

A Fiber Optic Single Well Seismic System for Geothermal Reservoir Imaging & Monitoring

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ABSTRACT

US Department of Energy has funded Paulsson, Inc. to develop a high temperature 3C borehole seismic source to be deployed in the same borehole as a large array of 3C fiber optic vector seismic sensors. The combination of a clamped source and clamped receivers will in combination create a borehole tool that can record single well seismic data. All components of the system will be designed to operate in a high temperature environment suitable for geothermal applications. This is not just a borehole logging system, this is a borehole seismic system which will be able to image objects 100s and even 1,000s of feet from the survey boreholes.

Fiber Optic based multi sensor systems have been shown to operate efficiently and economically in boreholes recording exceptional data. We have simultaneously operated Fiber Optic Seismic Vector Sensors (FOSVS), Distributed Acoustic Sensors (DAS), Distributed Temperature Sensors (DTS), and Distributed Strain Sensors (DSS) in the same borehole. Other fiber optic-based sensors are under development and will be combined with the current borehole sensor system.

Fiber Optic Sensors can currently operate to temperatures over 300°C. We have demonstrated in the laboratory that we can operate our fiber optic seismic vector sensors at 320°C for a week. If the silica-based core and cladding that make up the two inner layers of optical fiber are combined with an outer coating of gold as the final and third layer rather than polyimide used currently, operational temperatures up to 700°C have been demonstrated by other researchers. Using other metals for the coating even higher temperatures, up to 1,000°C, has been demonstrated. If pure silica core fiber is used in the sensor system, then the system is practically immune to hydrogen darkening allowing operations in geothermal reservoirs that often have a presence of hydrogen sulfide. One very large advantage with fiber sensors is that the sensors can be placed in boreholes while the instruments can be placed in a benign surface environment. Fiber optic-based sensors can thus be interrogated by lasers and instruments placed on the surface eliminating placing fragile instrument components in the high temperature borehole environment making the overall system much more robust.

Using fiber optic based seismic vector sensors, data with a Moment Magnitude smaller than M-5 has been recorded in a recent survey. In this case the source-receiver distance was about 2,000 ft and the maximum frequencies recorded were above 2,000 Hz. In the laboratory we have recorded high signal to noise ratio vector seismic data from a seismic source with an estimated energy of much smaller than 2.5 micro Joules with frequencies approaching 10,000 Hz. Many times, the development of geothermal resources require drilling deviated boreholes making deployment of sensor and sensor system using wireline technology impractical. To allow deploying our optical vector seismic sensors in deviated or horizontal boreholes, which will be common during the development of EGS resources, we developed a small diameter drill pipe-based borehole deployment system which includes a very robust clamping system. This system has proved to eliminate all the tube waves traveling in the borehole greatly enhancing the borehole seismic data and simplifying the data processing. In addition to the outstanding data this system can be designed to operate at extremely high temperatures. All the components, such as seals, in the current deployment system are rated to at least 300°C but can be upgraded to all metal components with a projected temperature rating of 1,000°C.

1. INTRODUCTION

In this paper we will discuss the incorporation of a multi component downhole seismic source with the optical seismic vector sensors to create a single well seismic system. The characterization of natural and induced fractures in Enhanced Geothermal Systems (EGS) can be improved by recording vector seismic data from a clamped high frequency 3C seismic source deployed in the same vertical, deviated or horizontal borehole as an array of seismic vector sensors. This will allow for a safe and an effective development of EGS resources by mapping in real-time natural and induced fractures and fluid flows near and far from the deployment wells. The vector sources and receivers can be deployed in either the borehole used for fracturing or in a nearby borehole. Deploying the system into the fracturing borehole before or after fracturing allows for the most detailed characterization while deploying the array in a nearby borehole will allow for real-time monitoring of the injection and fracturing process. Recording vector seismic data, recording both P and multi-component S waves, is critical to understand fractures, fracture directions and the fluid flow.

Borehole seismic acquisition techniques are the most effective and highest resolution techniques to investigate complex EGS reservoirs. Our approach to improve the EGS production process is to design, develop and laboratory test a more sensitive and more effective high temperature seismic survey and monitoring system by testing vector seismic sources deployed with seismic vector receivers in the same well. The single well seismic system is extremely sensitive to small changes in fracture properties and orientation, volumetric stress, pore pressure, conductivity, proppant distribution, fluids and saturation. The system can also monitor and map passive seismic data and data from surface seismic sources.

The clamped multi-component seismic vibratory source system has been designed and an axial prototype has been built. The prototype downhole seismic source was tested in the laboratory and in a small-scale field test achieving 10 – 1,600 Hz sweeps and a maximum force of over 1,509 N (339 lbf.). Paulsson, Inc. has previously developed an array of Fiber Optic Seismic Vector Sensors (FOSVS) that are using an interferometric optical sensing technique to measure seismic induced fiber strain between two Fiber Bragg Gratings (FBGs). This technique allows us to monitor and record dynamic fiber strain from near 0 Hz to 10,000 Hz. We can record seismic induced strains in the fiber as small as a few pm (10^{-12} m) making the sensors extremely sensitive. The overall objective of this project was to develop a large aperture fiber optic based single well seismic system by adding vector seismic sources to our current optical seismic vector sensors. We have designed the seismic sources to be deployed using the same clamping system used for the optical vector receivers which effectively couples the seismic energy to the borehole. The first source tested generates a borehole axial oscillating point force. Other directional seismic sources that will be included in the future will use torsional and radial source motions that generates complimentary radiation patterns. The new single well seismic system has been designed to be deployed using our existing small diameter drillpipe, so the sensor arrays can be deployed in vertical, deviated and horizontal wells. This system is seen in Figure 1. The source will be deployed on the same system concurrently with the receivers.



Figure 1. The Sensor pod housing during a deployment of a FOSVS Array. The same housing concept will be used for the downhole seismic sources. The downhole source will be longer than the receiver but with the same diameter.

A Single Well Seismic Source (SWSS) will allow high resolution and effective mapping and monitoring of subsurface structures and subsurface processes at a large distance from the sensor boreholes. An improved mapping and monitoring of EGS reservoirs will significantly increase the recovery of geothermal resources thus lowering the cost per kWh and make the process more environmentally compliant.

2. IDENTIFICATION AND SIGNIFICANCE OF THE PROBLEM

EGS reservoirs are complex, difficult and expensive to develop. The architecture and the dynamics of EGS are poorly understood resulting in a very ineffective and expensive development of the vast resources they represent. New approaches and new instruments are needed to improve the recovery factors of EGS resources.

Surface geophysical tools and techniques are not able to image the complex and often complex reservoirs in sufficient detail to provide accurate drilling targets or correctly monitor the reservoir development through fracturing to improve production of the EGS reservoirs. The result is not only inefficient, but often detrimental to the environment and ultimately almost always expensive geothermal production.

One solution is to deploy high resolution imaging and monitoring tools in wells as they are drilled in geothermal fields to provide guidance for subsequent wells. However, there are today no effective high-resolution reservoir imaging tools and instruments available for the geothermal wells that can diagnose in real or near-real time the natural and hydraulically induced fractures in sufficient detail to affect the production significantly.

What is holding back the development of geothermal resources is thus not the lack of the resources but rather the difficult development due to insufficient reservoir knowledge due to lack of effective imaging tools and technology. High resolution imaging technologies for geothermal wells will dramatically reduce the drilling and development risks for operators of EGS resources which will result in a step increase in production of geothermal energy. The imaging and monitoring of EGS reservoirs using effective seismic tools will also reduce the environmental impact of the resource development by drilling more productive geothermal wells resulting in fewer wells. Better

imaging will also result in reduced production cost that will increase the national geothermal resource base improving our energy independence.

The characterization of natural and induced fractures in Geothermal (EGS) Reservoirs can be improved by recording vector seismic data from a clamped high frequency directional seismic source deployed in the same vertical, deviated or horizontal borehole as an array of high frequency seismic vector sensors. This is not just another logging tool – this is a new and more accurate large volume seismic mapping and monitoring technique called “Single Well Seismic Imaging and Monitoring (SWSIM™)”. This will allow for the safe and the effective development of EGS resources by mapping natural or induced fractures and flows both near and far, many 100s up to several 1,000s of feet, from the deployment wells. The exact reservoir volume that can be imaged depends on the attenuation coefficient of the reservoir rock imaged and the noise in the wells. The vector source and receiver sensors can be deployed in either the borehole used for fracturing or in a nearby borehole. Deploying the system into the fracturing borehole allows for the most detailed characterization while deploying the source and receiver array in a nearby borehole will allow for real time active source characterization and passive micro seismic monitoring of the fracturing process. Recording vector seismic data, recording both P and S waves, is critical to understand the fractures and the directions of the fractures. Acoustic techniques provide much less information since they do not provide fracture directional information.

Geothermal wells are expensive and reducing the risk for the development of geothermal resources will allow operators to finance the development of Geothermal energy on the open capital market at a lower cost. An improved availability of capital for the industry will be a big driver for the increased development of Geothermal Resources.

The industry has attempted to develop high resolution combined borehole seismic source and receiver tools in the past but has largely failed due to the temperature limitation of associated electronics and the means to deploy the systems. In our opinion acoustic logging tools, although very useful, do not qualify as seismic tools since they operate at frequencies over several kHz, are not directional and can only image near the deployment boreholes. With the introduction of fiber optic instruments the temperature barrier has been overcome. Fiber optic systems place all expensive and fragile electronics for the receivers at the surface. Only the fiber and the associated metal mandrels are deployed into the wells. The standard high temperature fiber today is polyamide coated fiber capable of operating up to 350°C (662°F). For the extreme applications metal coated fiber can operate to 700°C (1,292°F) and higher. The fiber optic sensors are interrogated by laser pulses from the surface so the only temperature limiting factor is the temperature rating of the fiber. The seismic source components are rated to 250°C (482°F) and it will be placed higher in the well than the receivers so the temperature environment for the source is less extreme. The source and the source electronics will be placed at the surface in a controlled temperature and humidity environment. Regarding the deployment of the sensors in horizontal wells we have been overcome this issue by designing a deployment system around small diameter drill pipe technology.

Borehole geophysical acquisition techniques are today by far the most effective and highest resolution techniques to investigate the status of Geothermal reservoirs for a number of reasons. The borehole sensors are closer to the reservoirs, the data is not contaminated by surface geophysical noise and the data is not attenuated by the complex geology overlaying the EGS reservoirs. Our approach to improve the production process is to design, develop and field deploy a more sensitive and more effective geophysical monitoring system comprising of seismic vector sources and seismic vector receivers deployable into vertical and horizontal boreholes. We will develop this large aperture fiber optic based single well seismic data acquisition system by adding novel multi component high frequency seismic sources to our current optically based high frequency seismic vector sensors.

The single well seismic system can be deployed short or long term in vertical or horizontal boreholes. This system will be able to record both the absolute values as well as small changes in fracture properties, orientation and distribution, volumetric stresses, pore pressure, fluid conductivity, proppant distribution, fluid saturation in addition to allowing monitoring and mapping active and passive seismic data. The current fiber optic based seismic sensor array is deployed using a small diameter drill pipe deployed system and the same system will be used for the new optically based single well seismic system. This will allow the combined system to be deployed accurately and cost effectively into the horizontal boreholes that are required to effectively produce EGS reservoirs.

Paulsson has previously developed an array of Fiber Optic Seismic Vector Sensors (FOSVS), which functionally are accelerometers, using an interferometric optical sensing technique of the strain of the fiber between two Fiber Bragg Gratings (FBG's). The fiber is wound around a specialized spring-mass mandrel allowing the fiber to be dynamically strained in linear proportion to the seismic strain interacting with the borehole. This interferometric sensing technique allows us to monitor and record the dynamic fiber strain from near 0 Hz to over 10,000 Hz. We can record fiber strains as small as a few picometers (pm or 10⁻¹² m) making the sensors extremely sensitive. In the laboratory we have recorded events smaller than 2.5 μ J – the equivalent or smaller than a M-7 event. The large sensitivity will allow a large radial investigation volume using the single well seismic system.

Paulsson, Inc. has designed and manufactured a prototype of a small vibratory seismic source that is capable of being deployed in deep boreholes together with a large array of Fiber Optic Seismic Vector Sensors. The combination of the borehole seismic vibratory source and the downhole receiver array will create the first effective single well seismic system in the geothermal industry. The vision is to build a multi component borehole seismic source was inspired by Heelan (1953). The first actuator designed, built and tested is an axial actuator. This will be followed by torsional and radial actuators at later stages of the development project.

One of the radiation patterns described by Heelan (1953) is shown in Figure 2. This is the radiation pattern of a borehole axial, in this case a vertical, oscillating point force in a medium with a Poisson's ratio of $\nu = 0.25$. This is the actuator we are testing in the SBIR Phase I project.

What makes this single well seismic system possible is the optical design of the seismic vector sensors. The optical vector sensors are immune to the large current driving the source actuators. This was demonstrated in the laboratory and in the small field test conducted under the first phase of the system development.

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

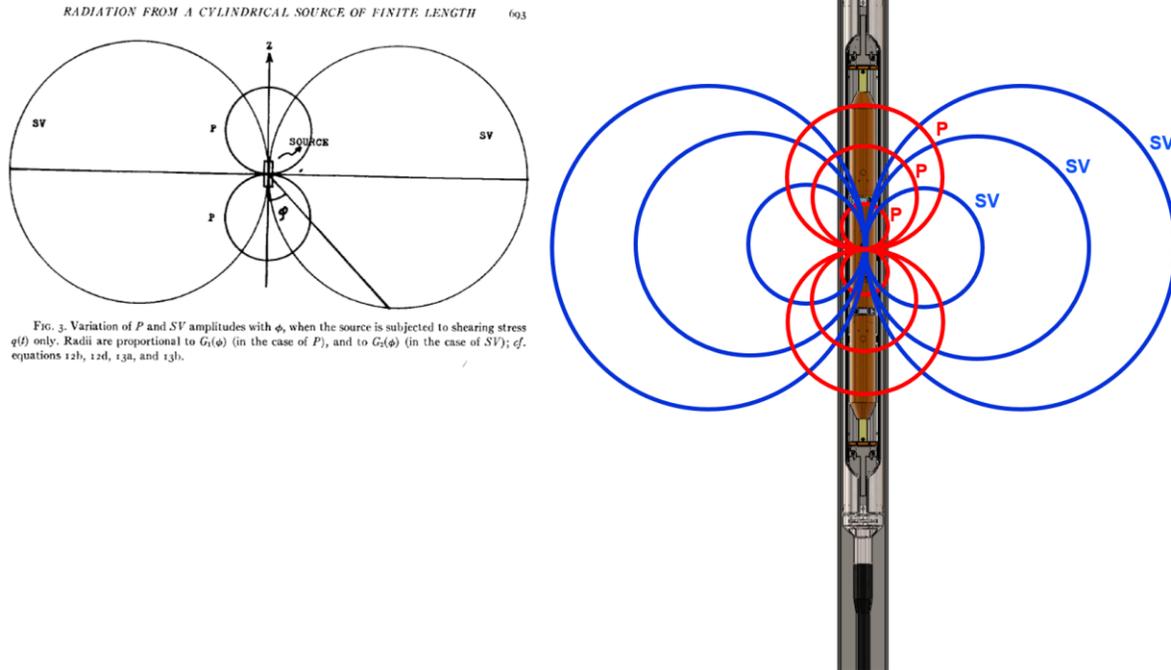


Figure 2. Radiation Pattern for an axial oscillating point force (Heelan, 1953) as clamped into a borehole.

The borehole multicomponent seismic sources will be designed to be deployed concurrently with the optical seismic sensors using our existing small diameter drill pipes allowing the sensor arrays can be deployed in vertical, deviated and horizontal wells. The seismic sources will be coupled to the borehole wall using the same high force hydraulic actuators using drill pipe pressurized fluid as used for the seismic receivers. This will maximize the coupling of the seismic energy into the formation and in the same time minimizes the energy coupled into tube waves. A fluid coupled seismic source couples most of its energy, ~99%, into tube waves while a clamped source couples most of its energy into seismic body waves. These effects in combination, good source coupling and sensitive vector sensors, will allow for a large investigation radius using the new single well seismic system.

The characterization of hydraulic fractures will thus be greatly improved by applying the new single well seismic system in either the borehole used for the hydro fracturing or in a nearby monitor borehole. A successful completion of this project would be a selection of prototype borehole seismic source actuators that can be packaged and tested so they can withstand and operate in severe environmental conditions such as high temperature, high pressure and corrosive fluids. A successful outcome under the Phase I part of the project will successfully demonstrate seismic actuator technology that can generate data on fiber optic sensors using an existing optical interrogator. A continuation of the project will encompass the building of a field system using the magnetostrictive based seismic source actuators and testing the system in one or several field trials concurrently with the existing fiber optic seismic vector sensors.

Magnetostriction is the property that causes certain ferromagnetic materials to change shape in a magnetic field. The Terfenol-D material was developed by the US Navy to be used as an effective acoustic source for sonar applications. Terfenol-D is an alloy comprised of Terbium, Dysprosium and Iron. Terfenol has the largest magnetostriction of any known material and is capable of efficiently converting energy from one form to another. In the case of electrical to mechanical conversion the magnetostriction of the Terfenol generates strains

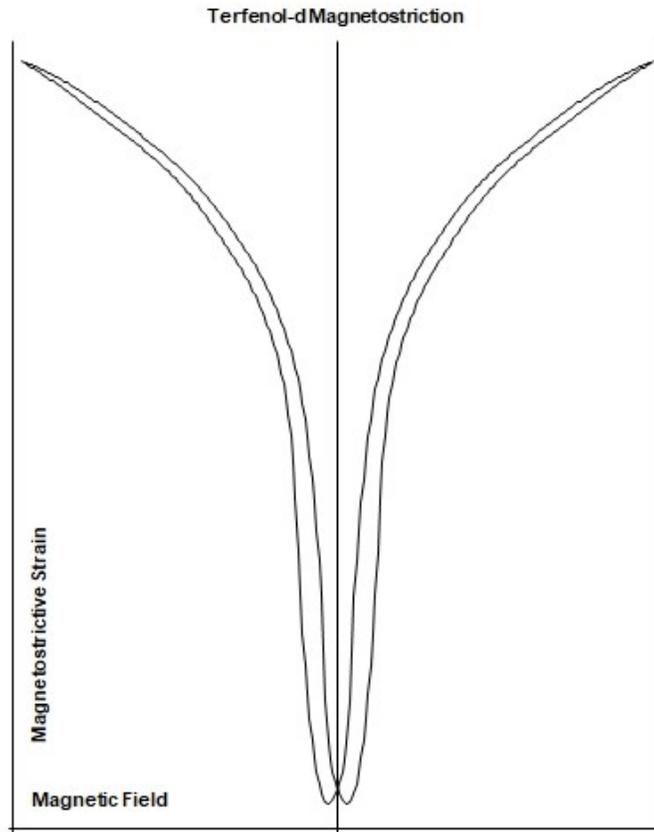


Figure 3. Terfenol-D expands with magnetic field of either polarity.

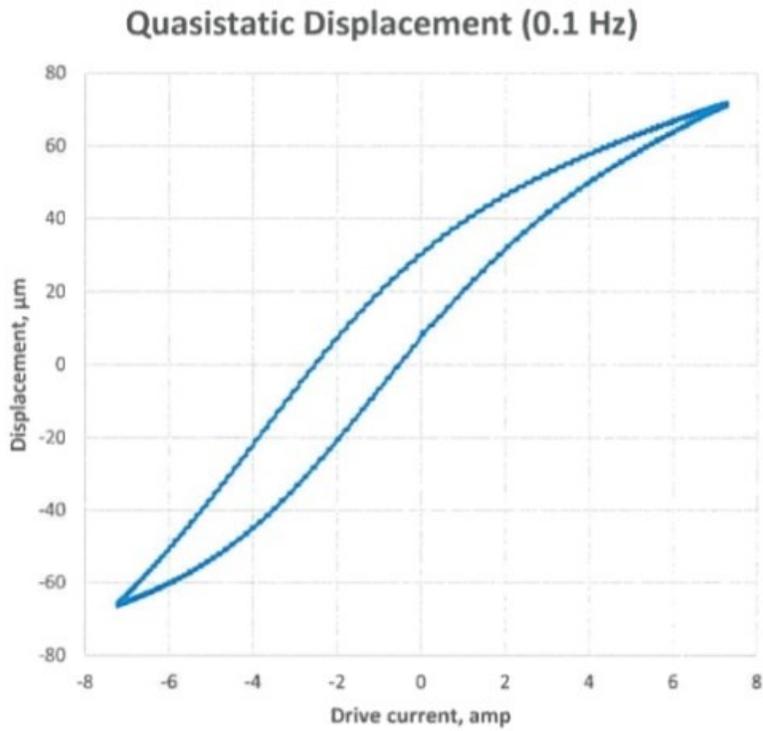


Figure 4. Tested actuator with permanent magnet bias

100 times greater than other magneto strictive materials and 2 – 5 times than traditional piezo ceramics. To effectively couple seismic energy into the formation it is critical that we use an actuator that can generate large displacements over a large range of frequencies.

The Terfenol material has a high Curie temperature (380°C) which enables the magneto strictive performance greater than 1,000 ppm to over 250°C. The large strain will allow for efficient coupling of the seismic energy even at low frequencies. An example of the strain generated by the Terfenol-D is shown in the Figure 3 and 4.

3. TEST OF THE PROTOTYPE DOWNHOLE SEISMIC SOURCE.

The specific technical objective with the research and development work in this project is to design, develop and test in laboratory conditions several seismic actuators that will act as the sources for the single well seismic system. These actuators will complement the existing optically based vector seismic and temperature sensors. These sensors will be incorporated into the deployment system used for the current seismic sensors. Under this Phase I research and development project we were able to design and laboratory test data for the new actuators recorded on our optical vector sensors. We also developed designs of suitable seismic sensor pods and a plan how to incorporate the seismic sources into our deployment system.

After the test fixture was manufactured the test fixture was mounted on a 4,000 lbs. granite block to simulate stiff clamping into a borehole. This assembly can be seen in Figure 5 on the left side of the picture. The actuator and the base plate of the test fixture were equipped with accelerometers to monitor the function of the actuator and the force generated as function of the frequency.

This vibratory axial source is designed to be able to generate a force that exceeds 2,000 N (450 pounds of force) and it is projected to be able to operate effectively from 10 Hz to 2,000 Hz. The seismic source will be encapsulated into a pressure vessel cable of operating at a 20,000-psi external pressure. The seismic source material can operate at temperatures up to 250°C (482°F).

Testing of the performance of the axial actuator started in the fall of 2018. These tests included several different sweeps ranging from 10 – 200 Hz up to 10 – 1,600 Hz at different drive levels. An example of the laboratory test data can be seen in Figure 6. The data will be recorded on accelerometers mounted both on the base plate and the reaction mass to confirm the force generated and the seismic energy coupled into the ground. The actuator itself experienced acceleration over 50g as measured on the reaction mass. We did not encounter any failures of the actuator system developed proving that the actuator is mechanically very robust.



Figure 5. This Figure shows the test set up of the first tests of the single well seismic actuator. The actuator test fixture is seen on the left side of the picture.

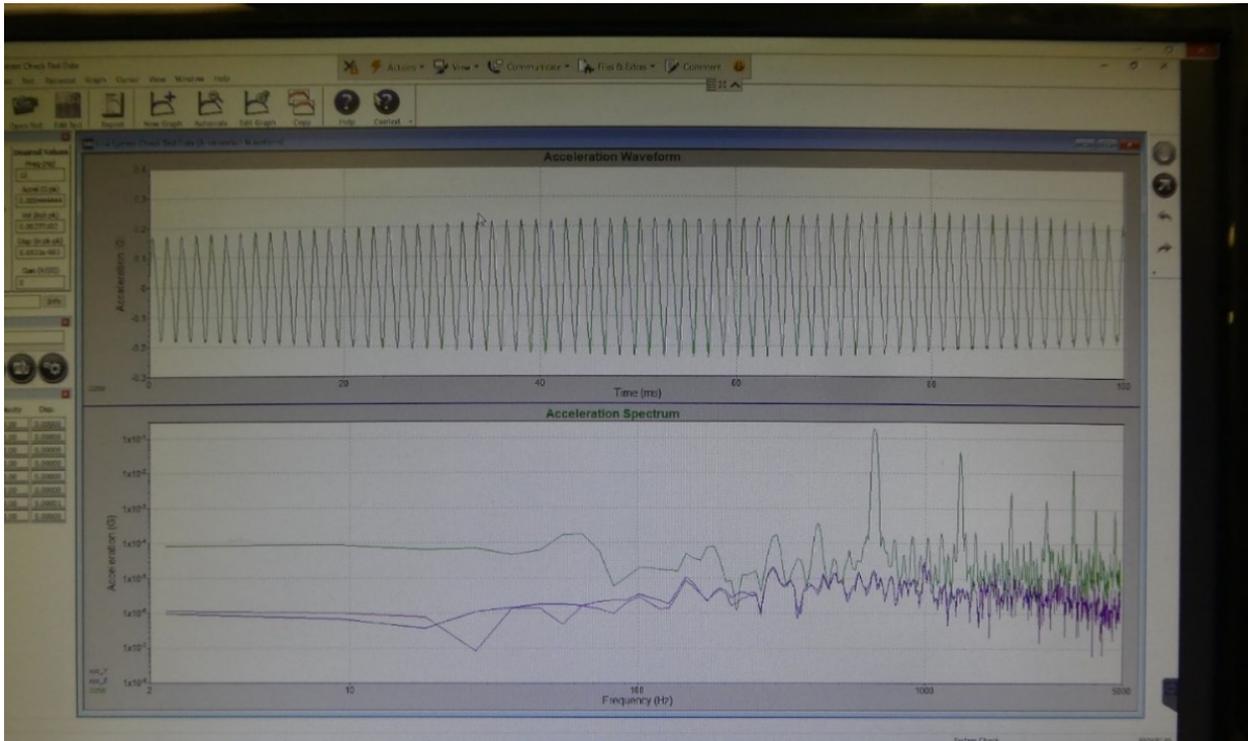


Figure 6. The data shown is from a test of the Axial Single Well Seismic Source sweeping from 10 - 1600 Hz. This photo is from our real time monitor of the data generated and recorded on three separate sensors.

Correlated Data: 10-410 Hz, 10 sec, 13.6 Vpp - Case 4

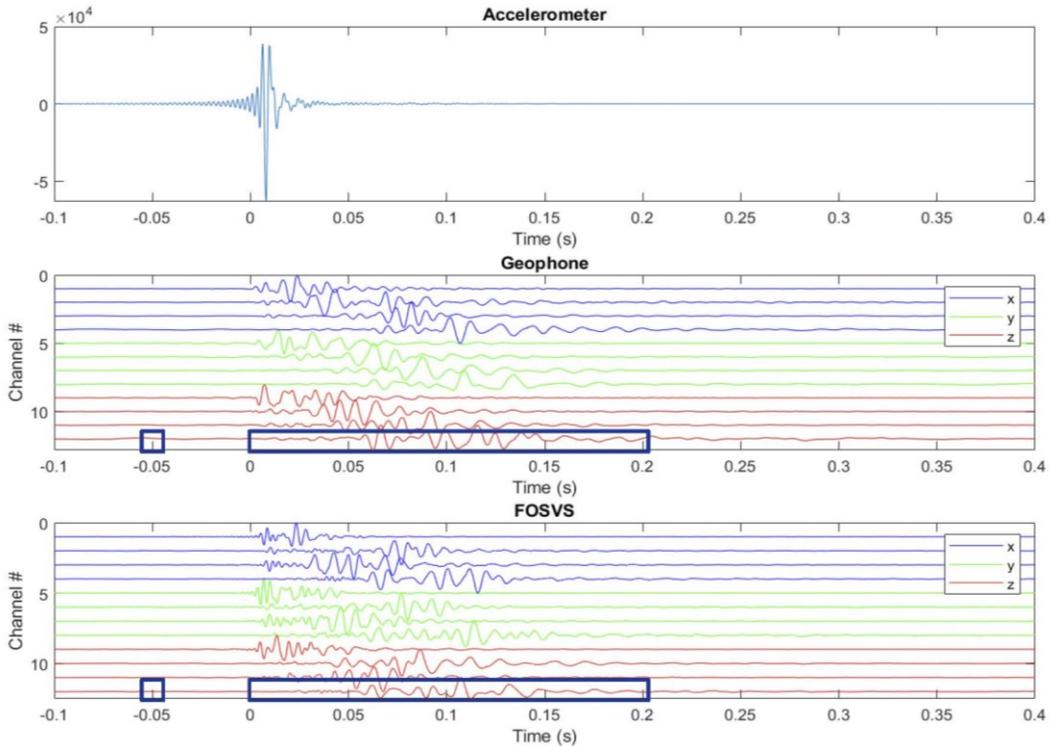


Figure 7 Correlated vibrator data recorded on a geophone and on the optical vector sensors with the S/N analysis window indicated.

Terfenol-D, Correlated Data: 10-410 Hz, 10 sec, 13.6 Vpp - Case 4 Force Generated: 1,509 N (339 lbf)

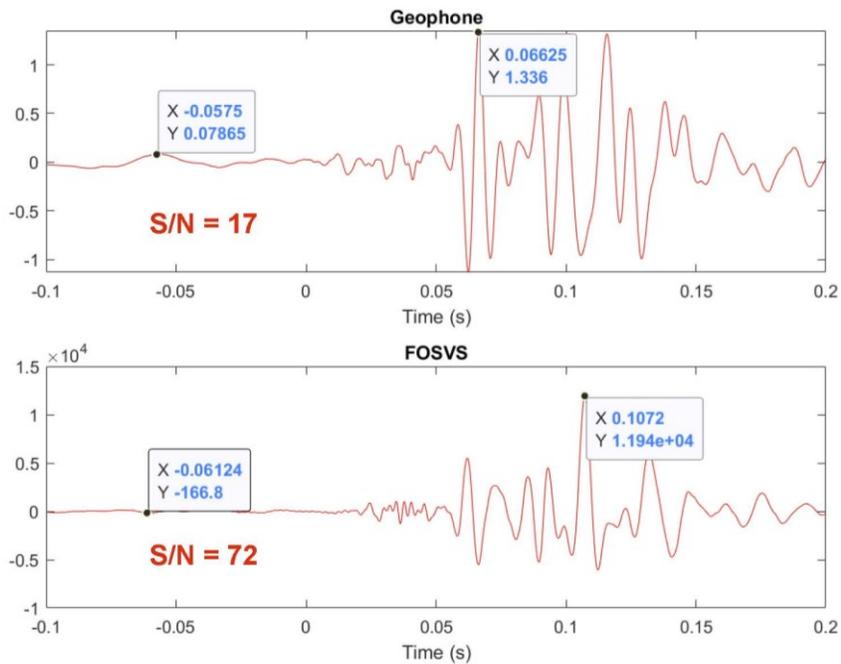


Figure 8. Terfenol-D correlated data.

In Figure 7 the Terfenol-D vibrator data are shown with the S/N analysis windows indicated. The data analyzed were from the z components (the vertical components) in the 3C geophone pod and the 3C FOSVS pod located 35 ft from the source positions.

In Figure 8 we show zoomed-in data from the Terfenol-D axial vibrator data from an offset of 35 ft from the source positions. The Terfenol-D data S/N ratio is 17 for the geophone and a S/N ratio of 72 for the FOSVS. It is interesting to note that the vibrator generates much higher frequency data than a 50 kg weight drop. It is also interesting to note that the FOSVS performs relatively better than the geophone when the higher frequency data is recorded.

The power of vibratory seismic sources is two-fold. First, the time distributed energy which provides a low instantaneous force, i.e. low instantaneous stress, which provides an effective elastic coupling of the energy. This issue is particularly important when the source is deployed in a borehole. Any source induced damage to the casing-cement interface would render the borehole seismic source unacceptable to any operations. Second, the correlation process used during processing the vibrator data improves greatly the S/N ratio of the energy transmitted allowing for a longer-range detection of reflection targets.

4. CONCLUSIONS

The results and findings presented in this paper show that the downhole vibrator tested will effectively and non-destructively couple significant broadband vector seismic energy into the formation next to a borehole. Paulsson projects that the Terfenol-D based downhole seismic vibratory source will be able to generate seismic reflection data from offset targets located several thousand feet away from the deployment borehole of the single well seismic system using the Paulsson large aperture Fiber Optic Seismic Vector Sensor (FOSVS) system. It is therefore our opinion that the downhole vibrator will be suitable for a single well seismic system and will allow the technology to provide valuable services to the EGS industry and the energy industry at large.

5. REFERENCES

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6. ACKNOWLEDGMENTS

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