Geothermal Technologies Office 2015 Peer Review

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Development of a 1,000 level 300ºC Fiber Optic Borehole Seismic 3C Array

Project Officer: Bill Vandermeer, DOE Golden Office
Total Project Funding: $4,009,450,
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Track 3 – EGS1

Paulsson, Inc. 1,000 level Project Relevance/Impact of Research

Project Objectives – How a large Fiber Optic Seismic Sensor (FOSS)™ array will impact the Geothermal Technologies Program's Goals

Images of geothermal reservoirs today generally lack the necessary details in order to effectively drill and produce the reservoirs. This is due to a combination of very complex geology at geothermal sites and a lack of high temperature instrumentation for wells.

A large 3C high temperature fiber optic based ultra-sensitive borehole seismic array, i.e. a large seismic antenna, that can be routinely deployed in geothermal wells …..

- **will allow for cost effective imaging of large volumes of the geothermal reservoir rock providing for highly accurate and fast 2D, 3D and 4D imaging.**
- **can map existing fracture zones and faults as well as determining the local horizontal stress conditions guiding the drilling of injection and production wells**
- **can map the micro seismic events much more accurately than short borehole arrays or seismic arrays deployed at or near the surface of the earth. More accurate mapping of the micro seismic events will generate a detailed dynamic reservoir model.**
- **can deploy large arrays to a depth of 30,000 ft in both vertical and horizontal wells by using a drill pipe base deployment system. The drill pipe based deployment system can also deploy other sensors such as temperature, pressure and chemical sensors and sample fluids.**

Paulsson, Inc. 1,000 level Project Scientific/Technical Approach

Project Objectives – Highlights of innovative aspects

- We have designed and manufactured a 300ºC borehole seismic demonstration system that requires no electric power or electric based signals to and from the borehole:
  - The sensors and data transmission are fiber optic based with no electronics deployed into the well
  - The deployment system is drill pipe based and clamping function is powered by drill pipe hydraulics
- Designed, manufactured and deployed a high temperature Fiber Optic Seismic Sensor
  - The fiber optic seismic sensor technology allows operation at 300ºC, 30kpsi and 30kft.
  - Fiber optic Seismic Sensor (FOSS)™ technology allows thousands of channels to be deployed into the borehole which makes it possible to build a ultra-large aperture array which in turn allows accurate 3D/4D imaging and monitoring and 3D micro seismic mapping
  - Fiber Bragg Grating (FBG) based sensors using interferometric interrogation technology are much more sensitive and have a larger bandwidth than traditional coil and magnet based geophones
  - Fiber Optic Vector Array (3C) allows the determination of the vector of the recorded seismic data
- Designed, manufactured and deployed a 300ºC drill pipe based deployment system
  - The deployment system is drill pipe based and is able to deploy 1,000 3C pods to 30kft into vertical, deviated and horizontal wells.
  - The clamping function of the downhole array is powered by the drill pipe hydraulics and generates very high clamping force which allows high fidelity seismic data to be recorded
  - A fiber optic system without electronics and clamping with pipe hydraulics will be extremely robust and have a long survival time in geothermal wells

Paulsson, Inc. 1,000 level Project
Accomplishments, Results & Progress

The most important technical accomplishments and progress and their significance from 10/2011 until 05/2015;

- **Test facility**
  - We have designed and installed a test facility where we can do dynamic testing of the Fiber Optic Seismic Sensor at temperatures up to 350ºC.
- **We have designed and tested the Fiber Optic Seismic Sensor**
  - Testing of the new Fiber Optic Seismic Sensors has been extremely favorable. The frequency response and sensitivity about 100 times than a coil geophone and we have proved they can operate to 320ºC.
- **We have designed and verified the deployment system**
  - We have done destructive testing on all deployment system components. The system is strong enough to be deployed into a well to 30,000 ft.
- **We have field tested the Fiber Optics Seismic Sensor System**
  - We have performed a field test in a borehole of the Fiber Optics Seismic Sensor (FOSS)™ system and proved that we can record data with a 2 µg acceleration to over 2,000 Hz with outstanding vector fidelity.
- **We have built a 15,000 ft long 16 level 3C Fiber Optic Array**
  - This array was completed in Q1 2015 and is now fully operational.

Borehole Seismic Imaging with Ultra long arrays

More Receivers = Better Images

Freq. Response – FOSS vs. Geophone
10 - 800 Hz Sweep, 600 µG @ 200ºC

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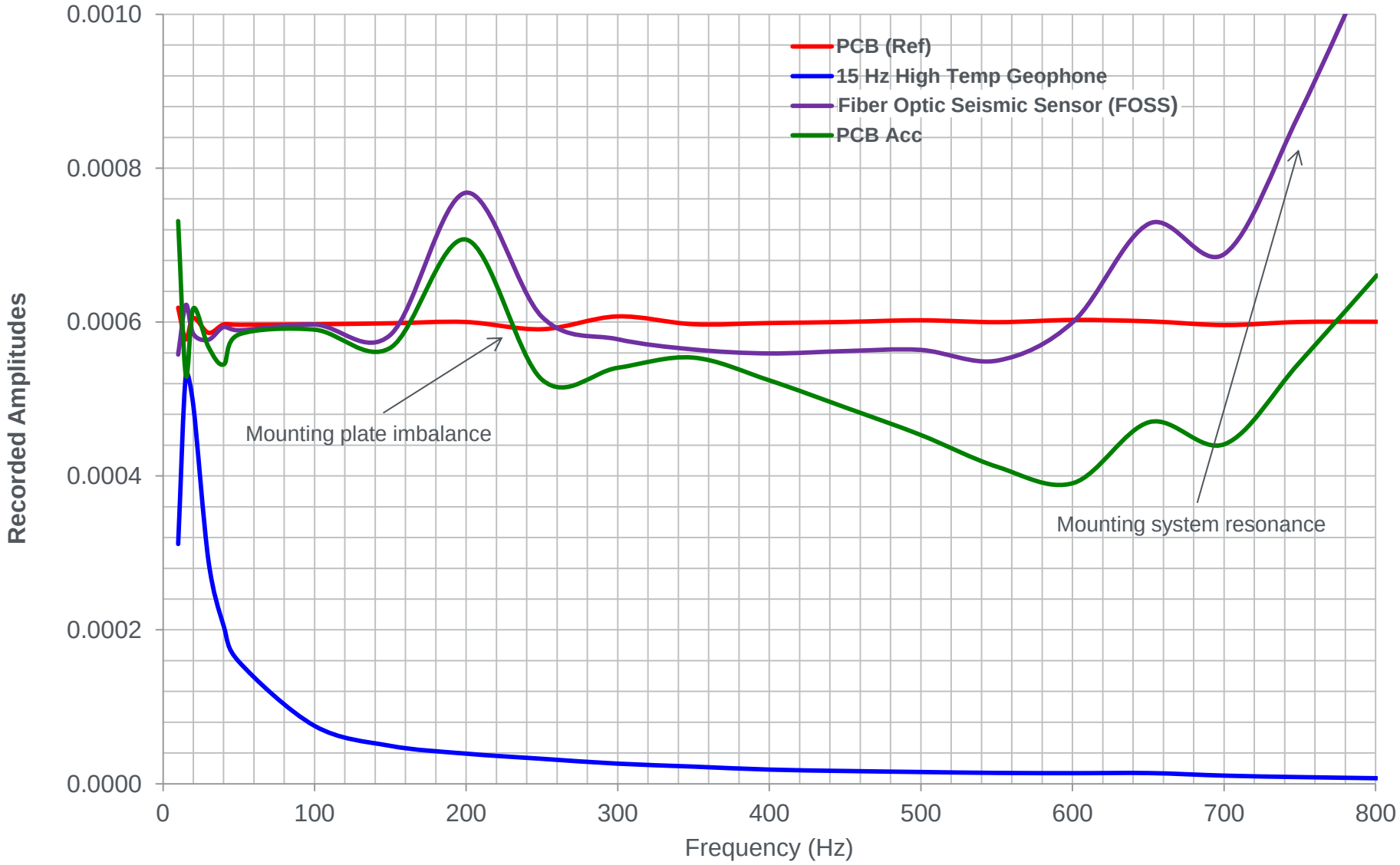

Response – FOSS vs. Geophone
Data from a single tap test

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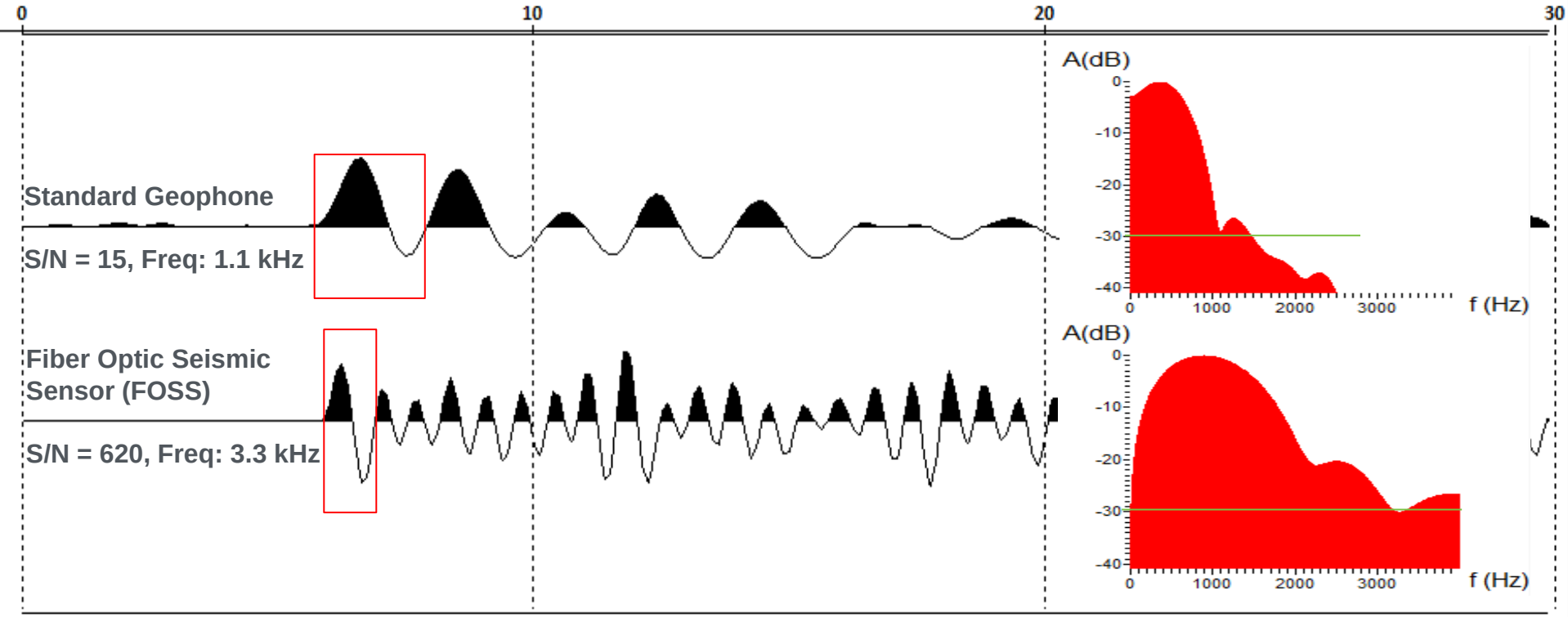
Fiber Optic Seismic Sensor (FOSS)™ vs. Standard Geophone

- 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



Fiber Optic Seismic Sensor (FOSS)
Radial Comp. Tap Tests 25 - 320℃

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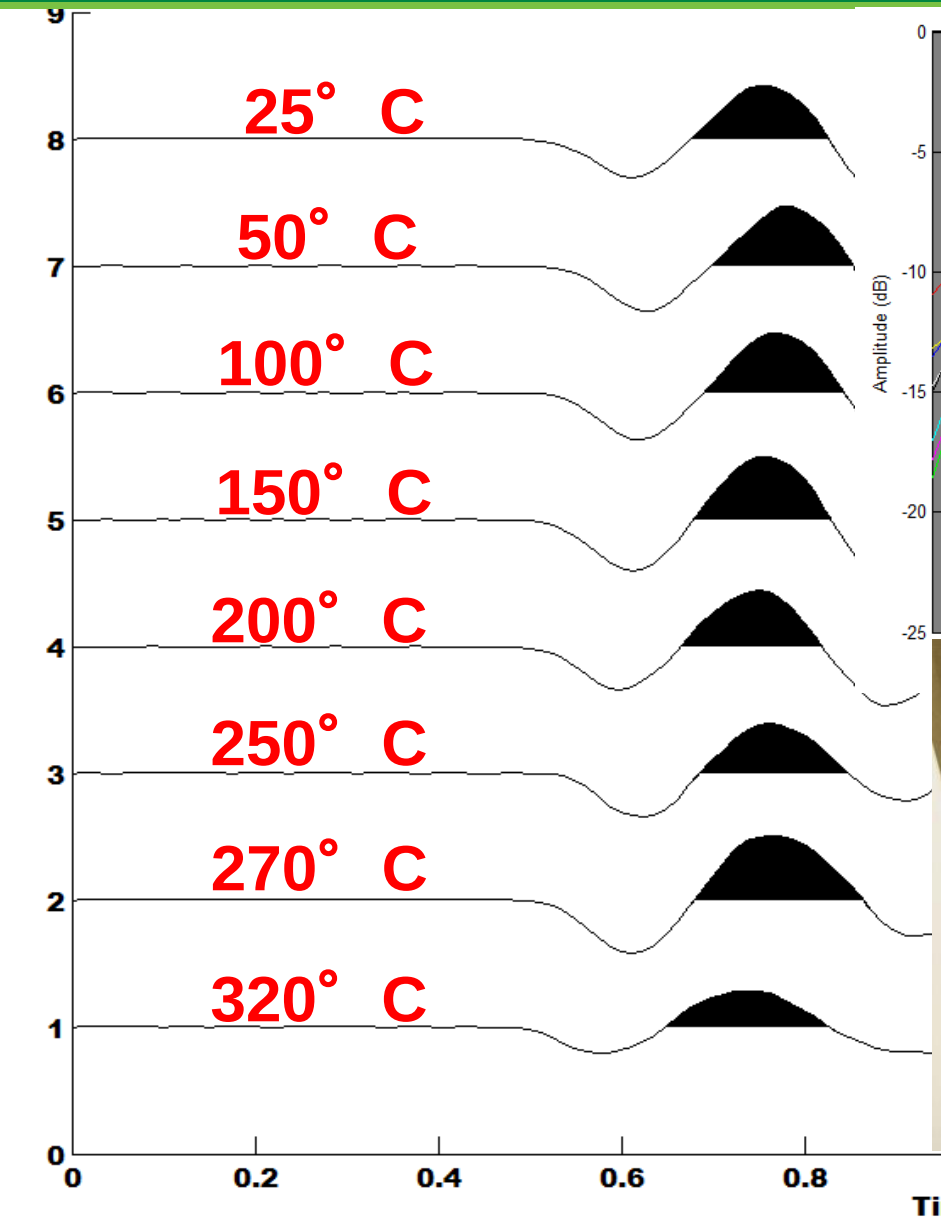
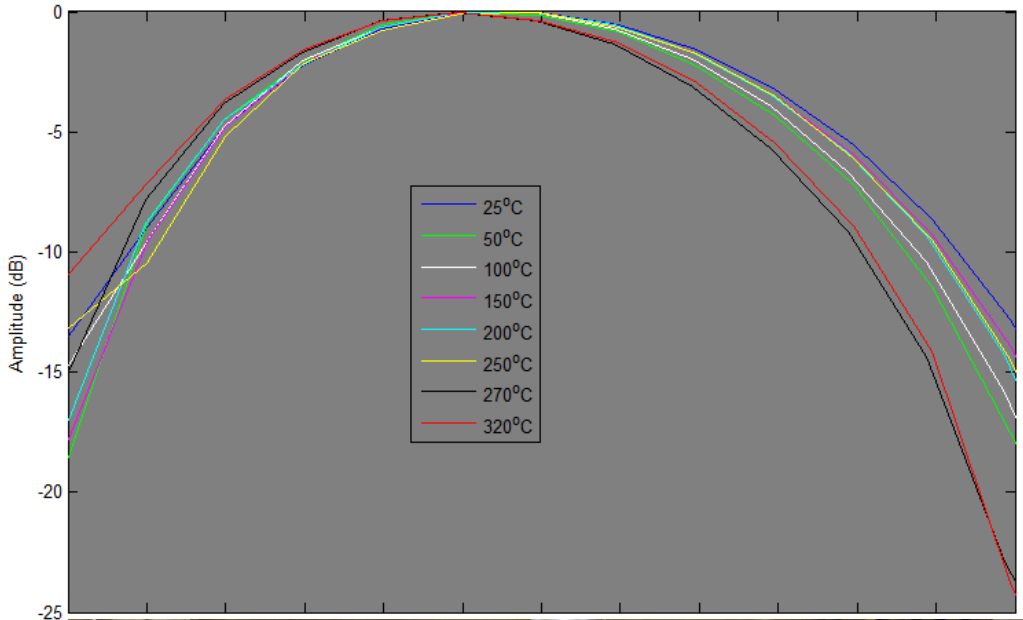
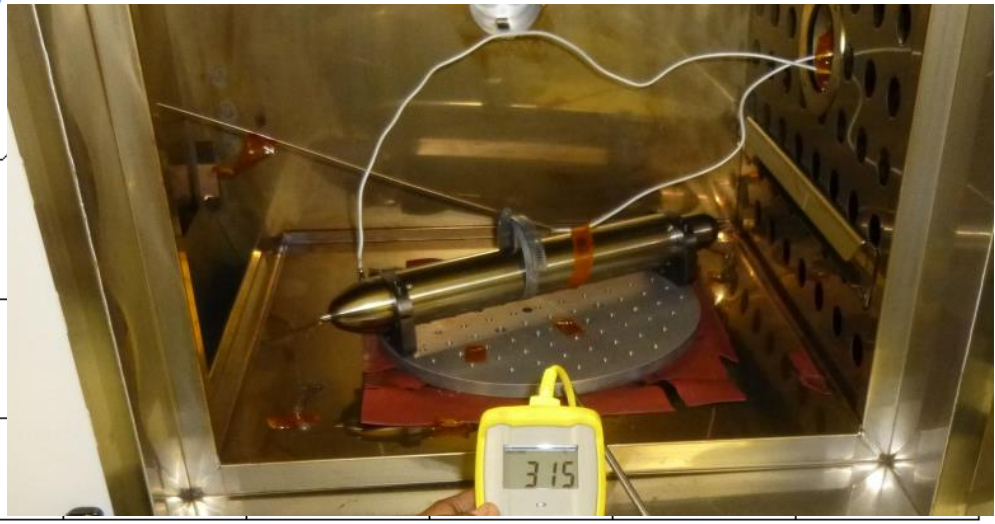
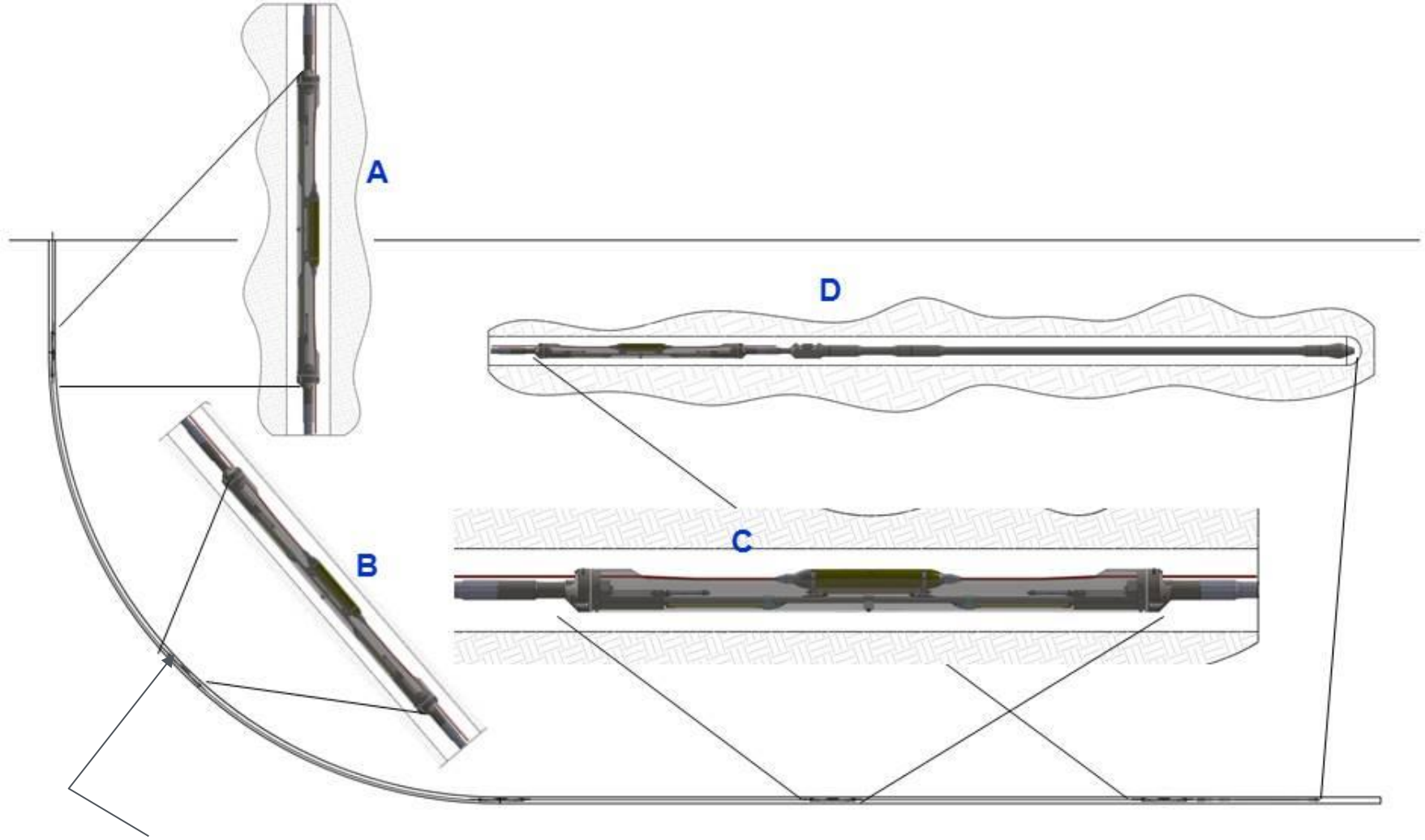






Drill Pipe Deployed System Housing and Clamping



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

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

Small TNT shots @ 1,200 ft (400 m) recorded on Fiber Optic Seismic Sensor

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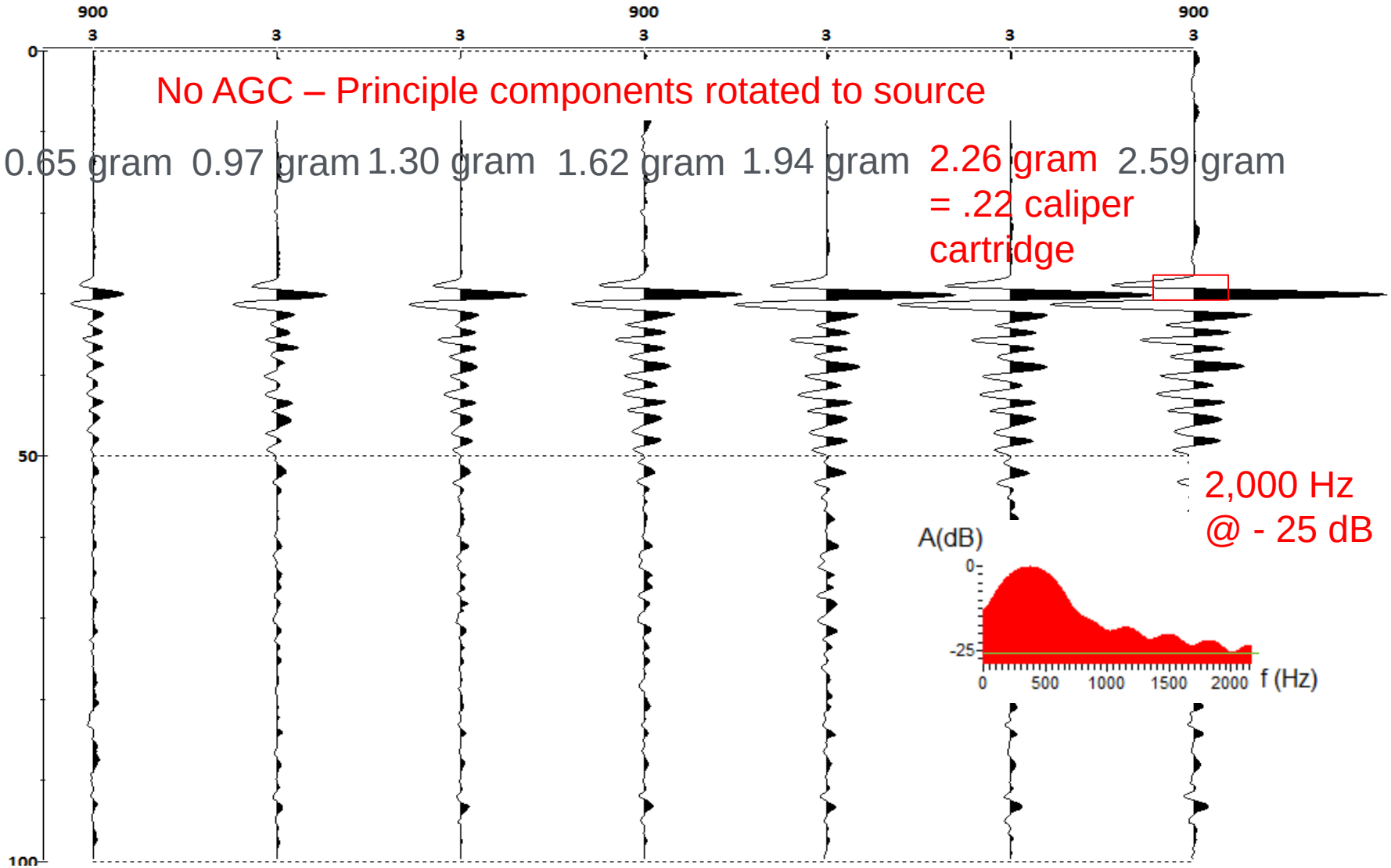

Seismic data Recorded on a FOSS mapped into absolute Acceleration

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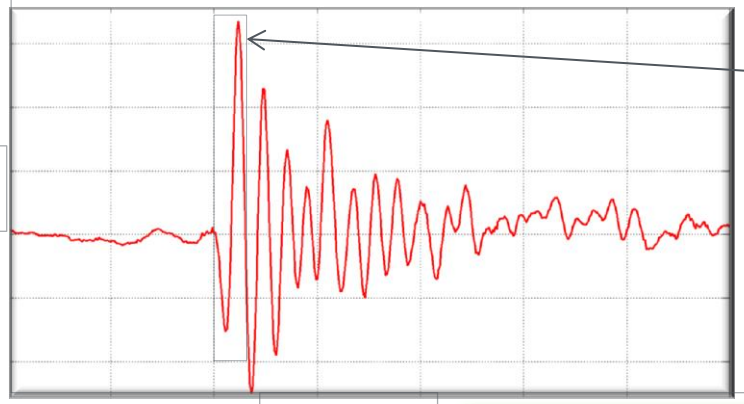
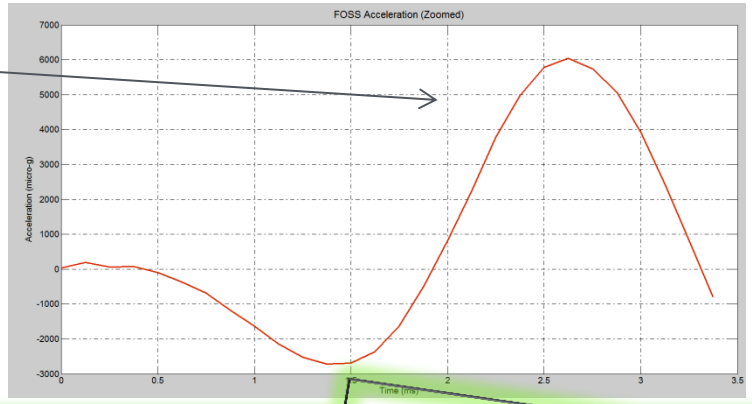
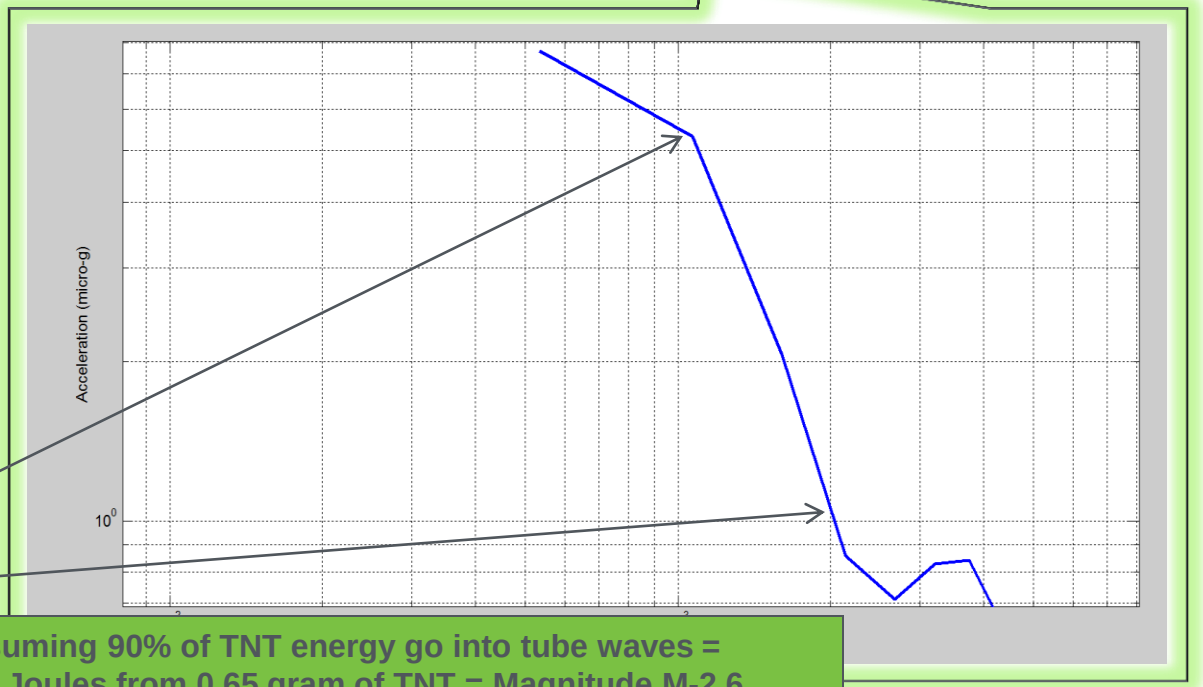




Quantitative Analysis of Data from 0.65 gram of TNT At a distance of 1,200 ft (366 m)

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 FOSS Well
Demonstrating outstanding Vector Fidelity

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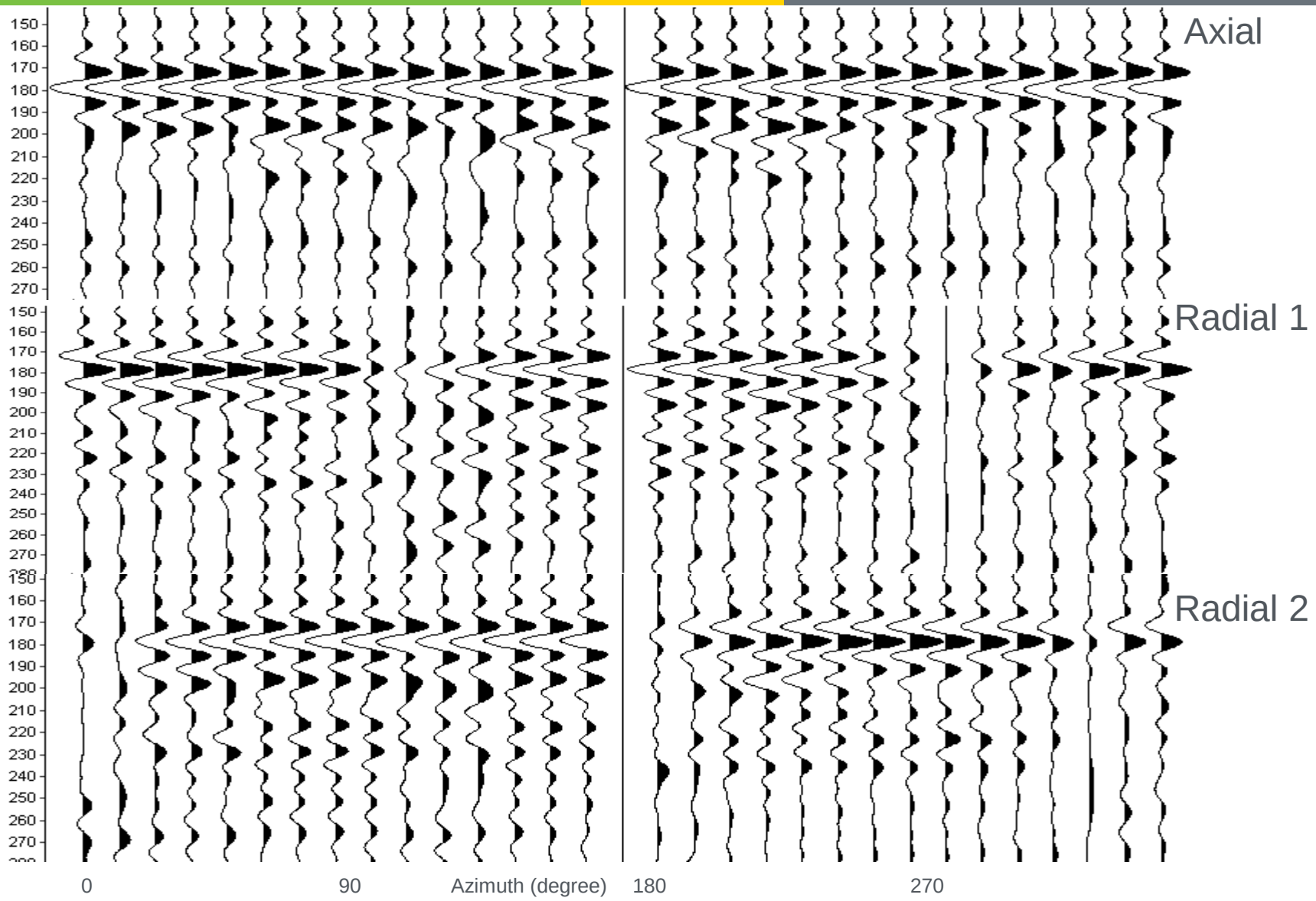

Paulsson, Inc. 1,000 level Project Future Directions

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- **Paulsson, Inc. will offer complete 300ºC fiber optic borehole seismic services to the geothermal industry**
  - **Paulsson, Inc. will continue to develop and expand the Fiber Optic Seismic Sensor (FOSS)™ technology after the GTO/DOE project.**
  - **Key activities in FY2015 is to field test the 16 level 3C system at the Geysers in California**
  - **We will investigate the use of advanced FBG based sensor technology to assure that we are using the most advanced interrogation technology available**
  - **Will offer the Fiber Optic Seismic Sensor technology to the geothermal industry at large.**
  - **Will develop real time Micro Seismic Monitoring capabilities**
  - **Will implement our technology in a Mini FOSS with an OD of 1”**

Milestone or Go/No-Go	Status & Expected Completion Date
Field Test of 16 Level System	In preparation – Expected survey Sept. 2015

Paulsson, Inc. 1,000 level Project Summary Slide – FY2015

- **Completed the design and testing of Fiber Optic Seismic Sensor and deployment system.**
  - **Demonstrated seismic data acquisition to 320° C**
- **Prototyped the design of the system optical electronics including the SEGY recording system.**
- **Completed a six level 3C system test in Q3 2013**
  - **Demonstrated ability to record M-2.6 in the field**
  - **Demonstrated outstanding vector fidelity**
  - **Demonstrated robust operation**
- **Completed a sixteen level 3C system in Q1 2015 operational to 15,000 ft into vertical or horizontal wells.**
- **Teamed with Calpine and LBL to perform a two well VSP and Micro Seismic study at the Geysers in Q3 2015**

The Geysers operated by Calpine

Field-wide Seismicity Analysis Oct 2013 – March 2014

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Note only M1.0 and larger located!

FOSS will detect and locate to M-4.0