Hydraulic fracture monitoring and optimization in unconventional completions using a high-resolution engineered fibre-optic Distributed Acoustic Sensor

P. Richter[1], T. Parker[1], C. Woerpel[1], Y. Wu[1], R. Rufino[1] and M. Farhadiroushan[1] present an advanced optoelectronic Distributed Acoustic Sensor that utilizes a new generation of engineered optical fibre with 100x (20 dB) improved sensitivity compared to that of standard fibres.

Introduction

Understanding fracture geometry and estimating stimulated rock volume (SRV) is the goal of operators in unconventional reservoirs. The industry has long been challenged with getting a good understanding of how wells and completions interact with each other. One of the biggest challenges is how to get a quantitative measure of the extent of fractures. Historically, companies have used many different technologies to better understand their completions. Tilt meters, microseismic geophone arrays, chemical tracers and pressure sensors are just some of the conventional technologies that have been used with a limited coverage to monitor the changes in the reservoir during hydraulic fracturing.

The Distributed Acoustic Sensor (DAS) and Distributed Temperature Sensor (DTS) are used for multiple measurements along the entire wellbore. During the hydraulic fracturing treatment, the acoustic energy distribution and temperature profiling are recorded in real time to analyse the fluid allocations per cluster as indicated in Figure 1.

The fibre is also used to acquire seismic and microseismic data at different stages of the well completion. Low frequency crosswell strain is also measured in an observation well or in an offset well. DTS data, with a fine resolution of 0.01°C, is used to indicate any hydraulic fluid contact (Hull et al., 2017; Jin and Roy, 2017). The combined microseismic, crosswell strain and temperature data are used to better understand rock properties, well interference and for optimizing the well spacing.

The utilization of distributed fibre measurements has been increasing over the past few years. By installing a permanent fibre cable on the outside of a casing string, measurements along the

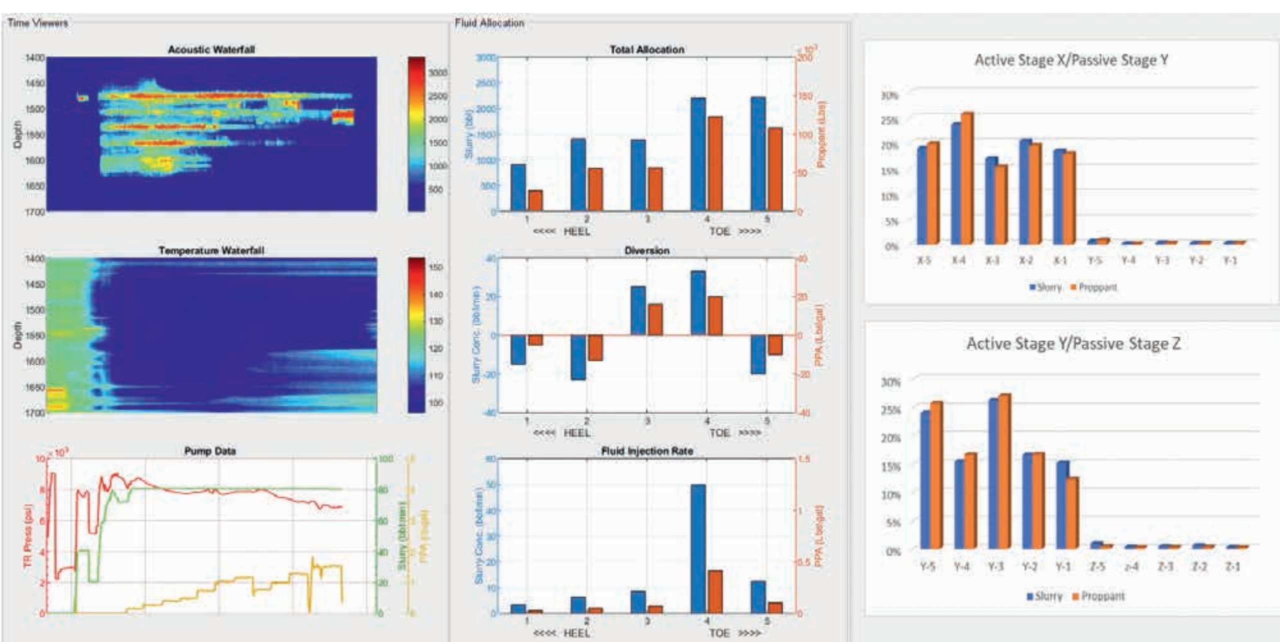

Figure 1 Distributed Acoustic Sensor (DAS) and Distributed Temperature Sensor (DTS) data recorded in real time on a permanent fibre installed on to the outside of the casing to analyse the fluid allocations per cluster.

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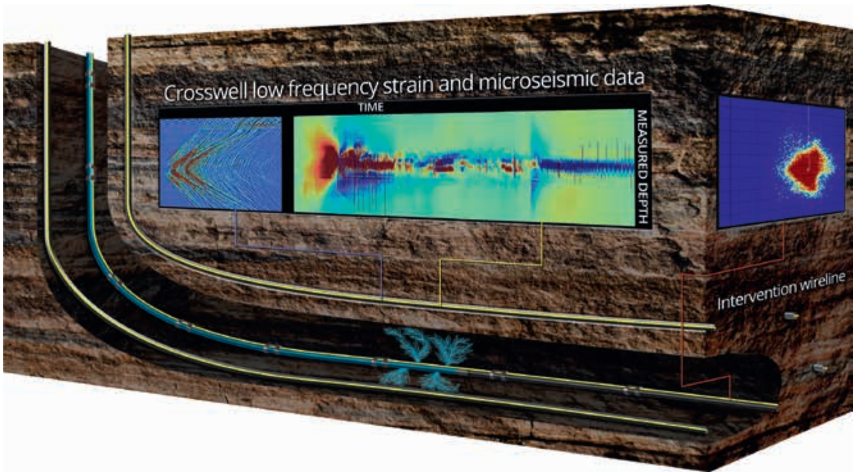

Figure 2 Real-time Hydraulic Fracture Monitoring (HFM) in multiple wells using engineered fibre deployed permanently and on a wireline intervention cable.

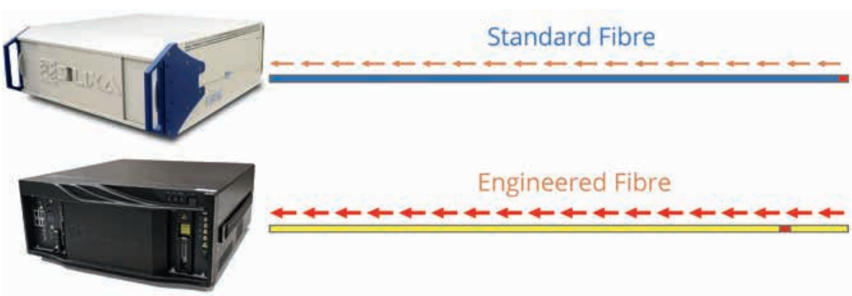

Figure 3 The DAS system using standard and engineered sensing fibre.

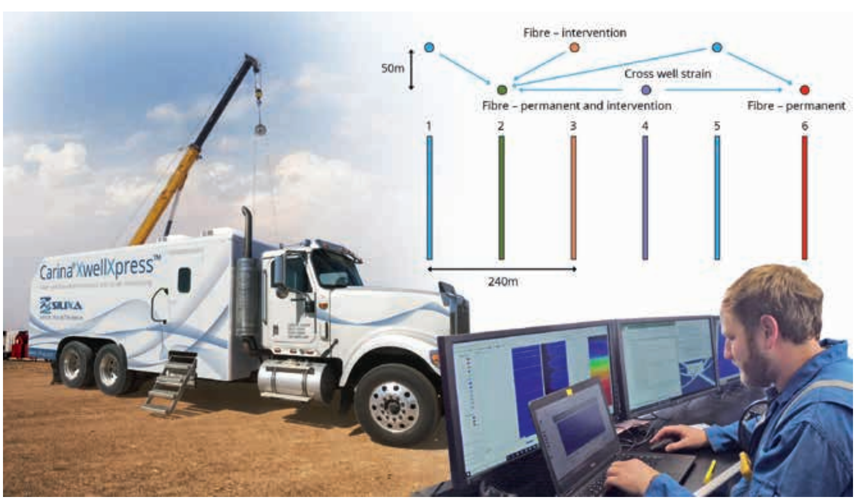

Figure 4 Multiple well monitoring using permanent and intervention engineered sensing cables. Intervention engineered fibre cable provides a new accessible dimension for crosswell monitoring.

entire wellbore can be achieved (Webster et al., 2013). However, the requirements for the cable orientation and directional perforation adds additional complexity and costs for the installation of the fibre and, therefore, limits the number of wells that can be instrumented with fibre and monitored simultaneously.

We present here an advanced Distributed Acoustic Sensor system (referred to here as Carina) that utilizes a new generation of engineered optical fibres (Constellation) with 100x (20 dB) improved sensitivity compared to that of standard fibres.

In addition, we have developed a retrievable wireline cable with engineered fibre that can be economically deployed for crosswell strain identification on frac hits, microseismic monitoring, and time-lapse Vertical Seismic Profiling (VSP) acquisition with unprecedented data quality. The wireline data can be combined with data from permanently installed fibres to provide a wide volume coverage for fracture monitoring and completion diagnostics as indicated on Figure 2.

High-resolution DAS with engineered fibre

The existing DAS systems utilize standard single mode fibre (Parker et al., 2014). However, a transformative improvement in the measurement sensitivity has been achieved by advancing the state of the DAS optoelectronics interrogator architecture, together with the introduction of next generation engineered fibre. This fibre is engineered with brighter backscatter along its length to capture and reflect more light back to the interrogator, as indicated in Figure 3. This is achieved without introducing significant loss to the forward propagating laser pulses.

The noise of DAS with engineered fibre is 100x (20 dB) lower compared to that when using standard fibre. In addition, the DAS performance is comparable to that of geophones around 10 Hz, but can far exceed the response of geophones in the range below 1 Hz. The highly sensitive low-frequency strain measurement provides valuable data for monitoring the crosswell poroelastic build-up within the reservoir and the detection of frac hits in the offset well.

The high sensitivity and wide dynamic range of the engineered fibre with its broadband and wide-aperture response can provide unprecedented data quality for both the permanently installed and intervention cables for fracture monitoring and completion diagnostics in multiple wells.

Fibre field deployment

Figure 4 shows an example of a fibre field deployment set-up in unconventional multiple wells. Two of the wells were installed with a permanent engineered fibre cable cemented behind the casing. However, it was recognized that acquiring addition data between the wells can be valuable in understanding the crosswell interference. This was achieved through the use of a new engineered intervention wireline cable pumped down in to an already completed well. The wireline cable also has a mono-conductor for being tractored downhole.

With the introduction of the wireline intervention cable, we have added flexibility in designing our monitoring programme. By utilizing a retrievable cable, we can now eliminate drilling risks and reduce the overall cost.

The high-quality data recorded both on the permanent and intervention cables can be fed into the completion design in near real time in order to optimize the operations on the current well pad and for future development plans.

Crosswell strain monitoring and frac hits characterization

The crosswell strain data, shown in Figure 5, was acquired on the wireline intervention cable utilizing the engineered fibre provides 100x (20 dB) higher sensitivity compared to standard fibre. As indicated, for the first time, we can easily identify critical strain effects and treatment processes including: pump start time, poroelastic effect, frac hits, pump stop time, and fracture closure in such an intervention deployment with unprecedented clarity. This new data allows completion engineers to map the depth, azimuth and speed of the fractures and feed that information back into the fracture models to validate and optimize the designs for the next operation.

To further validate the intervention response, the wireline cable was pumped down in the same well that has been instrumented with a permanent fibre behind the casing. As it can be seen in Figure 6, we can observe a strong similarity in the response of both cables.

The results indicate that there is a sufficient frictional coupling between the wireline cable and the inside wall of the casing. In addition, we can see the strain rate (in the order of tens of nano-strain per second) exerted on to the outside of the cable is transferred to the fibre inside the cable on both cases.

Distributed temperature data was also recorded along both cables with a fine resolution down to 0.01°C. The results confirmed that the low-frequency strain data are not affected by any observable temperature changes during this time interval.

Multiple frac hits can be observed following the tensional and compressional strain building up due to the poroelastic effects as the fluid is pumped into the reservoir.

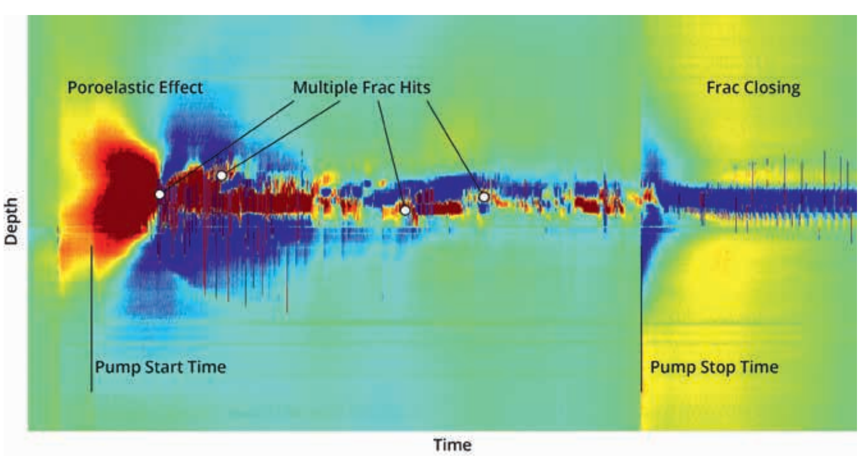

Figure 5 Colour map of the crosswell strain at depth versus time (600 m-wide over few hours).

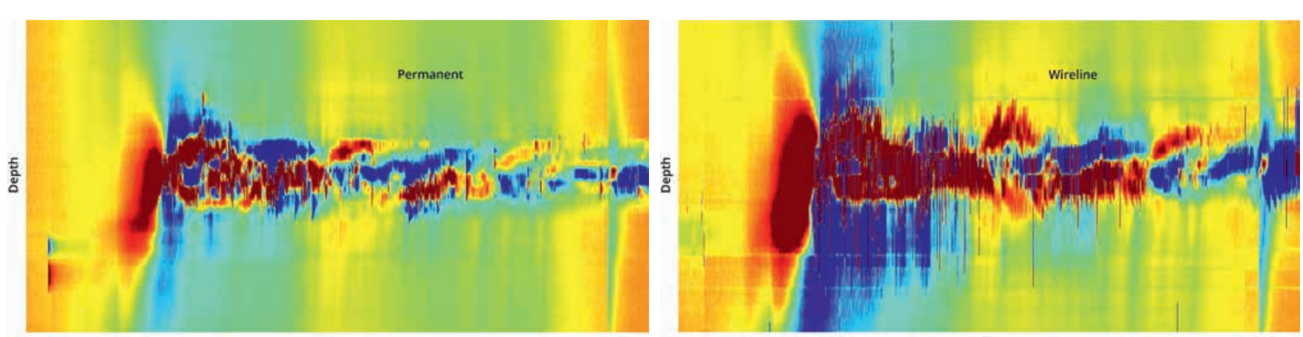

Figure 6 Low-frequency strain data on the wireline intervention cable (right) compared to the permanently installed cable cemented behind the casing in the same well (300 m-wide over a few hours).

Frac hits identification

As discussed previously, the engineered fibre deployed on wireline enabled us to acquire high quality distributed data between the wells. As shown in Figure 7, by simultaneous recording along three cables, each in a different well, we were able to map the fracture azimuth propagation through the formation and as passing through each fibre location. For illustrative purposes, an example of a fracture half-length is also displayed (Viegas et al., 2018). We can see that the wells closer to the frac well have a higher intensity of strain events and the farthest well does not actually experience a frac hit.

Figure 8 shows the dashboard of interactive software where the strain data was processed and the frac hits were identified in real time at the wellsite, including the direction and the magnitude, and the information was immediately fed back interactively into the completion designs plan.

Microseismic

The objective in hydraulic fracture monitoring (HFM) is to map the treated volume's height, length, width and azimuth. We assume this volume is closely approximated by a microseismic cloud of event locations or hypocentres. Until recently, only geophones had sufficient signal-to-noise quality to detect and locate a sufficient number of event hypocentres to map the fracture. Due to recent advances in optical fibre engineering a single fibre can collect data comparable to more than 5000 Z-component geophones.

If only one monitor well is available, only the origin time, measured depth and distance from the fibre, can be determined for each event. Plotting event time and measured depth on a strain waterfall shows strong correlation between strain and microseismicity, enhancing support for both. While an array in a single horizontal or vertical monitor well is not able to fully locate microearthquakes, two or more such arrays certainly can. Colocation finds the hypocentre which best fits arrival times at all monitor wells simultaneously. Therefore, colocation by two or more monitor wells is highly recommended.

Downhole geophones are three-component instruments, measuring ground motion in X, Y and Z directions. This polarization helps to constrain the source direction but is more difficult to

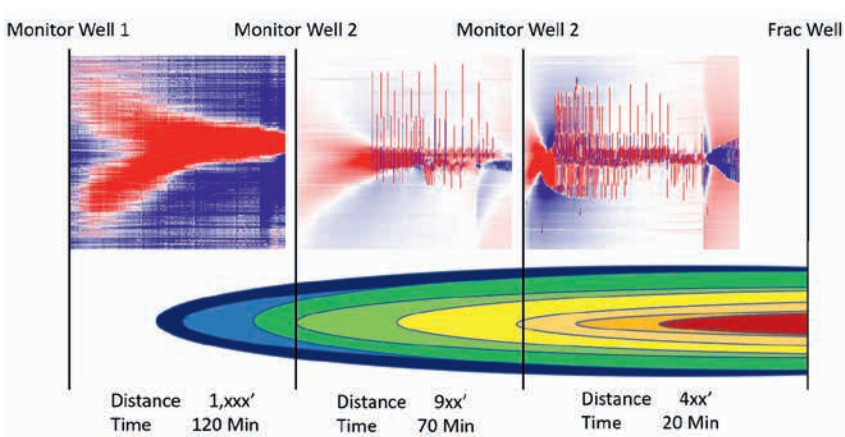

Figure 7 Monitoring the poroelastic effect and frac hits passing through three fibre locations.

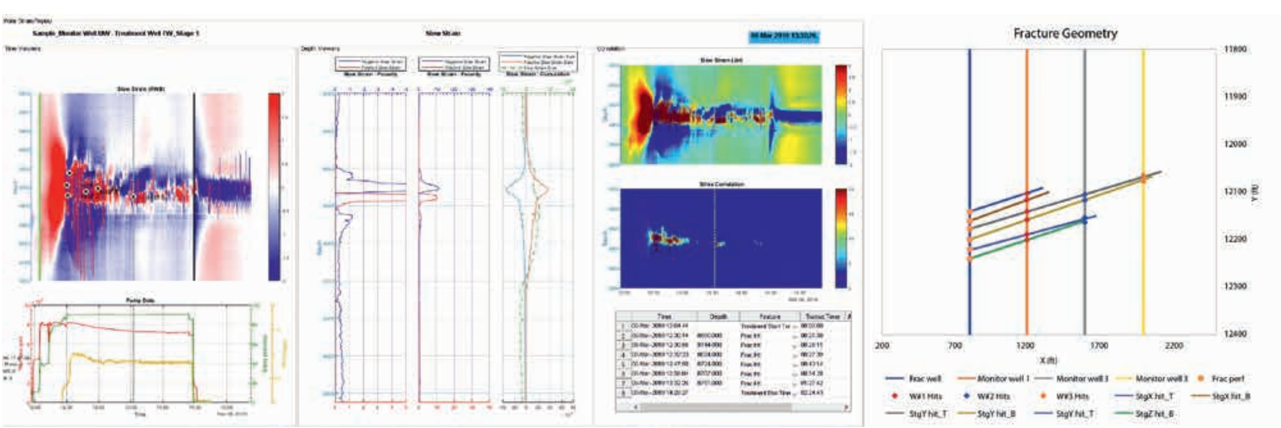

Figure 8 Dashboard of interactive software for strain data processing and identifying the frac hits in real time.

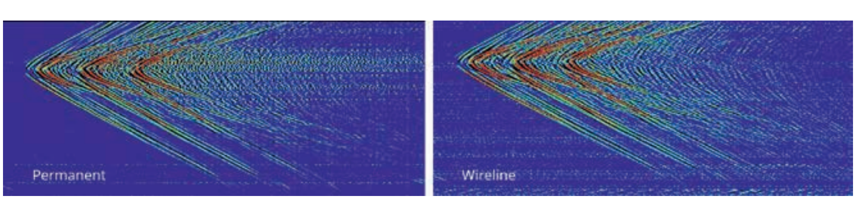

Figure 9 Comparison of the field microseismic event detection on the permanent and wireline engineered fibre.

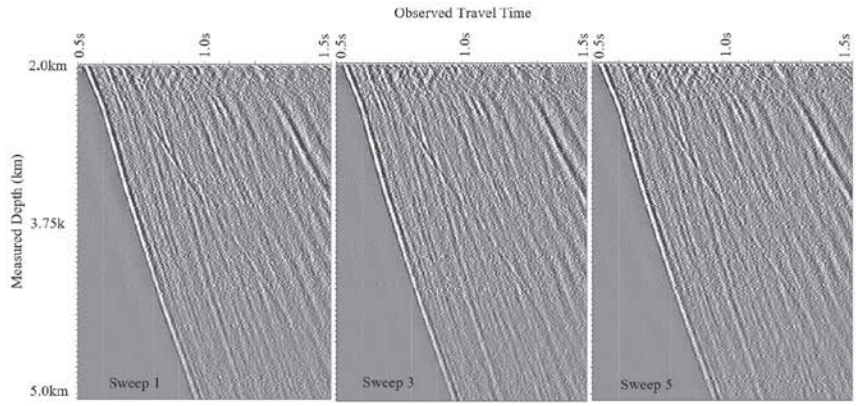

Figure 10 Raw VSP sweeps using intervention cable in a high deviated well.

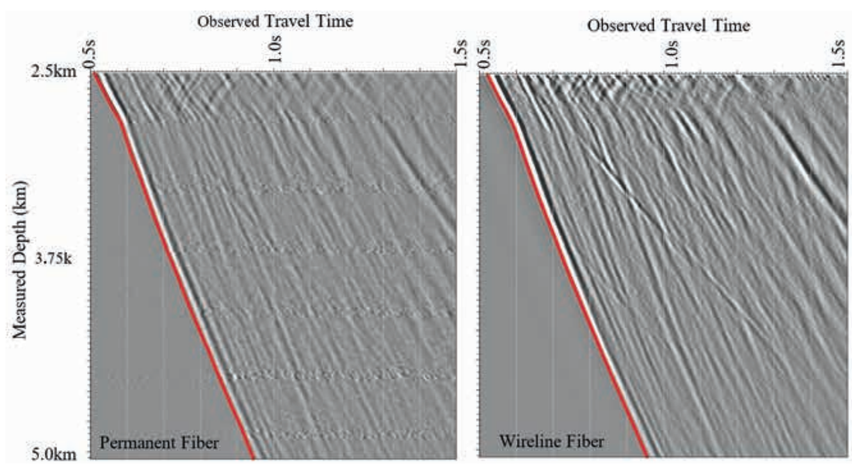

Figure 11 Permanent installed fibre (left)l vs Wireline Intervention cable fibre (right) VSP acquired during the same stage with the same source location.

measure and predict than simple arrival times. Refraction at stratigraphic boundaries and SH and SV shear wave interference complicate this problem. A fibre optic array in two or more wells requires only arrival times for hypocentre determination, negating the need for polarization modelling and measurements.

The initial impetus for live hydraulic fracture mapping was to enable modification of the treatment on the fly. For example, stopping a stage that is growing into a water-bearing zone or continuing a frac that had not achieved its desired length. Such incidents have indeed happened, but more commonly the value of live HFM is simply quality control. The operator can be assured that good valid fracture diagnostics are being recorded for each stage. Today critical fracture parameters, such as clusters per stage and cluster and stage spacing, can be tested and optimized for later stages of the same job.

Experience with geophones shows that data quality is dependent on the degree of coupling between the phones and the surrounding rock. Magnets, bow springs, and even strong locking arms do not provide ideal coupling because of the high mass of the recording tool and the very limited area of contact with the casing, typically only three points.

An engineered fibre laid inside a typical horizontal well contacts the casing over 5 km or more and is much lighter per metre of well than a downhole geophone recording tool. Direct comparisons have shown that this coupling enables data quality as good as fibre permanently installed in the cement outside the casing.

Both P and S arrivals from a microsesimic event can be seen over the entire cable length as shown in Figure 9. With the sensitivity of the measurement, we can see events in the vertical section as well as the horizontal, allowing for better location by taking in to account the wellbore trajectory.

It is worth noting that fibre optic HFM has:

- No moving parts to wear out,
- No downhole electronics to fail (particularly in high temperatures),
- It can be pumped down thanks to the low weight, and
- No polarization processing required.

Time-lapse Vertical Seismic Profiling (VSP)

An important aspect of time-lapse VSP is the effort to characterize the changes in the reservoir. In this case we recorded changes during frac activities, with VSP data acquired after each frac stage during the course of the project. Using this technology, the effectiveness of the frac design and ultimately the return on investment for the pad, can be continuously improved.

The increased signal-to-noise ratio allows the acquisition of fewer sweeps, therefore an increase in data quality that improves VSP datasets repeatability. Figure 10 shows raw sweeps from intervention wireline cable. The recent improvements in DAS measurements utilizing the engineered fibre means that we can collect high-quality VSP data in between stages without interfering with the overall operations.

Figure 11 shows a comparison of the same stage measured with permanent cable vs. intervention wireline cable. In addition, high-quality microseismic events can be correlated with 4D-VSP effects to help understand fracture complexity.

By having the improved sensitivity and broader bandwidth of the new engineered DAS system, we can now easily measure the changes at the reservoir before and after stages on the neighbouring wells to understand fracture half lengths and frac hits on a well (Byerley et al., 2018). This is achieved with a large antenna that could cover the entire well with few vibroseis sweeps. In addition, we can measure accurately time-depth pairs and velocities along the borehole and changes in velocity due to fracking activity. The ability of having multiple cables on a project allows for better understanding of dynamic changes in the reservoir.

Conclusion

The next generation of DAS system utilizing the engineered fibre offers 100x improvement in sensitivity compared to standard fibre and provides unprecedent data quality both on permanent and wireline intervention cables.

The intervention wireline cable can be economically deployed for crosswell strain identification on frac hits, microseismic monitoring, and time-lapse Vertical Seismic Profiling (VSP) acquisition. The wireline data can be combined with the permanently installed fibres to provide a wide volume coverage for fracture monitoring and completion diagnostics.

Much of the data is real-time or near real-time so that the combined data sets can be used within the completion workflow to better understand the key operational decisions with a high level of confidence.

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