

Time-lapse seismic monitoring at Pikes Peak, Saskatchewan

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Summary

We present two 2-D reflection seismic lines shot at the same survey location nine years apart at the Pikes Peak Heavy Oil field in Saskatchewan, Canada. Differences of the reflection data and acoustic impedance inversions are shown. The results indicate a lower impedance zone and a seismic traveltimes increase associated with areas where steam has been injected into the reservoir formation, the Waseca member of the Mannville Group. Three wells located near the two lines were used to constrain the interpretation and impedance values for the inversion. Jason Geoscience and Hampson-Russell's Pro4D software were used to invert, calibrate and difference the reflectivity and inverted sections.

Introduction

More than 35 million barrels of heavy oil have been produced from the Pikes Peak Heavy Oil field operated by Husky Energy near Lloydminster, Saskatchewan. Husky has been producing the field using steam drive technology since 1981. High pressure and temperature steam is injected into the reservoir to reduce the viscosity and mobility of the heavy oil and produced from neighbouring wellbores.

The producing formation is the Waseca in the Lower Cretaceous. The reservoir is an incised valley filled with estuarine deposits of homogeneous sand units, interbedded sand and shale units, and shale units (Van Hulten, 1984). The prolific homogeneous sands preserved at the base of the Waseca Formation are up to 30 metres thick and 500 metres below surface. Below other Lower Cretaceous sand and shale units is the Pre-Cretaceous Unconformity marking the top to the Devonian carbonates. The structure of the Pikes Peak field was created by dissolution of deep Devonian salts around the current field.

Acoustic Impedance Theory

Acoustic Impedance (AI) is different from reflectivity data in that it is an interval property rather than an interface property. A simple two layer model has acoustic impedance values of Z_i and Z_{i+1} , where $Z_i = \rho_i V_i$ for a given interval, i . Equation 1 (McQuillin, 1979) derives the reflection coefficient, R_i , at an interface. Rearranging Equation 1 to solve for Z_{i+1} gives Equation 2.

$$R_i = \frac{Z_{i+1} - Z_i}{Z_{i+1} + Z_i} \quad (1) \qquad Z_{i+1} = \frac{Z_i (1 + R_i)}{1 - R_i} \quad (2)$$

Given a reflectivity sequence such as a seismic trace and an initial acoustic impedance value, Z_i , the trace can be inverted to give acoustic impedance with time or depth as Equation 2 is used iteratively. We performed a type of 'trace based' inversion where information from non-seismic data sources constrains the results. AI has the effects of wavelet sidelobe energy and tuning removed which improves the interpretation of boundaries and allows evaluation of the internal rock properties.

Injecting steam in the reservoir formation reduces the AI. Another consequence is an increased traveltimes in the reservoir (Lines et al., 1990). Seismic data have been acquired over the field to determine the extent of accessed reservoir by the steam.

DATA

With the generosity of Husky Energy, 2-D seismic and digital well log curves were available for analysis. Husky acquired a 2-D seismic swath survey in 1991. It forms a grid of 29 north-south lines spaced every 100 metres over the field. In March of 2000, the University of Calgary AOSTRA (Alberta Oil Sands Technology Research Authority) group and Husky Energy acquired a single 4-C 2-D line in the same survey location as one of the 1991 (1-C) lines. The four components collected were P-wave, SV-wave, SH-wave and experimental surface microphone data. Two sets of P-wave data were collected: single phone and group arrays. Very little difference can be observed in the two stacked sections (Hoffe et al., 2000). The group array version was used in this study. The two lines were processed at Matrix Geoservices Ltd. using very similar workflows. Some differences can be expected in the two sections not only because of the production and steam injection history in the reservoir. The acquisition parameters and field conditions were different. For example, the 1991 lines used a vibroseis sweep of 6 seconds over the frequency range of 8-110 Hz. The 2000 line was swept for 16 seconds over 8-150 Hz. Also additional noise is expected on the 2000 line because many more pump jacks were in operation during acquisition than in 1991.

Three wells relatively close to the lines were used (D15-06, C08-06 and D02-06) because they had sonic and density logs run over the Waseca interval.

inversion Process

The most important aspect of the inversion process is the choice of wavelet. Because of the different frequency content of the two time-lapse lines two wavelets were required. Wavelets were estimated using a deterministic model driven approach that included the reflectivity of the wells logs. Wavelet estimation was an iterative process that improved as the synthetic tie and wavelet improved. Interpreted horizons and impedance logs were used to create an earth model, which in turn was used to spatially constrain the inversion process. Constraints were also set on a range of physically realizable AI values. After the sparse spike inversion of the seismic traces, the low frequency AI from the earth model and band-limited AI from the seismic inversion were merged to give a full AI section. Jason does not force the inversion to match the wells. It only requires the solution to lie within the prescribed constraints. Direct comparison of the two AI sections in the reservoir zone can be made because they are comprised of interval values and the wavelet has been removed.

Time-Lapse Analysis

Prior to subtraction of the reflectivity and impedance sections they needed to be compared and calibrated to adjust for static, amplitude and phase differences. It was critical that the time window for the calibration was above the zone of interest where the recorded seismic signal was not affected by the reservoir zone. Trace-by-trace comparisons provided the best results.

The reflectivity data difference, Figure 1, had the clearest difference section when a wavelet-shaping filter was applied to the 2000 line to match it to the 1991 line. Figure 1 shows the bottom hole location of wells 50 metres or less from the lines and have had cyclical steam injection and production from them since 1991. The most significant differences in the section are seen below the reservoir zone in the area of these production wells. An increase in travelttime through the reservoir zone on the 2000 data was caused by the presence of injected steam in the reservoir. This time sag did not allow the signal of deeper events to cancel. The differences are small at D15-06 location, the well furthest to the north (left), where no steam injection or production has occurred. Some smaller differences due to noise occur in the section where they are not anticipated.

The acoustic impedance difference is shown in Figure 2. Before the subtraction of the impedance sections the 2000 line required a band-pass filter, wavelet shaping and time and phase matching to calibrate it to the 1991 line. The most significant differences are seen in the zone of interest where there is a lower impedance zone. Unlike the results at D15-06 on the reflectivity difference, the lower impedance zone appears to reach this well and extend further to the south than anticipated. This difference raises some questions. Has the steam reached further than anticipated? If not, why the relatively large differences outside of the core of the production field? The greatest differences are seen in the reservoir interval but not excluded to lower impedance values. Has some post-steam cementation occurred to cause higher impedance values? 2-D seismic data alone cannot answer these questions.

Conclusions

The time-lapse analysis of the two lines shot nine years apart is very encouraging. The reflectivity difference shows the effect of increased travelttime of the seismic signal through the reservoir zone. The impedance difference indicates lower impedance in the reservoir zone as well but not excluded to the production area. It is difficult to clearly identify and quantify differences in the sections caused by noise and changes in acquisition parameters and conditions though it is suspected that they exist. The spatial sampling of this project was restricted to one 2-D vertical section. For a more powerful analysis time-lapse 3-D seismic data is required. 3-D would not only provide better spatial sampling but a greater statistical verification of results.

Acknowledgements

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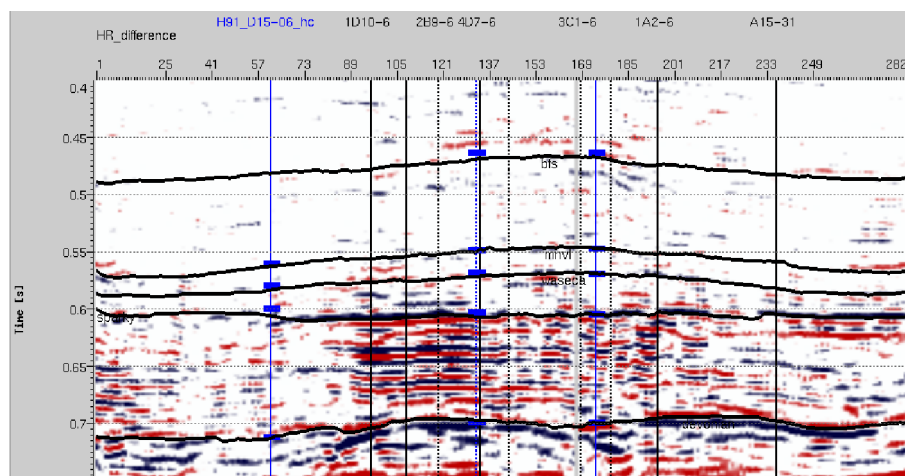


Figure 1: Seismic reflectivity difference section. A strong difference is seen under the zone of interest in the area of the injector/production wells. The difference is a result of the time sag associated with steam injection.

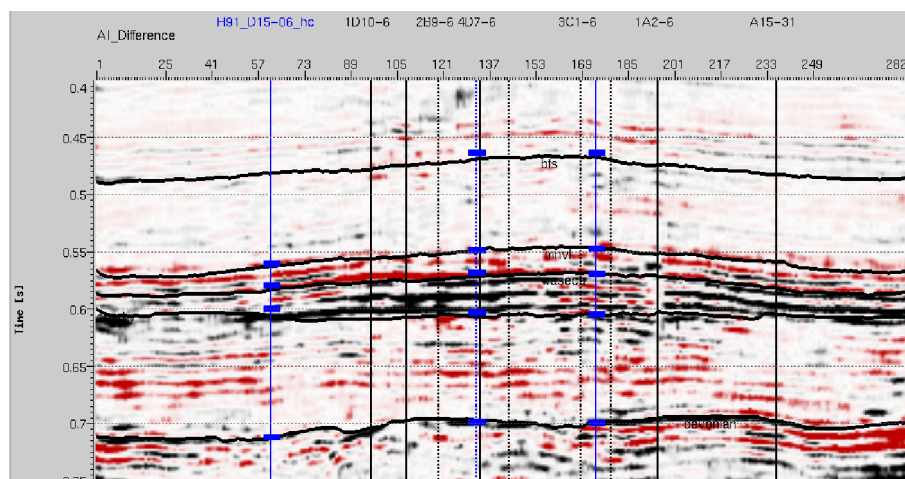


Figure 2: Acoustic impedance difference section. Dark (black) is negative impedance. Note the strongest difference is in the Waseca-Sparky interval. The lower impedance zone does not appear to be constrained to the injection/production area.