Optimizing hydraulic fracturing operations through time-lapse, multi-component and microseismic monitoring

Thomas L. Davis¹ and Oscar Quezada² present a study that determines which parts of the reservoir are being accessed by the hydraulic fracturing operation and which parts of the permeability continuum are being monitored by the various seismic methods.

Introduction
The future of shale reservoir development is dependent on our ability to use integrated technologies to improve the recovery factor. By characterizing the reservoir under dynamic rather than static conditions we can monitor the enhanced permeability field created by the hydraulic fracturing process. Natural fractures, faults and stress state profoundly influence the permeability field created by hydraulic fracturing. The permeability field is a continuum and is constantly changing as the reservoir is developed. Monitoring these changes can lead to an understanding of the enhanced reservoir volume surrounding stimulated wellbores while enabling a better estimation of the effectiveness of the hydraulic fracturing process in shale reservoirs.

Anadarko Petroleum Corporation (APC) and the Colorado School of Mines Reservoir Characterization Project (RCP) teamed up to conduct an integrated dynamic reservoir characterization study of a portion of Wattenberg Field, Colorado (Figure 1). Time-lapse, multi-component seismic data were acquired during the hydraulic fracture stimulation of 11 horizontal wells within a one square mile area, the Wishbone section (Figure 2). The purpose of this integrated study is to determine what parts of the reservoir are being accessed by the hydraulic fracturing operation and what parts of the permeability continuum are being monitored by the various seismic methods. In doing so, the integration of seismic and engineering technologies should help us optimize well spacing and other parameters including completion type and number of stages (Figure 3).

Dynamic reservoir characterization of Wattenberg Field, Colorado
The current recovery factor for the Niobrara/Codell reservoirs combined in Wattenberg Field averages 6%. We believe that the recovery factor could be significantly increased in the future using integrated seismic monitoring to improve the economic return on investment. The cost of conducting seismic monitoring operations at Wattenberg in a one square mile well spacing test is less than half the cost of drilling and completing one well in the section.

---

¹ Colorado School of Mines | ² Anadarko Petroleum
¹ Corresponding author, E-mail: tdavis@mines.edu
SPECIAL TOPIC: RESERVOIR MONITORING

image logs show open natural fractures as well as a considerable number of mineralized fractures with calcite fill.

The Niobrara/Codell interval is overpressured. Overpressures extend throughout the reservoir interval and several hundred feet above the reservoir into the basal part of the Pierre Shale causing stress relief in the overburden which is a critical factor in making the Niobrara a world-class reservoir. Evidence of pressure compartmentalization occurs in the reservoir set up by faulting associated with wrench fault tectonics (Nurhasan and Davis, 2016).

4D multi-component seismic monitoring

Two seismic surveys were acquired by Paragon Geophysical for APC and RCP. The first survey, the baseline, took place in June/July of 2013 after the wells were drilled but not completed. The second survey, the monitor survey, was acquired in September after the wells were hydraulically fractured, but generally before flowback. The first survey was conducted during relatively dry conditions but there was considerable noise present owing to operational efforts going on in the field at that time. The second survey was completed in September just before storm clouds darkened the skies as a prelude to a ‘hundred year flood’. Inova’s wireless system, the Hawk, was used to acquire the surveys. Vibrators (P and S-wave) were used as the source for the multi-component data acquisition.

The surveys acquired were nine-component (9-C) surveys with three components of source (one P and two orthogonal S-waves) at each source point and three component Vectorseis receivers at each receiver point. Approximately four square miles of surface seismic coverage was used to image the one square mile with full-fold coverage in the subsurface at 2290 m depth. The surveys were acquired to provide at least 60 fold at the Niobrara level in the 1.6 km image area in the subsurface. The surveys also provided rich azimuthal and offset coverage to enable pre-stack analysis and interpretation.

Processing was conducted by Sensor Geophysical in Calgary. They processed the P, PS and SS data. Data quality was good to excellent. Processing was undertaken to preserve the repeatability of the surveys. The time-lapse seismic data were processed simultaneously. Cross-equalization was performed on the datasets with the NRMS ranging down to .2 in the target interval for the P-wave data and .3 for the shear wave data.

Time-lapse results

Figure 4 shows a P-wave time-lapse anomaly within the reservoir interval (White and Davis, 2016). The majority of change is within the Niobrara C and Codell intervals. The change is caused by hydraulic fracturing and is related to the pressure field being increased while lowering the acoustic impedance. The amount of pore pressure increase associated with the hydraulic fracturing process was up to 3300 psi.

Overburden compaction in the Sharon Springs member of the Pierre Shale relates to the effectiveness of the top seal. The rocks within the reservoir interval are stress sensitive because they are overpressured naturally by the hydrocarbon maturation process. Pressurizing the middle Niobrara and the Codell increases the effective stress in the overlying and underlying intervals giving

The Niobrara is a mixed carbonate/chalk and mudrock/marlstone interval, approximately 300 feet (90 m) thick. Underneath the Niobrara is the Codell which is a dolomitic siltstone. The Niobrara and Codell reservoir intervals within Wattenberg contain recoverable reserves of 2 billion barrels of oil equivalent. Improving the recovery from the reservoir by just 1% could significantly impact the economics of this play. Integrated seismic monitoring has the potential to aid in increasing the recovery factor and thus justify the cost of monitoring during the life of field development.

The Reservoir Characterization Project (RCP) in conjunction with Anadarko Petroleum Corporation monitored a well spacing and completions test in one section (one square mile) of the field in which 11 horizontal wells were drilled and completed mid-year 2013 (Figure 2). A baseline multi-component seismic survey was acquired prior to the well drilling and then a monitor survey was acquired after the wells were stimulated, but not flowed back. During the hydraulic fracturing of the wells a surface microseismic survey was acquired. Seven wells were landed in the Niobrara and in the Codell (Figure 3). Well trajectories were designed to facilitate the hydraulic fracturing process more than staying in actual contact with the primary zone of interest. Most wells are drilled toe-up to facilitate gravity drainage. Formation image logs show open natural fractures as well as a considerable number of mineralized fractures with calcite fill.

The Niobrara/Codell interval is overpressured. Overpressures extend throughout the reservoir interval and several hundred feet above the reservoir into the basal part of the Pierre Shale causing stress relief in the overburden which is a critical factor in making the Niobrara a world-class reservoir. Evidence of pressure compartmentalization occurs in the reservoir set up by faulting associated with wrench fault tectonics (Nurhasan and Davis, 2016).

4D multi-component seismic monitoring

Two seismic surveys were acquired by Paragon Geophysical for APC and RCP. The first survey, the baseline, took place in June/July of 2013 after the wells were drilled but not completed. The second survey, the monitor survey, was acquired in September after the wells were hydraulically fractured, but generally before flowback. The first survey was conducted during relatively dry conditions but there was considerable noise present owing to operational efforts going on in the field at that time. The second survey was completed in September just before storm clouds darkened the skies as a prelude to a ‘hundred year flood’. Inova’s wireless system, the Hawk, was used to acquire the surveys. Vibrators (P and S-wave) were used as the source for the multi-component data acquisition.

The surveys acquired were nine-component (9-C) surveys with three components of source (one P and two orthogonal S-waves) at each source point and three component Vectorseis receivers at each receiver point. Approximately four square miles of surface seismic coverage was used to image the one square mile with full-fold coverage in the subsurface at 2290 m depth. The surveys were acquired to provide at least 60 fold at the Niobrara level in the 1.6 km image area in the subsurface. The surveys also provided rich azimuthal and offset coverage to enable pre-stack analysis and interpretation.

Processing was conducted by Sensor Geophysical in Calgary. They processed the P, PS and SS data. Data quality was good to excellent. Processing was undertaken to preserve the repeatability of the surveys. The time-lapse seismic data were processed simultaneously. Cross-equalization was performed on the datasets with the NRMS ranging down to .2 in the target interval for the P-wave data and .3 for the shear wave data.

Time-lapse results

Figure 4 shows a P-wave time-lapse anomaly within the reservoir interval (White and Davis, 2016). The majority of change is within the Niobrara C and Codell intervals. The change is caused by hydraulic fracturing and is related to the pressure field being increased while lowering the acoustic impedance. The amount of pore pressure increase associated with the hydraulic fracturing process was up to 3300 psi.

Overburden compaction in the Sharon Springs member of the Pierre Shale relates to the effectiveness of the top seal. The rocks within the reservoir interval are stress sensitive because they are overpressured naturally by the hydrocarbon maturation process. Pressurizing the middle Niobrara and the Codell increases the effective stress in the overlying and underlying intervals giving
rise to stress arching associated with the hydraulic fracturing process (Vinal and Davis, 2015). Fracture containment within the zone is evidenced from the P-wave time-lapse analysis and the associated microseismic data.

In the map view the change in P-impedance for the C Chalk is concentrated on the western side of the Wishbone section between two faults (Figure 5). The pressure field is influenced by the zone of increased permeability related to opening up natural fractures associated with wrench and listric normal faulting on the western side of the section. The faults on the west side cause pressure compartmentalization and sealing conditions to occur owing to their strike-slip or wrench fault movement creating fault damage zones and clay smear along the faults.

P-wave velocities are influenced by compressibility, rigidity and density whereas S-waves are influenced by rigidity and density. Compressibility in the Niobrara is affected by the fractures and the fluid in the fractures. S-waves are influenced by the presence of open fractures and shear wave azimuthal anisotropy is a measure of fracture density and fracture aperture. The physical process of hydraulic fracturing is intended to ‘break more rock’ and shear wave data enable us to see the rock breakage zones. The enhanced fracture network associated with the hydraulic fracturing process decreases the shear wave velocity. The areal extent of the shear wave anomalies is less than those of the P because we are seeing the fractured reservoir volume and not the pressure field that P-wave is sensing. As a result, there is considerable value in multi-component time-lapse data in monitoring shale reservoirs versus P-wave monitoring alone.

The P-impedance change in the C-chalk is pervasive on the western side caused by the pressure build-up associated with the hydraulic fracturing process and compartmentalization of the reservoir by faulting. Fracture zones, which are filled with fluid post-fracking and most likely to be providing conductivity to the wells, are shown by the shear wave azimuthal anisotropy change. The reservoir volume providing the effective reservoir conductivity, as evidenced by the shear wave data, is reduced compared to that shown by the P-wave data.

The first indication of shear wave splitting as a hydraulic fracturing monitoring technology was introduced by Atkinson and Davis (2011). Their work at Pouce Coupe Field, Alberta showed the interaction of hydraulic fracturing with the natural fractures in the Montney Formation. There the better-producing well was associated with increased fracture density created by interaction of the hydraulic fracturing stimulation with the local areas of high natural fracture density. Complex fracturing gives rise to microseismic clusters rather than long linear trends (Davis and D’Amico, 2016).

Time-lapse multi-component seismic fast (S1) and slow (S2) shear wave volumes have been created with a N20W predominant fracture orientation. Through pre-stack inversion impedance volumes are created for the S1 and S2 volumes prior to and after hydraulic fracturing of the 11 wells (Figures 6 and 7). Figure 8 shows the results of computing azimuthal shear wave impedance anisotropy from the shear wave impedance volumes. The difference between S1 and S2 is entitled pseudo seismic splitting and is a measure of shear wave azimuthal velocity anisotropy. The ability to differentiate the response of these two reservoir intervals separated by 100 ft (30 m) at 7000 (2132 m) to 7500 ft (2290 m) is truly remarkable and of considerable value for improving recovery in the Niobrara and Codell.

The shear wave data provides a robust means of imaging the reservoir volume that is being effectively stimulated. The P-wave data are more sensitive to effective stress and microseismic data shows fracture tip growth but does not link to the effective stimulated volume as a natural fracture opening may or may not create seismicity.

Multi-component seismic monitoring shows that P-waves identify pressure compartments, whereas shear waves respond to...
Overall the outline would tend to suggest a fairly uniform stimulated reservoir volume throughout the section with a clear westward event growth preference in response to an East to West completions sequence. This is in stark contrast to what the shear wave data show given the different reservoir changes these two methods are most sensitive to. In general, we believe that the P-wave data show the overpressure area was largely bounded by faults on the west side of the section. The shear wave data show the zones of high fracture density that are opened and propped during the hydraulic fracturing process. There is a greater volume of effective stimulated reservoir volume in the Codell than in the Niobrara C interval.

Figure 10 shows the variability of seismicity associated with the hydraulic fracturing process ranging from long linear trends to clustering of events. As shown at Pouce Coupe, Alberta the better wells are not associated with long, linear event growth trends. Instead the better wells are associated with clusters of microseismic events. The 2N well is one of the better producers in the section (Figure 11).

The interaction of a hydraulic fracture with natural fractures that exist in the shale can be complex. Natural fractures are planes of weakness in the fabric of the rock and the hydraulic fracture tends to seek out zones of weakness rather than create new fractures. The orientation of the natural fractures and the hydraulic fracture also plays a role as does in-situ stresses within the reservoir. A broad distribution of the associated fracture network occurs when there is a low differential horizontal stress and a high density of natural fractures. A very low level of seismicity may occur when opening pre-existing fractures.

Microseismic monitoring

Microseismic data were acquired using a surface array deployed by Microseismic Inc for APC. The event cluster density was mapped for each of the wells that were hydraulically fractured (Figure 9).
Natural fractures can have a profound influence on the effectiveness of the hydraulic fracturing process and are important to characterize prior to initiating the hydraulic fracturing process. The advantage of a baseline multi-component seismic survey is to establish the structural framework including the prediction of faults and fractures prior to the drilling and completion of the horizontal wells. In doing so well trajectories can be optimally planned/targeted and completions can be adapted based on the orientation of faults also plays a significant role in influencing the hydraulic fracturing process. Faults that are parallel or slightly oblique to the maximum horizontal stress are preferred planes of weakness for hydraulic fracturing fluid to go into the fault zone whereas faults that are perpendicular or largely oblique to the maximum horizontal stress can limit the propagation of hydraulic fracturing energy. Both cases are shown in Figure 12.

The orientation of faults also plays a significant role in influencing the hydraulic fracturing process. Faults that are parallel or slightly oblique to the maximum horizontal stress are preferred planes of weakness for hydraulic fracturing fluid to go into the fault zone whereas faults that are perpendicular or largely oblique to the maximum horizontal stress can limit the propagation of hydraulic fracturing energy. Both cases are shown in Figure 12.
The effectiveness of the process and to mitigate potential reservoir damage and environmental concerns. We need to move from static to dynamic reservoir characterization to fully understand the hydraulic fracturing process in a variety of reservoirs and reservoir settings. Permanent reservoir monitoring systems (PRM) enabling active and passive recording of the seismic wave-field have the potential to bring about change in shale reservoir development, provided the value of such monitoring can be embraced and utilized by all stakeholders in the development process.

If more reservoir rock can be accessed by additional hydraulic fracturing treatments over the life of the well by ‘refracturing’, additional reserves can be produced and the use of these valuable resources can be maximized. Refracturing is of great interest to the industry as it comes without the large capital expenditure of drilling and completing new wells to access incremental reserves. Refracturing costs are only 20-30% of the cost of drilling and fracturing a new well. One of the largest hurdles to such treatments is understanding where they should be applied along the wellbore. For refracturing to be most successful in shale reservoirs, the new fractures need to access areas of the reservoir that were not adequately contacted by the initial fracturing treatments. Monitoring will help to not only target areas for additional treatments, but it will also help us to understand how the rock reacted to and possibly changed the initial treatments. This information will help to optimize re-treatments and to determine how to best design and apply re-fracturing stimulations.

Conclusions

Seismic monitoring has the potential to play a critical role in reservoir management and do so over the extended life of an unconventional reservoir. Seismic monitoring comprising 4D multi-component seismic, vertical seismic profiles, and micro-seismic surveys provide a unique opportunity to monitor the permeability continuum and changing stress fields.

Multi-component seismic monitoring combined with micro-seismic monitoring can aid in understanding the hydraulic fracturing process and its effectiveness in creating contact with the reservoir. This understanding can aid in well placement and hydraulic fracture design to increase the recovery factor. Dynamic reservoir characterization can be used to increase recovery through refracturing or landing additional wells to access bypassed reserves.

A deeper time-lapse understanding of hydraulic stimulation in these different formations would mean a huge leap forward for oil and gas operators in the Denver Basin that will allow for the optimization of two of the most important technical factors in horizontal development: completions and well spacing. Monitoring the influence of rock mass and overburden change will also be pertinent to addressing environmental and societal concerns with hydraulic fracturing.

Acknowledgements

Special thanks go to APC and the RCP for jointly acquiring the Wattenberg monitoring data set and for collaboratively analysing and interpreting the results. Special thanks go to the sponsors of the Reservoir Characterization Project for their support of the study and to the students who worked on different aspects of this integrated study.

