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Distributed Acoustic Sensing Technology for Seismic Exploration in Magmatic Geothermal Areas

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ABSTRACT

Seismic methods are a cornerstone for the exploration of the subsurface. In comparison to seismic surveys at the surface, downhole measurements can help to gather more detailed information about rock properties as well as potential fluid pathways within geothermal reservoirs. Temperatures within geothermal wells, especially in magmatic environments, however, often exceed the temperature limitation of conventional seismic sensors. One way to overcome the lack of seismic downhole data for geothermal exploration is the application of the novel fiber optic distributed acoustic sensing (DAS) technology. For DAS, an optical fiber is used as seismic sensor. Lowering a fiber optic cable into a well, dynamic vibrations can be measured along the entire fiber with a high spatial resolution. As all electronics can be operated at the surface, the temperature tolerance for the measurement set-up, is defined by the operating temperature range of the fiber optic cable. Special optical fibers can be operated at temperatures up to several hundred degrees centigrade, therefore, closing the gap between the operating temperature limit of conventional seismic sensors and the requirements for a downhole application within geothermal wells. In this paper, the requirements for an installation of a fiber optic cable within a high-temperature well will be discussed, DAS data will be compared to conventional geophone data, and the benefit of applying the DAS technology for seismic exploration within the framework of the Iceland Deep Drilling Project (IDDP) will be outlined.

1. INTRODUCTION

Exploitation of supercritical geothermal systems is expected to yield a much higher energy output compared to conventional high-temperature geothermal wells, and has therefore been identified as a possibility to increase the geothermal development in magmatic areas. Nevertheless, no supercritical system has been successfully explored until today. Within the EC FP7 project IMAGE (van Wees et al., 2015), novel geophysical exploration and monitoring methods for such environments are developed, suitable to cope with conditions resulting from the higher reservoir temperatures and supercritical fluid properties. One of the geophysical exploration methods under investigation is the distributed acoustic sensing technology.

In recent years, the measurement of dynamic strain changes along optical fibers has been shown to be of growing interest for geophysical applications. Within the literature the technology is referred to as distributed acoustic sensing (DAS) or distributed vibration sensing (DVS) (e.g. Hartog et al., 2013). For fiber optic distributed acoustic sensing, an optical fiber is used as sensing element. Dynamic strain changes along the optical fiber can be measured and related to the ambient acoustic wave field. DAS/DVS surveys have been performed in many wellbores worldwide. Fiber optic acoustic data have been applied or suggested for well integrity monitoring (Hull et al. 2010, Boone et al., 2014), hydraulic fracturing monitoring (e.g. Molenaar et al., 2012), monitoring downhole equipment like electrical submersible pumps (Allanic et al., 2013), flow profiling (Cannon and Aminzadeh, 2013) as well as seismic applications like vertical seismic profiling (VSP) (Mestayer et al., 2011; Daley et al., 2013).

Within the framework of IMAGE, the DAS/DVS technology shall be used to image the subsurface along the IDDP-2 well (Iceland Deep Drilling Project) on the Reykjanes peninsula in Iceland. The IDDP consortium aims to drill into the root zone of a black smoker on land in order to produce supercritical geothermal fluid (Friðleifsson et. al., 2014). Within this well, a fiber optic cable shall be installed along the anchor casing down to a depth of 1200 m. DAS/DVS measurements shall be performed for passive seismic as well as ambient noise monitoring.

The DAS/DVS data will be processed together with data recorded by a seismic station network at the surface. Within IMAGE, a network of seismic stations has been deployed at the Reykjanes peninsula in spring and summer 2014 (Jousset et al., 2014). The network is composed of 20 broadband stations and 10 short-period stations. Furthermore, 23 ocean bottom seismometers were deployed in autumn 2014. First data from the seismic stations show that there is a strong ambient noise signal generated by the ocean (microseism) and nearby geothermal production wells. Furthermore, several small earthquakes occur in the region each day.

Within this paper, the DAS/DVS technology is introduced and compared to measurements with conventional geophones. Furthermore, the benefit of the DAS/DVS data acquired together with seismic data at the surface will be discussed for seismic exploration in magmatic geothermal areas.

2. DAS/DVS TECHNOLOGY

In order to measure the dynamic strain changes along an optical fiber induced by the ambient acoustic wave field, a laser pulse is launched into the fiber. Through elastic Rayleigh scattering, an optical signal is backscattered from every position along the fiber. Applying a coherent laser source, the backscattered photons from different positions within the fiber interfere with each other due to a different path length. Applying strain to the fiber, the relative position of the scattering molecules changes, changing the resulting interference pattern at the receiver, i.e. the phase of the backscattered signal. A high laser repetition rate, therefore, enables the operator to measure dynamic strain changes up to several kHz with a sampling resolution of down to 1 m for a cable length of several km (e.g. Masoudi et al., 2013).

The measured vibration along the optical fiber is dependent on the angle of incidence of the acoustic perturbation. While signals travelling along the fiber can be measured quite well, the broadside sensitivity is usually rather low (e.g. Lumens et al., 2013). Incorporating more than one fiber with a different sensitivity to broadside signals or adjusting the geometry of the fiber within the cable have been proven to be able to measure the acoustic field in more than one direction (Lumens et al., 2013). Even mechanical adjustments to the cable have been considered to overcome the 1D limitation of the optical fiber and to allow for three component measurements along the entire length of a fiber optic cable.

3. SEISMIC DOWNHOLE MEASUREMENTS IN HIGH-TEMPERATURE ENVIRONMENTS

For seismic surveys, usually three-component geophones are used. Such geophones can measure the seismic information at a single position. Incorporating many such sensors in a single measurement set-up and performing measurements at several locations within a well is time consuming and costly. Furthermore, measurements in geothermal environments often exceed the temperature tolerance of conventional seismic sensors. Within deep geothermal wells, temperatures are often in excess of 150°C. While high-temperature tolerant electronic circuits are available up to 175°C, and some more advanced materials like silicon carbide (SiC) and silicon on isolator (SOI) exist for even higher temperatures, hardly any geophones can operate under high-temperature conditions. Thermal flasking is another means to operate electronics in high temperature environments for a limited amount of time. For DAS/DVS measurements, only the optical fiber has to be lowered into the well. Seismic measurements can be performed along the entire length of the fiber simultaneously. As all electronics are operated from the surface, the temperature limitation of the measurement set-up is defined by the temperature rating of the fiber optic cable.

An optical fiber is composed of a central core and clade made of silica with some doping ions to adjust the refractive index of the glass. In order to give the light guiding silica the required robustness, a coating material is applied to the outside. The temperature tolerance of the coating material is of major concern for the operating temperature range of the optical fiber. In downhole applications, mainly polymer materials like polyimides have been used at temperatures above 200°C (e.g. Ikeda, 2003; Reinsch et al., 2013), although long term tests show limitations of such a material if subjected to temperatures close to 300°C (Reinsch and Henninges 2010). At temperatures above 300°C, only metal coated fibers can be applied for long term observations. Aluminum coated fibers are rated up to 400°C, copper coated fibers up to 450°C and gold coated fibers even up to 700°C. At present, fiber lengths in excess of 1 km, operating at temperatures above 400°C, however, can only be produced with copper coatings. For seismic surveys in a deep geothermal well, as desired for the IDDP-2 well, the DAS/DVS technology is therefore one option to close the gap between the operating temperature limit of conventional geophones and the requirements within magmatic geothermal environments.

4. CABLE INSTALLATION

In order to obtain a reasonable signal-to-noise ratio for the seismic survey, fiber optic DAS/DVS measurements can be performed using wireline or permanent cable installations. The major factor influencing the signal-to-noise (S/N) ratio of the measurement is the mechanical coupling between wellbore and the optical fiber. For wireline applications, the mechanical coupling between fiber optic cable and wellbore wall is rather undefined. The well path as well as the tension of the optical cable has an influence on the coupling. Although an optimal coupling has to be achieved by adjusting the cable tension prior to the seismic survey on-line, wireline fiber optic DAS/DVS measurements have been successfully used to acquire seismic data (Frignet et al., 2014).

In permanent installations, a fiber optic cable is installed permanently at the tubing or behind casing of a well. This type of installation allows for seismic measurements without well intervention and throughout the lifetime of the installation. Data from several VSP surveys shows that the S/N ratio can be rather low for installations behind tubing and much higher if the cable is cemented behind casing (e.g. Daley et al., 2013).

4.1 Installation within IDDP-2 Well

The IDDP-2 well is designed to be drilled down to a depth of about 3-5 km into the roots of a black smoker on land. The well is planned to be drilled in several sections. The fiber optic cable shall be installed at the outside of the anchor casing down to about 1200 m true vertical depth. It is planned to install the cable in a looped configuration with a turnaround for the cable at the bottom of the installation, allowing to access both ends of the cable at the surface. To be able to perform DAS/DVS measurements as well as distributed temperature sensing (DTS) measurements, the cable will be equipped with a single-mode and a multi-mode optical fiber. Additionally to the wellbore installation (z-direction), a surface layout of optical cable shall be deployed in x and y-direction in order to have a three-dimensional sensor array (Figure 1).

5. FIELD COMPARISON – KETZIN SITE

At the Ketzin CO_2 storage site, seismic downhole measurements were performed with conventional three component geophones as well as the fiber optic DAS/DVS technology. At Ketzin, an injection well and three observation wells are equipped with fiber optic cables in the annulus outside a 5-1/2" production casing. A DAS/DVS measurement was conducted from 27–30 May 2013 at Ketzin and data was recorded along a fiber optic cable of 5900 m length with a spatial resolution of 1 m. Data from the DAS/DVS survey is compared to data from a conventional zero-offset VSP. For the conventional zero-offset VSP, a VIBSIST source was used (Swept Impact Seismic Technique, SIST, Yang et al., 2010; Cosma and Enescu, 2001). Because of the lower sensitivity of the fiber optical cable (Daley et al., 2013), the DAS/DVS data were recorded with the seismic vibrator “Vibro-Truck Mertz M12” with a maximum peak force of 133.6 kN. 30 linear sweeps of 50 s length, with frequencies from 7–120 Hz were recorded.

Especially, the zero-offset VSP is affected by the poorly cemented production casing of the receiver well (Kazemeini et al., 2010; Daley et al., 2013; Götz, 2013). Casing and cementation of the observation well are shown on the left-hand side of Figure 2. From 460-565m, the production casing is cemented to the intermediate casing which is cemented to the formation. Between 669 m – 750 m, the production casing is cemented directly to the formation. Caused by this unfavorable situation, the zero-offset VSP wavefield recorded with the geophones (Fig. 2, 2nd from the left), is dominated by casing waves down 460 m (uncemented multiple casing strings). At 460 m the first onsets are shifted and the identification of first breaks is possible (cemented multiple casing strings). The signal strength again is seriously reduced between 565 m and 669 m, but the identification of phases is still possible (uncemented single casing string).

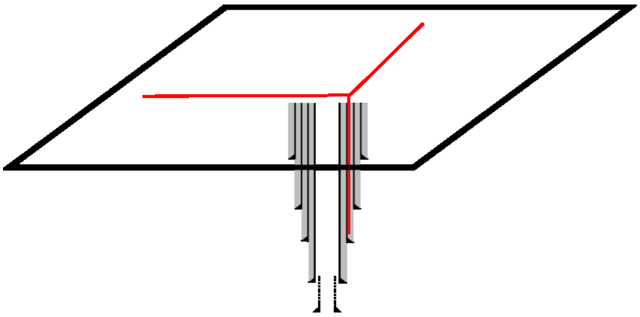

Figure 1: Conceptional design of the fiber-optic installation within the IMAGE project (not to scale). The cable (red) will be installed down to a depth of 1200 m. Some additional cable length shall be deployed at the surface to create a three dimensional sensor array.

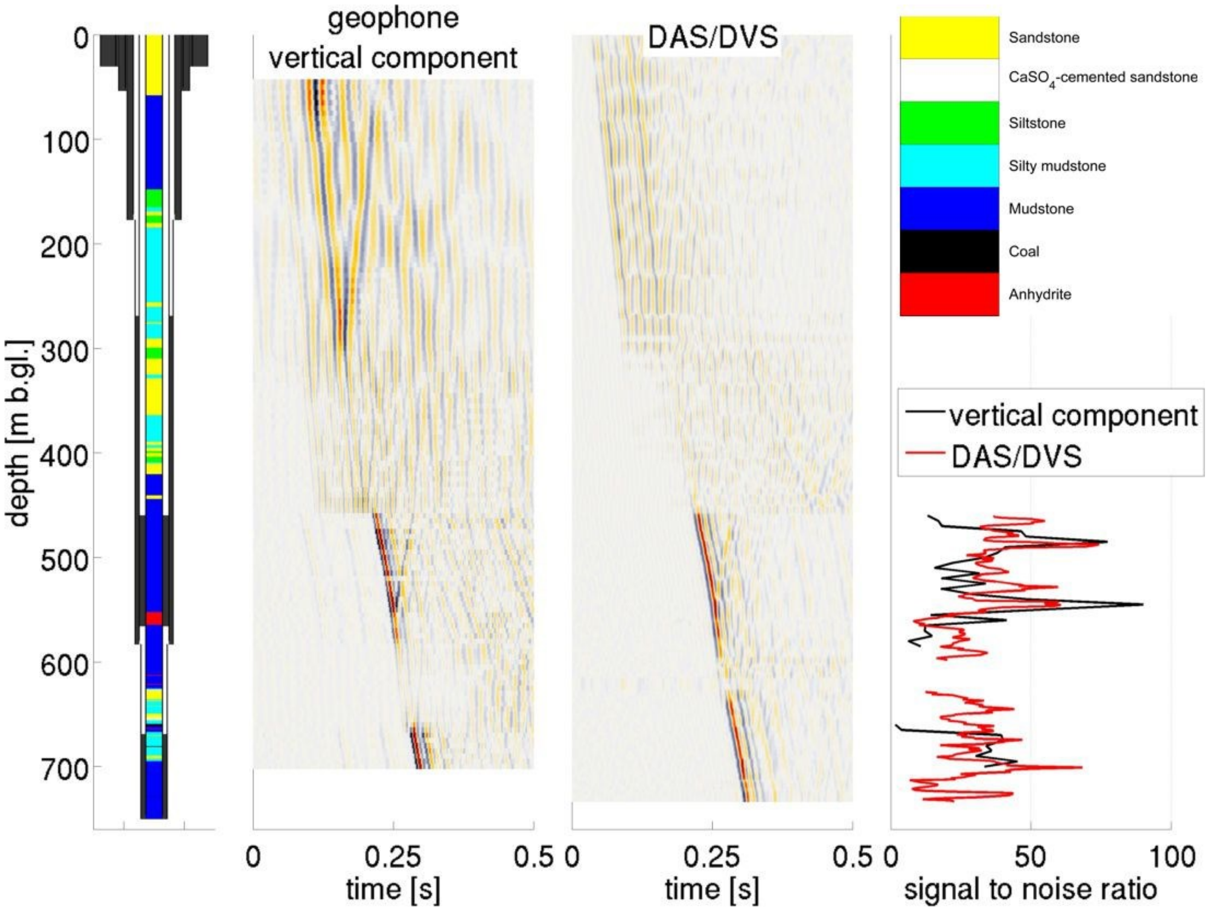

Figure 2: (left to right) Well completion of well Ktzi 202, vertical component of conventional geophone, processed data from DAS/DVS survey, well lithology and signal-to-noise ratio comparison for the depth interval 450-700 m. The optical fiber is installed behind the production casing. Cemented intervals are indicated by gray section in the well diagram.

The zero-offset DAS/DVS data recorded in the same well as the conventional zero-offset VSP (Figure 2, 3rd from the left) are also affected by casing wave in the upper part (uncemented multiple casing strings). Contrary to the conventional geophone data, weak first breaks can be identified between 310 m and 460 m depth (uncemented production casing, cemented intermediate casing). Above 310 m, the recorded wavefield cannot easily be linked to the cementation. The reason is still under investigation. In the depth range of the single uncemented production casing (565 m – 669 m), the DAS/DVS data maintain a higher signal strength than the conventional data, probably because of the deployment behind the casing.

For the conventional geophone data and the DAS/DVS data, the signal-to-noise ratio is calculated in depth ranges where the first breaks can be clearly identified (Fig. 2, right). With the DAS/DVS technique, the signal-to-noise ratio of conventional geophone recordings can be reached. However, for the Ketzin case, a real comparison is difficult, due to the different sources (VIBSIST vs vibroseis) and pre-processing methods (shift-and-stack vs correlation).

Apart from the well installation, about 30 m of fiber optic cable were buried in a 50 cm deep trench at the surface. On top of the trench, three component geophones were deployed in order to compare the S/N for the different recording techniques. Figure 3 shows a comparison between the signal measured by a three component geophone at the surface and the signal detected by the DAS system below the geophone. Both detectors were able to detect the signal generated by the vibrator with a reasonable S/N ratio, although the shape of the signal differs. For the geophone, all three components are measured separately, whereas the optical fiber is sensitive to a superposition of the components, depending on the angle of incidence of the seismic wave. Furthermore, the DAS/DVS technique measures strain, the geophone velocity.

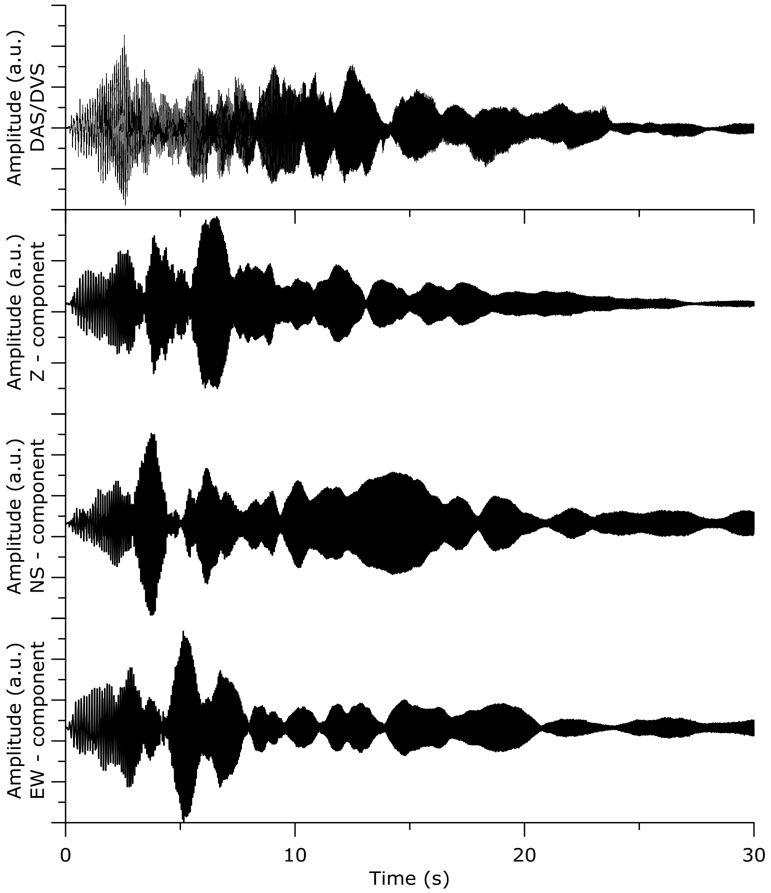

Figure 3: Comparison of measured signal from the optical fiber buried in a 50 cm deep trench (top) below a three component geophone (three traces at the bottom).

6. CONCLUSIONS

DAS/DVS is well suited to be used for seismic applications in geothermal environments. Data from a seismic survey at the Ketzin CO_2 storage site shows that the technology is able to measure seismic perturbations generated by a seismic source at the surface. Especially in well cemented sections, the seismic signal travelling through the formation is well detected. For the installation within the IDDP-2 well, it is therefore desired to cement the cable along the entire length of about 1200 m. The S/N ratio is expected to be sufficient to measure even small perturbations generated by seismic events in the subsurface as well as ambient noise generated by the nearby ocean or producing geothermal wells. Analyzing the DAS/DVS data together with data from the seismic network deployed at the surface can greatly increase the resolution of the seismic survey. Furthermore, bringing the IDDP-2 well into production, the seismic noise generated by a flowing geothermal well can be measured directly and compared to the signal received at the broadband station network. The application of the DAS/DVS technology for exploration is therefore considered to be a valuable method to perform seismic downhole measurements in high-temperature wells and therefore image geothermal reservoirs in magmatic environments.

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