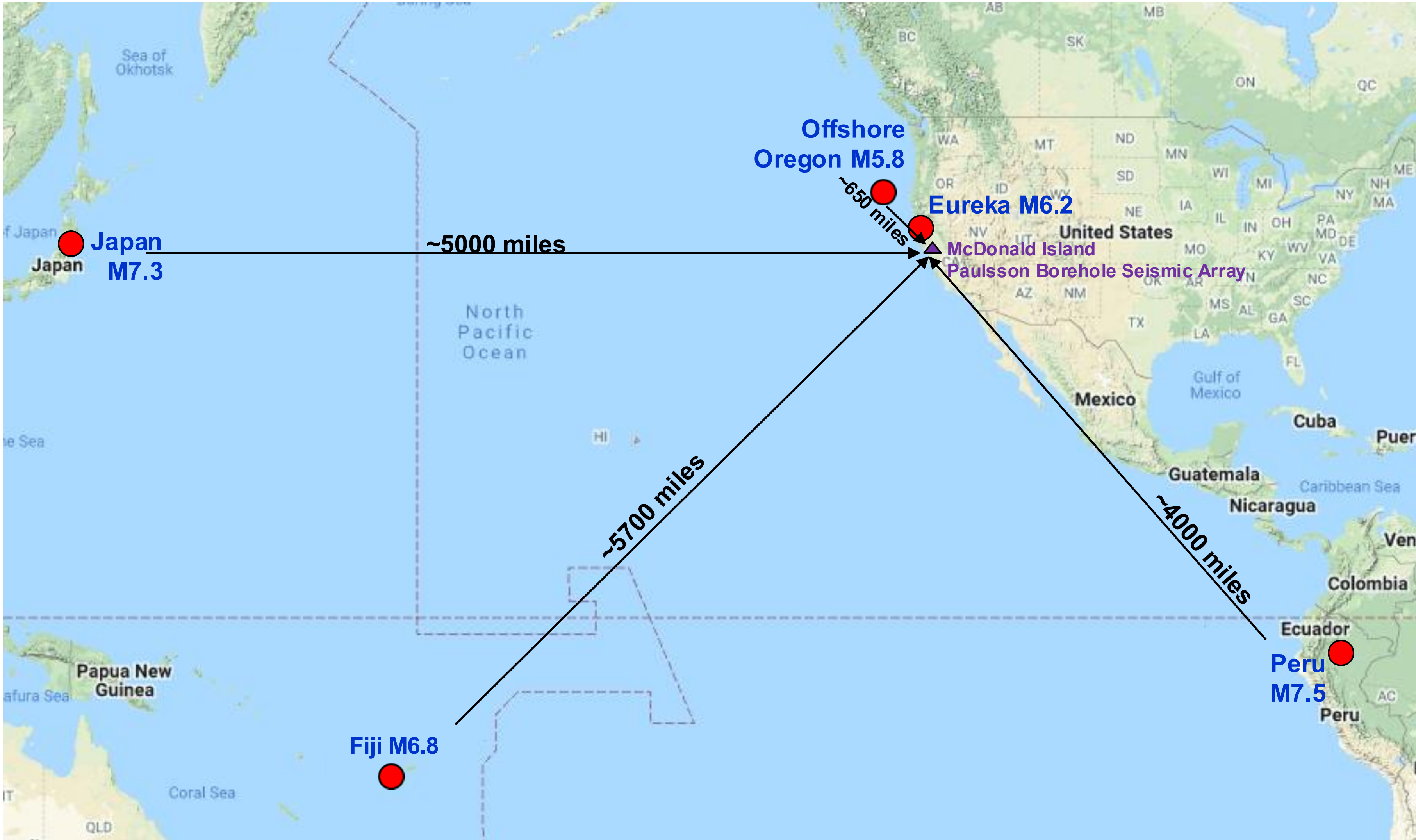
- M5.8 Earthquake = 30×10^{12} J = 30 TJ
- UTC 2021-12-08 01:21 Depth 10 km
- Last Large EQ on this Fault zone was in year 1700 = M9
- 40 in 10,000 years
- MTBEQ = 250 year

M5 – M6 Earthquakes: Oregon Offshore M5.8 Earthquake

UTC 2021-12-08 01:21:05 Depth 10 km

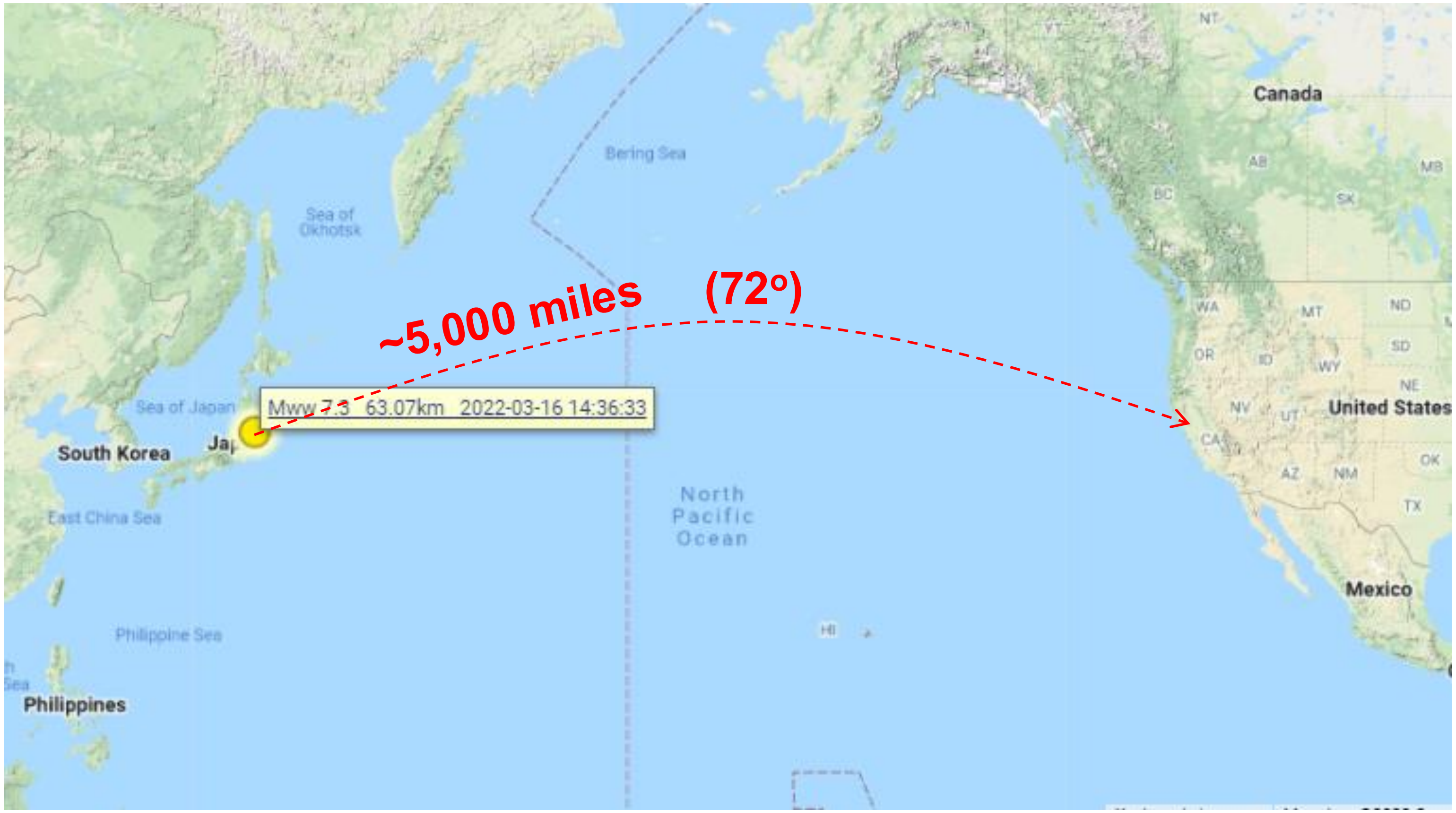


M5 or Larger Observed Earthquakes



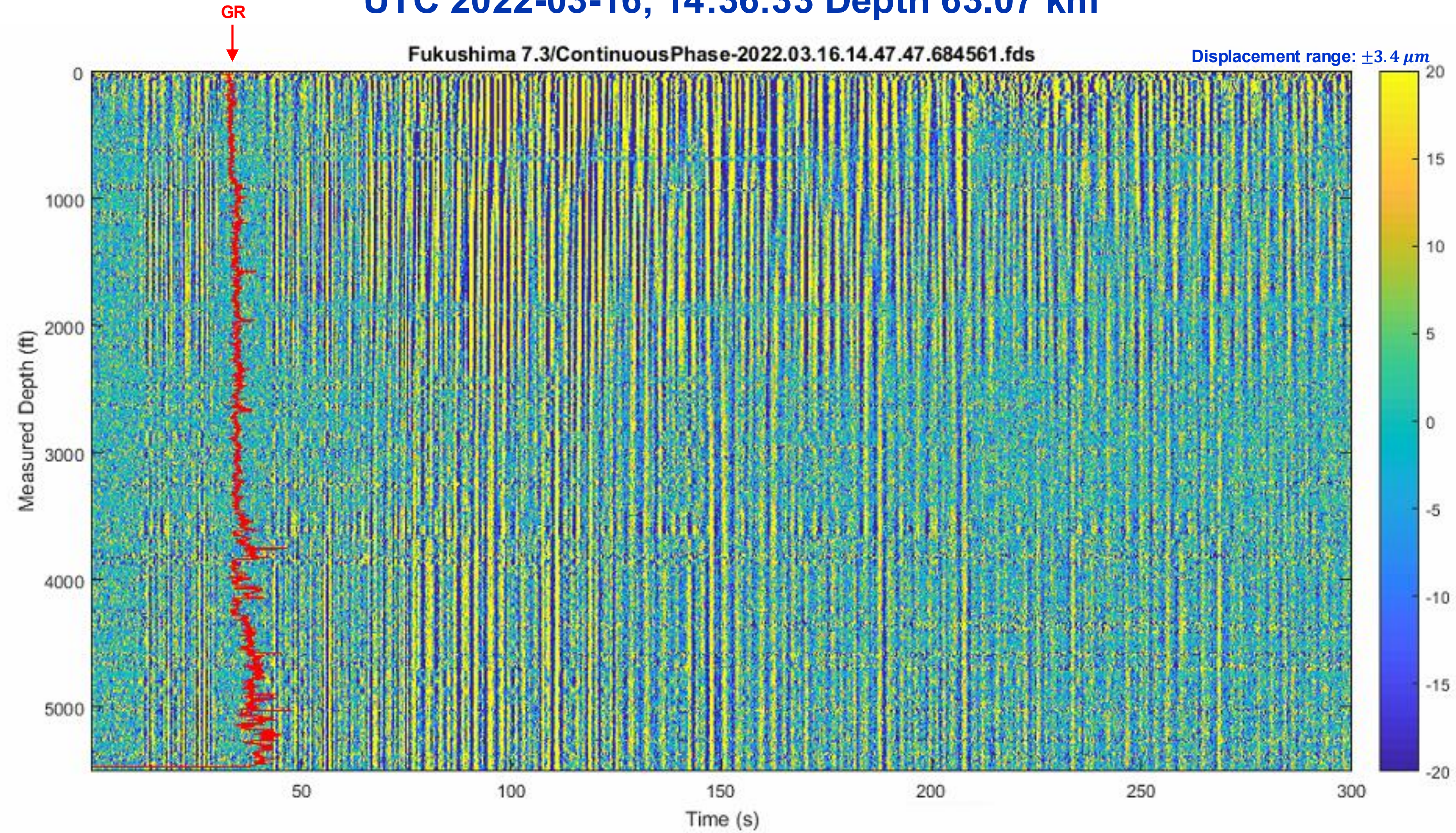
 Proprietary Material – Paulsson, Inc (PI).

M7 & above Earthquakes: Fukushima M7.3 Earthquake (1 Quadrillion Joules, 1x10^{15}, One Peta Joules) UTC 2022-03-16 14:36:33 Depth 63.07 km



Fukushima 2011 M9 Earthquake = 2x10^{18} Joules

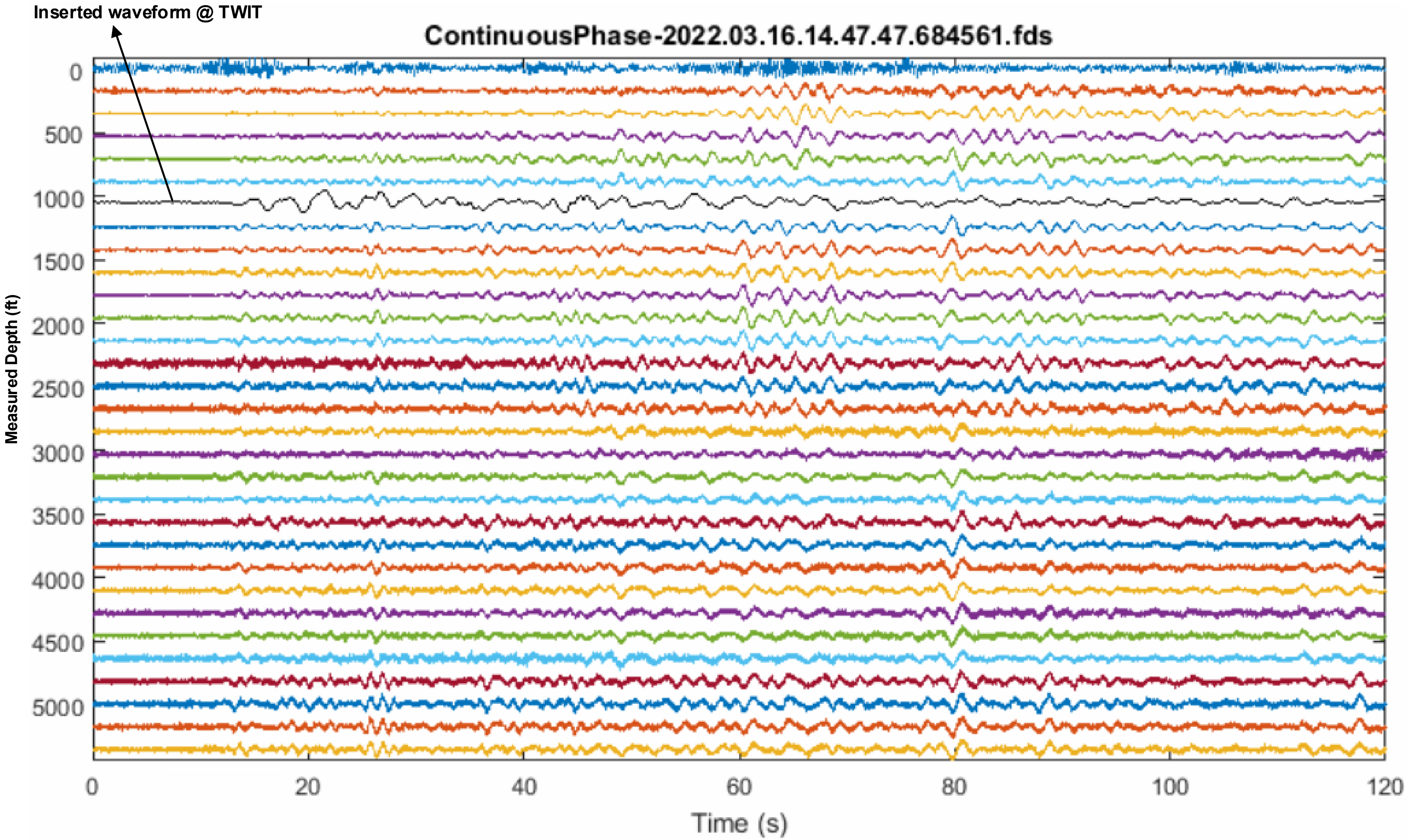
M7 & above Earthquakes: Fukushima M7.3 Earthquake
(1 Quadrillion Joules, $1x10^{15}$, One Peta Joules)
UTC 2022-03-16, 14:36:33 Depth 63.07 km



M7 & above Earthquakes: Fukushima M7.3 Earthquake

UTC 2022-03-16 14:36:33 Depth 63.07 km

waveforms



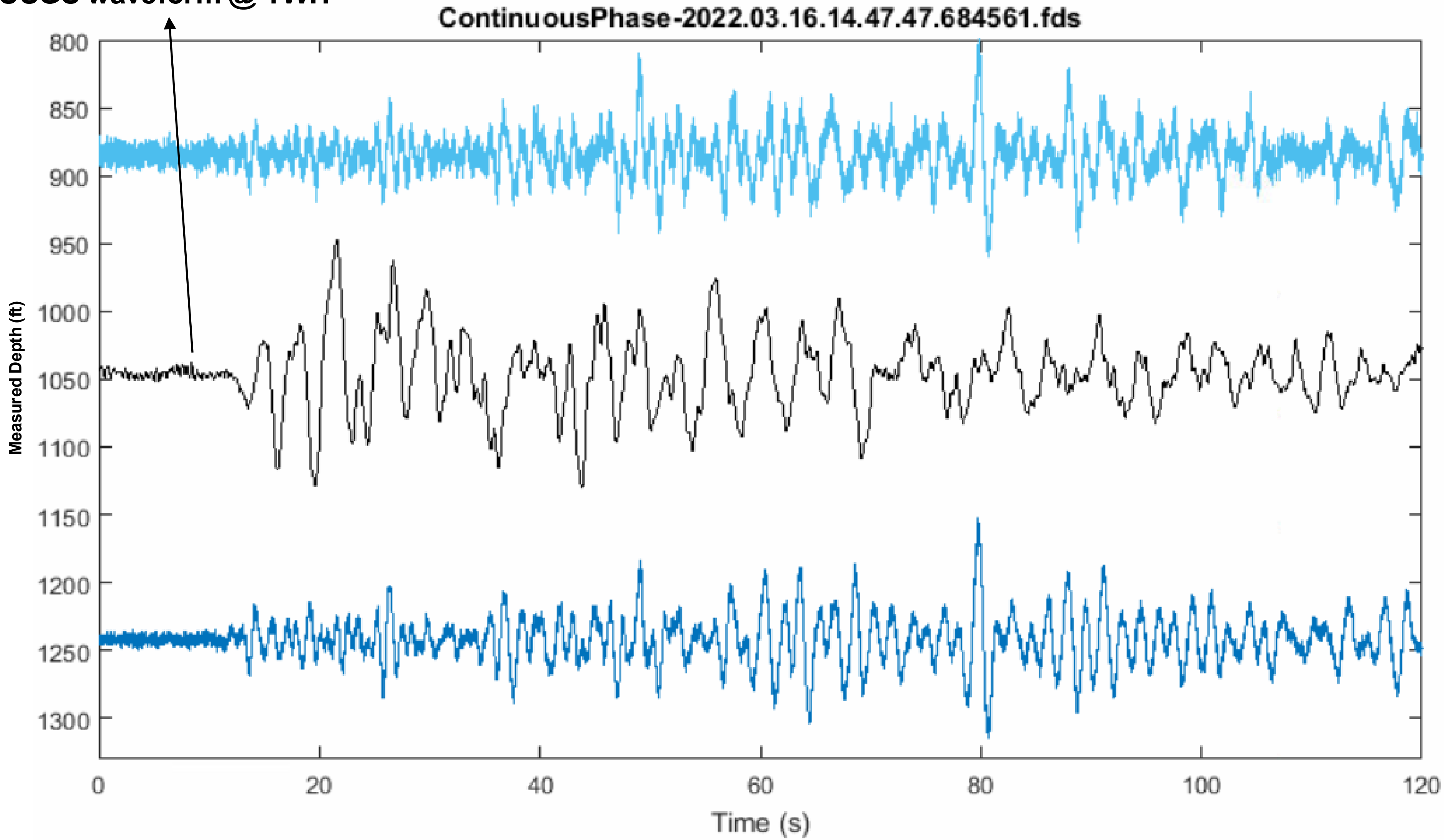
 Proprietary Material – Paulsson, Inc (PI).

M7 & above Earthquakes: Fukushima M7.3 Earthquake

UTC 2022-03-16 14:36:33 Depth 63.07 km

Zoomed In

USGS waveform @ TWIT



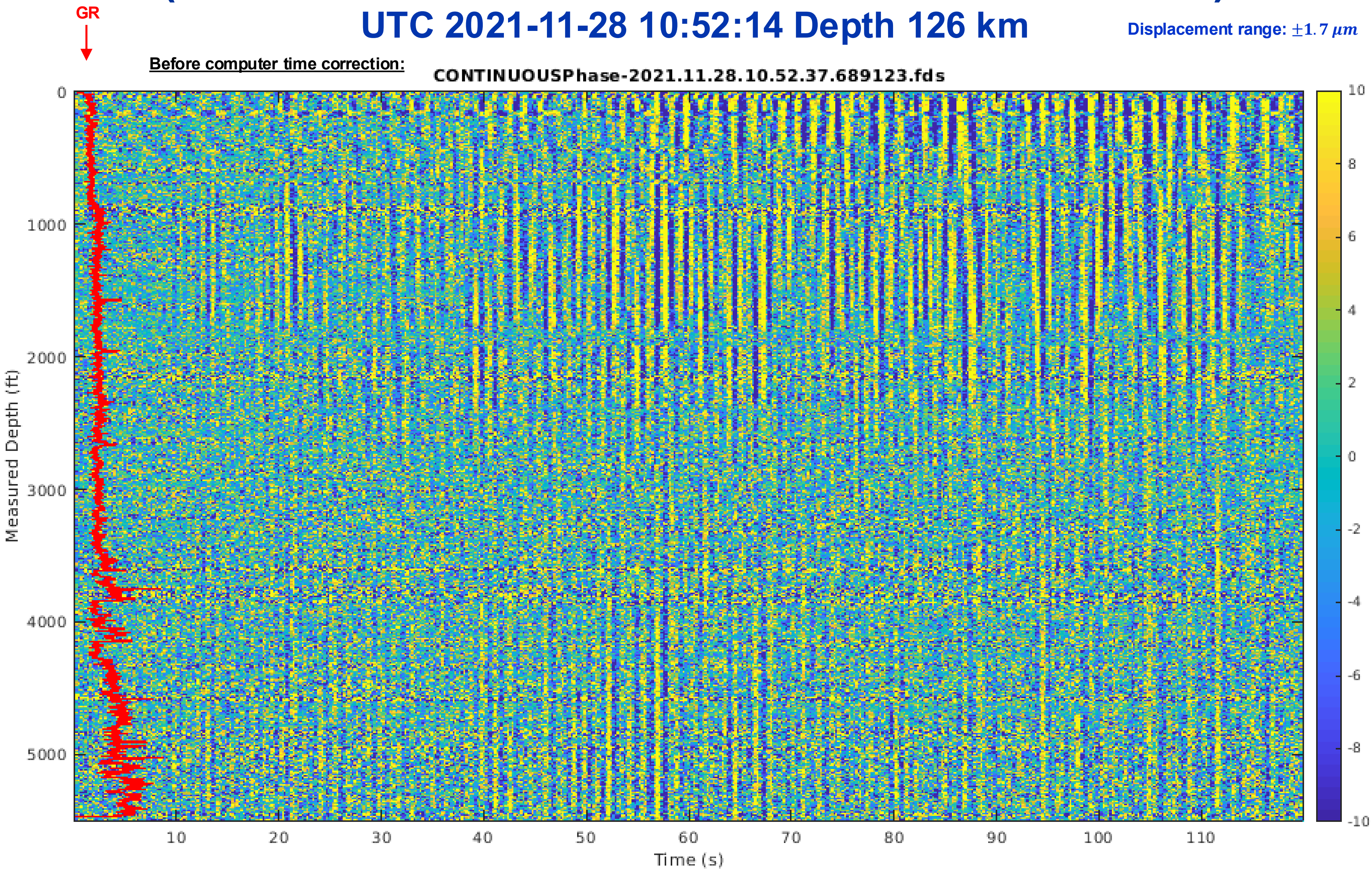
 Proprietary Material – Paulsson, Inc (PI).

M7 & above Earthquakes: Peru M7.5 Earthquake (5 Quadrillion Joules, $1x10^{15}$, Five Peta Joules) UTC 2021-11-28 10:52:14 Depth 126 km

M7 & above Earthquakes: Peru M7.5 Earthquake
(5 Quadrillion Joules, $1x10^{15}$, Five Peta Joules)
UTC 2021-11-28 10:52:14 Depth 126 km

Displacement range: $\pm 1.7\ \mu m$

Before computer time correction:

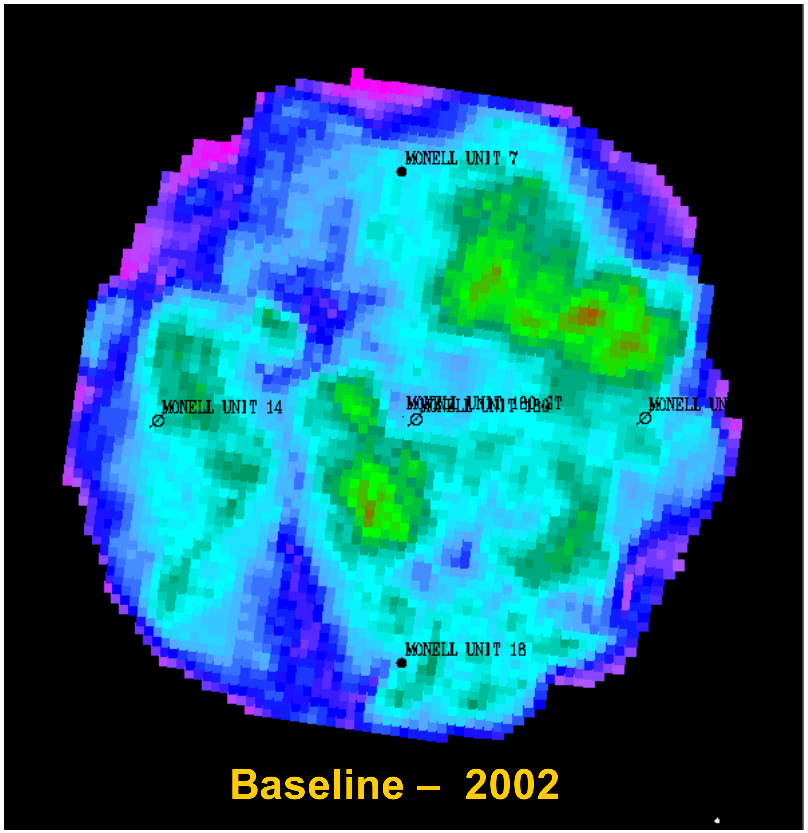


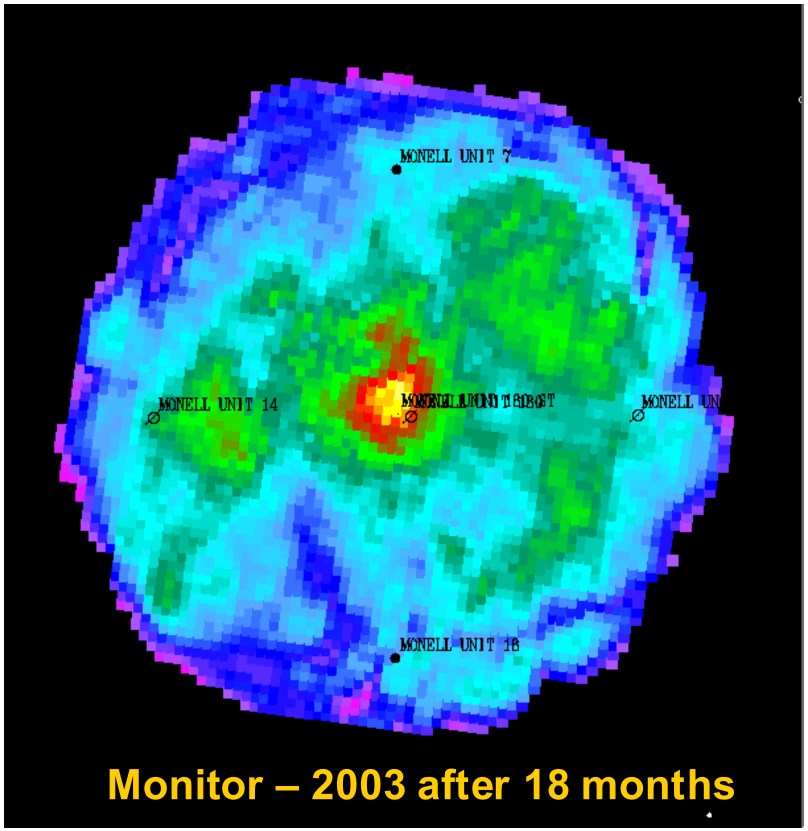
Monitor the Injection of CO2 as part of CCUS to Secure the Sequestration Process

In Summary:
We need Effective Sensors and Processing to Image and Monitor The Injection of CO_2 as part of CCUS to Secure the Process

Time lapse surveys to monitor CO_2 Injection
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.

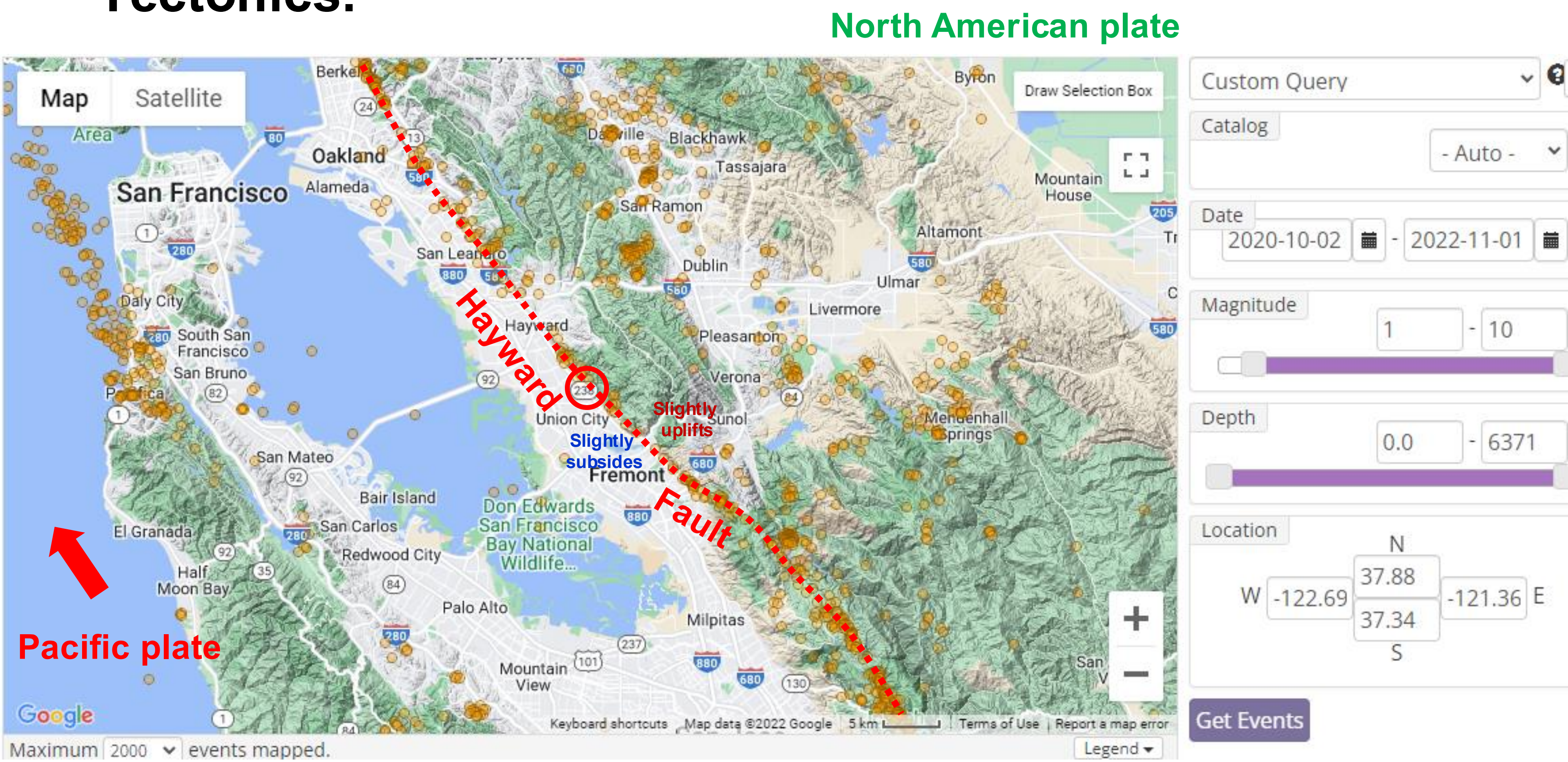
Presentation Outline

- Laboratory Tests of Sensors
- CCUS project with Battelle
- UGS project with PG&E
- Pipeline Monitoring (if time)

Hayward Fault Monitoring
Strain Test Results

Paulsson, Inc. (PI)
November 7, 2022

Tectonics:



The Hayward Fault has a strike-slip motion which is when one land mass moves, nearly horizontally in the opposite direction of the other on the surface. This movement causes stress, which results in earthquakes. The Hayward Fault is a strike-slip fault on the surface but changes to a low angle thrust fault as it descends under the Easy Bay Hills. This creates an uplift of the East Bay hills in the Fremont area exposing the rocks of the Briones Formation, which is a fossilerous rock made of marine shells. It is Miocene in age and can be correlated to other similar sediments throughout coastal California. https://www.msnucleus.org/haywardfault/signs/science.html

Location:

629 Tamarack Dr, Union City, CA

Point	Order Conducted	GPS Coordinates
1	3	37°36.617, -122°01.175
2	4	37°36.621, -122°01.186
3	5	37°36.623, -122°01.195
4	1	37°36.628, -122°01.213
5	2	37°36.631, -122°01.221
6	6	37°36.623, -122°01.193

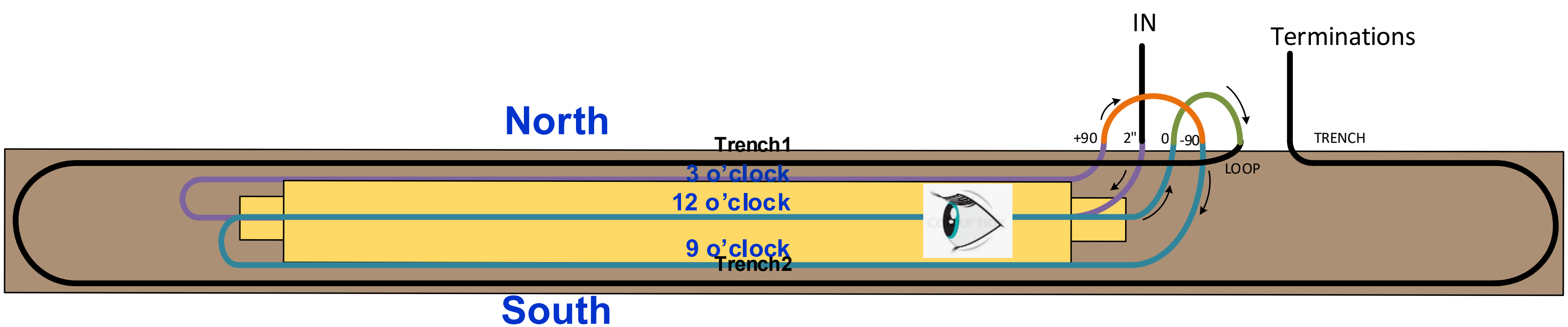
Instrumenting a Pipeline Crossing the Hayward Fault
The Hayward Fault is deemed to be the largest US Natural Event Threat

Multi-Optical (DSS, DAS, DTS) Fault Monitoring Project

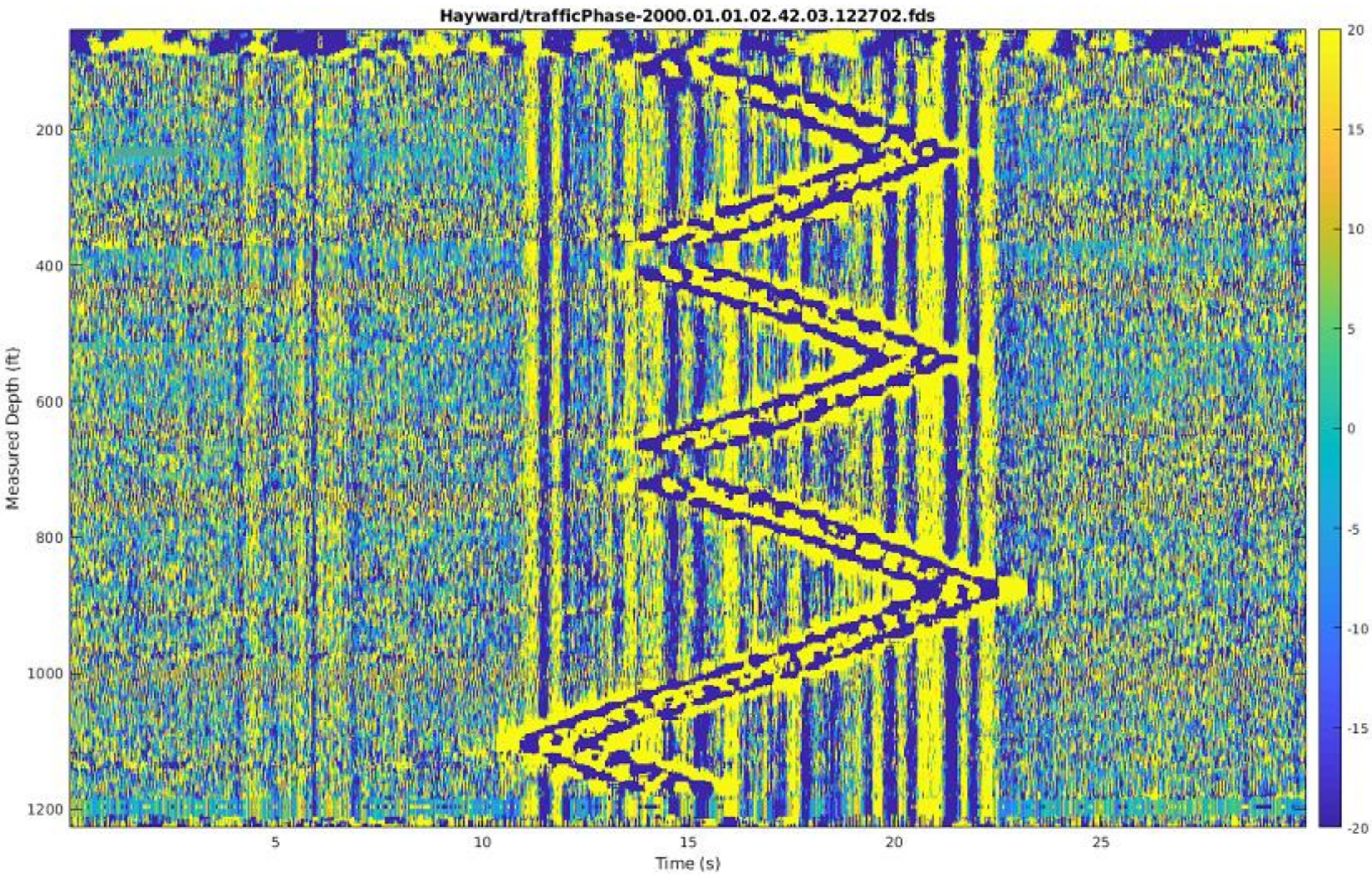
Optical Distributed Strain Sensing (DSS) - Spatial Resolution 1.0 or 2.0 meters
Optical Distributed Temperature Sensing (DTS) - Spatial Resolution 1.0 meter
Optical Distributed Acoustic Sensors (DAS) - Spatial Resolution 1.0 meter

Six Visits thus far:

1. December 2020
2. November 2021
3. January 2022
4. June 2022
5. November 2022



Event 7 – a car drives by the 6 fiber cables



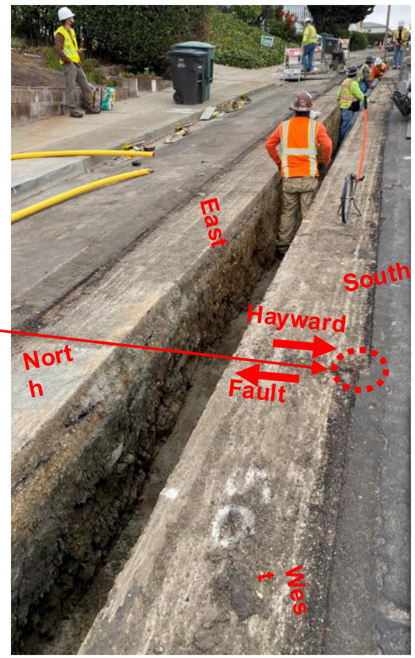
Field Photos, Union City, SF East Bay

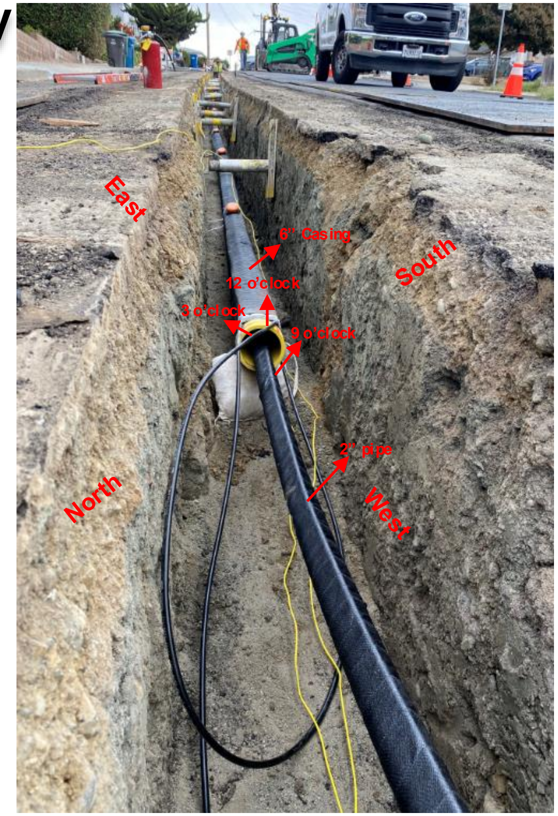
October 9, 2020 during fiber optic instrument install

The street was built about 66 years ago, and the fault offset is about 7 cm, so,

the fault movement speed is:

V = 7 cm/66yr ~= 1 mm/yr





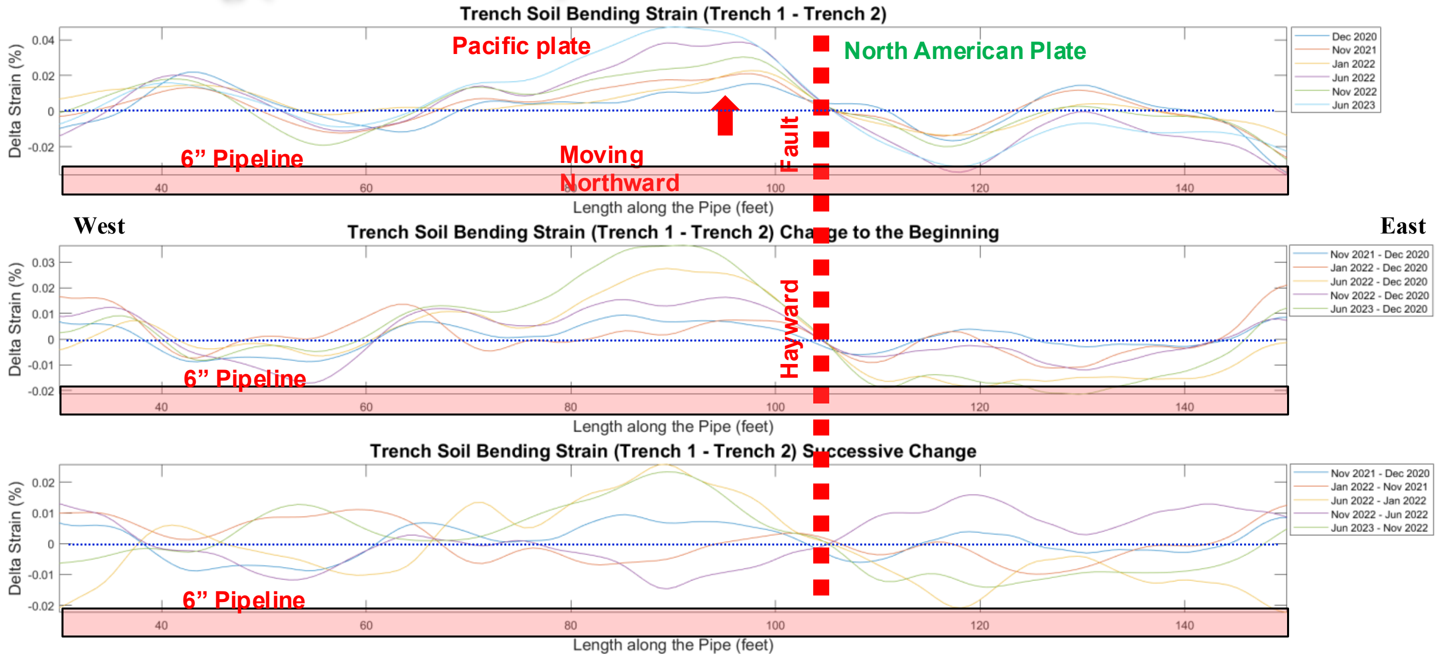
Field Photos, Union City, SF East Bay

The street was built 1957 or about 67 years ago in 2024 and the fault offset is about 70 mm, so, the fault movement, or creep rate is:

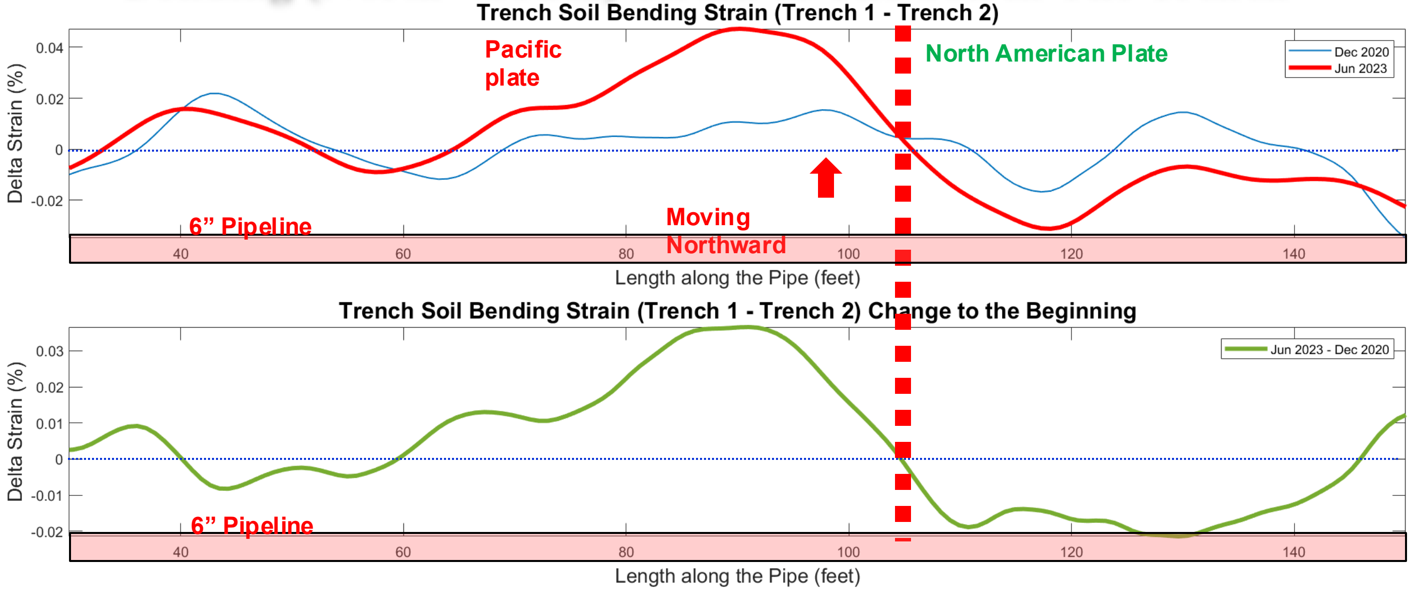
V = 70 mm/67 years ~= 1 mm/yr

Long term total strain is about 9 mm per year. The creep is 1 mm per year so the residual strain build up over 156 years is thus 156 years x 8 mm = 1,248 mm or about 50 inches or about 4 ft.

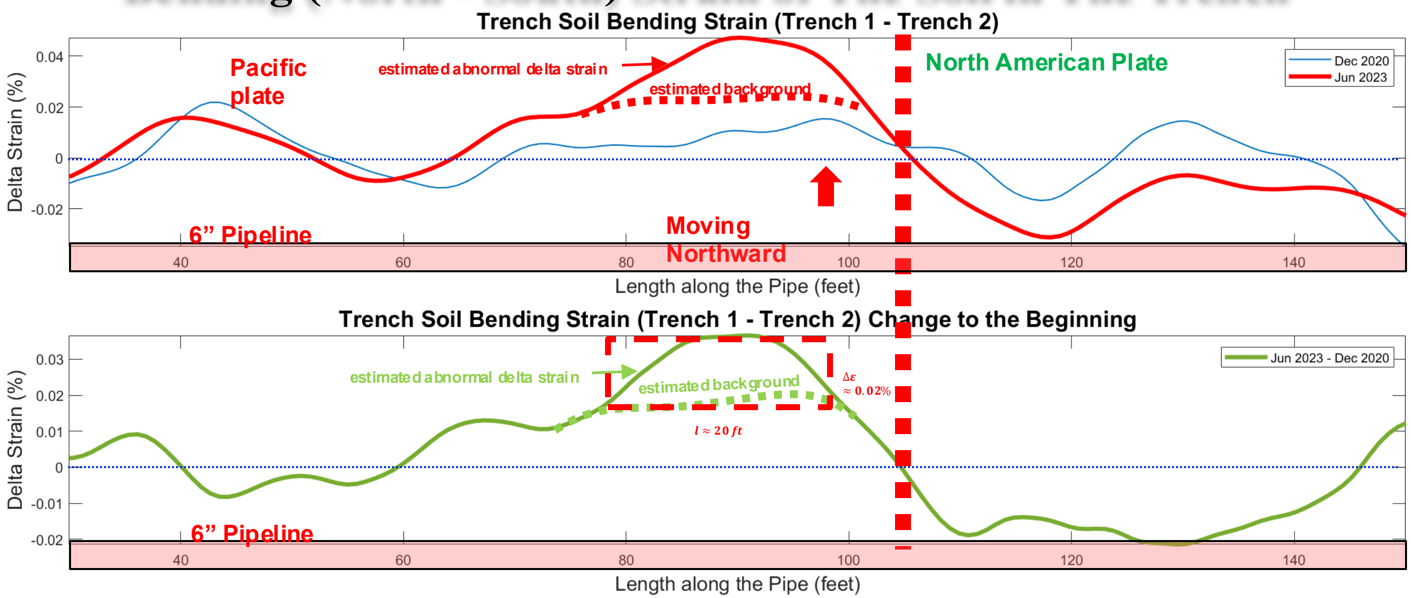
Bending (North - South) Strain of The Soil in The Trench



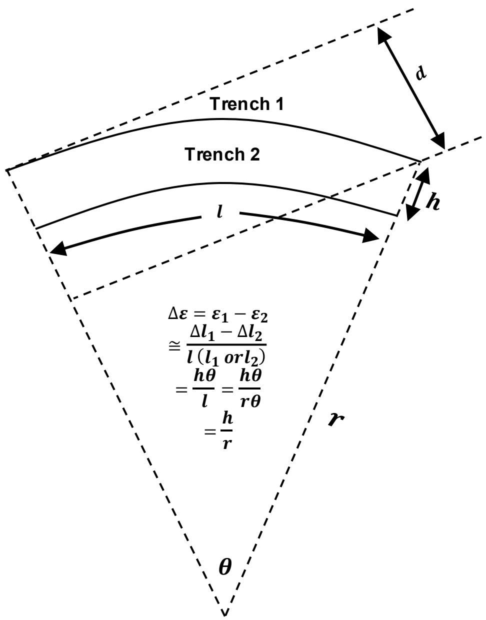
Bending (North - South) Strain of The Soil in The Trench



Bending (North - South) Strain of The Soil in The Trench



Fault Displacement Estimation



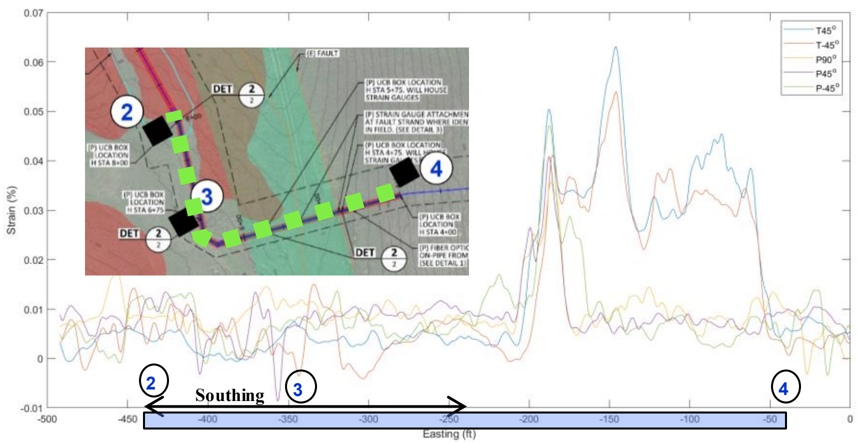
Bending Model Displacement Calculation

1. Average abnormal delta strain: $\Delta\varepsilon = \frac{0.02\%}{2} = 0.01\%$
2. Approximate cable spacing (north - south): $h = 2\ ft$
3. Bending radius: $r = \frac{h}{\Delta\varepsilon} = 20,000\ ft$
4. Approximate abnormal range: $l = 20\ ft$
5. Segment arc angle: $\theta = \frac{l}{r} = 0.001\ radian$
6. Displacement: $d = r - r * cos(\theta) = 0.01\ ft$ = 3.05 mm
7. Fault movement creep: $v = \frac{d}{T} = \frac{3.05\ mm}{2.5\ yr} \approx 1\ mm/yr$

Agrees with the on the ground measurement in previous slides.

Pipeline Monitoring

- Pipeline monitoring is used to monitor the integrity in pipelines.
- Early detection results in the least amount of economic impact.
- We place our strain, acoustic, and temperature sensors in a continuous array on pipelines to monitor the strain on the pipeline caused by the Earth's movements.
- Paulsson has installed two optical sensor systems on pipelines crossing fault lines in California.



Paulsson Installing Fiber Optic Distributed Strain, Acoustic and Temperature Sensors on a PG&E 34" Gas Pipeline Crossing The Calaveras Fault. Paulsson is now monitoring the pipeline peripodically. Detected a strain of 15-20 mm/year on the pipeline as it crosses the Calaveras Fault

In Summary

- Distributed Acoustic Sensors (DAS) are suitable for:
  - Recording large seismic events such as earthquakes.
  - Recording data near and in the well or borehole such as leaks in borehole tubing and casing

- Fiber Optic Seismic Vector Sensors (FOSVS) Arrays are suitable for:
  - Monitoring Seismic and Acoustic events in the Formation
  - Monitoring Formation Fluid Flow events in the Formation
  - Monitoring and locating Fracturing in the Formation
  - Recording high frequency P and S waves – up to 10kHz
  - Determine the location of Seismic and Acoustic events

Acknowledgement

- The research discussed in this presentation has been supported by the following grants:
  - DOE Contract DE-FE0004522 (2010)
  - RPSEA Contract 09121-3700-02 (2011)
  - DOE Contract DE-EE0005509 (2012)
  - California Energy Commission Contract GEO-14-001 (2013)
  - DOE Contract DE-FE0024360 (2014)
  - DOE SBIR II Grants DE-SC0017222 & DE-SC0017729 (2018)
  - DOE SBIR II Grant DE-SC0018613 (2018) Downhole Source
  - DOE SBIR II Grant DE-SC0022678 (2022) Optical Sensors

The support and assistance from these grants made it possible to develop the fiber optic sensor and deployment technologies described in this presentation. The support from Karen Kluger for DE-FE0004522, Bill Head for RPSEA Contract 09121-3700-2, Bill Vandermeer for DE-EE0005509, Cheryl Closson for GEO-14-001 and Bill Fincham for DE-FE0024360 and SBIR Grants DE-SC0017222/17729/18613 is gratefully acknowledged.

We have Data and Instruments.

Let’s Work Together!

For More Information and Ideas for Collaboration Please Contact

bjorn.paulsson@paulsson.com

www.paulsson.com