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Shear-wave splitting analysis aids in time-lapse study

The interpretation of reservoir complexities can improve completion success.

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A study combining the processing and interpretation of the Pouce Coupe time-lapse multicomponent surveys investigated two horizontal well hydraulic stimulations of the Montney shale. The processing was greatly improved over previous unsatisfactory results by deploying new methods to better preserve vector fidelity, improve prestack shear-wave splitting analysis and layer stripping, and enhance time-lapse repeatability. The results show a strong correlation between the magnitude and orientation of seismically derived induced reservoir azimuthal anisotropy and individual stage production. The baseline characterization provides a strong argument that drilling and completion practices must be driven by the interpretation of the local-scale reservoir complexities that will improve completion success.

Earlier research found promising results relating to shear-wave seismic anisotropy changes within the Montney shale unconventional reservoir by analyzing the multicomponent time-lapse seismic surveys. Researchers also concluded that the previous seismic processing was inadequate and required technical improvements to extract meaningful reservoir characterization solutions.

In response, the data have been reprocessed, and integrative methods of processing and interpretation have been applied as a consequence of focusing the objective on azimuthal anisotropy mapping. Interpretation of the azimuthal anisotropy within the reservoir interval was determined post-stack using shear-wave velocity anisotropy (SWVA) quantified by the time delays between the fast shear and slow shear travel times of the base of the reservoir event. The baseline was interpreted for *in situ* reservoir conditions, and two hydraulic fracture stimulations were monitored to determine the induced azimuthal anisotropy. The azimuthal anisotropy responses were then linked to production log data characterizing the contribution of flow from individual stage locations.

Montney shale example

The Pouce Coupe time-lapse converted-wave surveys were acquired in 2008 to characterize and monitor changes within the unconventional reservoir caused by hydraulic fracturing. The dataset includes a baseline survey acquired after drilling the location's two horizontal wells (2-07 and 7-07) and two monitor surveys that were obtained subsequent to each of the two corresponding hydraulic fracture treatments (Figure 1).

Due to the proximity of the field to the Rocky Mountain deformation belt, the stress regime is strongly azimuthally anisotropic, with the maximum horizontal stress being up to 1.8 times the magnitude of the minimum horizontal stress. The characteristic tight nature of the Montney unconventional reservoir requires flow pathway heterogeneities such as natural fractures to be accessed for economic development.

The fracturing of the reservoir rock creates azimuthally dependent shear strength and ultimately causes the shear velocities to be different parallel and perpendicular to

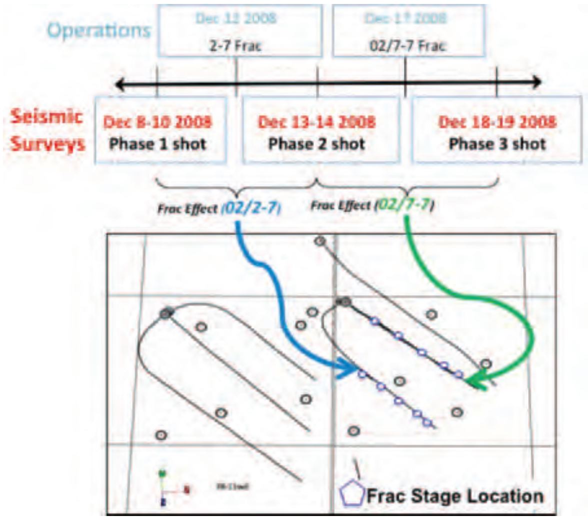

FIGURE 1. The Pouce Coupe field seismic data consist of a baseline survey and two monitoring surveys of the horizontal well frac treatments. (Modified from Atkinson and Davis, 2011. Images courtesy of Sensor Geophysical)

fracture planes. The use of converted waves for near-vertical fracture interpretation is encouraging because the orientation of the dominant open fractures may be determined and also because the velocity differential may provide the ability to characterize fracture density. In comparison, microseismic surveys potentially monitor the volume of reservoir that has reacted to the hydraulic fracture treatment, but little is known about how fractures react after proppant is distributed to keep the fracture permeability pathways open. This is one application of multicomponent seismic technology where the use of converted waves for imaging reservoir azimuthal anisotropy shows great promise.

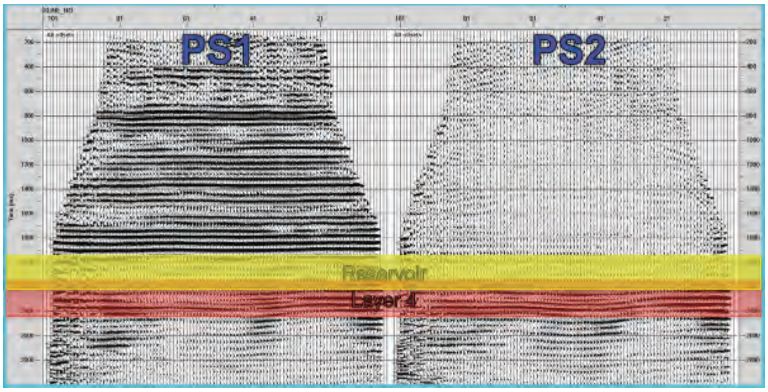

FIGURE 2. The reservoir interval is located between 2,100 ms and 2,400 ms (outlined in yellow). The final window for the shear-wave splitting analysis is shown by Layer 4 (2,150 ms to 2,450 ms).

The stacked fast and slow (PS1 and PS2) volumes (Figure 2) allow for the vertical arrival time differences of the PS1 and PS2 waves to be analyzed within the reservoir more precisely. The post-stack approach of estimating the SWVA from shear-wave splitting time delays is a horizon-based measurement. The SWVA is determined from the difference of travel times between the PS1 and PS2 images of a known seismic marker at the base of the reservoir when there is a lack of coherent reflection energy with the reservoir. This method estimates an effective SWVA anisotropy over the reservoir interval.

Determining natural fracture orientation and density

A fundamental part of prestimulation unconventional reservoir characterization is determining the natural fracture orientations and their density. The baseline characterization of the SWVA shows very low-magnitude natural shear-wave azimuthal anisotropy conditions – less than 3% (Figure 3A). The small SWVA values may be due to nonpreferential orientation of open natural fractures. Although the anomalies are small, the SWVA maps exhibit two main trends oriented northwest and northeast. Independently, subsurface image log interpretation reveals that the Montney formation has two fracture sets: one oriented parallel to the regional maximum horizontal stress direction and a perpendicular set. Based on the PS1 orientations determined by the shear-wave splitting analysis (Figure 4), it is observed that the principle fast shear-wave orientation varies over the local field scale and may correspond to the two dominant fracture orientations.

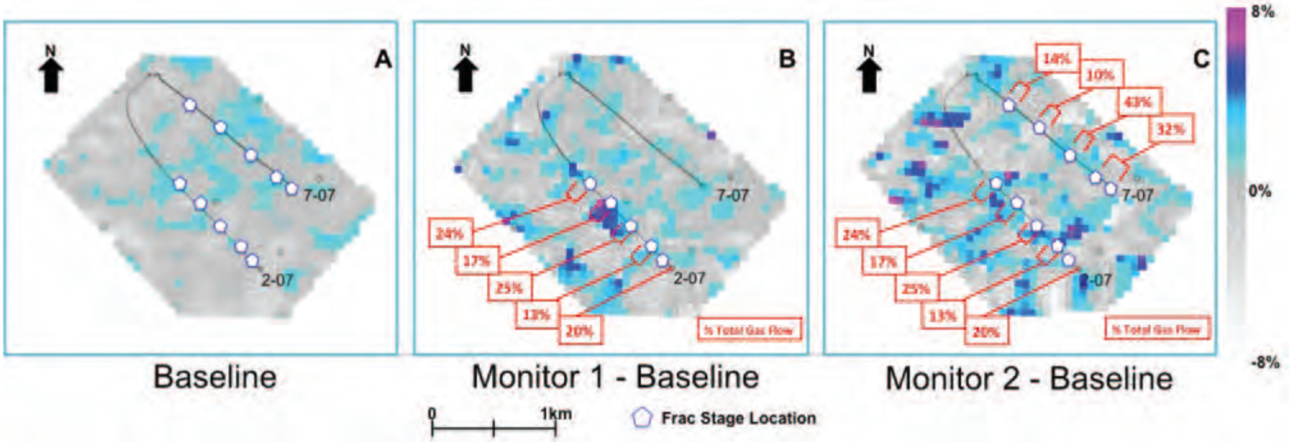

FIGURE 3. The shear-wave splitting was averaged over the Montney reservoir interval. Spinner production data are highlighted by frac stage and represented as percentage of total gas flow. A: Baseline SWVA from shear-wave splitting time-delays. B: SWVA difference between monitor 1 and baseline after the completion of the 2-07 well. C: SWVA difference between Monitor 2 and baseline after the total completion of 2-07 and 7-07 (hydraulically fractured and propped).

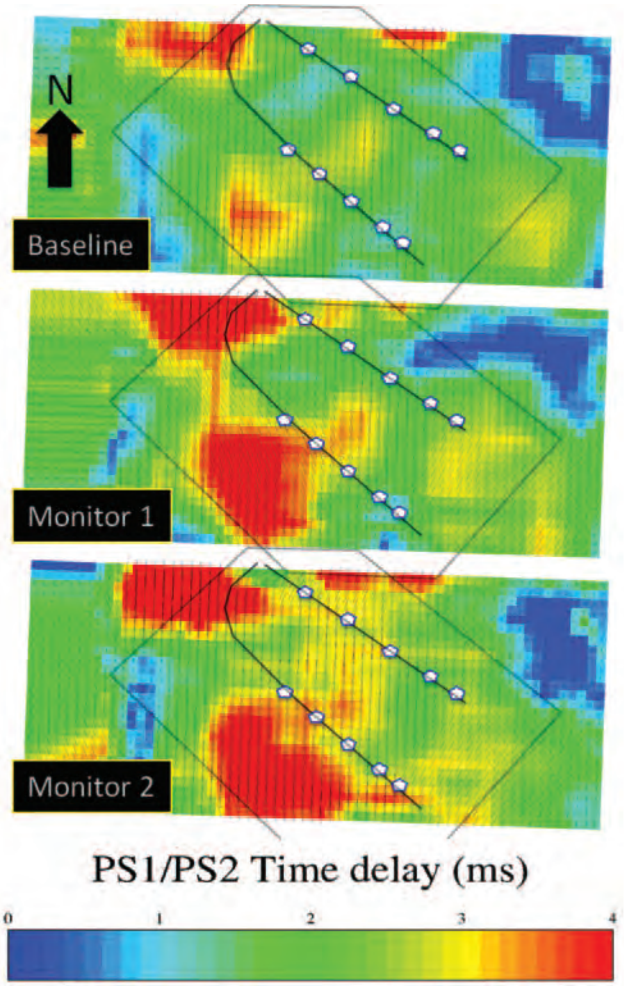

FIGURE 4. Prestack time-delay and PS1 azimuth estimates resulting from the layer stripping procedure down to the reservoir level are displayed for all three vintages of the Pouce Coupe time-lapse seismic survey.

Interpreting anomalies using converted-wave data

After the completion of the 2-07 well, three induced SWVA anomalies are present (Figure 3B). The linear induced anomaly at the southern (toe) portion with values between 3% and 5% SWVA may be associated with a wrench fault trending parallel to the present-day regional maximum horizontal stress direction. This minor offset fault is one of many over the survey area that was only possible to interpret using the converted-wave data. The SWVA anomalies located at the center and heel stages have values between 4% and 7% SWVA and build only south of the wellbore, representing preferential propagation. The dominant orientation of the highest magnitude anomaly is a result of the hydraulic fracture interacting with the perpendicular natural fracture set and is interpreted as opening fractures against the regional maximum horizontal stress.

Figure 3C shows the overall completion effect of the two horizontal wells. It is believed from the lack of new time-lapse SWVA anomalies near the 7-07 well that the majority of the energy of the completion was lost into the open fractures of a previously interpreted wrench fault, causing the representative SWVA anomaly to grow in size and strength. From the microseismic data analysis (not shown here) it was observed that the microseismic events were focused at the toe of the 7-07 well and propagated toward the 2-07 well, supporting the SWVA results. The other two anomalies near the 2-07 well previously discussed decreased in magnitude and became much more diffuse, representing the equilibrating of reservoir pressure and the fractures closing on the proppant. The dominant fracture orientations did not change between the baseline and monitor surveys (Figure 4), implying that the natural faults and fractures control the displacement of the hydraulic completion energy and the induced anomalies may correspond to propping of preexisting fracture networks.

The final SWVA signature may reflect the overall connectivity of the open fracture network. It is interesting to compare the shear-wave splitting anomalies with the spinner production data collected for each stage perforation location. In Figures 3B and C, the spinner data are portrayed as percent of total gas flow. The percent of total gas production is ultimately related to natural fracture permeability and hydraulic stimulation success. The baseline fracture locations and density relate to the success of each hydraulic fracture stage and should be used in completion design (Figure 3A). The induced anomalies are related to the ultimate hydrocarbon deliverability and are interpreted to be the propped fractures (Figure 3B and C). From multicomponent seismic reservoir characterization and monitoring, the optimum perforation locations can be determined, resulting in an increase of producible gas. E&P

References available on request.

Acknowledgments

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