Introduction

Recent research has shown that distributed acoustic sensing (DAS) data is effective for monitoring hydraulic fracture operations. In particular, the low-frequency components (< 0.5 Hz) of DAS data have the potential to constrain the position and time of fracture hits occurring near a fiber optic cable deployed in an offsetting well (e.g. Ichikawa et al., 2019; Ugueto et al., 2019). In addition, as DAS observes responses proportional to the strain or strain rate, low-frequency DAS (LF-DAS) data might indicate the effect of “stress shadow” and “relaxation” along the fiber (Jin et al., 2017). To understand the meaning of these responses and improve the accuracy of data analysis, it is important to compare with other observation results including distributed temperature sensing (DTS) and microseismic.

In this study, we used passive DAS data and DTS data acquired in the Montney tight gas area and applied data processing to detect hydraulic fracturing related responses in an offsetting well. Firstly, we focused on the LF-DAS data and created strain rate and cumulative strain maps for detecting certain types of responses related to fracture hits on the fiber. We also clarified the overlapping effects of previous stages, such as fracture connections, using a multi-stage map. Secondly, we performed an integrated analysis using DTS and high-frequency DAS (HF-DAS) data. We compared LF-DAS and DTS data to understand the high amplitude response observed in the strain rate map. We also used the HF-DAS map to evaluate the possibility of identifying the estimated fracture hit time more precisely. Through these studies, we show the effectiveness of LF-DAS data analysis for monitoring hydraulic fractures.

Data acquisition overview

The fracturing operation in this study was performed in 2017. Fiber optic cables were permanently installed behind casing through the entire lateral length (3000 m) of a horizontal observation well. Figure 1 shows the position of study wells A, B, C, and D with a well spacing of 200 m. Two cables were installed in well C, one for DAS and the other for DTS. The zipper fracturing technique was used, starting with wells A and D, and then wells B and C. This study focused on the monitoring data of well A and D, so well C had not yet been perforated at the time of this observation. Passive DAS data was recorded with 4 kHz sampling at 1.02 m intervals during the entire fracturing operation. DAS measures responses proportional to the strain rate observed at each point along the horizontal observation well. DTS data was recorded at 1.01 m intervals. Due to the observation devices, the sampling interval was about 30 seconds but there were some variations of several seconds.

**Figure 1** The position of operation and observation wells. Grid size is 500m x 500m.

LF DAS data analysis method and results

The recorded DAS data was filtered to extract the low frequency band. For each stage, the data was extracted with a start time set at 20 minutes before the start of fracking, then down-sampled from 4 kHz to 1 Hz using an anti-aliasing filter (0-0.5 Hz). A median filter and a DC removal filter were applied for noise attenuation. A strain rate map was then made from this filtered data. The strain rate
data was integrated in time to create a cumulative strain map. In this study, the zero strain point was set at the data start time.

Figure 2 demonstrates the LF-DAS data analysis results. Figure 2(a) shows the strain rate map and Figure 2(b) shows the cumulative strain map with injection pump rate curve. The vertical axis is the channel number, showing a 1000 m section of the DAS data parallel to the offsetting fracture stage location. The completion design includes 5 clusters per stage with 25 m cluster intervals. The fracture order was from the toe to heel, and the images show the toe direction at the top of the map and the heel direction at the bottom. The horizontal axis is time, ranging from 20 minutes before the stage starts to 40 minutes after the stage ends. As seen in Figure 2(a), there are two to three red lines of expanding points from 30-50 minutes after the operation start time and these points are highly correlated to the parallel projected perforation points. The amplitude is reversed immediately after the end of the operation and a similar effect can be observed in the middle of the operation when the rate was reduced temporarily. From these observations, we can be confident that the responses observed in the strain rate map are strongly related to the hydraulic fracturing operations. Figure 2(b) shows that the influences of the local amplitude changes that can be seen in Figure 2(a) are eliminated and the expanding points can be detected easily. Stars in the figure are the estimated fracture hit position and time which were identified by the points of rapidly increasing amplitude.

Figure 3 shows an example of the multi-stage cumulative strain map. In Figure 2, the estimated fracture hit position can be identified not only near the projected perforation position but also in the area parallel to the previous stage zone. This response arrived sooner after the stage start relative to others. It can be estimated from Figure 3 that this response was affected by the previous stage as the expansion responses would have continued from the previous stage time. In addition, as some expansion responses were observed in the same channel in different stages, it might indicate fracture connections from the other stage’s perforation. Through these observations, it is considered that the multi-stage map has the potential to clarify the inter-stage effect of the complex fracture propagations.

**Integrated data analysis with other observation results**

We focus on the DTS and the HF-DAS data for integrated analysis. To start the DTS integrated analysis, DTS sampling rate alignment and noise attenuation was necessary. Spline interpolation was applied to the recorded DTS data to fix the sampling interval to 30 seconds. Linear noise was detected covering the entire channel at the same time so the average temperature was calculated each time and eliminated from the data. Through this process, the data indicate perturbation from the average temperature of the imaging area. Lastly, a moving average filter was applied in the time direction for noise attenuation. Figure 4 shows DTS and LF-DAS data from the same position. This map shows the first fracturing stage so effects from previous stages are not present. As we see in the figure, compressing responses observed in the LF-DAS data and high temperature responses observed in the DTS data seem to appear in the same position and time. Jin et al. (2017) suggested that the compressing responses observed near the fracture hit position could be related to stress shadowing and our observations might support this interpretation. Feather-shaped expanding responses detected in the LF-DAS data could not be observed in DTS data; these DAS specific responses seem unlikely to reflect property changes of the rocks.

For integration of the HF-DAS data we constrained the large data set (>500 GB) to a short time window surrounding the estimated fracture hit time detected by the cumulative strain map. A band-pass filter (10-15-200-250 Hz) was applied to eliminate the low-frequency effect and detect some fracture related responses. Figure 5 shows the high-frequency data near the estimated fracture hit position and time. Figure 5(a) shows the same range of channels as Figure 2 and shows a 15 second window extracted at the point indicated by the green arrow in Figure 2(b). Figure 5(b) is a magnified view of Figure 5(a) with a traditional seismic wiggle display. The observed responses have different characteristics from the low-frequency components. For example, multiple responses can be detected within the same channel and these responses are concentrated around the estimated fracture hit time. If these responses indicate the fracture hit, they tightly constrain the fracture hit time which could be very useful for geomechanical modelling.
Figure 2 Partial 1000 m amplitude map of the LF-DAS components with injection pump rate curve (top). This data includes the entire operation of one stage. (a) Strain rate map (b) Cumulative strain map with estimated fracture hit position and time (star in the figure).

Figure 3 Partial 1000 m multi-stage cumulative strain map with injection pump rate curve (top). This data includes the two stage operations and the later half is the same stage as shown in Figure 2.

Figure 4 Partial 1000 m of the LF-DAS strain rate map and the DTS temperature perturbation map with injection pump rate curve (top). Compressing response in the LF-DAS map and high temperature response in the DTS (shown by the orange dotted line) seem to be related.
Figure 5 Partial seismic gathers of DAS data near the estimated fracture hit time. (a) Partial 1000 m gathers (b) Partial 100 m gathers with limited display from 0.5 to 3.5 seconds. The same color circle shown in (a) and (b) indicates the same responses.

Conclusions

LF-DAS data analysis for the Montney tight gas area successfully detected valuable responses related to hydraulic fracturing operations. Strain rate maps may indicate pressure changes related to fracture hits, and DTS data corroborated the LF-DAS results. Fracture hit position and time could be estimated from the cumulative strain map, and HF-DAS data have the potential to detect the fracture hit time more precisely. Since LF-DAS data could become the standard recording method for achieving optimal operations during hydraulic fracturing, it is important to continue to evaluate DAS data and gain further insight into what causes low frequency strain responses near the fiber.

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References