Crosswell seismic imaging of a tight-gas reservoir

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Summary

We analyze data from a crosswell seismic survey that was conducted in 2004 at the Noel gas field located in northeastern British Columbia and operated by BP Canada Energy Company. The goal was to create high-resolution images of gas-bearing, but tight, sandstone channels 2400m to 2650m deep in the Cadomin and Nikanassin formations. Recording between two wells approximately 145m apart employed hydrophones and a piezoelectric vibrator source. The dominant frequencies in the crosswell seismograms are about 1000Hz to 1500Hz, with wavelengths on the order of 4m to 6m. Compared to wavelengths of about 100m that are usual for surface seismic data, the shorter wavelengths in the crosswell data provide significantly better resolution of beds 10m to 25m thick. A P-wave velocity tomogram was created from first arrival times using a back-projection that accounts for head wave arrivals. Wavefield separation isolated up- and down-going reflections. These reflections were mapped with a VSP-CDP method using ray-tracing and guided by the velocity tomogram. Seismic boundaries on the velocity tomogram and the reflectivity image correlate closely with the known geology.

Introduction

The Noel Gas Field operated by BP Canada Energy Company is located in northeastern British Columbia. Tight, gas-bearing sandstone channels exist at depths of 2400m to 2650m. Gas production from these target zones may be stimulated by hydraulic fracturing. Before deciding whether or not to go forward with a hydraulic fracturing program, BP Canada wished to have more detailed information regarding the continuity of the sand channels. To this end, BP Canada contracted Z-Seis Corporation in 2004 to conduct high-resolution crosswell seismic survey between two wells, 00-A97-E and 02-A97-E. At the survey depths, the wells are separated by about 145m.

Analysis of crosswell data usually involves two procedures: tomographic imaging of P-wave velocities using first-arrival times as input (Peterson et al., 1985), and mapping of observed reflections to create a reflectivity map (Stewart and Marchisio, 1991; Harris et al., 1995). In this study, we applied both techniques to obtain the seismic structure between the wells to compare with the known geology.

Figure 1 shows the geological formations and boundaries encountered by the wells, along with the natural gamma-ray and P-wave sonic logs (low gamma activity and low transit times, i.e., high velocities, deflect to the left). Of primary interest is the Cadomin formation, described as sandstone and persistent sandy conglomerate. Below the Cadomin is the Nikanassin formation with the Monach, Beattie Peaks, and Monteith members. Zones where tight gas sand channels exist, namely, the Cadomin, lower Monach, and upper Monteith, have been colored in yellow. The remaining zones are largely shales and siltstones.

The natural gamma-ray logs closely follow the geology, with low activity coinciding with the sands in the Cadomin, lower Monach, and upper Monteith. Higher gamma-ray activity in the other members is due to the presence of shales and siltstones. These gamma-ray logs delineate the geological boundaries with precision.

The sonic logs, although rather noisy, also follow the geology. The sonic transit times in the shales and siltstones are on average larger than those in the sandstone formations. From the sonic log transit times, we find that the P-wave velocities are about 5.2 to 5.6 km/s in the sandstones, and about 4.5 to 5.0 km/s in the shales.

The geological structure is essentially flat-lying, as is indicated in Figure 1 by the horizontal alignment of formation boundaries intersected by the wells and the geophysical logs.

Crosswell Seismic Acquisition and Field Results

A piezoelectric vibrator controlled by a linear sweep was used as the source for the crosswell survey. The sweep was 1.1 seconds long, beginning at a low frequency of 100Hz and ending at a high frequency of 2000Hz. The listen
Crosswell seismic imaging of a tight gas reservoir

period was 1.6 seconds. The digital sampling interval was .125ms, resulting in a Nyquist frequency of 4000Hz. Raw field data, i.e., the pilot signal and the received signals, were recorded for post-acquisition crosscorrelation. During acquisition, an array of ten hydrophone receivers covered depths from 2300m to 2650m at 1.5m intervals in Well 00-A97-E. The source occupied the same depth range at 0.75m intervals in Well 02-A97-E. This procedure produced a dense network of more than 59,000 rays crossing the rock section.

Example seismic traces are shown on Figures 2 and 3. Figure 2 is a common depth or zero-offset gather, for which source and receiver depths are equal. Figure 3 is a common receiver gather with the receiver at a depth of 2484m. We note the obvious variation of first arrival times with depth. The first arrival times from the zero-offset gather have been plotted on Figure 1 to emphasize their correlation with the geological formations. Fast arrivals are observed through the sandstone layers (low gamma-ray activity), while slower arrivals are associated with shales and siltstones (high gamma-ray activity). The crosswell first arrival times are consistent with the sonic transit time logs.

Figure 2: Zero-offset (in depth) seismograms recorded with a piezoelectric source and hydrophone receivers.

Figure 3: Common receiver gather with receiver depth at 2484m. Peak-to-peak times reveal a dominant frequency of about 1000Hz.

Velocity Tomogram

For the flat, horizontally-layered geology, the main features of the seismic velocity structure in the rock section are determined by the first arrival times of the common depth (zero-offset) seismograms shown on Figure 2. A P-wave velocity tomogram was created by using first-arrival time picks from the zero-offset gather and gathers with source receiver depth-offsets of -50m, -25m, 25m, and 50m. We used a back-projection algorithm (Peterson et al., 1985). Egregious imaging artifacts are eliminated by constraining the tomogram to have a layered structure. Improved definition of boundaries between adjacent low- and high-
Crosswell seismic imaging of a tight gas reservoir

velocity layers was achieved by carefully accounting for first arrival times from head waves.

In a low-velocity layer at locations close to the boundaries separating it from the higher-velocity zones above and below it, first arrival times will be from raypaths that follow refracted trajectories that go through the higher-velocity zones. The corresponding arrival times are faster than if the paths had remained entirely within the low-velocity formations. If arrival times from these head waves are used in tomogram creation without consideration for this “speed-up” behavior, a bias is produced toward higher velocity values in the low-velocity zones. This bias causes a loss of contrast with the higher velocity zones above and below.

Figure 4: P-wave velocity tomogram.

We can remove the bias and improve the contrast if, instead of using the first arrival times strictly, we identify the low-velocity zones (using the first-pass tomogram, natural gamma-ray logs, and the geology intersected by the wells) and make corrections to the zero-offset arrival times before creating a second-pass image. The corrections to the zero-offset arrival times through low-velocity zones are made in a way that is consistent with refraction into and out of the high-velocity zones above and below. A tomogram created with the corrected arrival times will then (1) account for refraction; (2) correlate better with known geology; (3) define geological boundaries more sharply; and (4) have more accurate velocity values.

The P-wave velocity tomogram, created from first-arrival travel times corrected for head wave arrivals, is shown on Figure 4 together with the gamma-ray logs and the geological formations. The tomogram clearly delineates the sandstones, siltstones, and shales. Velocity values are in the range 5800 to 6200 m/sec for the sandstones and 5100 to 5500 m/sec for the siltstones and shales.

Figure 5: Up-going wavefield from the gather of Figure 2.

Reflectivity imaging

To produce a reflectivity map, we follow a procedure similar to those used by others (Stewart and Marchisio, 1991; Lazaratos et al., 1995). The main steps in the processing flow are:

- sort to common source/receiver gathers;
- remove first arrivals to isolate reflections;
- FK filtering for up-going reflections;
- FK filtering for down-going reflections;
- VSP-CDP mapping of reflections;
- apply statics to align mapped reflections;
- stack the aligned reflections.

Figure 3 is an example of a common receiver gather. We removed the first arrivals by subtracting a running average.
Crosswell seismic imaging of a tight gas reservoir

(mean filtering). Alternatives that can be used to remove the first arrivals are median filtering (Stewart, 1983) and FK filtering; however, in this case, the results are not overly sensitive to the specific method.

Figures 5 and 6 show the up- and down-going reflections from Figure 3 after first arrival removal and velocity filtering in the FK domain. Both up-going and down-going reflections from all the possible common receiver and common source gathers are mapped using the VSP-CDP technique (Wyatt and Wyatt, 1984). Automatic or hand statics are applied, and the corrected maps are stacked to obtain the final reflectivity map.

We used the velocity tomogram as a guide to devise a horizontal-layer model for Snell’s Law ray-tracing to obtain time and geometric information for the VSP-CDP mapping. Even when ray-traced reflection points are used, it is generally the case that statics corrections must be applied to align the mapped reflections before they stack properly (Lazaratos et al., 1995). This is especially true when the true velocity structure is complex, and/or when we have high-frequency, short-wavelength data.

Figure 6 is the reflectivity map created using reflections from the Noel crosswell seismic dataset. The figure emphasizes the good agreement of the crosswell reflections with the known formation boundaries and the natural gamma-ray logs.

Conclusion

The seismic boundaries on both the velocity tomogram and the reflectivity map show good continuity across the rock section between the wells. They correlate well with the geological layers intersected by the wells, and with the geophysical logs. The resolution on the reflectivity map is on the order of 5m to 10m, consistent with the dominant frequency (1000Hz) and wavelengths (5m to 6m) in the seismic data. Tomogram P-wave velocities are in the 5.8 to 6.1 km/s range for the sandstones of the Cadomin, Lower Monach, and Monteith geological units, and in the range 5.2 to 5.5 km/s for the shales and siltstones. These velocity values are higher than those calculated from the sonic logs transit times (5.2 to 5.6 km/s for sandstones, and 4.5 to 5.0 km/s for shales). It is not known whether or not the sonic transit times had been compensated for the well diameters.

Acknowledgements

We thank BP Canada Energy Company, in particular Geoffrey Fraser, for providing the crosswell seismic data, the geological information, and the well logs used in this study. We also express our gratitude to sponsors of the CREWES Project for their continued support.
References


