Application of distributed fibre-optic sensing to geothermal reservoir characterization and monitoring

Michael Mondanos[1*] and Thomas Coleman[1] present highlights and example data from the deployment of distributed fibre systems at both hydrothermal and EGS sites.

Introduction

Geothermal reservoirs offer unique characterization challenges due to the harsh environment that downhole tools are subject to and the discrete and spatially discontinuous hydrothermal features that make up the reservoir. Enhanced Geothermal Systems (EGS) offer great potential for dramatically expanding the use of geothermal energy by allowing development of traditionally inaccessible thermal resources; thus, offering the possibility to significantly reduce carbon emissions to combat anthropogenically induced climate change. However, EGS development offers an additional set of challenges as reservoir engineers have the burden of not only characterizing the existing reservoir, but to dynamically guide reservoir enhancement in heterogeneous media with a fine degree of resolution and accuracy. Developing EGS resources will require highly advanced and novel characterization and monitoring methods and technologies.

Geophysical data can provide some of the most spatially extensive information about the subsurface and has a long and successful exploration role in the oil and gas industry. Continuous monitoring of the subsurface is of great importance especially in operations where the permeability is enhanced during hydro-shearing (expanding existing fractures) and hydraulic tensile fracturing (to create new fractures). Optimization of enhancement processes can be achieved through localization of the geologic structures (e.g. fracture zones), seismic monitoring during stimulation, and characterizing the resultant hydraulic connectivity between injection and production wells. Seismic methods, which utilize elastic waves provide incredibly detailed images of geologic formations and structures play an important role in monitoring changes in the subsurface. Time-lapse (4D) seismic imaging techniques have become commonplace for monitoring the movement of fluids in oil and gas reservoirs and carbon sequestration. They have also been applied to geothermal reservoir characterization. Detection and localization of microseismic events during reservoir stimulation can provide an indication of fracture development to guide stimulation efforts.

Therefore, there is a need for long-term seismic monitoring to facilitate 4D imaging techniques and microseismic surveys. However, the relatively high cost, high level of invasiveness of deployments, and often significant time-delay between data acquisition and availability of the interpretable results can impede the use of seismic methods that involve deployment of numerous conventional geophone receivers. One of the ways to address these issues is to design permanently deployed sensing arrays as they decrease land impact and speed-up acquisition and processing. Recent advancements in distributed acoustic sensing (DAS) technology makes fibre-optic cables a key component of such receiver arrays, including those deployed in high temperature wells. Predominantly these systems have been developed for the oil and gas industry to assist reservoir engineers in optimizing the well lifetime. Nowadays these systems find a wide variety of applications to characterize the subsurface, including freshwater aquifers, CO_2 capture and storage reservoirs, and geothermal fields.

Here we present highlights and example data from the deployment of distributed fibre systems at both hydrothermal and EGS sites. This includes a field where a fault dominated reservoir supports a 22 MWe power plant and a new research site that will serve as a focal point for development of EGS. At both sites distributed acoustic sensing and distributed temperature sensing were used.

Technology

Optical time domain reflectometry (OTDR) is the underlying principle enabling distributed sensing, in which an incident pulse of light is coupled into an optical fibre and the backscattered light sampled. As the incident pulse travels along the fibre a small amount of light is scattered and recaptured by the fibre waveguide in the return direction. Through analyses of the backscattered signal and roundtrip transit time from launching end to point of interest dynamic profiles of the state of the optical fibre at all locations can be developed (Figure 1).

The principles of distributed temperature sensing (DTS) are well known and are based on the detection of a very weak inelastic Raman backscatter light resulting from the interaction of the incident light pulse with molecular lattice thermal vibrations energy along the fibre. The new DTS uses an advanced optoelectronic technology that can measure temperature changes down to 0.01^{o}C with a fine spatial resolution of less than 1m.

The Distributed Acoustic Senor (DAS) is based on a novel digital optical detection of elastic Rayleigh backscatter resulting from minute built-in inhomogeneous variations of refractive index along the fibre. The DAS system can capture the full acoustic field amplitude and phase at every point along the fibre over a wide frequency and dynamic range. The acoustic energy induces strain

[1] Silixa LLC

[*] Corresponding author, E-mail: Thomas.coleman@silixa.com

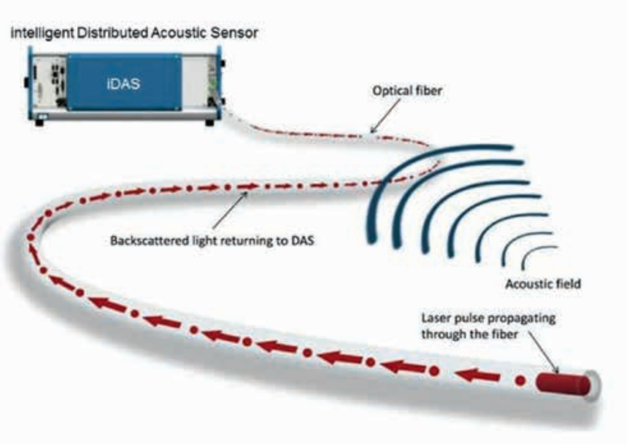

Figure 1 The iDAS provides digital acoustic measurements along the entire length of an optical fibre.

along the fibre and the DAS interrogator measures changes in the local axial strain down to sub-nanostrain resolution (Parker et al., 2014).

Improvements in DAS system architecture paired with precision engineered optical fibres are recent developments that allow for next generation DAS to have a 20 dB (100x) improvement in SNR compared with existing systems (Richter et al., 2019).

Hydrothermal deployment at the Brady Hot Springs Field in Western Nevada

A multi-disciplinary team led by the University of Wisconsin-Madison with partners from academia and industry developed and deployed a highly detailed geothermal reservoir monitoring system including distributed fibre-optic sensing at Brady Hot Springs Nevada as part of the US Department of Energy-funded PoroTomo project (Feigl et al., 2019). Optical fibre cables were deployed on in a shallow surface trench and in an observation well. The project developed a monitoring methodology to characterize the geothermal reservoir with a 100 m spatial resolution of combined seismology, geodesy, and hydrology parameters at depth that could be scaled to deployments for monitoring greater reservoir depths and subsequent volumes. The integrated technology developed as part of PoroTomo can be utilized at other hydrothermal and EGS sites to enhance reservoir understanding through estimation of subsurface formation parameters and their uncertainties to improve operations at existing facilities and guide new development efforts.

Field measurements

A dense seismic array to image the shallow structure in the injection area of the Brady Hot Springs geothermal power plant was deployed. The array was composed of 238 three component, 5 Hz nodal instruments, 8700 m of a 6.1 mm abrasion- and rodent-re-

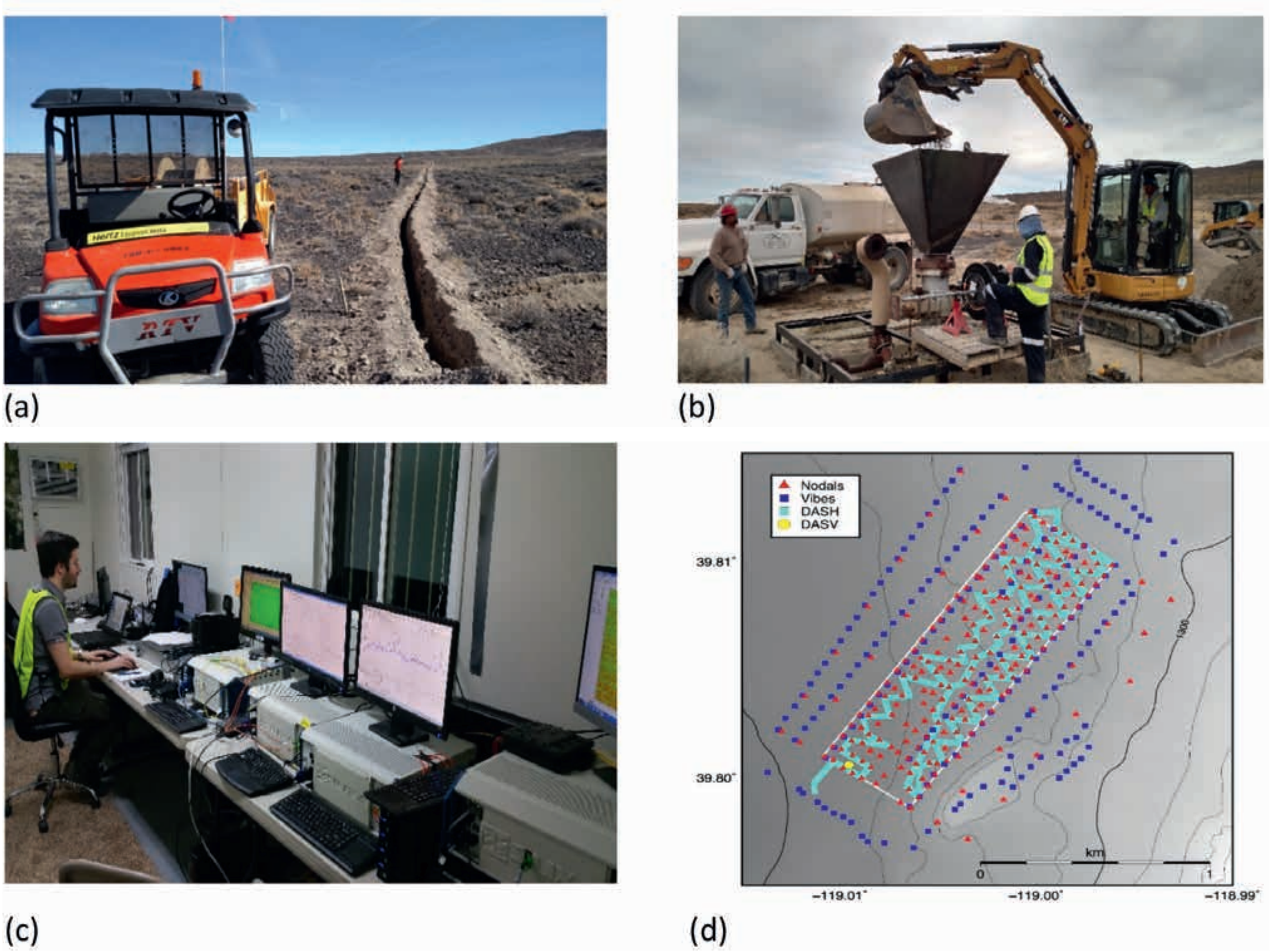

Figure 2 Deployment of a permanent fibre-optic systems at the Brady Hot springs Nevada. (a) optical fibre cable trench, (b) cable installation in the well, (c) DAS and DTS equipment (d) Map showing the instrumentation deployment. Red triangles are nodal geophones, blue squares are the vibroseis points, cyan line is the trenched fibre-optic cable, and the yellow circle is the borehole containing the vertical fibre-optic cable (Parker et al., 2018).

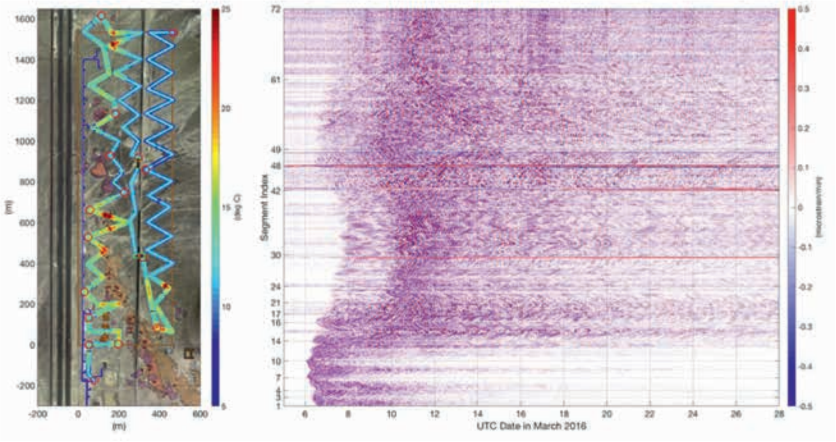

Figure 3 DTS (left) and DAS (right) data from the 8700 m trenched cable on 15 Mar 2016 recording cable temperature and a seismic event, respectively (Miller et al., 2018).

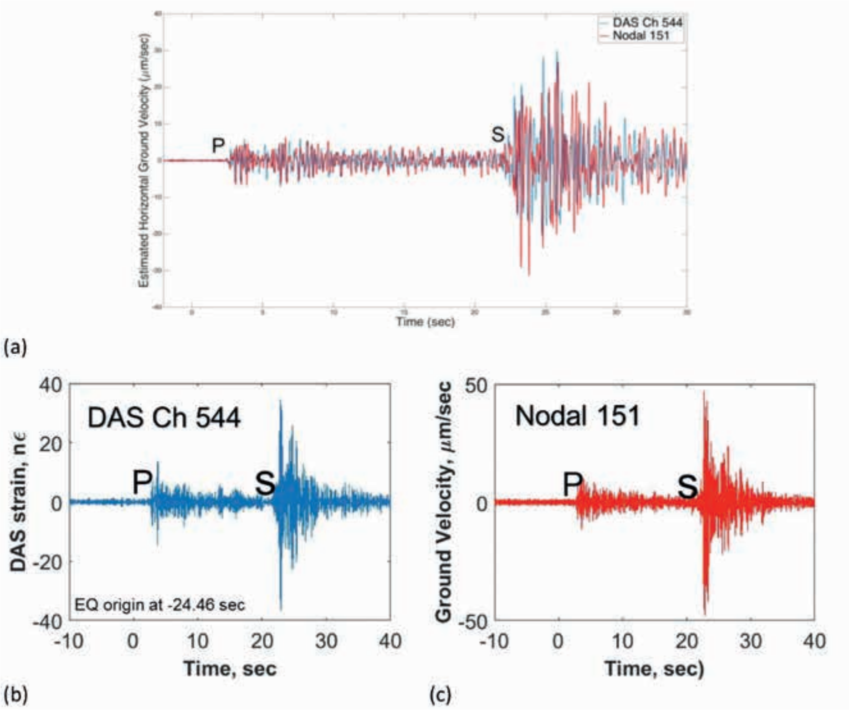

Figure 4 Time series of particle velocity at Brady as recorded by DAS channel 544 (blue) and a co-located Nodal seismometer at station N151 (red) (modified from Feigl et al., 2017).

sistant fibre-optic cable with acrylate-coated fibres rated to 85°C installed horizontally in surface trenches (Figure *2*a) to a depth of approximately 0.5 m, and 363 m of a 3.2 mm fibre in metal tube cable with high temperature acrylate coated fibres rated to 150°C was installed vertically in a borehole (Figure *2*b). The geophone array had about 60 m instrument spacing in the target zone, whereas DAS channel separations were about 1 m with an averaging (gauge) length of 10 m. DTS data was collected on the trenched fibre with 1 m sampling resolution (2 m spatial resolution) and in the borehole with 0.13 m sampling resolution (0.29 m spatial resolution). DAS and DTS data were recorded continuously over a 15-day period in both the surface and downhole fibre-optic cables while a series of changes to pumping and injection were made in the reservoir.

The native values of the acoustic output were in units proportional to the strain rate. A linear conversion can be made to convert these values to absolute strain rate. Conversion from strain rate to strain is possible with a simple time-integration step. This processing step has the effect of boosting the low-frequency energy in the signal and flattening the noise spectrum. Hence data which is converted to strain units can provide output which is well suited for seismic processing when applying some commonly used routines. This processing step also has the effect of putting iDAS data in phase alignment with geophone data, although the dimensions of the data are in terms of strain and not speed (m/s) as is commonly measured with a geophone. The DTS units were set up in a double-ended measurement configuration and raw backscattered Stokes/anti-Stokes signals were used to calculate temperature on board the DTS instruments.

Selected applications demonstrated at Brady's hot springs

Earthquake seismology

Permanent DAS arrays can be used for detection and localization of earthquakes. Figure *4* compares a seismogram calculated in the direction of the DAS cable segment with a time series of strain measured by DAS. The recordings show the ground motion about 25 seconds after a magnitude 4.3 earthquake occurred near Hawthorne, Nevada on March 21, 2016 at 7:37 UTC with an epicentre approximately 150 km from the study site. The waveforms indicate that a co-located DAS channel and seismometer record ground

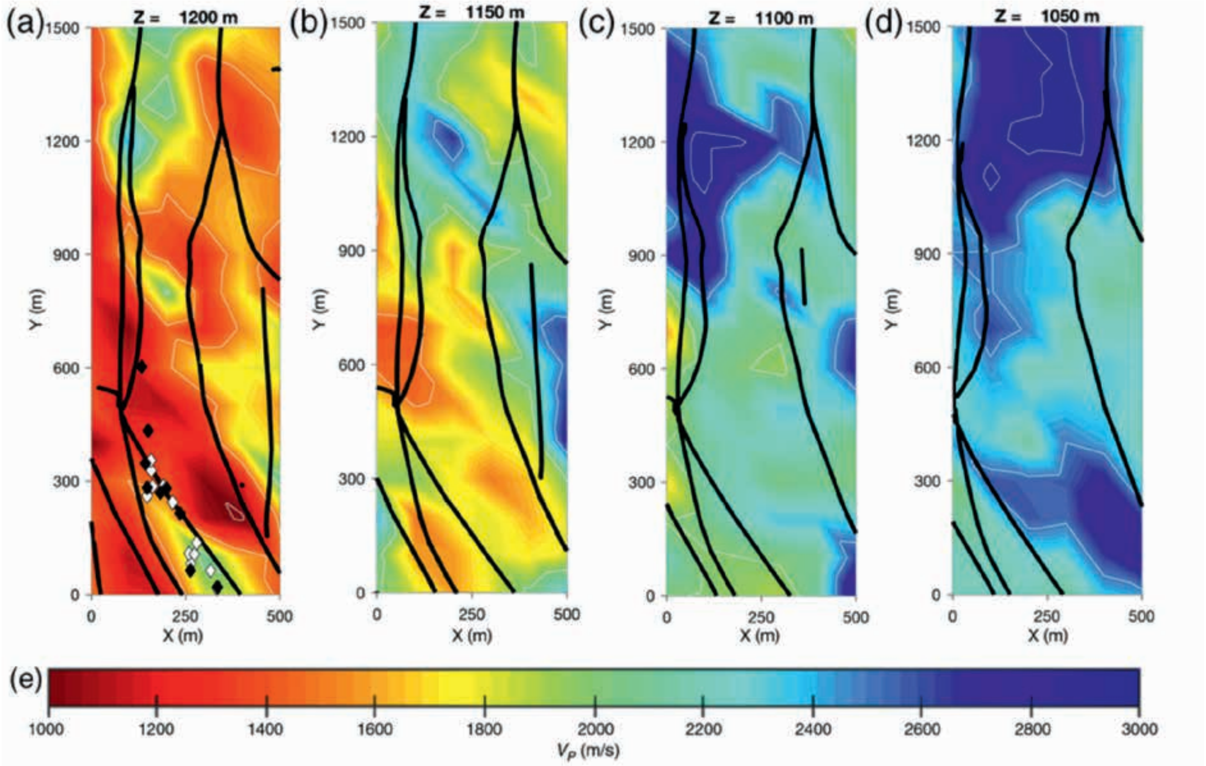

Figure 5 Depth slices (a-d) through the 3D P-wave velocity model with respect to the WGS84 ellipsoid. Black lines are intersected faults and black and white diamonds are fumaroles and mudpots respectively. P-wave velocity colour scale (e). (Parker et al., 2018).

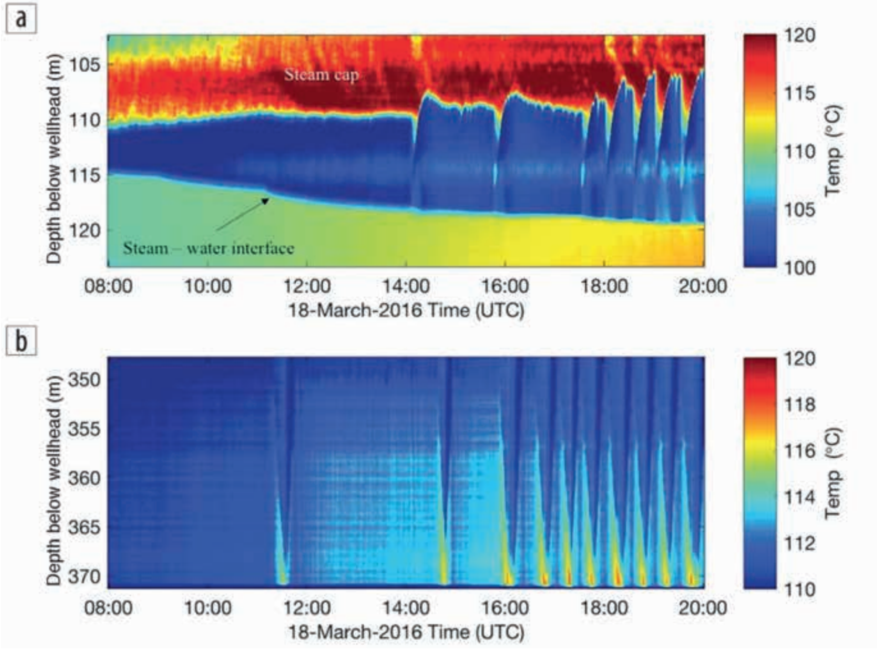

Figure 6 (a) Increase in depth of the steam-water interface and the onset of phase change occurring due to the resultant depressurization. (b) Periodic convection pulses occurring at 30-minute intervals observed in the open interval 11 hours after the onset of pumping in a production well. (Patterson et al., 2017).

motion proportional with one another. Good SNR was demonstrated in the seismic frequency band, and along with the large number of time synchronous sensors and large N capability indicate DAS arrays have a role to play in earthquake seismology (Wang et al., 2018).

Seismic tomography

Over the 15-day continuous DAS and seismometer deployment, active source seismic data was collected using a large vibroseis truck and 196 source positions. Twenty second sweeps were from 5-80 Hz and were collected in three modes (vertical, horizontal and transverse) with three sweeps per mode at each source location. This set of sweeps was repeated up to four times at each source location during the survey. P-wave arrivals were automatically picked from the data and the travel times used to invert for the P-wave velocity structure in 3D (Parker et al., 2018). An area of 2000 m x 1300 m was modelled with good resolution to about 250 m depth. Modelled velocities are in agreement with geologic features present at the study area including the known locations of local faults and fumaroles and low near-surface velocities may provide new insight into the depth of the water table. Depth slices of P-wave velocity obtained from the tomogram are presented in Figure 5.

Thermal and hydraulic characterization

DTS measurements in the observation borehole allowed for hydrothermal dynamics to be monitored with spatio-temporal detail not achievable with traditional pressure-temperature (P-T) logging methods (Figure 6). DTS data was analysed by Patterson et al. (2017) and provided a means to monitor the water-steam interface, convective processes in the open interval, and temperature recovery following injection of a cold water 'slug'. The thermal recovery data allowed for inversion of the borehole thermal diffusivity profile using a finite-difference heat-transfer model. The thermal diffusivity model may assist with future reservoir modelling or evaluation of thermal resources. The analysed results indicate that the monitoring well is hydraulically connected to the production well and that faults are the governing hydraulic connection to the reservoir.

EGS deployment at FORGE

The Frontier Observatory for Research in Geothermal Energy (FORGE) is a site and US Department of Energy effort dedicated to providing a testbed to accelerate development of breakthrough technologies and techniques for EGS. The facility is located near Milford, Utah on the western flank of the mineral mountains. The reservoir consists primarily of granite and quartz monzonite below near surface alluvium. The research site will be developed with activities focused on refining drilling, stimulation, and subsurface imaging technologies to allow for optimized injection-production with the ultimate goal of providing a means to sustain long-term fluid flow and energy transfer from an EGS reservoir (Moore et al., 2019). In April 2019, limited reservoir stimulation activities were conducted at three depths in a 2 km-deep borehole. This testing was carried out to allow for refinement of stimulation designs for future phases of the project and to evaluate imaging techniques for monitoring fracture propagation. A ¼ inch stainless steel fibre optic cable with multi-mode, single-mode, and precision engineered sensing fibre rated to 150 °C was clamped to the outside of the casing (Figure 7b) and cemented in the annulus of a 1 km monitoring borehole located approximately 350 m from the stimulation well and completed at the surface in a stainless steel enclosure (Figure 7c). Both DTS and next generation DAS data were collected during stimulation activities. DAS data will be used for detection and localization of microseismic events generated by the stimulation.

Preliminary results

DAS and DTS data were collected continuously during the two weeks of stimulation activities. The temperature profile in the observation well was constant as expected. Numerous microseismic events were detected associated with the stimulation as well as several far offset events attributed to regional seismic activity. Analyses of the microseismic data is preliminary. However, clear P-wave and S-wave arrivals were present as well as potential P-wave multiples attributed to a deep reflector (Figure 8). Changes in velocity are clearly evident, and the time-delay and move-out of

Figure 7 (a) Installation of ¼ inch stainless steel fibre-optic cable with DTS and next generation DAS fibre in a 1 km observation borehole at FORGE. (b) Cable clamped to the casing. (c) Surface completion of cable in stainless steel enclosure. (d) 2 km-deep well during stimulation activities.

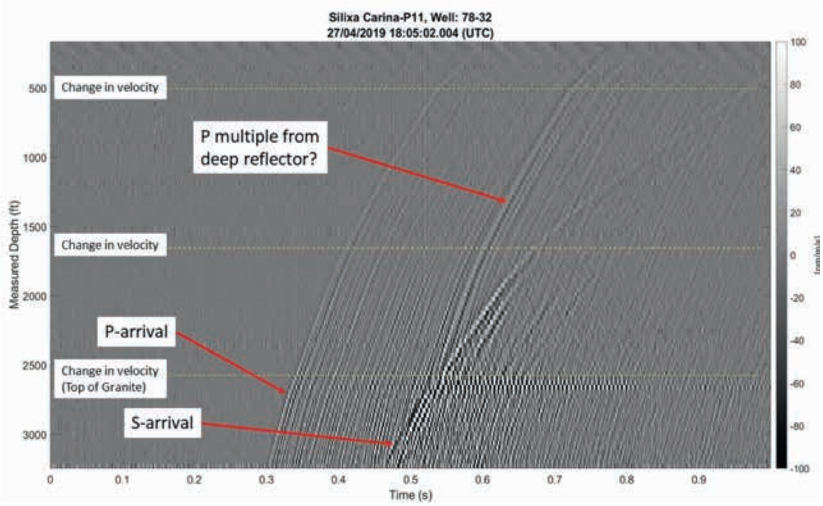

Figure 8 Example of microseismic event measured with next-generation DAS system during stimulation. Clear P-wave and S-wave arrivals are present as well as changes in velocity with depth.

the P and S-wave arrivals will be used in combination with the site velocity model and survey geometry to locate events in depth-distance from the monitoring well. Microseismic event locations will help to evaluate the extent and geometry of stimulated fractures.

Conclusions

Geothermal reservoirs offer unique monitoring and characterization challenges. The harsh, high temperature downhole environment and heterogeneous nature of discrete hydraulic features usually governed by discontinuous fractures and faults requires robust measurement technology with advanced resolution capability. Distributed fibre-optic sensing cables have been demonstrated to be suitably robust for extended duration installations in geothermal fields. Cables can be installed trenched at the surface, deployed into existing boreholes, or cemented behind casing in permanent installations to provide enhanced coupling. Both DTS and DAS are readily combined in a single cable installation, and significant improvements have brought DAS technology close to having SNR on par with traditional geophones. Permanent installations provide access to monitoring without having to intervene and disturb the well. Borehole DAS installations are often associated with VSP surveys. However, tomographic seismic, earthquake seismology, and microseismic applications have also been demonstrated at a geothermal field. The spatio-temporal resolution achieved with DTS allows for characterization of hydrothermal processes as well as estimation of thermal diffusivity with depth. EGS development further focuses the need for dynamic reservoir characterization to allow for monitoring technology to provide feedback to guide stimulation activities which will require continued development and refinement of advanced sensory, analyses, and imaging technologies. Based on developments over the past few years, it is likely that fibre-optic distributed sensing will enable surveys to be part of the subsurface geothermal characterization toolkit for the foreseeable future.

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