Cross-Well Imaging Offers Higher Resolution

Modern cross-well seismic represents the next stage in the ongoing evolution of advanced seismic imaging technology. By deploying both seismic transmitters and receivers down hole, directly in the zone of interest, operators can image subtle reservoir details as fine as a few feet between wells up to a mile or more apart.

By Bruce Marion

HOUSTON–With crude oil prices hovering around $100 a barrel, operators of mature fields, enhanced oil recovery projects, and unconventional plays throughout North America are taking a fresh look at how to optimize development strategies and extract remaining resources efficiently and cost effectively.

For example, a West Texas operator has drilled step-out wells in a shallow carbonate formation to investigate undeveloped oil reserves. Based on encouraging results, the operator priced a limited 2-D surface seismic program to help guide the development. Despite the survey’s small size, the price tag was still rather steep because of typical permitting, mobilization and logistical complexities. Fortunately, advancements in cross-well seismic technology provide a faster, simpler, higher resolution alternative—at a lower cost.
Cross-well or interwell, seismic technology deploys both seismic transmitters and receivers down hole, directly in the zone of interest, using standard wireline conveyance. State-of-the-art cross-well seismic profiles can image subtle reservoir details as fine as a few feet between wells up to a mile or more apart. This is 5-10 times the vertical resolution of surface seismic (Figure 1). The payoff can be dramatic.

The operator of a tight gas reservoir in Wyoming optimized infill well spacing by combining hydraulic fracture micro-seismic monitoring data with detailed cross-well seismic, and increased his recovery factor by more than 40 percent. A New Mexico operator successfully imaged complex reef structures that were below surface seismic resolution, initiated horizontal drilling to target high-porosity zones, and boosted oil production in subsequent wells by 300 percent.

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Reservoir-Scale Imaging

To acquire conventional 2-D or 3-D seismic data, source and receiver arrays are placed on the earth’s surface, providing images of large-scale geologic features. To calibrate surface seismic with finer-scale well information and further enhance the seismic image, vertical seismic profiles (VSPs) may be acquired by placing receivers down hole while sources remain at the surface.

A good VSP can double the vertical resolution of surface seismic. However, both approaches are plagued by attenuation of the seismic signal caused by shooting through a weathered, near-surface layer and hundreds or thousands of feet of overburden. By placing both source and receiver down hole, cross-well seismic bypasses that issue altogether.

Cross-well acquisition operations require simultaneous access to two or more existing wells (Figure 2). A downhole source is lowered with wireline to the bottom of one well, and a receiver array is placed in one or more adjacent holes. As the source is moved up the wellbore, it transmits sound waves through the reservoir between the wells to the receivers, where it is recorded.

Typically, the receiver array is repositioned a number of times, based on pre-survey modeling, and the process is repeated until the interwell zone of interest is covered uniformly.

In development since the 1990s, cross-well seismic systems were more like a science experiment until a few years ago because of various technical limitations. For one thing, early cross-well source technologies generated mostly compressional (P) wave energy, so they lacked the shear (S) data operators needed to fully understand hydraulic fracture propagation and other important reservoir characteristics.

In addition, borehole sources were not yet powerful enough to reach between wells much more than a few hundred feet apart. Advanced technologies were necessary to expand the operational envelope. The primary roadblock was figuring out how to drive a 40,000 pound vibrator truck several miles down a 4.5-inch hole in the ground.

Breakthroughs in cross-well seismic technology have overcome traditional barriers. The state of the art in cross-well seismic imaging systems integrates efficient, multilevel receivers with a new downhole vibrator to deliver up to 100 times the resolution of surface seismic data. This powerful, dual-axis source technology delivers 4,800 pounds of force per axis, generating very high-bandwidth acoustic waves from 30 to 600 hertz. It delivers both P and S wave energy between wells up to 1.25 miles apart, achieving an unprecedented vertical resolution of 5-10 feet. Reservoir-scale measurements include P and S velocities, reflectivity, anisotropy, and attenuation.

Cross-well technology brings seismic acquisition directly into the reservoir interval, providing a completely independent measurement of subsurface geology. Today’s cross-well seismic imaging empowers operators in two primary ways:

- They can characterize highly complex conventional and unconventional reservoirs in greater detail than ever.
- Using time lapse profiles, they can monitor subtle changes in a reservoir over time that result from primary production, waterflooding, EOR activity, or hydraulic fracture stimulation.
Brownfield Optimization

Many conventional brownfields were developed with no surface seismic or poor seismic data. As a result, operators often lack sufficient understanding of the structural and stratigraphic heterogeneities that impact the flow of oil and gas.

Cost-effective cross-well seismic technology allows them to obtain high-resolution seismic “by the mile,” without the permitting and environmental delays or logistical challenges of surface seismic acquisition. All it takes is a couple wireline trucks. Geologists and engineers now can delineate thin reservoirs and bypassed pay, detect subseismic features that undermine waterflood conformance, target horizontal wells with greater precision, develop appropriate completion strategies, and book incremental reserves.

Consider an example in which cross-well seismic imaging. Using existing wellbores, 11 2-D cross-well profiles were acquired in a zig-zag pattern across the structure, placing the source and receivers well below the weathered layer. The longest cross-well profile was 1.25 miles.

For the first time, geoscientists achieved a high-resolution seismic interpretation of the target interval, which revealed previously undetected faulting (Figure 3). By incorporating the new understanding of fault geometry in the remapping process, the company has conducted a successful strategic infill drilling campaign.

Enhanced Oil Recovery

Two requirements for success in today’s EOR projects are enhanced reservoir characterization and effective monitoring of fluid movement. High-resolution cross-well seismic is ideal for both applications.

During a small-scale carbon dioxide pilot program in a West Texas carbonate reservoir, the operator acquired time-lapse cross-well seismic profiles between a pair of wells, before and after initial injection. Cross-well seismic provides sufficient resolution to identify the 1-3 percent changes in seismic velocity typical of CO2 movement.

In this case, several months following the start of injection, the CO2 front appeared to jump above the target reservoir about halfway between the injector and producer. At nine months (Figure 4), velocity changes indicated the flood had arrived above the perforated interval. The well made no additional oil. What happened?

Analysis of cross-well imaging revealed distinct wavelet terminations, which the geologist interpreted as open, vertical fractures. Because of reservoir complexity, engineers were unable to design an effective CO2 flood and decided not to scale up the pilot to full-field implementation. Time-lapse cross-well seismic data provided missing information needed to prevent the operator from wasting a considerable amount of money.

Enhanced recovery methods have proven to be successful in Canada. Ten years ago, Canada had only 5 billion barrels of proved oil reserves. Since then, it has added a staggering 170 billion barrels, thanks to widespread deployment of EOR methods in Canada’s heavy oil deposits.
As global demand continues to rise and oil prices remain high, the industry is pursuing an increasing number of EOR initiatives. Modern EOR techniques not only increase recoverable reserves, they help sustain long-term production and maximize return on investment. Also, producing more oil from a known reservoir is environmentally prudent, and some EOR practices reduce greenhouse gas emissions.

Monitoring cross-well seismic velocities can benefit any company involved in or planning thermal recovery operations in heavy oil deposits, such as occur in Canada or Kern County, Ca. Changes in cross-well seismic velocity caused by steam flooding are large enough—typically about 25 percent—that it may not be necessary to shoot a baseline profile prior to injection. If recovery problems occur in certain wells, running a single cross-well snapshot using adjacent wellbores can provide “steam diagnostics” capable of identifying undetected geologic features that impede flow.

After a couple years of steam injection, for example, one operator noted that only the lower half of the reservoir produced oil. Having a few temperature observations well in the field did not explain what was preventing the steam from reaching the rest of the interval. Acquiring cross-well seismic profiles between selected wells successfully identified a thin shale barrier running across the entire field. With this new understanding of the reservoir, engineers could take appropriate measures to further enhance recovery.

Emerging Applications

Cross-well seismic technology was developed to improve reservoir characterization and flow monitoring in conventional oil and gas fields. However, it proved so valuable that operators soon applied it in unconventional plays as well, beginning with tight gas sands requiring hydraulic fracture stimulation. This opened the door for exciting new applications of cross-well imaging in today’s shale plays, where microseismic fracture monitoring is already widespread.

Integrating these two, complementary downhole seismic measurements will almost certainly lead to greater understanding of hydraulic fracture dynamics in heterogeneous shale reservoirs.

One emerging application of crosswell seismic imaging is improved seismic velocity modeling. Using microseismic data to locate where the rock is breaking as a result of hydraulic treatment depends on placing microseismic events precisely in 3-D space. That, in turn, depends on an accurate seismic velocity.

Unlike sonic log data typically used in microseismic calibration, cross-well seismic profiles provide a direct measurement of velocity in the same frequency band and along a similar travel path as the microseismic survey. Advanced cross-well technology also incorporates anisotropy—variations in seismic velocity based on angle and direction. This information should alleviate concerns about velocity expressed by some shale operators, and enhance the accuracy of locating microseismic events.

Just as they do in conventional fields, cross-well surveys in unconventional plays provide higher-resolution geologic imaging, revealing subtle faults and heterogeneities in reservoir and completion quality that impact fracture performance. Early adopters are experimenting with integrated cross-well and microseismic data to make more informed decisions before implementing large-scale development approaches to horizontal well spacing or multistage completion design.

Finally, time-lapse cross-well seismic profiles—shot before and after hydraulic fracturing—can give operators a better understanding of effective drainage area. Pre/post changes in cross-well seismic properties, such as P and S velocity and attenuation, indicate where fracture stimulation may have induced permanent changes in reservoir porosity and permeability, even in areas of low microseismic response.

Consider, for example, the observations of a seven-stage fracture treatment in a tight gas reservoir in the Piceance Basin. In most stages, cross-well and microseismic measurements correlated fairly well. However, results differed unexpectedly in two areas (Figure 5). While stage two produced few microseismic events, cross-well seismic showed significant changes in the ratio of P to S velocity after fracture stimulation.

Geologists believe that particular zone, which contains coal, may be naturally fractured. One possible interpretation is that hydraulic fracturing broke the rock just enough to connect with existing fractures, and the pressure change caused by injecting proppant showed up clearly on the time-lapse cross-well survey.

Putting all the pieces together, the drainage area of this zone may be larger than one would surmise from microseismic data alone. The two measurements also differed in stage six, but the reasons are not yet clear. Integrating cross-well seismic with microseismic is still in its infancy, but the possibilities are intriguing.

Better Lateral Spacing

While many unconventional plays were developed with vertical wells, today’s shale assets are being produced primarily with horizontal laterals. Acquiring time-lapse cross-well seismic between horizontal wellbores is an emerging application that has not yet been deployed commercially. Early in development planning, cross-well data could help operators determine the optimal spacing of laterals and the proper density of fracture completions.

How? Imagine drilling three horizontal wellbores. Before completing any of them, cross-well seismic sources and receivers are placed in the two outer laterals, shooting horizontally across the lateral in between. By stimulating the central wellbore first and acquiring another cross-well survey immediately after fracture treatment, an operator can map the effective drainage area with greater confi-
dence. Well spacing and fracture stages can be modified as needed to boost production.

A number of oil and gas companies are looking at this and other emerging applications of modern cross-well seismic imaging in unconventional shales.

To improve the economics of both mature fields and unconventional plays, North American operators and service companies have focused considerable brainpower and resources on driving down the unit cost of production through greater operational efficiency. Despite tremendous gains, the industry may be reaching the technical limits of such “well-centric efficiency.”

The next step change will require a new focus on “reservoir-centric effectiveness.” Operators will need to understand the rocks in far greater detail. Then they will be able to craft unique development strategies for each reservoir and eliminate every well—indeed, every completion—that is not economically viable.

The secret, ultimately, lies in better integrating diverse information. Advanced cross-well seismic surveys provide new, high-resolution data at the reservoir level and at the reservoir scale. Integrating cross-well seismic with high-quality well and microseismic data will lead to more accurate reservoir characterization and better fluid monitoring over time.

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