Geological interpretations from seismic data at Pikes Peak, Saskatchewan

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ABSTRACT

Coincident vertical array and multi-component 2D seismic lines are interpreted and integrated with geological data to further understand the geology of the Pikes Peak heavy-oil field in Saskatchewan. Using vertical array seismic data, a salt isochron method predicts the reservoir trap configuration and identifies the risk of bottom water in the Waseca reservoir. An interpretation of multi-component data over the reservoir interval allows for the calculation of the compressional to shear wave velocity (V_P/V_S) ratio. This ratio is compared with the percentage of sand in the reservoir interval from wells adjacent to the seismic line. Filtering for noise and the effects of steam and heat in the reservoir, the ability to predict the percent of clean sand in the reservoir has an 80% correlation coefficient.

INTRODUCTION

Husky Energy operates the field which is located 40 km east of Lloydminister, Saskatchewan. Over 42 million barrels of heavy oil have been produced from the Waseca Formation using steam-assisted recovery techniques. Figure 1 is a map of the Pikes Peak field with the location of wells and seismic lines. H1991 and H2000 refer to the overlapping time-lapse 2D seismic lines shot in February 1991 and March 2000, respectively. The H2000 data were acquired in two geophone configurations – vertical array and multicomponent (Hoffe et al., 2000). Four wells were used for synthetics ties.

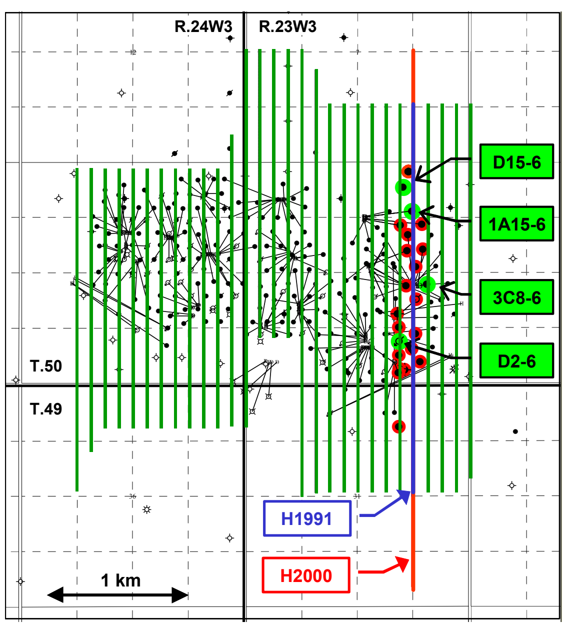

FIG. 1. Map of Pikes Peak field with wells and seismic coverage. 24 highlighted wells project 110 m or less on to the time-lapse seismic lines, H1991 and H2000.

The geological analysis of the Pikes Peak heavy-oil field follows from the time-lapse and multi-component analysis of two seismic lines (Watson et al., 2002). The geological setting and stratigraphy of the Waseca reservoir at Pikes Peak was described in detail by Van Hulten (1984). Two observations that Van Hulten made about the Waseca reservoir using well data were further investigated using the 2D seismic data that was acquired over the eastern portion of the field in March 2000. The first observation was how the heavy-oil is structurally trapped at Pikes Peak by differential salt dissolution in the deeper Devonian section. A seismic isochron method illustrates where the risk of bottom water in the reservoir interval is present on the flanks of the structure. A second observation was the amount of clean sand in the reservoir and how it can vary laterally. The same V_P/V_S ratio method used to identify areas of steam injection is further evaluated to quantitatively predict the percent of clean sand (< 45 API on the gamma ray log) in the reservoir. The V_P/V_S ratio method was used by Stewart et al., 1996 and Margrave et al., 1998 to evaluate the sand versus shale trends in the Glauconitic Formation at Blackfoot, Alberta. For both investigations, it is advantageous that interval traveltimes are used because the effect of processing statics is mitigated.

SALT ISOCHRON METHOD

The main mechanism that creates the trap at Pikes Peak is the partial dissolution of Devonian aged salts. The familiar name of this salt interval is the Prairie Evaporite. Figure 2 is a stratigraphic chart for the Pikes Peak area. The Prairie Evaporite is part of the Elk Point group. Regionally, this salt unit ranges in thickness from 0 to 150 thick. It is found approximately 825 meters below surface at Pikes Peak.

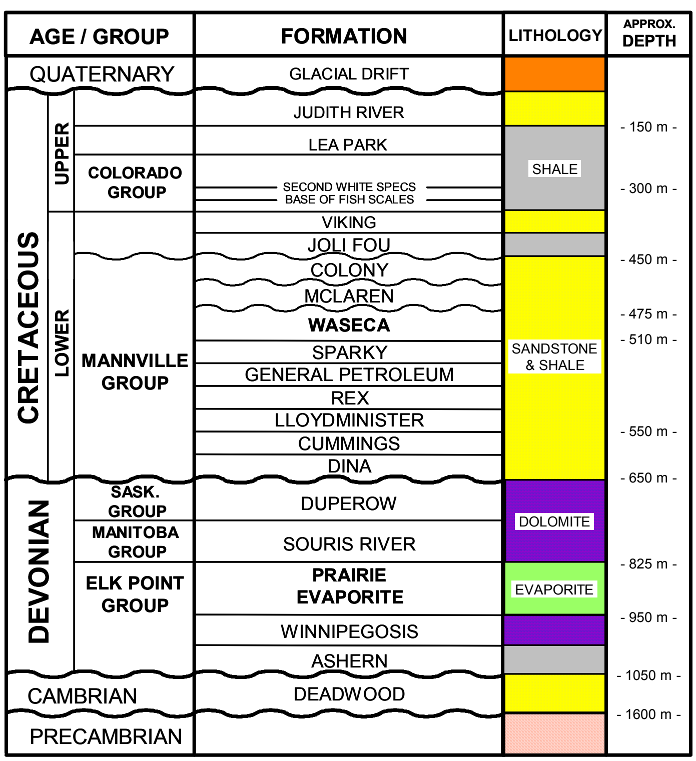

FIG. 2. Stratigraphic chart for the Pikes Peak area.

Figure 3 is a map of the greater Lloydminister area indicating the wells that were used to generate a cross-section of deep wells that penetrated through the Prairie Evaporite (after Van Hulten, 1984). The cross-section A-A' is shown in Figure 4.

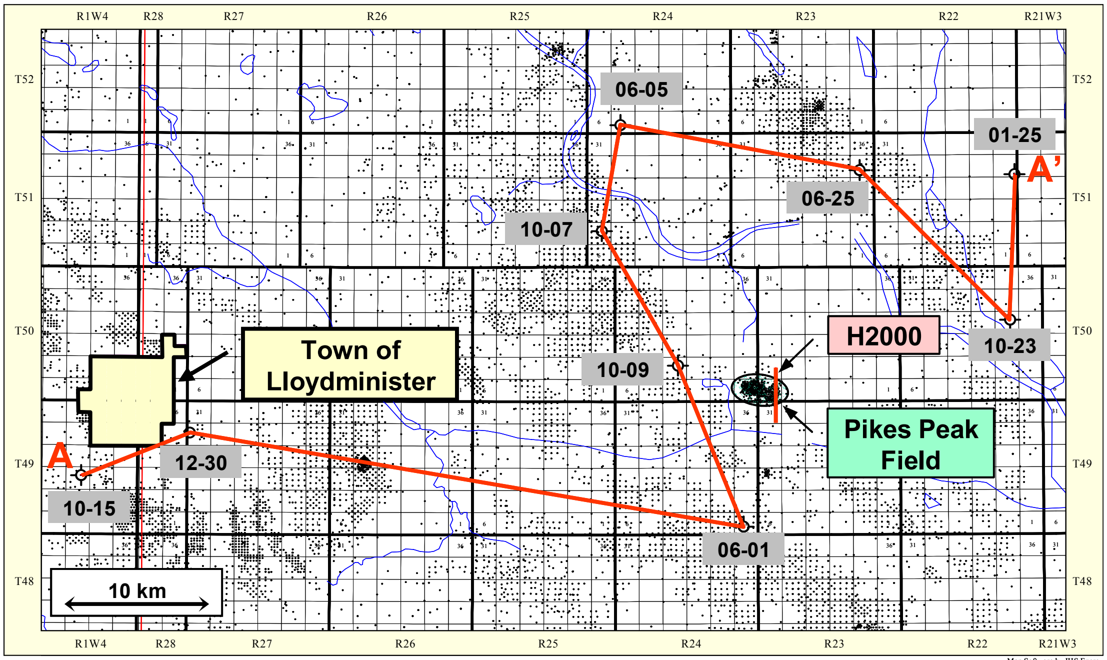

FIG. 3. Map of the greater Lloydminister area with cross-section A-A'.

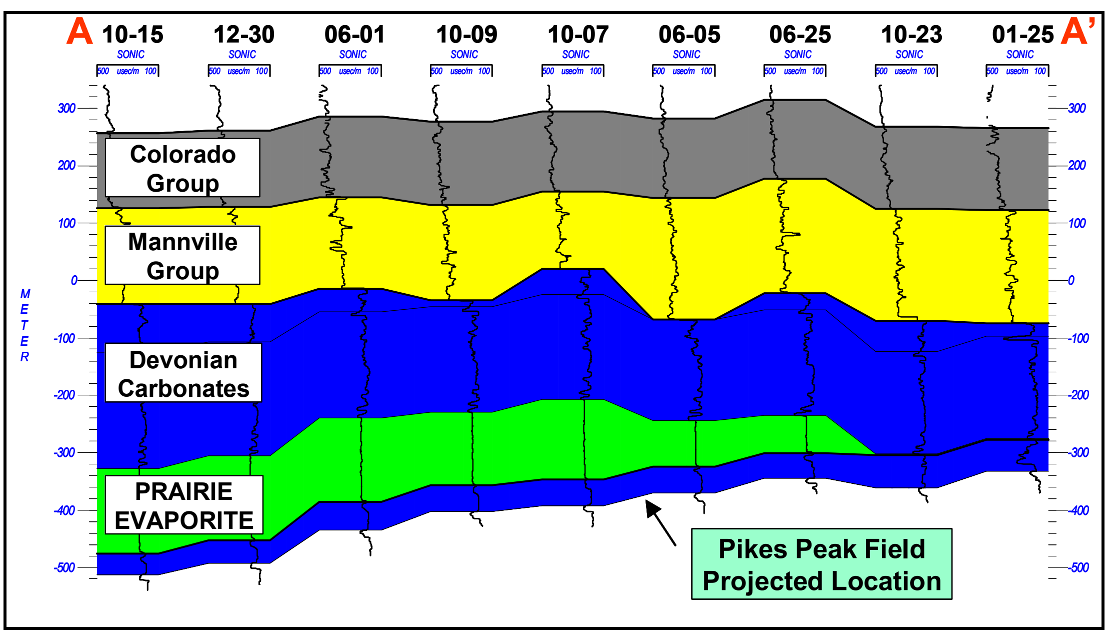

FIG. 4. Structural cross-section A-A' created with sonic logs (modified after Van Hulten, 1984). Note how the thickness of the Prairie Evaporite varies from 150 to 0 m (west to east) counter to regional dip (east to west).

As demonstrated in the cross-section, the salt unit thins from west to east along regional dip but there are exceptions where more (or less) salt was preserved. Dissolution occurred as the salt was exposed to fresh or low salinity water. The controls on the flow of this fresher water is uncertain but may be related to basement involved faulting which can act as a conduit. No wells within the Pikes Peak field were drilled deep enough to reach the Prairie Evaporite. The closest deep well, 10-09-50-24W3, was drilled seven kilometres west of the H2000 seismic line. A synthetic 'jump' tie was made to the middle of the H2000 (vertical array) seismic line. This tie is shown in Figure 5. The consistency of the geology above and below the Prairie Evaporite throughout the Lloydminister area allows for a high confidence tie. The tie is poorer at the top Devonian because different Devonian formations may subcrop at the Pre-Cretaceous Unconformity over the distance between the well and the seismic line. This subcrop variation can explain the difference in the acoustic response at the Pre-Cretaceous Unconformity.

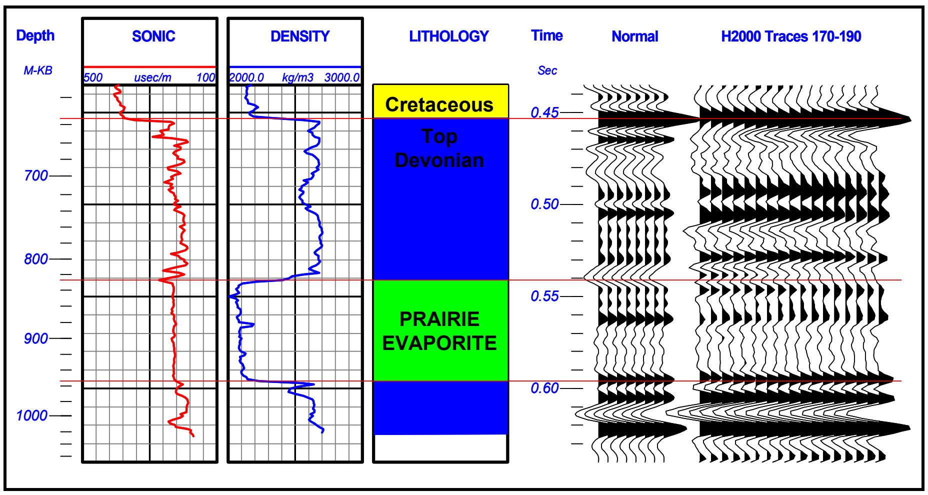

FIG. 5. Synthetic (normal polarity) tie from well 10-09 to H2000 over the Devonian section.

The synthetic tie was used to interpret the entire H2000 (vertical array) seismic line. (Note that the vertical P-P section from the multicomponent survey could have been used for this analysis but the vertical array data had a higher signal-to-noise ratio.) The top and base of the salt unit was interpreted and is shown in Figure 6. The base of salt is flat (in traveltime). The top of salt has structural relief. The Waseca reservoir interval is also interpreted. The Waseca interval subtly drapes over the salt structure. This drape suggests that the timing of the salt dissolution was post-deposition of the Waseca. The observed drape higher up in the section (BFS) may be caused by a combination of the salt dissolution and the differential compaction of the sand and shale Waseca interval. The thickest portion of the Waseca is dominated by sand which does not compact as much as where the shale content is higher and the Waseca is thinner.

The Prairie Evaporite isochron thickness or interval traveltime was calculated by subtracting the top of salt traveltime from the base of salt travel time. Shown on the left axis of Figure 7 is a line graph of the Prairie Evaporite isochron thickness along the length of H2000. On the right axis is the structural position of bottom water (metres above sea level) in the 24 wells within 110 metres of H2000. Where present, the blue bars represent the vertical thickness and structural position of bottom water in each well.

For example, the open-hole logs from well 1A15-6 (Figure 8) indicate that this well has 4 meters of fully water saturated sands at the base of the Waseca. The resistivity logs are used to discern the heavy-oil (high resistivity) saturated from the water (low resistivity) saturated sands.

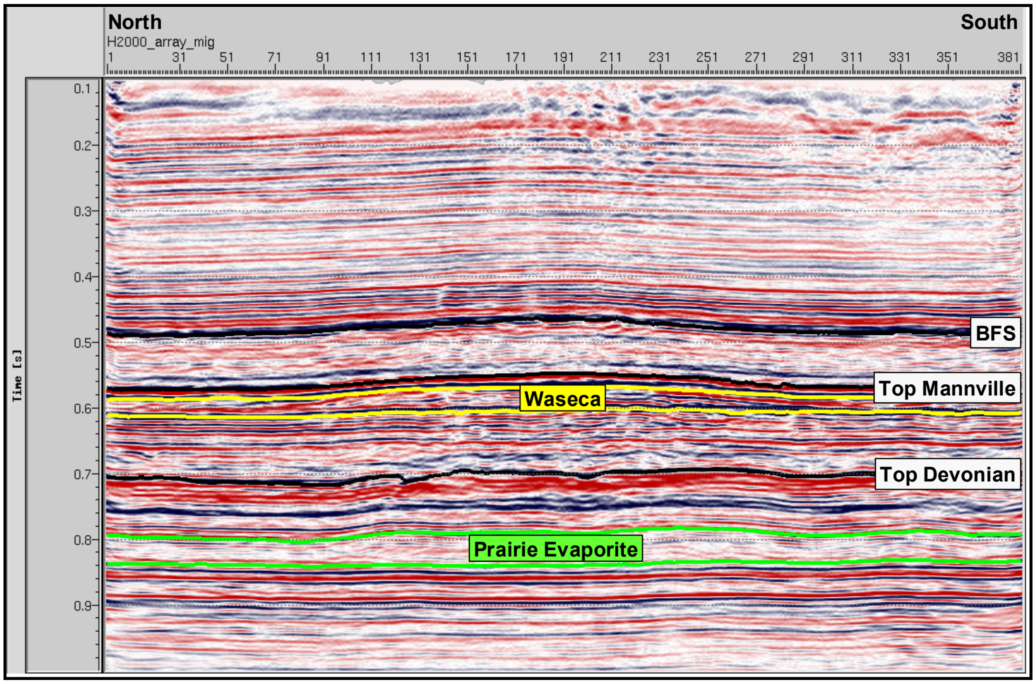

FIG. 6. H2000 (vertical array) seismic line with an interpretation of the top and base of the Prairie Evaporite and other major horizons.

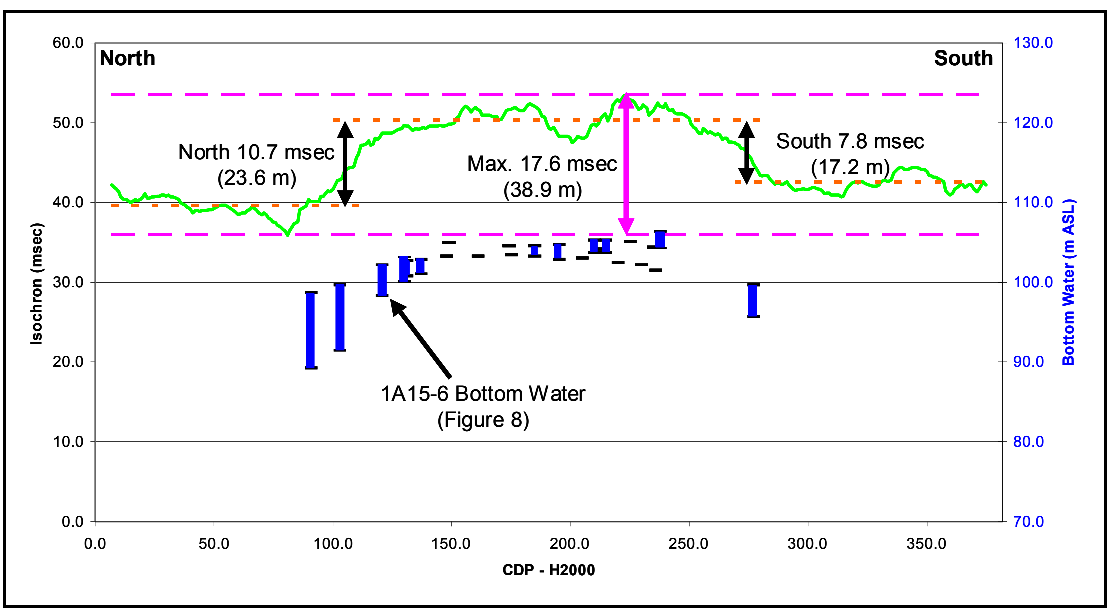

FIG. 7. Chart of the isochron thickness of the Prairie Evaporite (left axis) and the structural position of bottom water in the Waseca reservoir in the wells along H2000 (right axis)

The most salt preserved is from CDPs 100 to 270. Using the sonic logs from the wells in the regional cross-section A-A' the velocity of the Prairie Evaporite interval was calculated by integrating the sonic transit time. The average velocity was 4412 m/s with a standard deviation of 38 m/s (or less than 1%). Taking the product of interval traveltime and the average velocity, the relative thickness of salt removed could be estimated. Over the length of the line the maximum amount salt thickness difference was 17.6 msec or 38.9 m. Compared with the central portion of the line, the north end of the line had an average of 10.7 msec or 23.6 m more salt dissolved. Similarly, the south end of the line had an average of 7.8 msec or 17.2 m less salt than the central portion of the line.

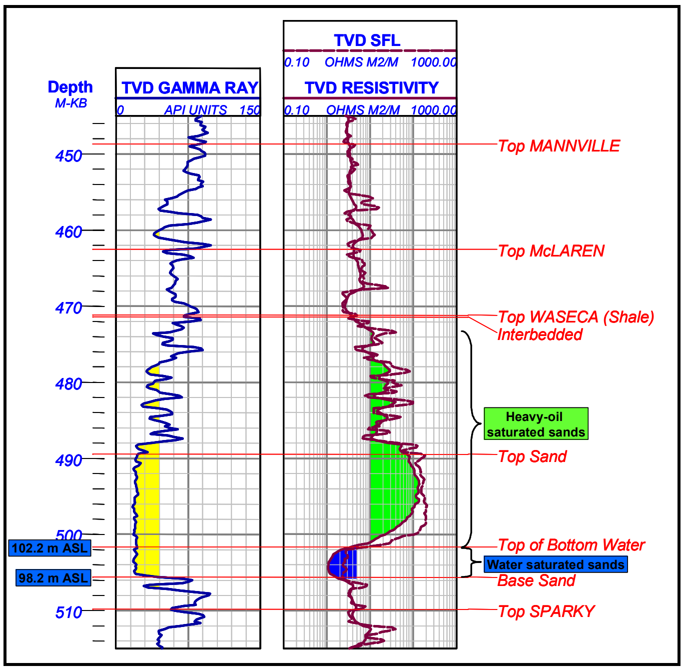

FIG. 8. Gamma ray and resistivity logs from sample well, 1A15-6, over the upper Mannville. 4 m of bottom water is present at the base of the Waseca sands.

Most of the producing wells are found in the central portion of the line in the structurally highest positions. The three wells outside of the 100-270 CDP range (two to the north and one to the south) are non-producing wells. The presence of bottom water in the Waseca is a concern for reservoir engineers at Pikes Peak. If the steam that is injected into the reservoir connects to the bottom water, the bottom water acts as a thief zone. The steam will preferentially go into the bottom water zone. The heavy-oil will not be heated sufficiently to reduce its viscosity which allows it to flow. This can result in a significant loss of heat energy.

One other observation from the structural position of the bottom water is that the heavy-oil – water fluid contact is not flat. Van Hulten made this observation and suggested that it was related to structural movement combined with the inability of the high viscosity oil to move and re-establish a flat fluid contact. The structural movement can be explained with the differential dissolution of the Prairie Evaporite or differential compaction.

V_P/V_S SAND ANALYSIS

In Watson et al., 2002, an anomalous drop in the V_P/V_S ratio was seen at a well, 3B8-6, that was undergoing steam injection during the acquisition of multi-component version of H2000. It was qualitatively observed that on the scale of the entire seismic line there was smooth trend line in the V_P/V_S ratio indicating a long-period effect that corresponded to the thickest Waseca sands. The shale content is higher in the wells to the north and south. (Note there were twice as many CDPs in the multicomponent data acquired than in the vertical array data.)

Using the interpretations from Figure 9, the V_P/V_S ratio is calculated using interval traveltimes with the equation below:

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

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 ratio equation is derived by expressing the thickness of a depth interval in terms of P-wave and S-wave traveltime. For this technique to work properly it is imperative that the interpreted intervals on the two sections are geologically time equivalent. The smaller window, Waseca-Sparky, was examined first but noise overwhelms the ratio plot and it is difficult to infer any steam effects. On the left axis of Figure 10 is a plot of the V_P/V_S ratio for the Mannville-Lower Mannville interval. This analysis was much less noisy and steam effects could be detected at the 3B8-6 well.

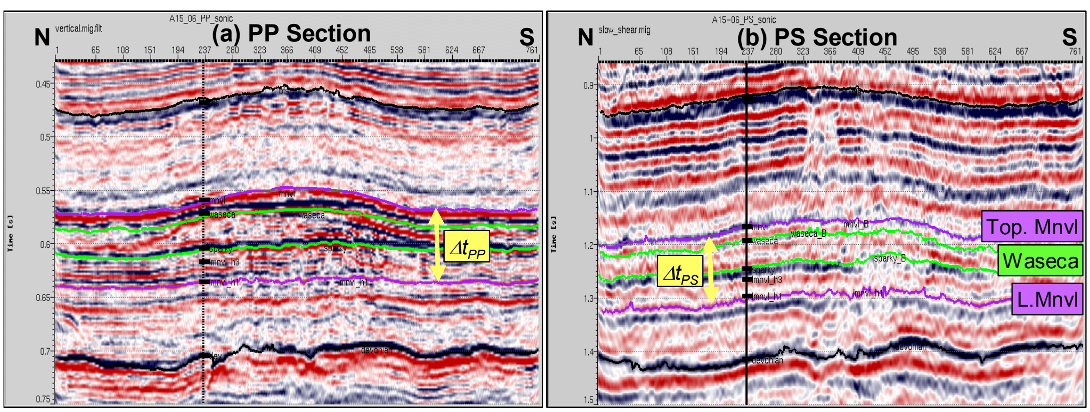

FIG. 9. Interpreted (a) PP (vertical component) and (b) PS (radial component) H2000 sections. Note the different time scales (modified after Watson et al., 2002).

The low frequency trend observed in the V_P/V_S ratio analysis (Figure 9) has a high correlation with an evaluation of the sand percent in the wells along the H2000 2D profile. On the right axis of Figure 10 is a plot of the percent of sand in the Waseca interval. The percent sand was measured by taking the net pay (less than 45° API on the gamma ray log) and comparing it to the gross thickness of the Waseca. For example, the gamma ray log from well 3B9-6 (Figure 11) has 18 m of clean sand using the 45° API cut-off. The Waseca is 31.7 m thick at this well. Therefore, 57% of the Waseca is clean sand at this well location. This measurement was made for 23 (of 24) wells within 100 m of H2000. One well was excluded because it was an outlier and over 100 m east of the H2000 survey. The geology or sand percent in the reservoir can vary significantly over short distances (less than 50 m). The trends of V_P/V_S ratio and the percent sand in the wells match very well.

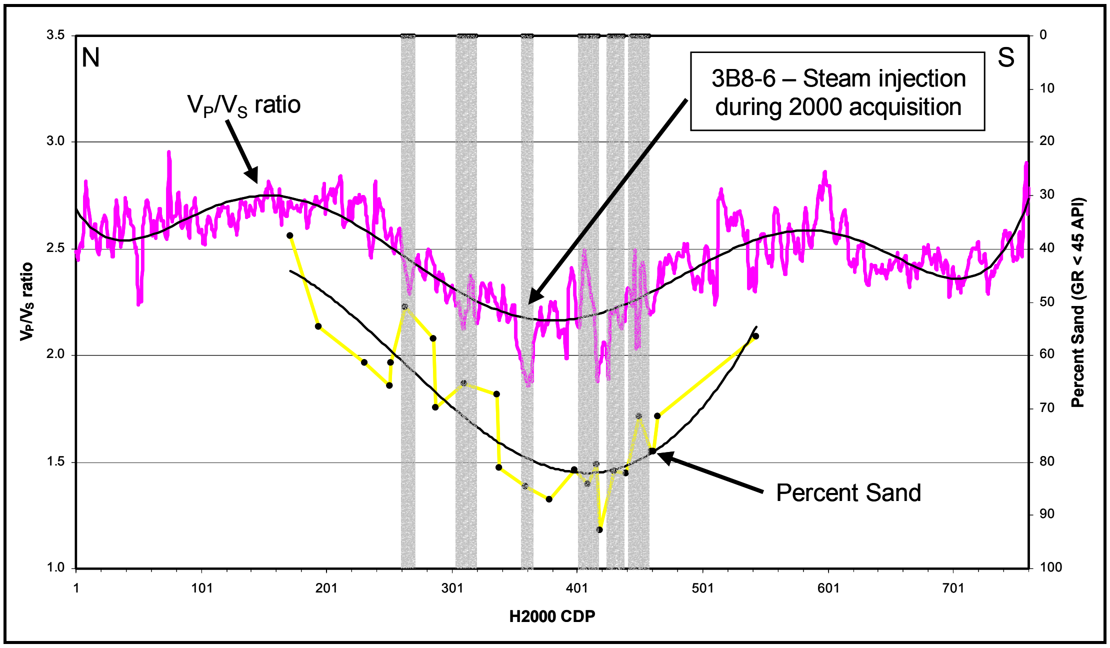

FIG. 10. Comparison of V_P/V_S trend line (left axis) with percent sand (reversed right axis) in the wells along H2000 (converted wave) (modified after Watson et al., 2002)

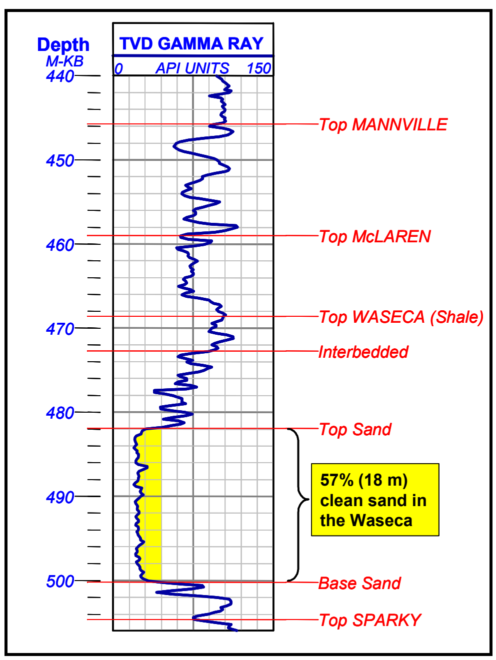

FIG. 11. Gamma ray log from well 3B9-6 indicating 57% sand (or 18 m) within the Waseca interval using a 45° API cut-off.

Figure 12 is a cross-plot of sand percent versus V_P/V_S ratio, taken from the polynomial trend line. The polynomial trend line filters out the effects of steam injection and noise. This cross-plot gives an 80% correlation coefficient using the 23 wells. The 80% correlation is very high given these quick changes in geology and the noisy data. It suggests that the V_P/V_S ratio can be a robust method to discern sand quality in a mixed lithology reservoir.

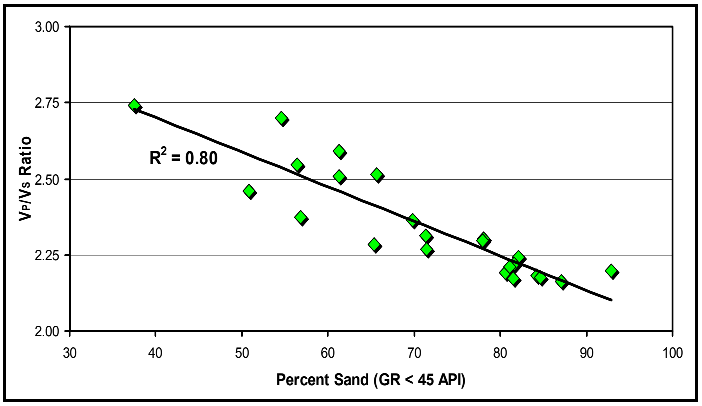

FIG. 12. Cross plot of V_P/V_S trend line versus percent Waseca sand in 23 wells along H2000

CONCLUSIONS

Seismic data have the advantage of imaging a larger and continuous portion of the subsurface than well data can provide. The cost is resolution. Working within the boundaries of that resolution and appropriate scaling of well data allow the integration of the two data types. This dual investigation successfully shows how the understanding of a mature reservoir can be enhanced through this data integration. The salt isochron method provides a predictive tool to assess water bottom risk in the Waseca reservoir at Pikes Peak. The V_P/V_S ratio method can predict with high confidence where the thickest clean sands are found. Both of these methods can be used as the geoscientists and engineers delineate the remaining potential in the Waseca reservoir at Pikes Peak. The results of this study and the Watson et al. (2002) paper demonstrate how much reservoir surveillance and understanding can be gathered from a single multicomponent survey at any time in the development of a field.

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