Hydraulic frac-hit corridor (FHC) monitoring and analysis with high-resolution distributed acoustic sensing (DAS) and far-field strain (FFS) measurements

Y. Wu[1]*, P. Richter[1], R. Hull[1] and M. Farhadiroushan[1] utilize advanced high-resolution distributed fibre-optic sensing technologies on both simulated wells as well offset wells to understand the near wellbore geomechanics and the far-field effects of the simulation on the offset wells.

Introduction

Distributed fibre-optic sensing (DFOS) has been utilized in unconventional reservoirs for hydraulic fracture characterization for years. Typically, we install a permanent fibre external to the wellbore casing to understand the uniformity and efficiency of individual clusters and stages during the completion process. Such a fibre records the acoustic, thermal and strain effects along the stimulated well but the fibre can also be used to record the far field deformation effects of adjacent stimulations and can be utilized in a similar way to a string of single component hydrophones to record microseismic activity (Hull et al., 2017). The high broadband response of the high resolution DAS can be utilized to understand the low-frequency strain that is co-occurring along with the geophysical (microseismic) events during the deformation processes and high-resolution distributed temperature sensor (DTS) can be utilized to measure thermal effects due to hydraulic fluid contact. The DAS fibre-optic system can record up to 25 kHz to sub-hertz signals at thousands of points along the fibre. The low-frequency band from around 1 Hz and below is interpreted as a strain measurement. These low frequencies allow us to clearly identify and examine fracture opening and closing, stress shadow creation and relaxation, as well as mechanical isolation between stages (Jin et al., 2017). What is relatively new over the past year are the advances in the distributed acoustic sensor (named Carina) that utilizes an engineered fibre (named Constellation) to provide 100x (20dB) improved sensitivity and can also be deployed temporarily in offset horizontal wells allowing thousands of stages far-field strain (FFS) to be recorded and analysed quickly (Richter, 2019). As operators have reduced well spacing to maximize resource recovery as well as increased the volumes that are pumped, FFS data processing and analysis has also evolved to better understand the geomechanical interactions between stages and wells.

In this paper, we introduce the Frac Hit Corridor (FHC) as a new concept that we use in our data processing and interpretation. Here the frac hit can be directly measured and picked from the crosswell strain data. From this measurement we can determine some attributes of the hydraulic fracture including far-field frac width and the fracture overlap between individual stages. The effect of stage isolation will also be examined.

As we often record, the near-wellbore fracture development with permanent fibre systems, we can incorporate the acoustical, thermal and geophysical effects of the deformation to further develop a full picture of well completions (Richter et al., 2019). Advanced analysis and statistical results are typical deliverables which can be compared to other wellbore datasets including pressure, tracer, production, and completions.

Here, we show that the far-field strain (FFS) is a direct measurement of fracture interactions, and the FHC provides a method to evaluate the hydraulic fracture. We can provide real-time deliverables to the engineering and geoscience teams to confidently optimize the frac model and completion design on the fly. While both the permanent and retrievable deployment of the fibres can provide an understanding of the fracture geometry and propagation, the retrievable deployment is more flexible for

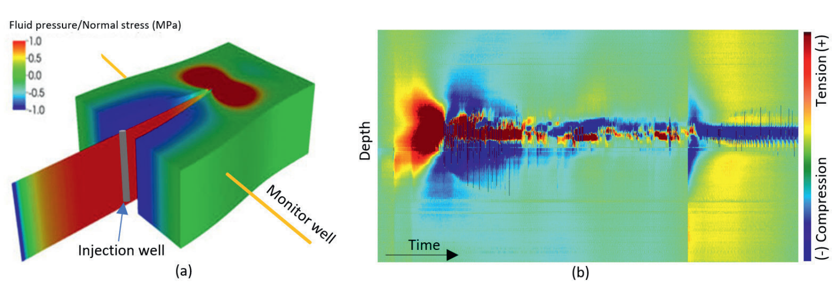

Figure 1 Far field strain (FFS) monitor model and real results: (a) single hydraulic fracture strain response modelling (modified from Settgast et al., 2017), fibre optics cable deployed in the monitor well; (b) FFS real result monitored from DAS cable deployed in the far-field monitor well: x-axis is time, y-axis measures the depth of the fibre

[1] Silixa
* Corresponding author, E-mail: yinghui.wu@silixa.com
DOI: 10.3997/1365-2397.fb2020045

operations planning and is a lower cost solution to the current permanent installation methods.

Far-field strain (FFS) monitoring basics

Distributed acoustic sensing (DAS) and distributed temperature (DTS) can be utilized to understand three key hydraulic fracture regions, which include the wellbore, near-wellbore, and far-field regions (Ugueto et al., 2019). Ugueto summarizes the most used direct and indirect diagnostic tools for each region. Here we discuss the far-field strain response often recorded 200 m or more away from the hydraulically stimulated well.

Figure 1 (a) describes the linear elastic response of a single hydraulic fracture model through a solid material as run using the GEOS program (Settgast et al., 2017). The colour of the solid elements represents the material stress normal to the fracture, where compression is negative (blue colour), and tension is positive and highlighted in red. Significant tension is generated in front of the fracture tip as the fracture propagates and compression occurs along the sides of the fracture as the hydraulic fracture opens.

Figure 1 (b) is a typical far-field strain (FFS) plot monitored from DAS cable deployed in far-field region well as shown in Figure 1 (a), the colour bar is the strain intensity alone the fibre cable – blue and red indicate compression ('-' as closure) and tension ('+' as opening) respectively. Here the X axis is time, Y axis is measured depth along the fibre. As the pumping starts, fracture initiation occurs. As the frac tip approaches the monitor well early in time, the characteristic yellow-red tension of the fracture tip is observed. As the fracture tip passes the monitor well we can see either the compression of the fracture near by or as the fracture starts to open with tension applied on the cable, compression can be observed above and below. As the fracture development occurs around the monitor offset well, we can see a good example of the compression-tension-compression feature or blue-red-blue of the fracture generation through time as the fracture interacts with the fibre. It is important to note we can also see the fracture change in its polarity (tension flipping to compression) when pumping stops, which is interpreted as fracture closure. In summary, the FFS is direct measurement of frac hit or interaction along the monitor well, from the time of the pump start till the next stage.

Deployment and installation

Figure 2 (a) shows an example of field deployment set-up in multiple unconventional horizontal wells. Two of the wells here have a permanent fibre cable cemented behind the casing (c) and two of the offset wells contain the retrievable fibre optic wireline cables as shown on Figure 2 (b). Permanent fibre is often used for understanding the near well bore effects of the completion, how much fluid is exiting the well through each cluster (frac allocation/cluster efficiency), as well as can be also used for offset well completions monitoring. With the retrievable fibre we can monitor offset wells' frac operation and far-field deformation, which will be discussed later in this paper. The retrievable fibre offers a very sensitive method for recording offset well interactions and provides further flexibility to the operations. The retrievable fibre optic wireline cable can be pumped down or tractored in a well ready for completion or tractored in a well that has already been completed. A tractor can be used as the fibre optic wireline cable that also has a standard mono-conductor that powers the tractor downhole.

Multiple monitor wells provide options to characterize the frac interactions from different zones and between well spacings as well as to co-locate microseismic events. As for the data quality, studies show similar responses are recorded for the fibre optic cable deployed inside the casing compared to the cable permanently cemented behind the casing (Richter et al., 2019).

Frac hit picking

The far-field strain frac-hit compression-tension-compression or blue-red-blue features can be monitored in real-time during the pumping. Figure 3 shows the interactive software dashboard of strain data as the frac hits are identified. The top-left dashboard uses a blue-red colour to identify the compression-tension feature. The middle part of the display shows the frac hit which is easily identified or 'picked' by the engineer. This platform can identify critical strain effects and treatment processes including the poroelastic stress effect, frac hits depth and time, pump stop time, time of the closure of the fracture, and the zone of open fractures here called the frac hit corridor (FHC).

FHC is the fairway of the major fracture development. In Figure 3, the light-blue rectangular dots on the left panel are used to define the corridor top and bottom. The middle panel highlights the strain traces for a time about halfway into the stage and shows the strain dropped sharply. Further, here we can interpret where along the fibre the tension goes to neutral and we can interpret the bottom of FHC. We can interpret the FHC both during pumping as well as at closure after pumping has stopped. Normally, the FHC recorded during pumping is wider than the closure FHC as some open fractures might close off during pumping. The closure FHC measurement represents when the fracture closed off abruptly after the pumping stopped. In order to analyse fracture propagation during pumping, we will use the open FHC for processing and analysis in this paper.

Multiple frac hits can be identified reviewing the compression-tension-compression feature. Here we can see as the stress builds up, there are multiple and often adjacent fractures

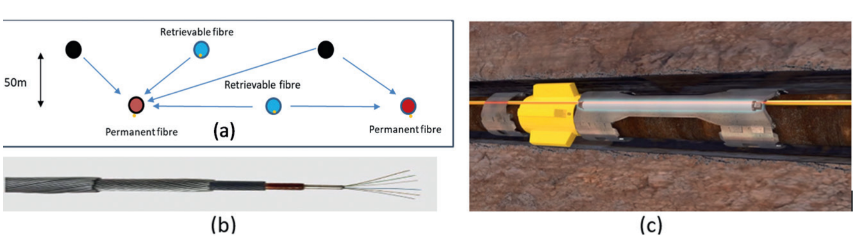

Figure 2 Multiple well monitoring using permanent and retrievable deployments. (a) gun barrel view, small orange circles present deployed fibre outside casing for permanent installation, inside casing for retrievable fibre interventions; (b) is a typical retrievable wireline fibre cable with six different fibres including two single mode, two multimode, and two engineered constellation fibres (refer to P. Richter et al. 2019); (c) example of a permanent installation, orange fibre cable installed outside of casing later cemented in place.

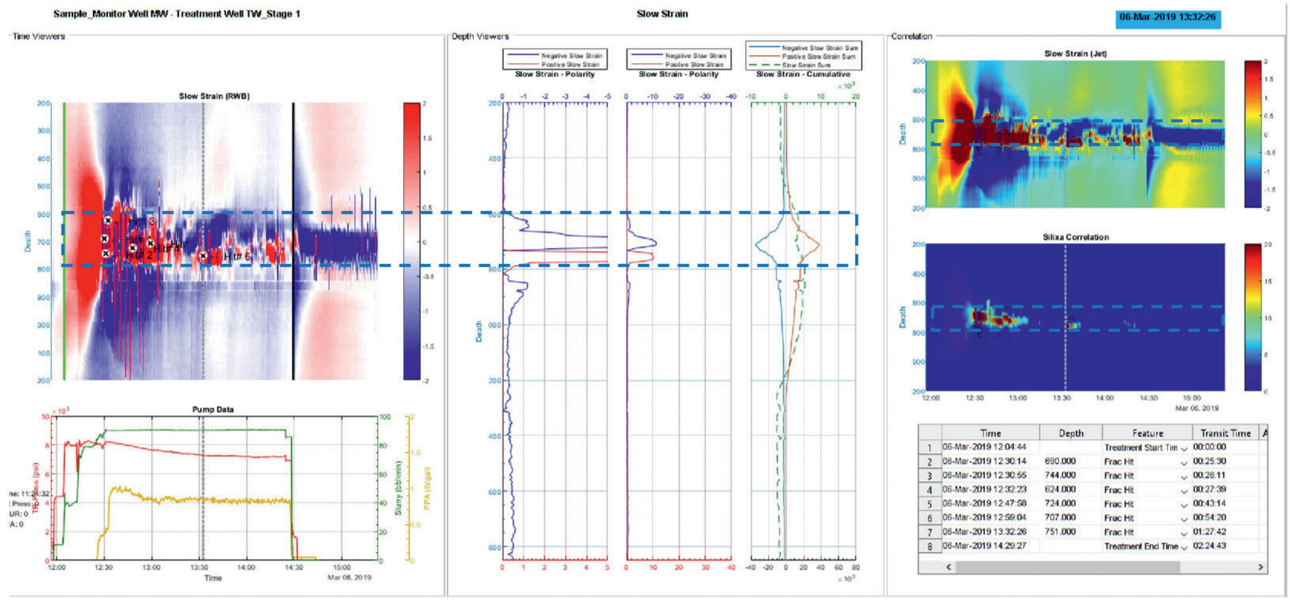

Figure 3 Dashboard of interactive software for FFS data processing, frac hits and frac hit corridor (FHC) picking. Left top: strain data coloured by red-blue scale presents tension-compression; Left bottom: pumping data; Centre: strain curves red=tension, blue=compression; Right top/middle: strain heat map; Right bottom: frac hits picking data.

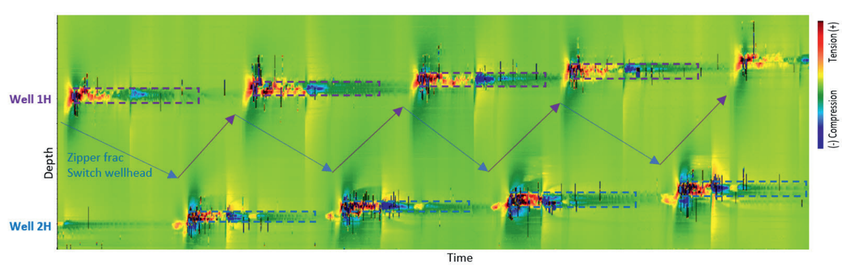

Figure 4 Multi-stage 24 hours zipper frac FFS plot. Well 1H and 2H were zipper fracked; frac hit corridor (FHC) presented by dot line rectangle. Monitor well 3H parallel to treatment well 1H and 2H.

interacting with the offset fibre well. Distributed temperature data was also recorded along fibre cables, which confirmed that the low-frequency strain data was not affected by any observable temperature changes during this time interval.

These types of data and their interpretation allows the completion engineers and geoscientists to map the fracture width, depth, azimuth, and speed of the development of the hydraulic fractures and feed that information back into the fracture models to validate and optimize the designs for the next operation. As this can be done in real-time at the wellsite, including the direction and the magnitude of the interaction as well as the relationships to pump volumes, the operator can optimize the completion designs for the specific well spacing.

Far-field frac hit corridor (FHC) analysis

FHC can be interpreted as far-field frac width, as it is directly measured. The far-field data also allows us to examine the amount of overlap between stages on the offset well. Here we can look at the relationships of multiple stages.

Figure 4 is a strain plot from a zipper frac operation. Well 1H and 2H are both horizontal wells parallel to the monitor well as the two wells were 'zipper' fracked, both frac wells hit the monitor well as shown. In the plot the X-axis is time, Y-axis is depth, and the top of the display is heel ward. The 1H first hits the monitor well at the heel side, then 2H hits the toe side, and so on. Arrows identified the 'zipper frac' when pump switched wellheads. In the eight picked stages, 1H FHC width were relatively consistent compared to 2H. These frac strain effects can be correlated to the completion design (stage spacing, perforation design, etc.) to help understand uniformity of the completion as measured away from the stimulated well.

FHC stage overlap can be utilized for far-field stage isolation analysis, overlap can be simply interpreted as adjacent stages that stimulated the same rock within the same formation. FHC gap means there were some stages that may not have reached as far as the monitor well in the far-field region and left some rock unstimulated. Figure 5 presents multi-stage frac overlap vs. gap analysis for different completions schedules: X cluster vs. Y cluster, with diverter vs. no diverter. Figure 5 (a) presents FHC width at Y-axis of Measured Depth (MD), as each stage top and base are measured, overlap index calculated by difference between the current stage base and previous stage top:

$$O_i = C_i^b - C_{i-1}^t$$

O_i is current stage overlap length, C_i^b is the current stage corridor bottom MD, C_{i-1}^t is previous stage corridor top MD. Only adjected stages overlap indexer can be calculated, if $O_i > 0$, there is overlap between two stages; if $O_i < 0$ there is a gap between two stages suggested. In Figure 5 (b), for example, stage 19 was overlapping stage 18, as we had near-wellbore DTS data on this job, we could confirm the overlap was related to a leaking plug.

Based on previous discussion of both near-wellbore and far-field monitoring, a 3D model can be built combining the permanent cluster allocation and retrievable FFS results. Here we can examine the orientation of the frac hit corridor as generated from the well undergoing the completion. (Figure 6). The velocity of the propagation through the interwell space as well as the frac hit intensity can be calculated for further analysis.

Near-well fracture monitoring

DAS can also of course be utilized to understand the more traditional near-well effects of the hydraulic stimulation along the well. Here we are typically monitoring the energy across the perfs within a few tens of centimetres of the well. As the fibre is located outside of the well its orientation needs to be located and the perforation gun needs to be oriented in order to avoid damaging fibre. These permanently acquired fibre data can be used to visualize and understand important downhole parameters such as active perforations, flow rate, etc. (Jayaram et al., 2019). The DAS and 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 fluid and proppant allocations per cluster as indicated in Figure 7. DTS temperature recorded during and after the stimulation provides a window into understanding the treatment effects such as leaking plug or poor stage isolation. DAS energy and DTS can be utilized to understand the amount of fluid movement through the perforation clusters.

Figure 7 presents permanent DAS and DTS monitoring results. On the left is single stage frac monitor results recorded through time: top left (a) is an acoustic RMS energy plot, with more red indicative of higher energy observed at each cluster; middle left (b) is DTS results, red means high temperature, blue means cool fluid moving through the fibre; bottom left (c) is pump curve, red=pressure, green=slurry rate, yellow=proppant concentration. Middle top (d) is a single stage fluid allocation; middle bottom (e) is the allocation between current active stage vs. the previous passive stage; there was no noticeable communication between two stages on the DAS. (f) on the very right is a multiple stage DTS result, red=hot blue=cold, stage isolation can be easily identified: stage A, C shows good isolation at plugs, while stage B and D shows clear pumping communication with the previous stage. It is interpreted that for stages B and D there is some loss of fluid into the prior stage either through or around the plug or external to the casing.

Integrated analysis

It is important to have the far-field data be integrated with the near-wellbore data as displayed above. This data integration allows us to map the near wellbore origin of the fracture, the fracture propagation from perforations to offset the monitor well, as well as the geometries and dynamics of the inter well space.

The high-resolution DFOS in the far-field monitor well can provide full lateral coverage a with high sensitivity that can also be combined with the near field data in the treatment well. By using both the near and far field DAS data, we can gain a 3D understanding of the fracture mechanics to calibrate our models. Tied in with other associated measurements such as pressure sensors, microseismic, tilt meters, or tracers we can further enhance our understanding of fracture mechanics and optimize the completions. As the industry continues to look for cost-effective ways in a low-price oil environment to provide mission critical data on completions and their optimization, we can leverage some of our learnings from both near and far field data. It is also possible to apply our learnings to evaluate frac efficiency mainly using the far-field measurements in offset wells by rapid deployment of retrievable fibre optic sensing cables. This can also provide a more cost-effective solution compared to current permanent installation methods (Richter et al., 2019).

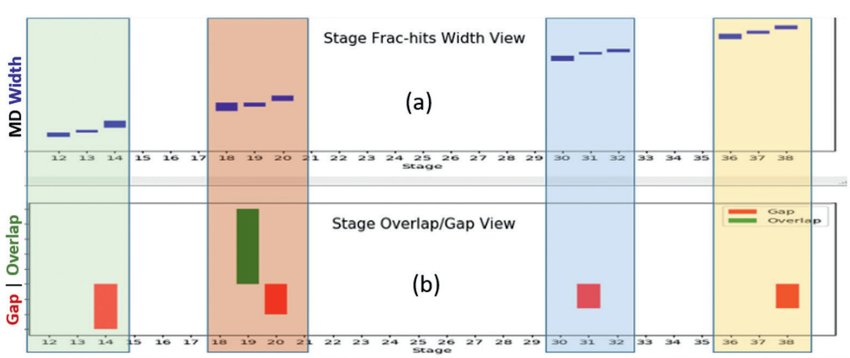

Figure 5 FHC overlap/gap analysis for multi-stage frac. (a) presents corridor width on Y-axis; X-axis is stage number; (b) presents stage overlap or gap between its previous adjacent stage; red is gap, green is overlap.

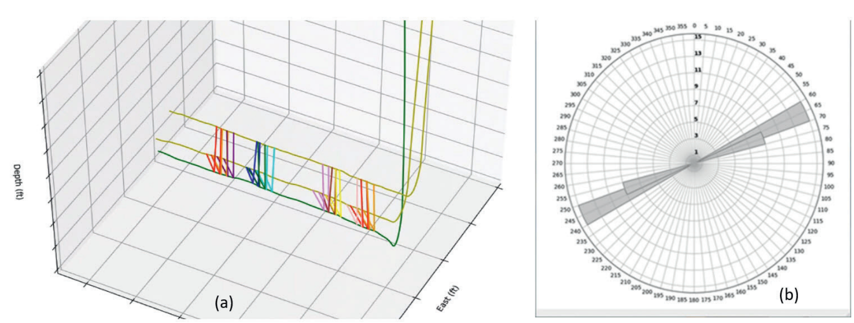

Figure 6 3D model and statistical analysis; two monitor wells deployed with DFOS. (a) 3D view: green = treatment well, yellow = monitor wells, FHC coloured by stage. (b) Rose diagram view of FHC azimuth.

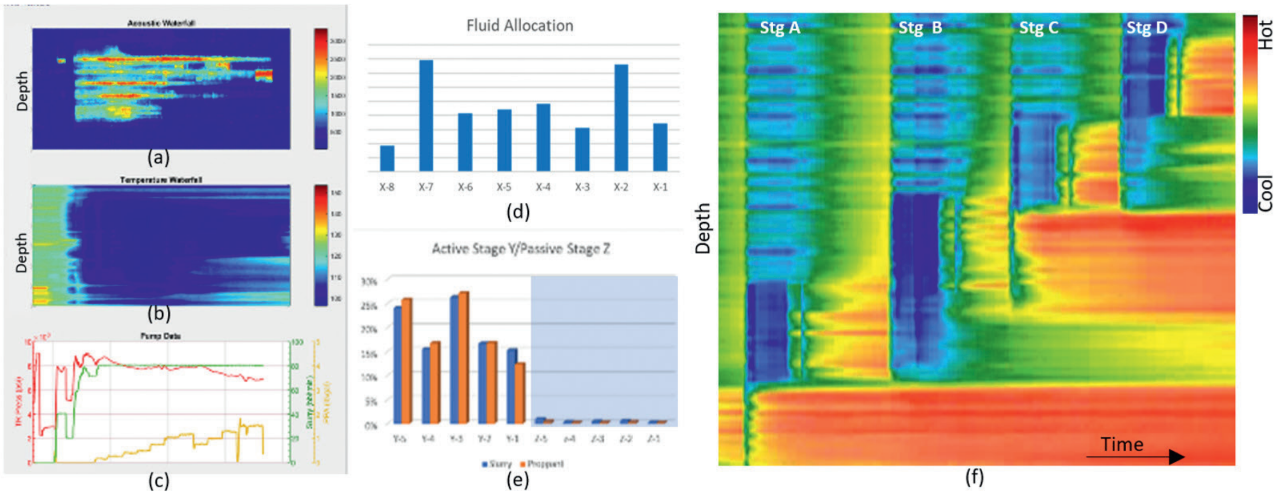

Figure 7 Hydraulic frac monitoring results from permanently installed fibre cable. It presents single stage DAS RMS energy (a), DTS temperature (b), pump data (d), fluid allocation by perforation cluster (d); (e) presents two stages with good isolation identified by cluster allocation; (f) shows multiple stages of the DTS result showing good isolation at stage A, C, and bad isolation at stage B, D.

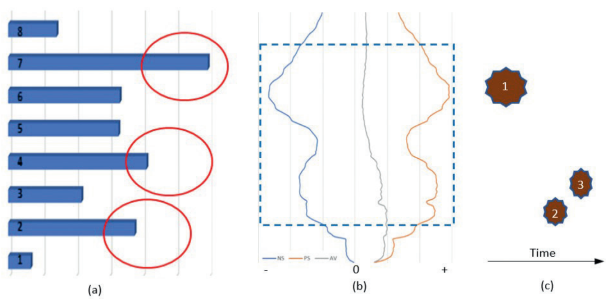

Figure 8 Correlation between near-well and far-field. (a) near-well cluster activity by DAS acoustic allocation, x = energy, y = cluster; (b) cumulative FFS, x = strain intensity, right means tension (orange), left means compression (blue), grey = average strain, blue dot rectangle presents frac hit corridor (FHC); (c) picked frac-hits, x = time, y = MD, the number in the star is sequence of hit, start size presents hit intensity.

Figure 8 presents a single-stage DFOS data correlation between near-wellbore and far-field: (a) near-wellbore permanently installed DAS allocation by cluster. Three major active clusters are identified by red circles; (b) the far-field cumulative strain is the total strain observed at the monitor well, correlated to the three major clusters propagation. The picked frac hit corridor (FHC) is the blue dot rectangle identifying major fractures at the monitor well; (c) frac hits picked based on a method introduced previously in this paper (Figure 3), the first hit arrived with the largest intensity correlated to cluster #7, the second hit correlated to cluster #2 shown in (a) with less allocation comparing to cluster #4, which was correlated to the third hit, but cluster #2 arrived earlier than cluster #4. With this approach, combined frac fairway FHC cluster efficiency can be understood based on FFS.

Advanced analysis can be integrated with the statistical results and related measurements e.g. downhole gauges, perf erosion images, tracer, flowback monitoring, etc. Beyond modelling and comparing the near wellbore DTS and DAS, the microseismic data can also be integrated into these data. This combination and calibration can help with understanding preacquired microseismic data sets, analysis methods such as r-t plot, b-value, focal mechanisms can also be introduced for conductivity analysis (Wu et al., 2016). Most importantly, the microseismic detection range can be over 100 ft (305 m), geological information can be tied in, engineering data can also be further defined by key relationships between fluid, pressure, and acoustic activity within a stimulation stage. With this application, more data sets can be integrated to microseismic analysis, which was extensively used to image hydraulic fracture growth in unconventional reservoirs and applied to proof and optimize frac designs and a field development plan for years.

Conclusions

Far-field strain (FFS) is a direct measurement on frac interactions. Fracture opening and closing can be identified by red-blue features, and frac-hits can be picked at high resolution in depth and time. FFS can be correlated to near-wellbore fractures monitored by permanent fibre. Both permanent and retrievable deployment give full understanding on fracture geometry and propagation. FHC provides a method to evaluate hydraulic fracture efficiency. Real-time deliverables provide the geoscientist and completion engineer with the confidence to optimize the frac models and design in real-time. Retrievable deployment of fibre is more flexible for the operations planning. Multiple deployment of retrievable fibre can improve coverage and data qualities at a low cost compared to a permanent installation.

Acknowledgements

We would like to thank all our operators and collaborators for sharing their experiences with us, their contributions as well as their permission for the use of those data. We would like to thank our colleagues for their dedicated work and contributions, for their expertise in developing and implementing these engineered fibre optic tools and systems.

References

Hull, R., R. Meek, H. Bello, D. Miller. [2017]. Exploration of Case Histories of DAS Fiber-Based Microseismic and Strain Data, Monitoring Horizontal Hydraulic Stimulations Using Various Tools to Highlight Physical Deformation Processes (Part A). *Unconventional Resources Technology Conference (URTeC)*, Abstracts.

Jayaram, V., Hull, R., Wagner, J. and Zhang, S. [2019]. Hydraulic Fracturing Stimulation Monitoring with Distributed Fiber Optic Sensing and Microseismic in the Permian Wolfcamp Shale Play. *Unconventional Resources Technology Conference (URTeC),* Abstracts, Doi: 10.15530/urtec-2019-291.

Jin, G. and Roy, B. [2017]. Hydraulic-fracture geometry characterization using low-frequency DAS signal. *The Leading Edge*, **975**, 975-980.

Johannessen, K., Drakeley, B.K. and Farhadiroushan, M. [2012]. Distributed Acoustic Sensing – A New Way of Listening to Your Well/Reservoir. *SPE Intelligent Energy International*, SPE-149602-MS.

Parker, T. [2014]. Distributed Acoustic Sensing – a new tool for seismic applications. *First Break*, **32**, 61-69.

Richter, P. [2019]. High-resolution DAS In Frac Design. *Hart Energy*.

Richter, P., Parker, P., Woerpel, C., Wu, Y., Rufino, R. and Farhadiroushan, M. [2019]. Hydraulic fracture monitoring and optimization in unconventional completions using a high-resolution engineered fibre-optic Distributed Acoustic Sensor. *First Break*, **37** (4), 63-68.

Settgast, R., Fu, P., Walsh, S., White, J.A., Annavarapu, C. and Ryerson, F. [2017]. A fully coupled method for massively parallel simulation of hydraulically driven fractures in 3-dimensions. *International Journal for Numerical and Analytical Methds in Geomechanics*, **41**, 627–653.

Shuang Zhang, Pioneer Natural Resources; Hewei Tang, Rice University; Robert Hurt, Vikram Jayaram, and Jed Wagner,

Shuang, Z. Tang, H., Hurt, R., Jayaram, V. and Wagner, J. [2020]. Joint Interpretation of Fiber Optics and Downhole Gauge Data for Near Wellbore Region Characterization*. SPE Hydraulic Fracturing Technology Conference and Exhibition,* SPE-199715-MS.

Ugueto, G., Huckabee, P., Wojtaszek, M., Daredia, T. and Reynolds, A. [2019]. New Near-Wellbore Insights from FiberOptics and Downhole Pressure Gauge Data*. SPE Hydraulic Fracturing Technology Conference and Exhibition*, SPE-194371-MS.

Wu, Y.H., Zhao, X.P., Zinno, R.J., Wu, H.Y., Vaidya, V.P., Yang, M. and Qin, J.S. [2016]. The Application of Microseismic Monitoring in Unconventional Reservoirs. In: Zee Ma, Y. and Holditch, S.A. (Eds.) *Unconventional Oil and Gas Resources Handbook*, 243-287, Elsevier, The Netherlands.