Crosswell Seismic Fills the Gap

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Much is being written about using seismic methods as reservoir management and monitoring tools. However, when we try to apply these methods there are always issues of vertical resolution.

Figure 1 illustrates the relationship between the level of resolution and the seismic measurement technique.

Core and log data provide high vertical resolution, but sample only a small volume of rock. On the other hand, surface seismic methods sample large rock or reservoir volumes, but have limited resolution. Surface-based seismic methods often fail to resolve the important small-scale features which allow one to characterise the reservoir for such applications as flow simulations or the accurate placement of directional wells.

Crosswell seismic profiling fills the gap between data types that provide high resolution (but small sample volume) and data types with lower resolution (but high sample volume). It is conducted between wells with the source and receivers placed inside the wellbore, as illustrated in Figure 2 (page 11).

The receiver arrays are held fixed in one well while the source is slowly drawn upwards in the other well and is “fired” at preset intervals. After one source “run,” the receivers are

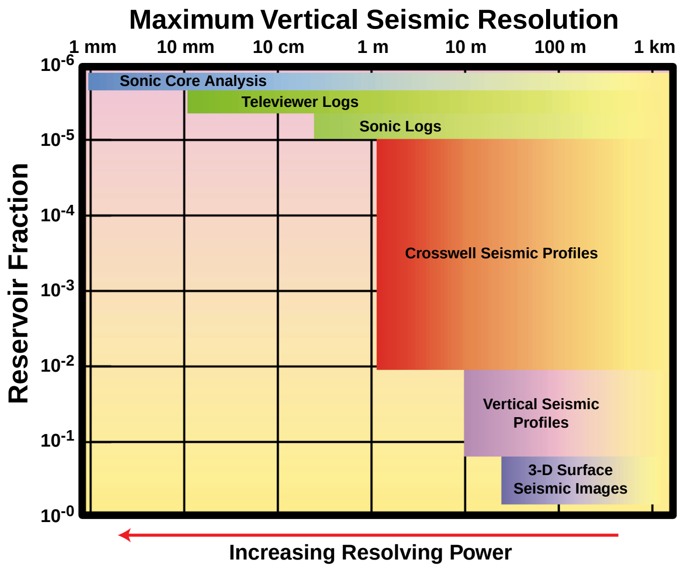

Figure 1. Seismic methods trade coverage of the reservoir for resolution because it is impractical today to achieve both high resolution and high coverage. Crosswell methods fill a resolution “gap” between sonic log measurements and vertical seismic profiles

relocated and the source run is repeated.

The typical spacing between adjacent source points ranges from 2.5 feet (0.8 meter) to 20 feet (six meters). Receiver separation is usually similar. It is possible for these systems to acquire 20,000 or more traces in a single, 24-hour day.

A complete survey can be as small as a few thousand traces or as large as several hundred thousand traces. Such factors as the well separation, the thickness and structure of the imaging target and the frequency content of the received signal dictate the necessary size of a survey.

The distance between the source and receivers, which is on the order of the well spacing, is considerably less than the propagation distances associated with surface seismic methods. The short propagation distances, combined with avoidance of weathered zones, allow the use of frequencies at least an order of magnitude higher than used with surface seismic methods, resulting in a proportionate increase in spatial resolution.

Crosswell surveys currently employ a frequency band between 20Hz and 2000 Hz, depending on the type of source used, the distance between wells and the attenuation characteristics of the zone under investigation. Resolution on the order of 10 feet (3 meters) is possible.

Crosswell processing is similar to surface seismic processing in that it includes velocity estimation (“travel time tomography”) and reflection imaging. Reflection imaging usually

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provides more resolution than the velocity image ("tomogram") and depends critically on the accuracy of the velocity model for good results.

In Figure 3 we have compared a crosswell velocity image and reflection image with modern surface seismic data, a sonic log and core data. All of these data were collected in a carbonate reservoir in the Permian Basin of West Texas.

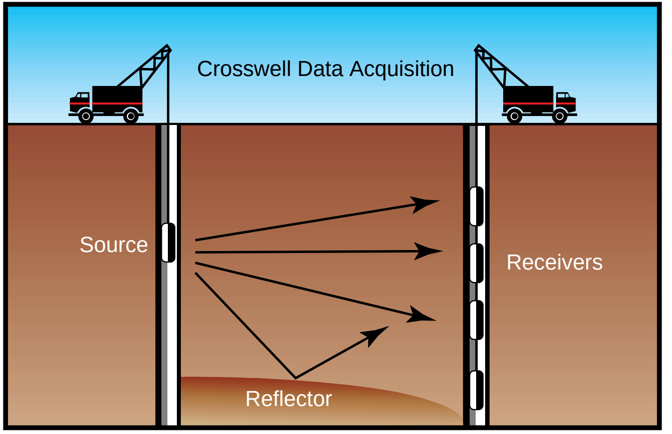
Crosswell methods are not a replacement for 3-D surface seismic technology in areas where the frequency content is similar and where surface accessibility is not a problem. It is 2-D by nature and the insufficiencies of 2-D versus 3-D seismic data are well-documented in the literature. However, by requiring multiple profiles, a 3-D perspective can be achieved. One should view crosswell profiling as being complementary to both surface seismic methods and logging methods (as illustrated in figure 1) and it is best targeted at locations where the enhanced resolution between wells can serve a critical need.

Applications

Crosswell profiling is a technology for reservoir delineation, development, characterization and monitoring, but not exploration.

Monitoring changes in reservoir conditions (e.g. saturation or pressure) is easier than absolute

See **Crosswell**, next page



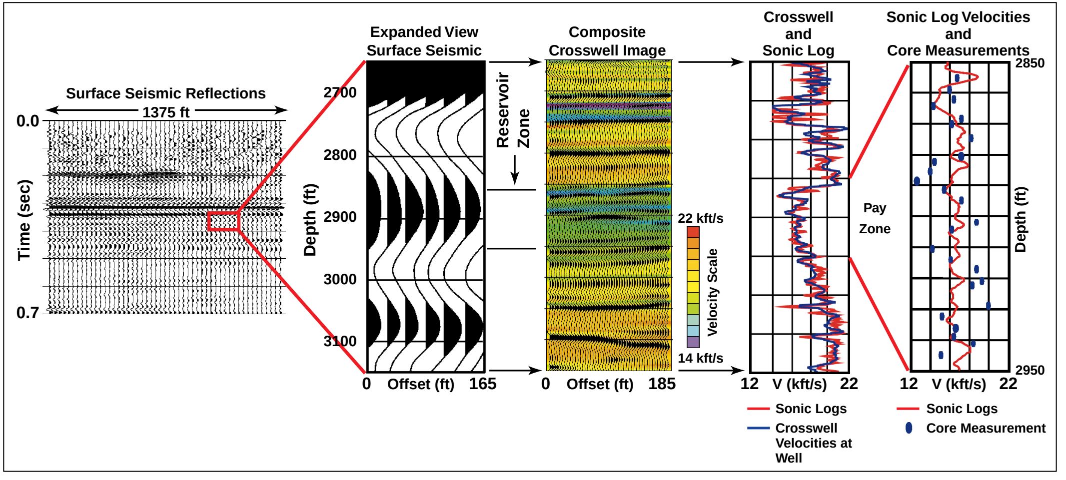


Figure 2 (top right). Crosswell data are collected by placing a seismic source in one well and a receiver string in a nearby well. Energy which propagates directly between wells without being scattered serves as the basis for constructing velocity images (tomograms). Energy which is reflected is used to construct reflection images. Figure 3 (right). The crosswell reflection and velocity images (center) fill the resolution gap between modern surface seismic data (left), and the sonic log data (right center) and core measurements (far right). These data are from a west Texas carbonate reservoir.

Crosswell

from previous page

imaging of reservoir properties (e.g., porosity), but monitoring requires multiple visits to the same site in order to obtain time-lapse images. In the United States, a majority of the crosswell activity has been in the San Joaquin Valley of California and the Permian Basin of West Texas, but there has been recent work in the Mid-Continent and the Gulf Coast as well.

In the San Joaquin Valley, the primary interest has been managing the heat budget of thermal recovery processes. The well separations are usually small, the reservoirs shallow and the thermal recovery processes create large velocity changes that make it easy to monitor the progress of thermal fronts. The images used for monitoring are predominantly time-lapse tomograms, although reflection imaging has been used as well.

The main difficulty with using crosswell profiling in this environment is that the sedimentary rocks are often quite attenuating, which can restrict the useful upper frequency range and a powerful source may be required to propagate energy between wells.

A second problem is that some wells will not hold water for a sufficient period of time, which prevents the use of fluid-coupled sources and receivers.

In West Texas, the reservoirs are dominantly carbonates with favourable attenuation characteristics. As a result, frequencies as great as 2,000 Hz can propagate over hundreds or thousands of feet between wells. The high degree of vertical variability in the acoustic impedance in these carbonates generates many reflections helpful for reservoir characterization. The combination of smaller well separations associated with these mature fields and the good propagation characteristics permits the successful use of relatively low powered, high frequency sources that are cost-effective to deploy.

Although there are a variety of applications for which crosswell profiling is technically feasible, for some of them the technique is currently too expensive to implement on a routine, operational basis. For example, successful imaging of CO_2 -saturation and pressure effects on a vertical scale of three meters has been attained in a pilot flood in a carbonate reservoir in West Texas, but the cost of data acquisition under high pressure conditions, combined with the need to collect several “snapshots” over time, may limit the routine use of the technology for this application.

One of the first applications where it is felt that crosswell profiling is likely to find wide operational acceptance is in providing an accurate “roadmap” for directional wells. It is becoming an increasingly common practice to optimise recovery in a reservoir by targeting specific units for a directional well.

Directional wells are relatively expensive, and in areas where the structure or stratigraphy between wells is not easily predicted using traditional data types, crosswell methods may be the only way to obtain the high resolution information one needs to plan where to drill – or to make the decision as to whether to drill.

Acquisition Systems

The acquisition systems currently available commercially are based on two different source technologies:

❒ A small airgun that is impulsive and relatively widebanded.

❒ Piezoelectric elements that are swept in frequency in a manner similar to surface vibrators.

Both sources are frequently used with hydrophone receiver arrays. The airgun system has been used successfully in clastic rocks in Kansas at a well separation exceeding 2,000 feet (600 meters), while the piezoelectric system has been used in carbonates at a well separation of 1,800 feet (550 meters).

Greater well separations are possible and are slated for future projects. An axial hydraulic vibrator is currently under development by a cooperative Research and Development Agreement (CRADA) between the U.S. National Laboratories and numerous industry partners and was scheduled to be commercially available by now. Because of its relatively high power, we expect it to be applicable to large well separations and to other acquisition geometries such as that found in a 3-D reverse VSP or in a single-well mode (where the source and receiver are in the same well).

Summary

Crosswell images fill a resolution gap between the more traditional reservoir data types.

Crosswell velocity tomograms and reflection images exhibit resolution better than modern surface seismic images do, but less resolution than log measurements. For many reservoirs, information about heterogeneities at the scale imaged by crosswell methods is critically important.

For some applications, crosswell technology is currently moving from being a purely research activity to being an operational technique.

Among the current barriers it faces in gaining a wider acceptance are the cost of data acquisition, the potential disruption to normal field operations and insufficient experience using technology in a variety of environments.

The cost of data acquisition is dropping quickly, however, due to hardware improvements and the expanding experience base. It is expected that future improvements in data processing will reduce the disruption in field operations by carefully scheduling the survey during normal maintenance activities or before tubing is placed in a new well.

Recent advances in multi-level receiver systems that can operate through production tubing and can be used simultaneously in multiple wells will permit more rapid data acquisition, reduce field disruption and reduce costs. More and more case studies will expand the routine acceptability of crosswell profiling.

(Editor’s note: Harris is an associate professor of geophysics at Stanford University; Langan is a staff geophysicist at Chevron Petroleum Technology. Also contributing were Spyros Lazaratos of TomoSeis Inc., and Mark Van Schaack of Stanford.)