Heavy-oil reservoir characterization using elastic wave properties

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SUMMARY

Two interpretation-based analysis techniques are used to delineate the steamed reservoir at Husky Energy's Pikes Peak heavy oil field in Saskatchewan. Two 2-D seismic lines were acquired over the field in near-coincident locations nine years apart to image the Waseca reservoir zone. The isochron method uses the interval traveltime differences to detect a relative time lag in the reservoir in the area where steaming and heating have occurred. The V_P/V_S ratio method compares interpreted traveltimes around the reservoir for P-P (compressional) and P-S (converted) wave data to delineate areas of steam injection. The interpretations were constrained using normal and converted wave synthetic ties from wells along the lines.

INTRODUCTION

Husky Energy Ltd. has operated the Pikes Peak heavy-oil field 40 km east of Lloydminster, Saskatchewan since 1981. Over 35 million barrels have been produced. Steam drive technology has been used to enhance recovery. The effective viscosity of the oil is reduced and the mobility is increased in the reservoir with the injection of high temperature and pressure steam. The oil is produced either from neighbouring wellbores or through the same wellbore used for injection (cyclic).

The Lower Cretaceous aged Waseca formation is the producing resevoir. At Pikes Peak the Waseca is 450 metres below surface. It is an incised valley filled with estuarine deposits of a basal homogeneous sand unit, an interbedded sand and shale unit, and a capping shale unit (Van Hulten, 1984). The main producing zone is the homogeneous unit. It ranges between 5 and 30 m of net pay within the field. Dissolution of deep Devonian salt units around the flanks of the field set up the combination structural and stratigraphic trap. The oil is 12º API and approximately 25000 centipoise dead oil viscosity.

This work directly follows reflectivity and acoustic impedance differencing studies done at Pikes Peak (Watson and Lines, 2001). Results showed that injecting steam in the reservoir reduces the acoustic impedance. Another consequence is an increased traveltime in the reservoir (Lines et al., 1990). V_P/V_S ratio analysis was previously done on Blackfoot data (Stewart et al., 1996). Relative changes in the compressional velocity to the shear velocity are expected from core tests taken from the field.

DATA

Seismic, well log and production data were provided by Husky Energy. Figure 1 is a map of the Pikes Peak field. Husky acquired a 2-D seismic swath survey in 1991 which forms a grid of 29 north-south lines spaced every 100 metres. To investigate time-lapse effects and collect 3-component data the University of Calgary AOSTRA (Alberta Oil Sands Technology Research Authority) group and Husky returned to the field in March 2000 to acquire a repeat line on the eastern side of the field. During acquisition four components were collected: P-wave (vertical and array), SV-wave, SH-wave and experimental surface microphone data. The original and repeat seismic data were processed at Matrix Geoservices Ltd. using similar workflows. Acquisition and processing differences in the two surveys are summarized in Table 1. The most significant difference between the two surveys was the final bandwidth. Both surveys were conducted in the winter, possibly minimizing ground-coupling differences. The time-lapse lines are referred to as H1991 and H2000. H2000 extends to the north beyond H1991.

The wells (D15-6, 3C8-6 and D2-6) were used to create synthetic ties to the P-wave seismic data because they had original sonic and density logs over the Waseca interval. One well, 1A15-6, was used to tie to the converted wave (PS) seismic data because it had a dipole sonic run in 2000. The seismic interpretation was constrained with these forward model ties.

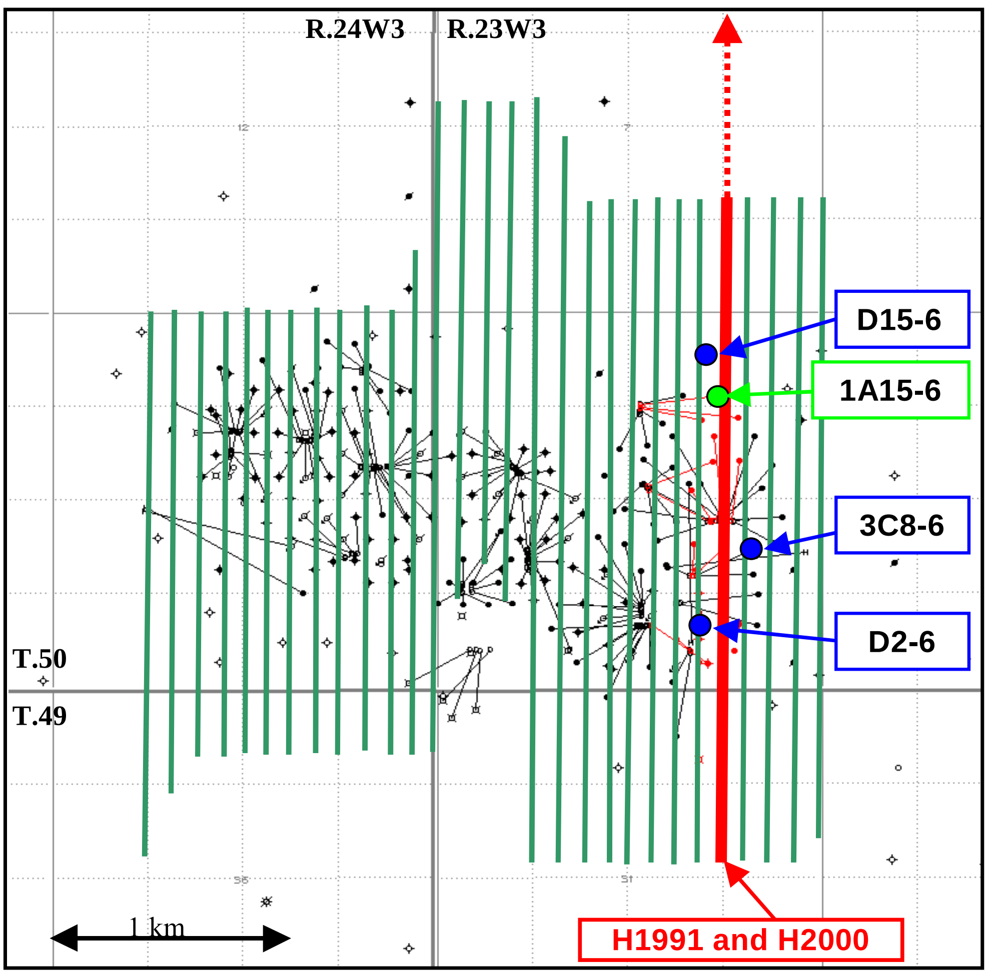

FIG. 1: Map of wells and seismic coverage at Pikes Peak, Saskatchewan

H1991	H2000
February 1991	March 2000
PP (array)	PP (array and single), PS (radial and transverse), and microphone
6 sec	16 sec
8-110 Hz non-linear	8-150 Hz non-linear
3 vibrators over 20 m	2 vibrators over 20 m
4 sweeps/vp	4 sweeps/vp
10 m drag length	No drag
40 m source interval	20 m source interval
20 m group interval	20 m group interval
9 geophones over 20 m	6 geophones over 10 m
30 CDP fold	66 CDP fold
Bandwidth 14 – 110 Hz	**Bandwidth 14 – 150 Hz**

Table 1: Summary of survey differences at Pikes Peak.

ISOCHRON ANALYSIS

The isochron or delay time analysis method used the interpretation of the Waseca interval for the two vintages of lines. The H1991 and H2000 geophone array data were used. The use of traveltime intervals eliminates any concern for static differences in the post stack data. The bandwidth differences meant that there was greater resolution for picking events on the H2000 stack. As a result, slight differences caused by tuning in the interpretation were anticipated. The interpretation of the Waseca-Sparky interval on both versions is shown in Figures 2 and 3.

At each CDP the ratio of the H2000 to H1991 Waseca interval traveltimes were calculated and plotted in Figure 4. With the injection of steam and heat in the reservoir in the time between the two surveys a drop in VP is expected. This decrease translates into an increase in the H2000/H1991 isochron ratio. The estimated position and width of the steam zone from injection and production data was projected onto Figure 4 from six wellbores near the line (Husky, 2000). The three wells on the left (1D10-6, 2B9-6 and 3B8-6) were drilled during the time period between the two surveys. The ratio rises above unity in this section of the line. Conversely, the ratio drops below unity along the portion of the line where three older producers (3C1-6, 1D2-6 and 3B1-6) were more active in 1991 than in 2000. More heat and steam was present in this portion of the reservoir in 1991 and are responsible for the ratio reversal. These results suggest that the compressional velocity is showing sensitivity to more than just the steam zone radius around the wellbore. The total area of the heated reservoir also affects V_P.

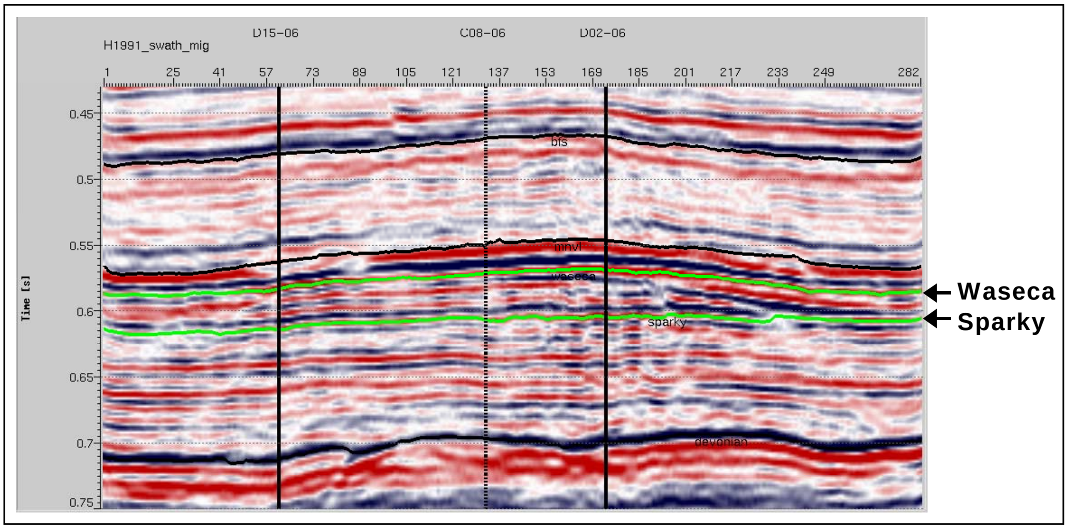

FIG. 2. H1991 interpreted P-wave section.

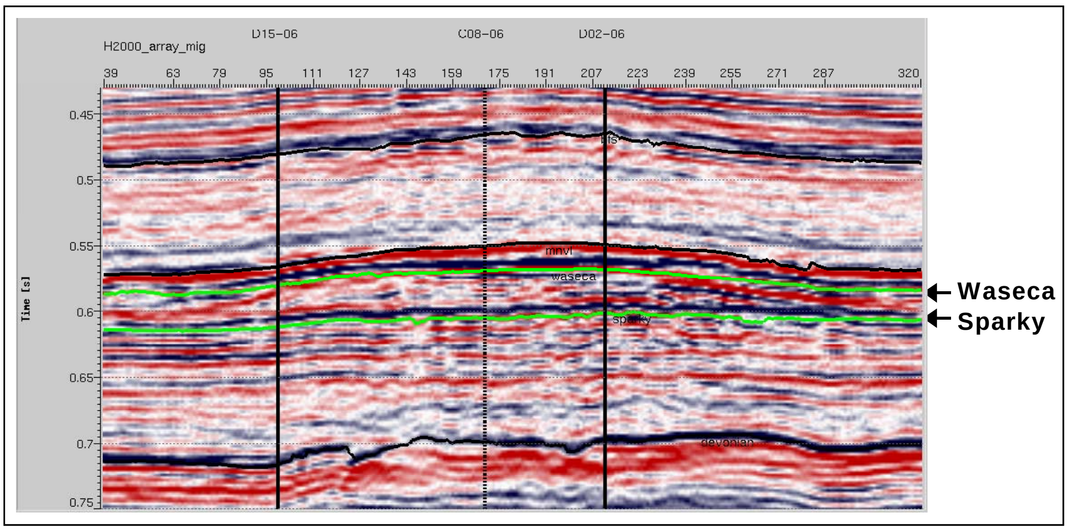

FIG. 3. H2000 reflectivity section (Note higher frequency content)

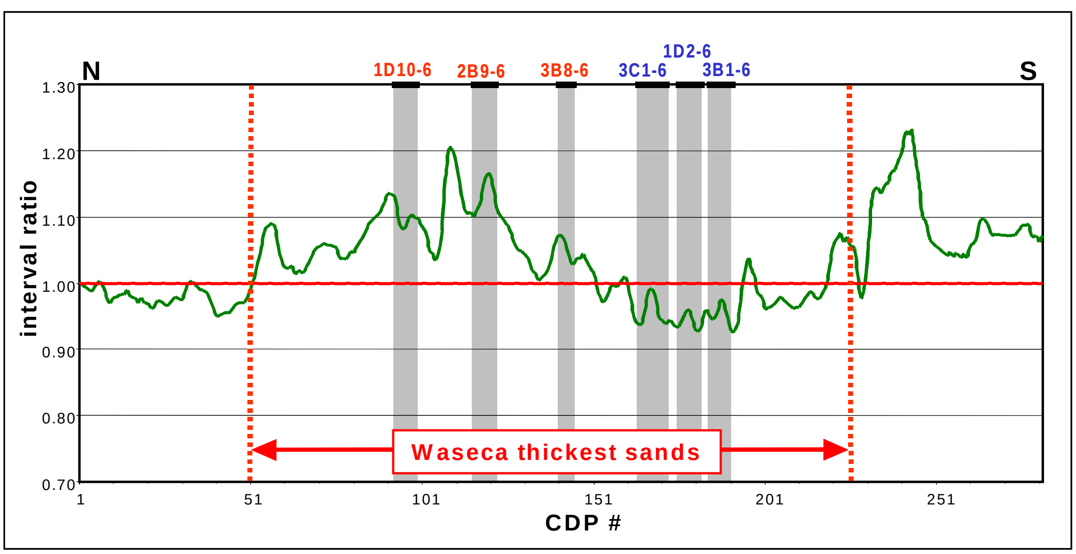

FIG. 4. H2000/H1991 ratio of Waseca interval traveltimes for P-wave arrivals

V_P/V_S RATIO ANALYSIS

In the previous Blackfoot case, thicker sands versus shale were detected using V_P/V_S ratio analysis. In this heavy oil case the addition of steam into the reservoir has the effect of decreasing both V_P and V_S. Core tests were done by Core Laboratories on samples from the Waseca interval. The effect of temperature on compressional and shear velocities was investigated. Figure 5 shows that V_P and V_S both decrease with temperature but V_P decreases at a greater rate. Based on this previous work and core tests, similar effects were expected and investigated at Pikes Peak.

The V_P/V_S ratio analysis was also interpretation based but only involved the multi-component data from H2000. No converted wave data was collected in 1991. The vertical (PP) and radial (PS) components were used. For the P-P interpretation the vertical component of the 3C geophone was used. For the P-S interpretation the radial component was used. There was no appreciable signal on the transverse component. The radial converted wave section required a synthetic that accounted for the wave conversion and the reduced bandwidth in the order of 8 – 40 Hz. A P-S synthetic with several offsets was created using the CREWES synth.m Matlab program (see Figure 6) because there is no mode conversion at zero offset.

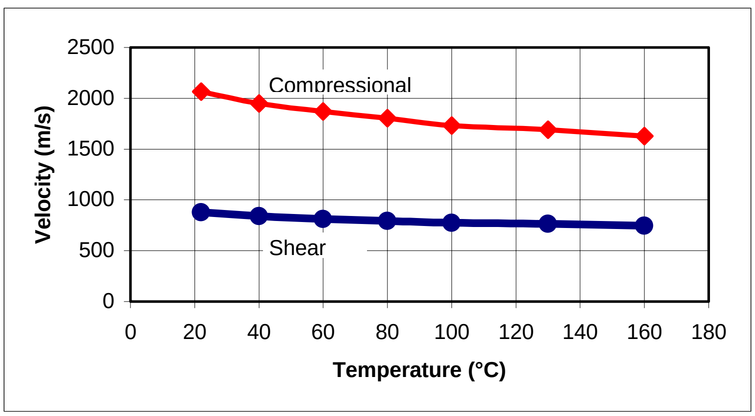

FIG. 5. Effect of temperature on compressional and shear velocities on a core sample from Pikes Peak D2-6-50-23 (Source: Core Laboratories)

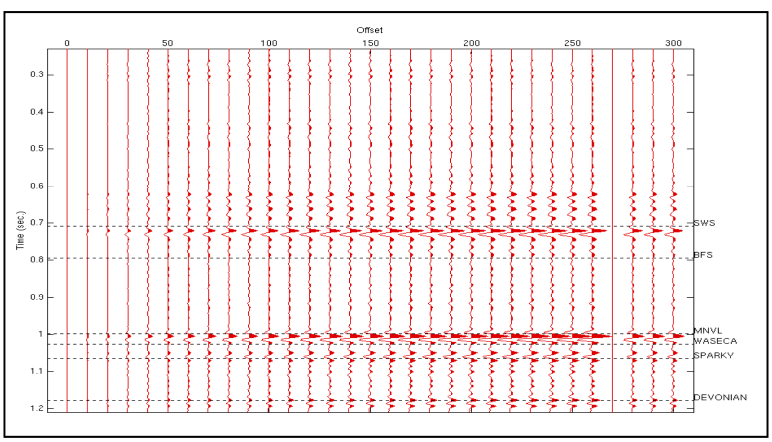

FIG. 6: Converted wave synthetic created at 1A15-6

Figures 7 and 8 show the interpretations of the two sections. There are two intervals on each section considered to be depth equivalent based on the synthetic ties. The Waseca-Sparky interval (same as Figure 3) and a larger Mannville–Lower Mannville interval are interpreted. The P-S section has a different time scale. The significantly lower bandwidth affects the resolution of picking horizons on the P-S section. The P-S stacked section also exhibits more noise. Fortunately, at 1A15-6 tie point the S/N is relatively higher around the zone of interest. Noise cones can be seen on the section to the south (right) of 1A15-6 in the area that coincides with active pump-jacks. The interpretation was forced through the noisier portions of the line.

The V_P/V_S ratio is calculated using interval traveltimes with Equation 1.

$$\frac{V_P}{V_S} = \frac{2\Delta t_{PS} - \Delta t_{PP}}{\Delta t_{PP}} \tag{1}$$

where, Δt_{PP} is the traveltime of an interval from the P-P section and Δt_{PS} is the interval traveltime from the P-S section. The smaller window, Waseca-Sparky, was examined first and the V_P/V_S ratio plot is shown in Figure 9. Noise overwhelms the ratio plot and it is difficult to infer any steam effects. Figure 10 is a plot of the Mannville-Lower Mannville interval. Noise is still present on this section but some distinct anomalies can be seen around the wells with the most recent steam injection. In particular the response at 3B8-6 is a pronounced drop in the V_P/V_S ratio. Steam injection was occurring in this well at the time of the 2000 seismic acquisition. The width of the anomaly fits very well with the predicted steam zone radius. At the wells 1D10-6 and 2B9-6 there is a smaller response. It had been 12 and 26 months, respectively, since steam had been injected in these wells.

On a larger scale, the smooth trend line indicates a long-period effect along the length of the line. The low in the middle corresponds very well to the thickest homogeneous Waseca sands with higher shale content to the north and south. This is similar to the lateral lithology effect that was observed at Blackfoot.

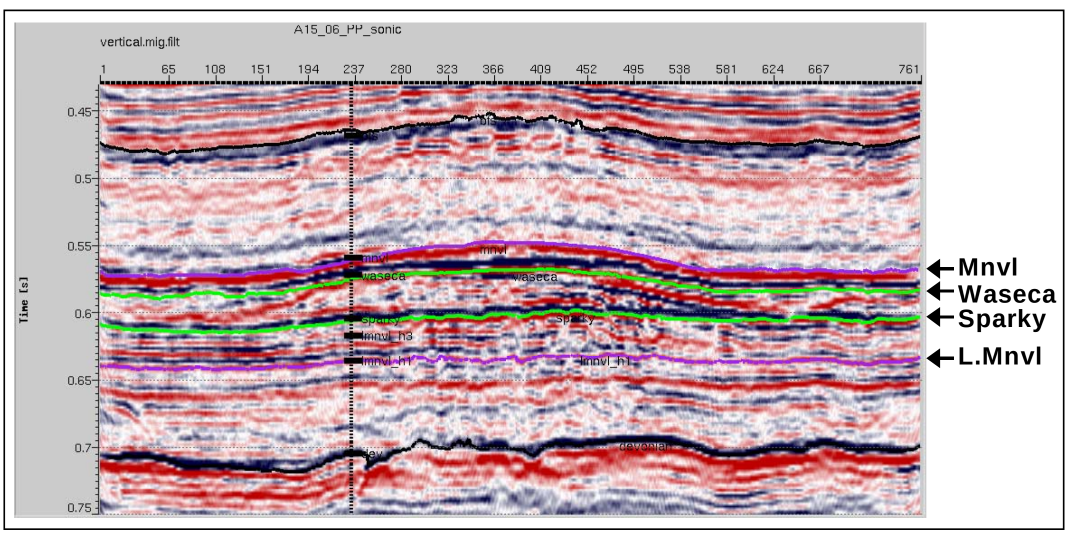

FIG. 7: H2000 interpreted P-P section (vertical component)

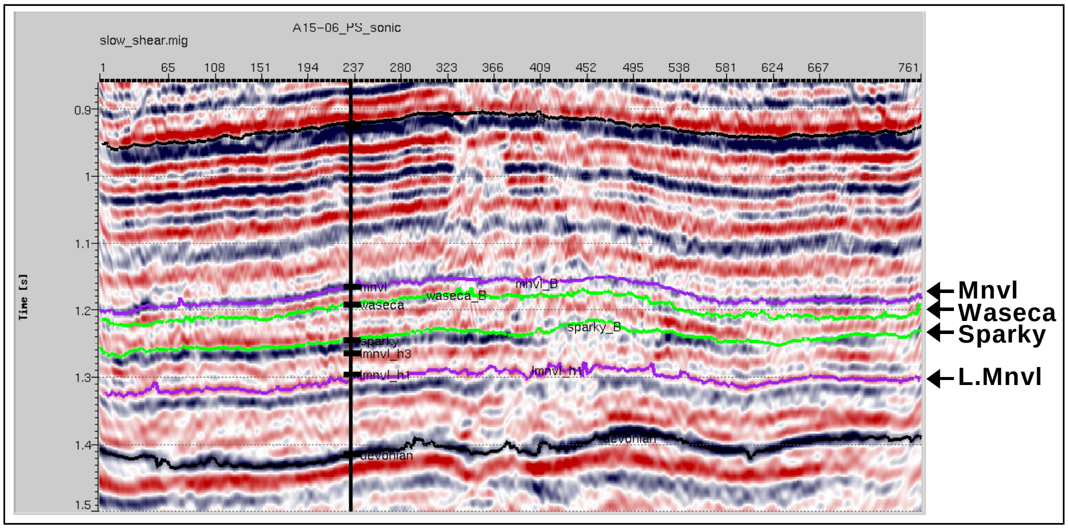

FIG. 8: H2000 interpreted P-S section (vertical component) (Note: different time scale)

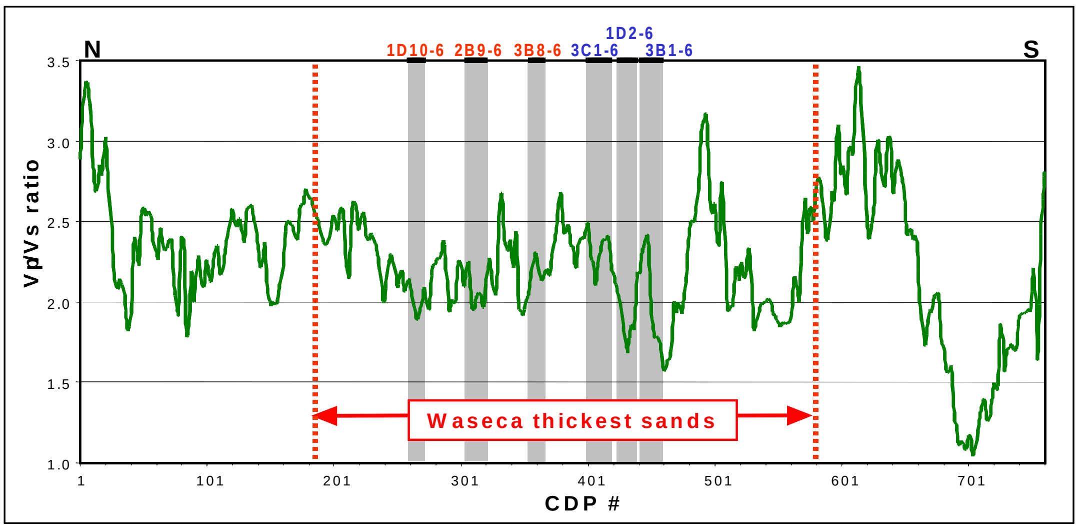

FIG. 9: VP/VS ratio plot of Waseca-Sparky interval.

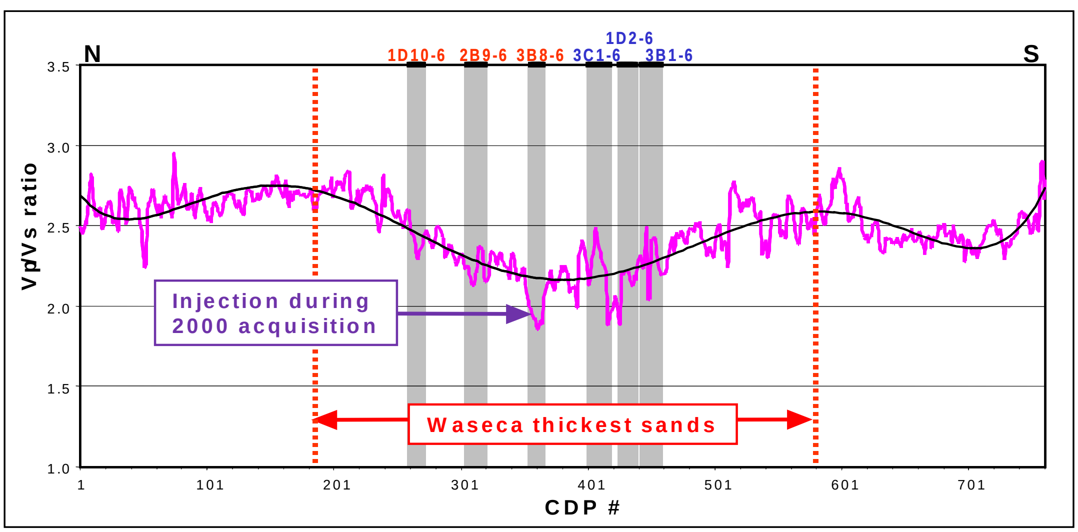

FIG. 10: VP/VS ratio plot of Mannville-Lower Mannville interval.

CONCLUSIONS

With interpreted seismic sections, these two relatively simple and quick techniques provide further insight into the effect of steam injection for heavy-oil reservoirs. In general, the anomalies were located where expected based on drilling results and injection/production data. A direct steam response can be inferred from the V_P/V_S ratio plots. Potential lateral lithology changes were observed. The time-lapse isochron analysis provided clues about the extent of the heated reservoir. These results, based on interval interpretations, are very sensitive to tuning and resolution. Bandwidth and phase must be carefully considered during interpretation to ensure that the same depth equivalent events are being tracked.

In this work and in previous inversion analyses the results are limited by the 2-D image. 3-D seismic data provides a dimension that allows the interpreter to validate anomalies statistically with the increased spatial sampling, eliminate the need for jump ties and take advantage of the volume perspective to view these anomaly types in a more convincing manner.

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