Delineating a sandstone reservoir at Pikes Peak, Saskatchewan using 3C seismic data and well logs

Natalia L. Soubotcheva and Robert R. Stewart

ABSTRACT

To maximize the production from mature fields, it is important to know the shape of the reservoir and its continuity. In this paper, well log data and multicomponent seismic are combined to delineate a sandstone reservoir at the Pikes Peak heavy oil field, Saskatchewan.

We generate PP and PS synthetic seismograms to correlate events with the surface seismic data. The productive formation has a Vp/Vs value noticeably lower (1.7) than the overlying formations (which are around 4.4). The top of the productive interval is interpreted as a PP impedance drop (to 5010 m/s*g/cc) and PS increase (to 3066 m/s*g/cc). Inversion and various seismic attributes were used to predict the density along the seismic line: the Waseca oil sands are characterized as a low-density (2.17 g/cc) zone.

INTRODUCTION

The Pikes Peak oil field is located 40 km east of Lloydminister, Saskatchewan (Figure 1) and produces heavy oil (12° API) from the Waseca sands of the Lower Cretaceous Mannville Group. Hulten (1984) provided a comprehensive geologic description for the Waseca formation in and around the Pikes Peak field. Over 42 million barrels of heavy oil have been produced at this site over the last 22 years. Presently, it is one of the larger oil fields in Canada with a daily production of about 8000 barrels. (Husky Energy reports, 2004).

Considerable effort has been expended to understand the effects of steam injection in this area. Lines (2001) performed an AVO study to map the steam chamber. Zou (2001) conducted time-lapse seismic modelling at Pikes Peak. Watson (2004) investigated acoustic impedance inversion and showed the stratigraphy of the reservoir. Xu and Stewart (2001) reported on the acquisition and processing of VSP data. Newrick et al. (2001) presented an investigation of seismic velocity anisotropy at Pikes Peak using VSP data.

The primary objectives for this paper are to i) correlate the well logs and surface seismic data, ii) generate the PP and PS synthetic seismograms, and iii) analyze the Vp/Vs along the seismic line as extracted from PP and PS seismic data using time-thickness. In addition, post-stack seismic inversion methods were used to estimate impedance values. A cokriging method was next applied to integrate the sparse well measurements and the seismic data to estimate the density along the seismic line. Finally, a low density zone was detected at the southern part of the seismic line.

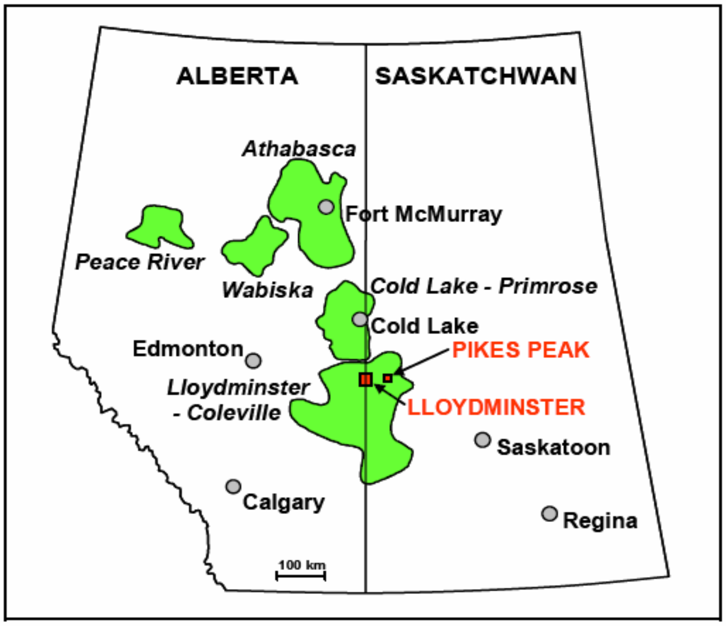


FIG. 1. Map of major heavy-oil deposits of Alberta and Saskatchewan, and location of the study area. (Watson, 2004)

GEOLOGY

The Pikes Peak heavy oil field is situated in the east-central part of Western Canada sedimentary basin. The productive Waseca formation is located about 500 m below the surface, and its thickness varies from 5 to 30 m. (Figure 2).

The top of the Precambrian basement lies at a depth of approximately 1600 m. There are essentially Devonian and Cretaceous age formations above the basement. The dominant lithologies of the Devonian formation are limestone and dolomite, with the exception of the Prairie Evaporate, which consists largely of salt. The dissolution of this Devonian salt played an important role in forming the hydrocarbon trap at Pikes Peak.

There is a 250 Ma gap between the Devonian and Cretaceous formations. This boundary is also known as PreCretaceous Unconformity. A variety of mixed sand and shale cycles were deposited above this Unconformity, and they formed the Lower Cretaceous Mannville group. The Cretaceous strata dip largely to the southwest (Hulten, 1984).

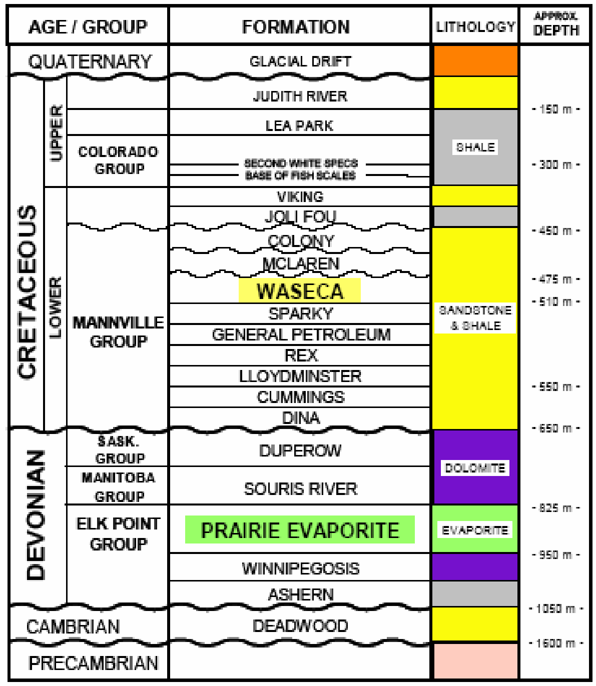


FIG. 2. Pikes Peak stratigraphy (after Core laboratories Stratigraphic Chart for Saskatchevan).

The productive Waseca formation consists of three main facies (Hulten, 1984). From the top to the bottom they are:

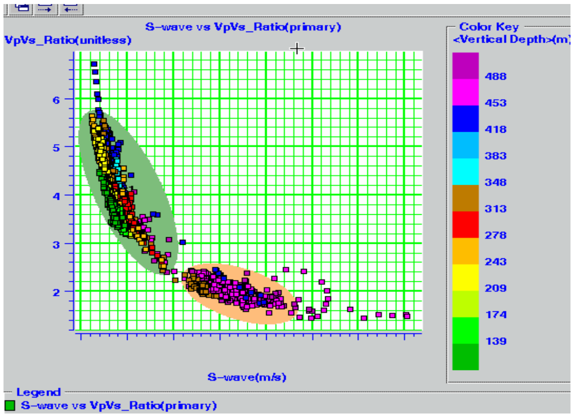
1. sideritic silty shale unit;

2. interbedded sand and shale unit;

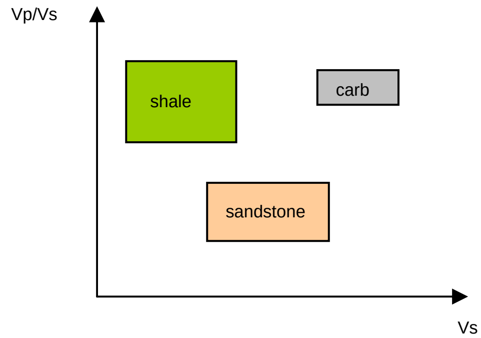
3. homogeneous sand unit.

The homogeneous sand, which is saturated with heavy oil, is the main target for development. This unit has the greatest thickness and continuity across the reservoir. The sands are well sorted, fine to medium grained. The interbedded unit is characterized by lamination of sand and shale, which makes well log data “highly variable” in this part of a section. The upper shale unit plays the role of a cap for the hydrocarbon trap. It has low porosity and permeability, and creates a seal over the oil or water saturated sand. The trapping mechanism at Pikes Peak is considered to be both structural and stratigraphic: its stratigraphic component comes from the sealing shale unit and the structural component is determined by the dissolution of the Prairie Evaporite.

Available log suites for most wells include P-wave sonic, density, gamma-ray, resistivity and SP logs. A simple way to differentiate the lithologies is to crossplot the Vp/Vs ratio versus Vs. (Figure 3).



(a)



(b)

FIG. 3. (a) Vp/Vs versus S-wave velocity for the well 1A15-6 and (b) a schematic lithology estimation using P- and S-wave data (from Treitel and Lines, 1994).

This crossplot was created for well 1A15-6 which of all the wells is the closest to the seismic line. Different colored points represent different depths. We can delineate two distinct zones of Vp/Vs and Vs values using this plot. In our case, two major types of lithology were selected. Applying this result to the cross section (Figure 4), we can observe the upper shales (green) between 130 and 440 m, the interbedded sand and shale (blue) between 440 and 460 m and the homogeneous or oil sand unit (purple) at a depth 460 – 510 m for this well. This result slightly varies from well to well at Pikes Peak, however the same sequence is observed along the whole section from north to south

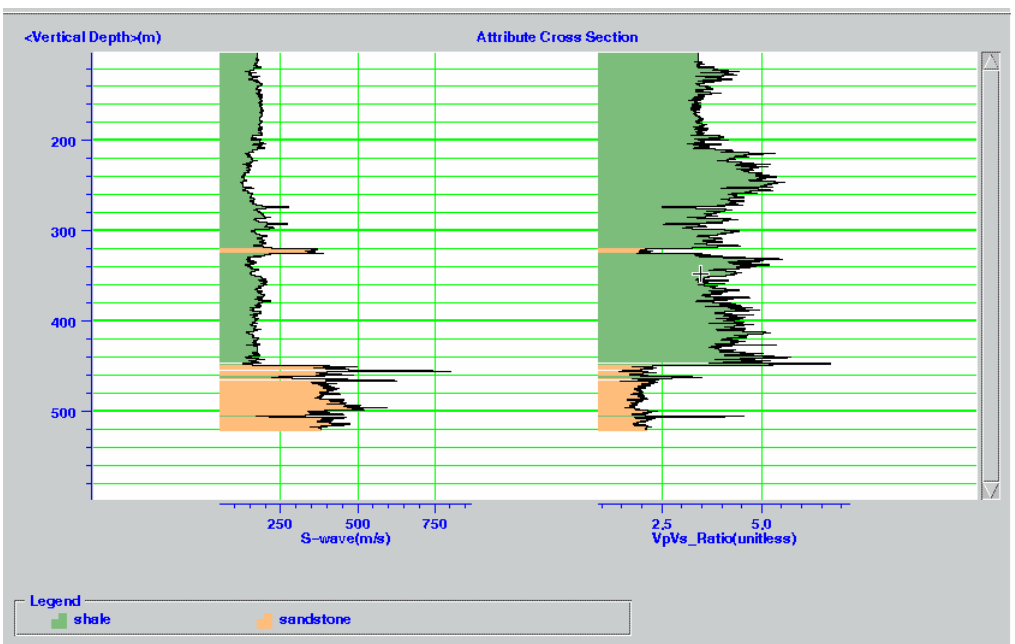
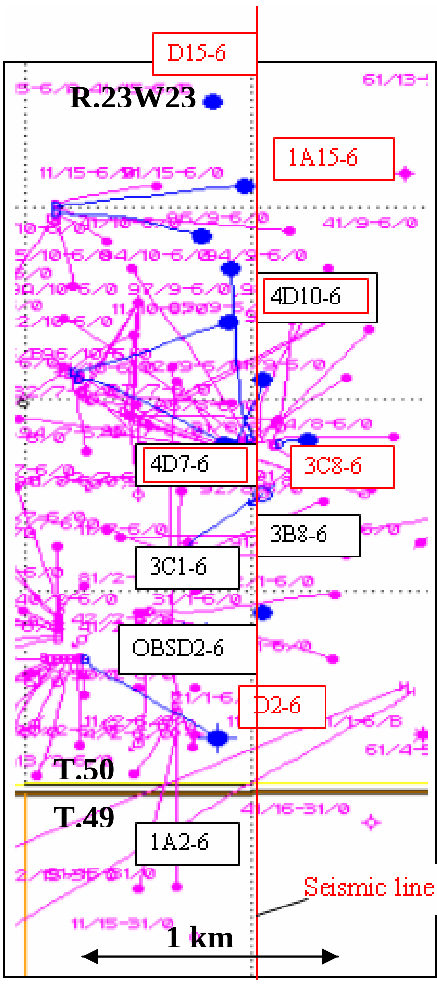


FIG. 4. Cross section for the well 1A15-6 delineating zones with different lithology: shales, interbedded sand and shale and oil sand.

WELL LOG CORRELATION TO SEISMIC DATA

A three-component seismic line, shot with a Vibroseis source, was collected in March 2000 by the CREWES Project and Husky Energy (Figure 5). This line was about 3.8 km long with a receiver interval of 10 m and a source interval of 20 m (Hoffe, 2000). Nine wells, closest to seismic line (lie within 110 m of the 2D seismic line) were used for this project.



well	CDP
D15-6	195
1A15-6	231
4D10-6	252
3C8-6	337
4D7-6	339
3B8-6	360
3C1-6	409
OBSD2-6	416
D2-6	419
1A2-6	462

FIG. 5. Map of the Pikes Peak field, Saskatchewan with the well list used in the project.

The starting point of this geophysical interpretation is the correlation of the well logs to the seismic data. By convolving the reflectivity and wavelet at the well location synthetic traces (blue color) are generated. Then each pick from the synthetic trace was correlated to each pick from real seismic data (red color). (Figure 6). The well log was tied to datum according to this correspondence.

Figure 6 demonstrates this application for well 1A15-6 corresponding to data around CDP 231 on the seismic line.

Six blue traces on the left represent the zero-offset synthetic seismogram for this well. After proper correlation, we can see that our synthetic trace (in blue) matches the real seismic trace, extracted at the well location (in red). The similarity between these two traces is shown in the window below (correlation – 64%).

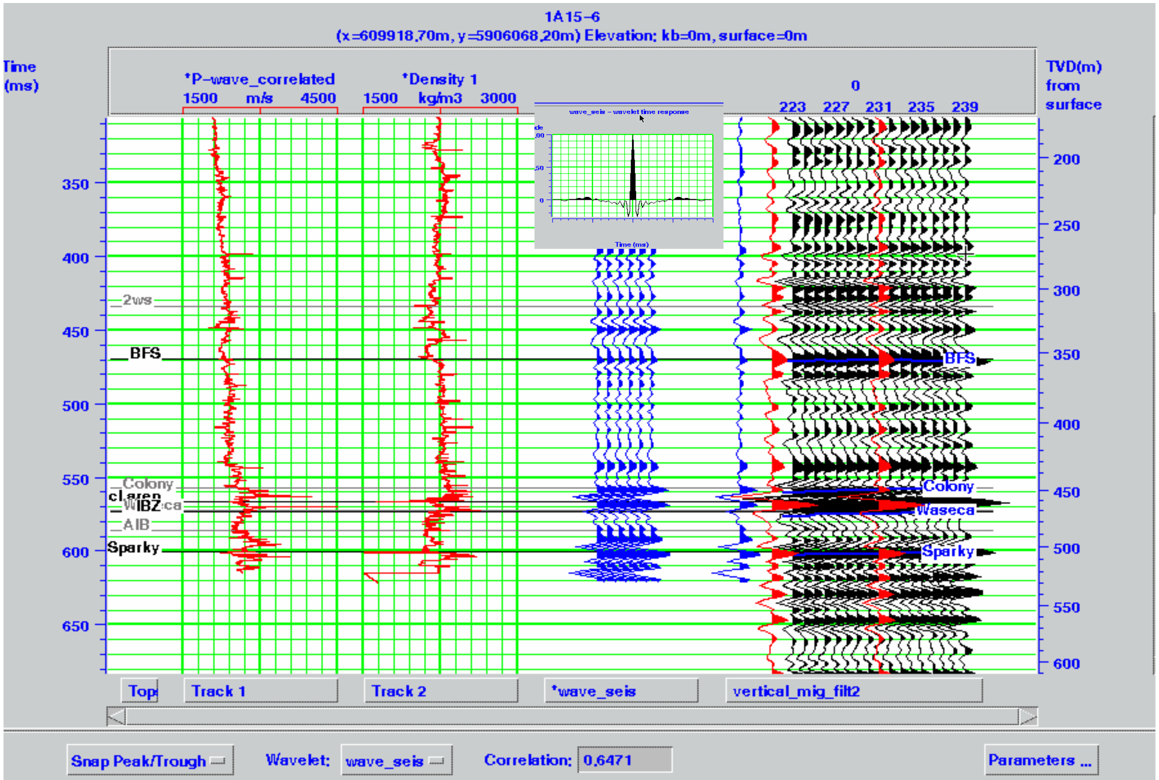


FIG.6. Well log, synthetic and seismic correlation for the well 1A15-6.

The wavelet for the synthetic seismogram was extracted from the seismic data, and we assume that it is constant with both time and space. The wavelet parameters are: wavelet length – 200 ms, taper length – 25ms, sample rate – 2ms, frequency spectrum 10-150 Hz (the same as the final filter used in the seismic data).

According to this correlation four possible layers have been identified (Table 1). The well did not encounter the Devonian level. However, according to Hulten (1984), this formation would be found at about 640 m, and it is mainly represented by dolomite.

Table 1. Four layers from correlation of the well 1A15-6 and the PP seismic data.

Formation Name	Depth of Top (m)
BFS (Base of Fish Scale)	357
Colony	453
Waseca	474
Sparky	507

Similarly, the other wells from the project were correlated to the surface seismic data and the PP and PS synthetic seismograms were generated for the wells of interest.

We can assemble well logs, synthetic seismograms, VSP data, and surface seismic data into a composite plot, which often allows a more confident interpretation (Figure 7). The VSP at Pikes Peak was conducted in the D15-6 well, which is fairly close to our seismic line. This well was chosen because it had not been used for reservoir steaming, and it penetrated all the major area formations (Osborne and Stewart, 2001).

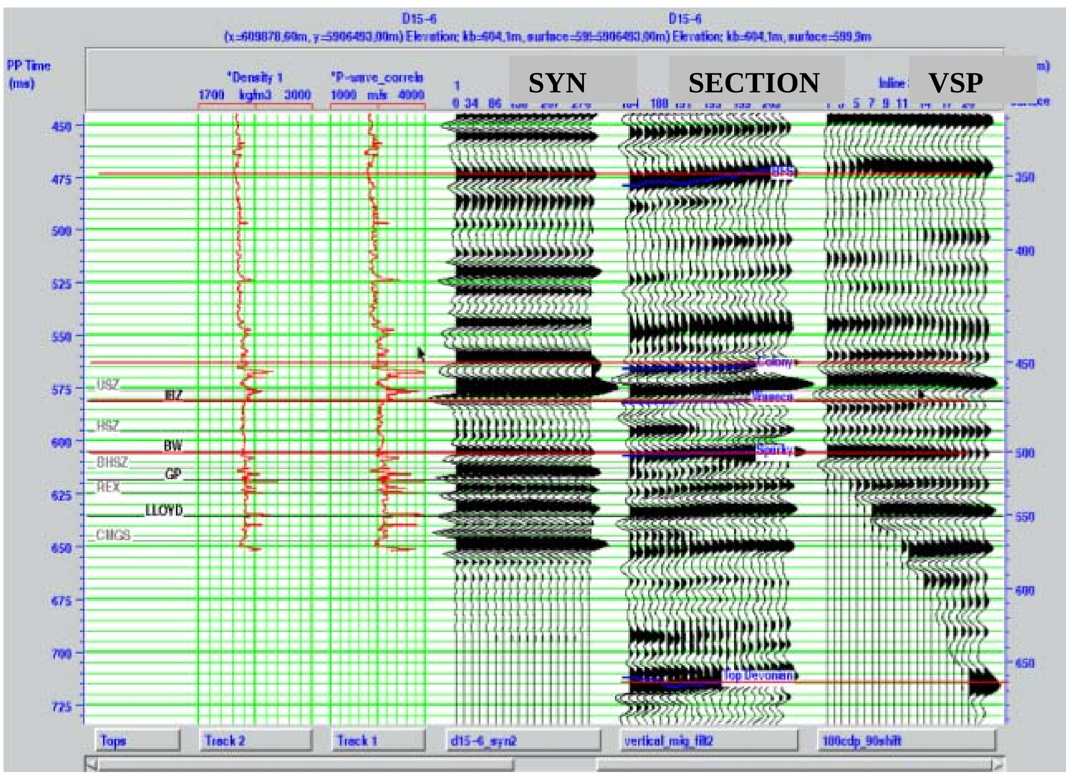


FIG. 7. Composite plot for the well D15-6 showing logs, synthetic seismograms, surface seismic and 180 m offset VSP; where the bandwidth for the synthetic and seismic data is 8-140 Hz and for VSP 8-120 Hz (Osborne and Stewart, 2001).

According to the acquisition parameters (Osborne and Stewart, 2001), the last geophone was clamped at a 514.5 m depth in the well. If we refer to Figure 7, the last event registered by VSP has about the same depth.

As we can see from the Figure 7 the VSP confirms our preliminary interpretation. All the main events correlate well with all types of information.

VP/VS ESTIMATION

Dividing P-sonic velocities by the S-sonic velocities provides a Vp/Vs value (Figure 8), which is important for oil-saturated sand discrimination. So, the productive formation has Vp/Vs noticeably lower (1.7) than the overlying formations (around 4.4).

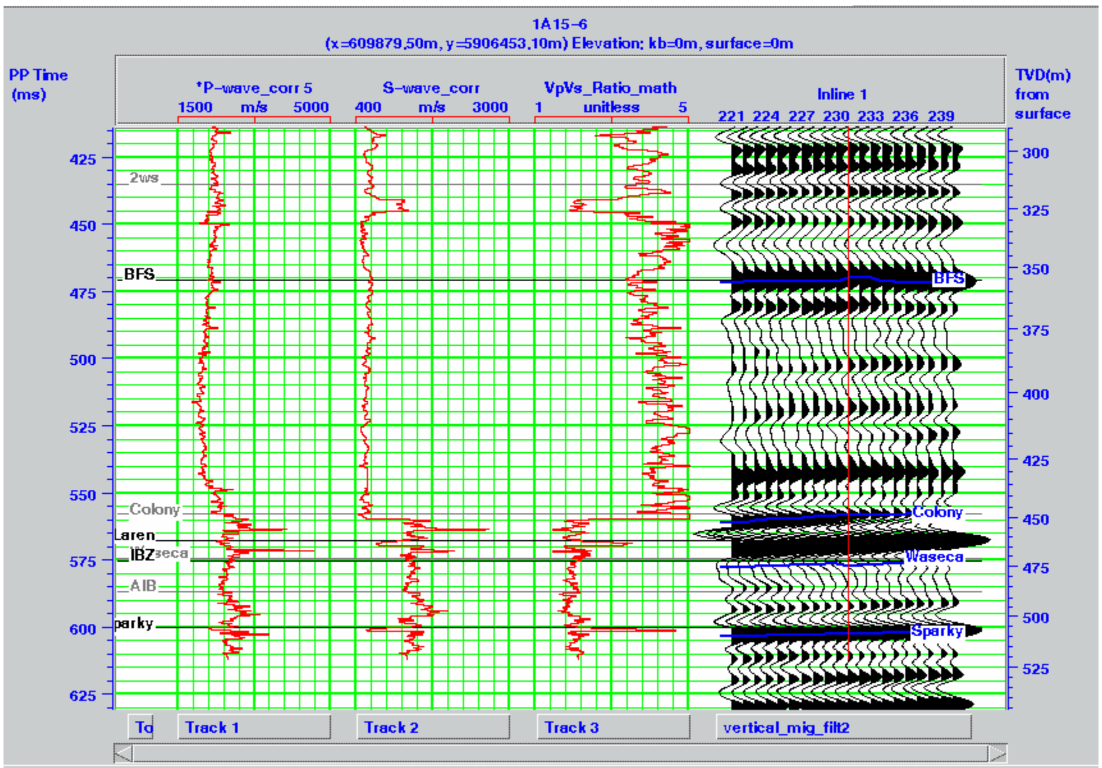


FIG. 8. Calculated Vp/Vs ratio for well 1A15-6.

Since we have now interpreted both PP and PS horizons, we can link the corresponding horizons in the multicomponent seismic interpretation package, ProMc. The program calculates a Vp/Vs value between the horizons and plots the color section of Vp/Vs along the entire line. This color Vp/Vs overlay is shown with a PS line in Figure 9.

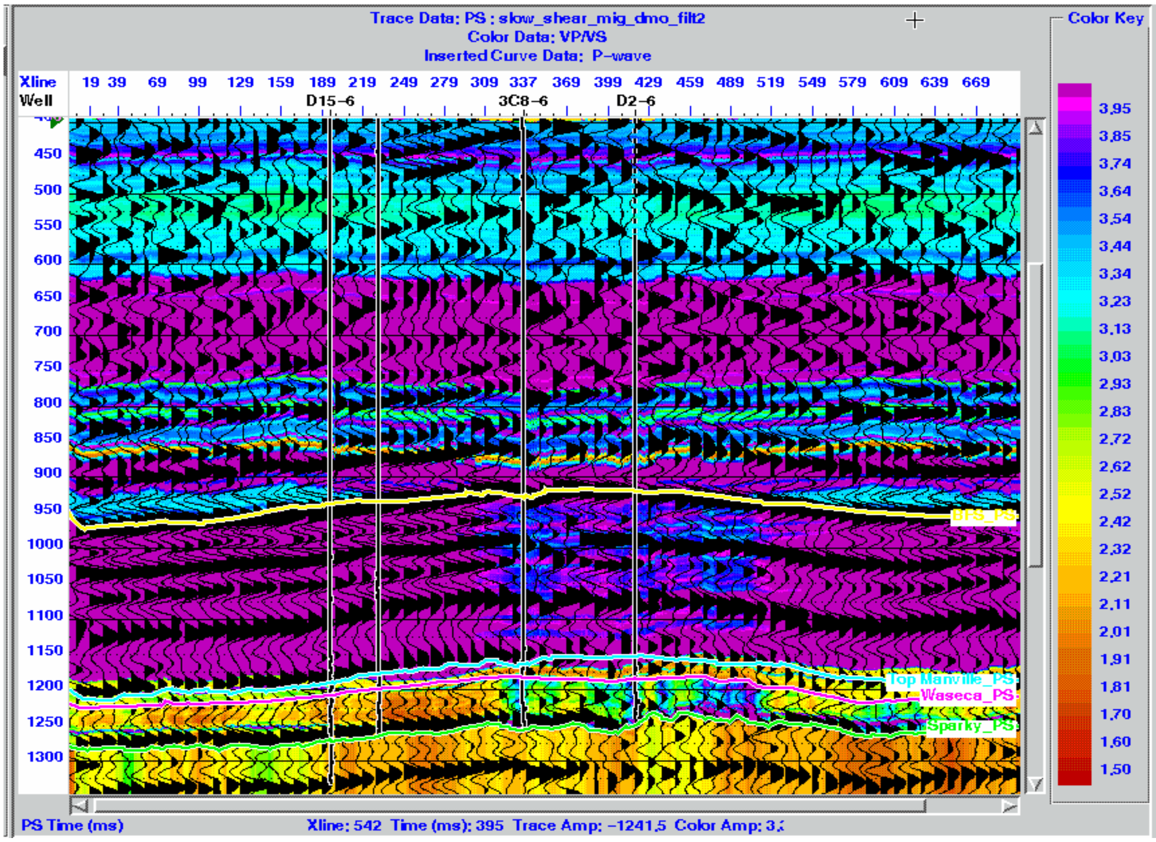


FIG. 9. Vp/Vs ratio along the PS section.

To compute the Vp/Vs along the seismic line ProMc uses the following formula:

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

where Δt_{PP} and Δt_{PS} - the time thickness between the interpolated horizons on PP and PS data set accordingly.

A drop from 4.4 to 3.6 in the seismic Vp/Vs value may be explained by effect of steam injection into the wells. It was shown by Watson (2003) that the injection of the steam causes increase in travel time and a decrease in both Vp and Vs velocities. However, Vp decreases at a greater rate than Vs, which causes Vp/Vs to drop near the recently injected wells: 3C8-6 and D2-6. Wells D15-6 and 1A15-6 do not exhibit any anomalies since they were not recently injected.

We can trace the general tendency of Vp/Vs: it is quite high in the Mannville shale (around 4) and goes down in the productive sand interval with the exception of coal layers. The coal layers typically have higher Vp/Vs. In our case, this value goes up to almost 4 within thin coal layers of Waseca (at about 600 ms). The productive interval has Vp/Vs of around 1.5 which is in reasonable accord with the well log data (Figure 8).

The Waseca-Sparky time interval of almost 25 ms correlates to a depth thickness of around 35 meters. Thus the Vp/Vs indicator represents an average across this depth interval.

PP INVERSION

Inversion can be defined as a procedure for obtaining models which adequately describe a data set. (Treitel and Lines, 1994). For this seismic case, post-stack migrated data play the role of the data set to be inverted, and the acoustic impedance is the desired property to estimate. Our zone of particular interest is the Waseca formation, which will be analyzed in detail in terms of the impedance anomalies. Since all inversion algorithms suffer non-uniqueness, it is important to use some external information to limit the number of possible models, which agree with the input seismic data. Well log data provides the additional information to constrain our model and to make the inversion result more accurate.

With our wells now correlated to the seismic data, we can proceed with the inversion in the software package Strata. Using the convolution model of seismic traces, $S(t) = r(t) * w_s(t)$, and the wavelet extracted from the seismic data, we begin the inversion process.

The initial geologic model was based on four sonic logs and four structural horizons. Then, this model was used to constrain the inversion.

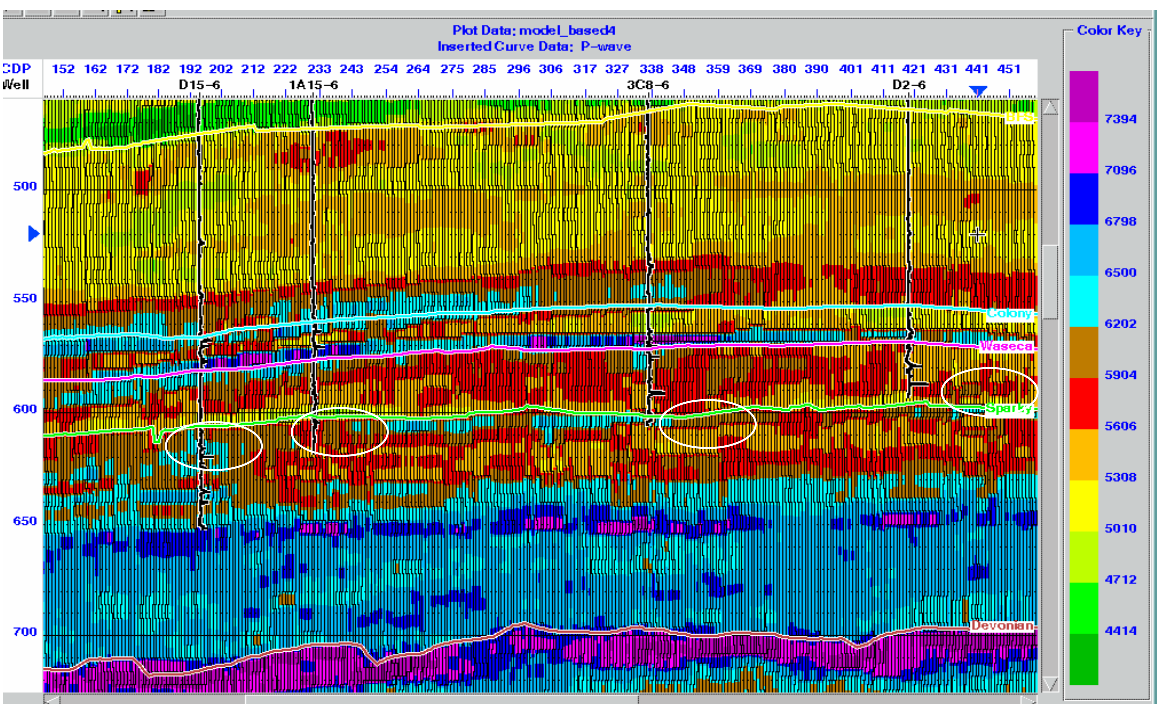


FIG. 10. Model-based PP inversion.

We tried a number of inversions, but one of the best results (as determined by continuity and correspondence to well information) is shown in Figure 10. As expected, the impedance increases with depth with the exception of the productive zone (yellow color on the picture). The sand channel appears here as a low impedance anomaly.

PS INVERSION

First, we transform the PS dataset to the PP time domain. After picking the horizons and extracting the wavelet for PS data in the PP domain, we employ the same inversion routine to invert the data using S wave reflectivity. Thus the PS inversion flow mainly repeats the PP inversion flow with the difference that the initial model is created using an S-Impedance. Since at Pikes Peak we only had one S-wave sonic, it was used to construct the initial model. PS horizons in PP time were also included into the model.

The result of the model-based inversion with the corresponding well is shown in Figure 11. Here the productive formation is recognized as an impedance increase (as opposed to a decrease in the PP case).

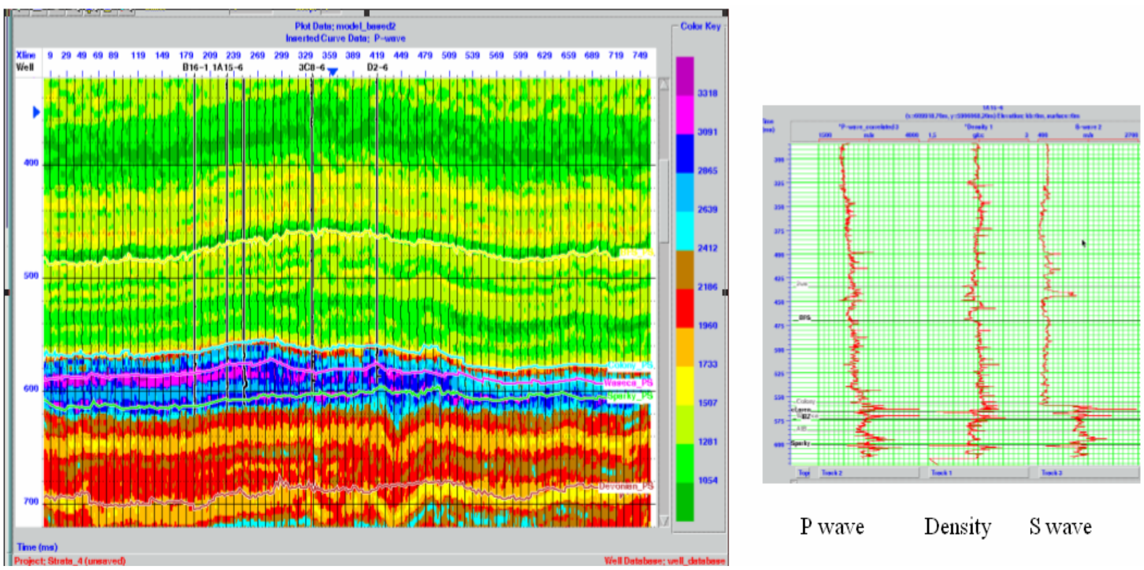


FIG. 11. Model based inversion result (left) and input well logs (right).

The reason for this is a considerable increase in S-wave velocity within the Waseca formation. (Figure 11, right) This velocity contrast results in an abrupt impedance change at the top and the bottom of the oil sands (even though density is decreasing). The same tendency can be traced laterally across the whole section.

The high impedance zone looks a bit wider than the Waseca interval. The reason for this is the behavior of S-wave sonic log, which gives the higher velocities in Colony, Waseca and also at the top of the Sparky.

The result shown in Figure 11 is quite approximate and only serves as an indicator of S-wave velocity changes.

Since we now have inverted both PP and PS data, it is possible to take a ratio of them. Figure 12 was obtained dividing the inverted PP dataset with corresponding PS dataset.

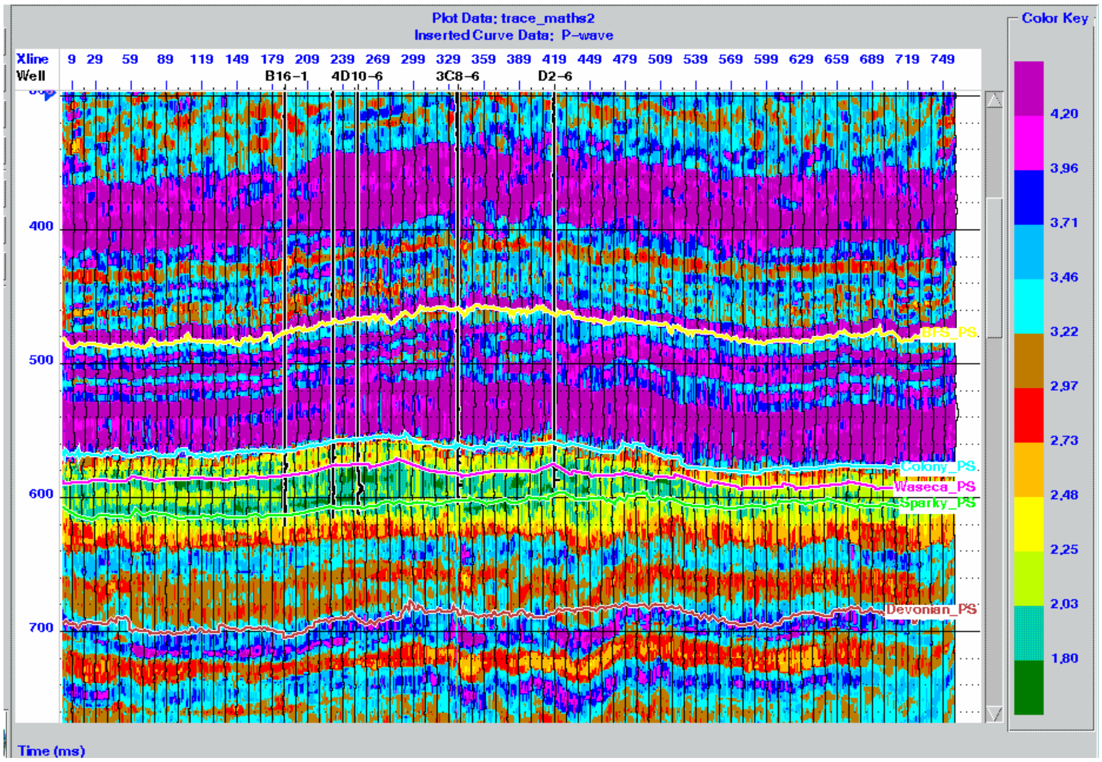


FIG. 12. The ratio of PP inversion to PS inversion in PP time (trace increment equal 10).

We can observe some similarity between this image and Figure 9 (colored Vp/Vs section). The productive formation is recognizable on both sections as having low values of Vp/Vs (Figure 9) and low values of the impedance ratios (Figure 12).

DENSITY PREDICTION USING WELL LOGS AND SEISMIC DATA

Mapping the physical properties of a reservoir is important for assessing and developing its hydrocarbon content. The Pikes Peak heavy oilfield is a heterogeneous reservoir, so we employ geostatistical methods (from the Emerge Software package) to predict the rock properties between drilled wells. The geostatistical idea is to find and quantify the relationship between the log and seismic data at the well location and use this relationship to predict or estimate the log property at all locations of the seismic line using cokriging techniques.

In this paper, we attempt to predict the density logs along the seismic line using multi attribute analysis.

Our aim is to find an operator, which can predict the density logs from the neighboring seismic data. The desired operator can be found by analyzing different seismic attributes. Geostatistical methods sometimes use external attributes to improve the final prediction. Since we have two inverted datasets (for PP and PS data), it might be helpful to use one of them as an external attribute. The single attribute analysis, conducted for the PP and PS datasets and their inversion results (Figure 13), revealed that P inversion result gives the lowest minimum error in the density prediction (68.25 kg/m3) and has the best correlation coefficient (0.57). So, this dataset was chosen as an external attribute to predict the density along the seismic line.

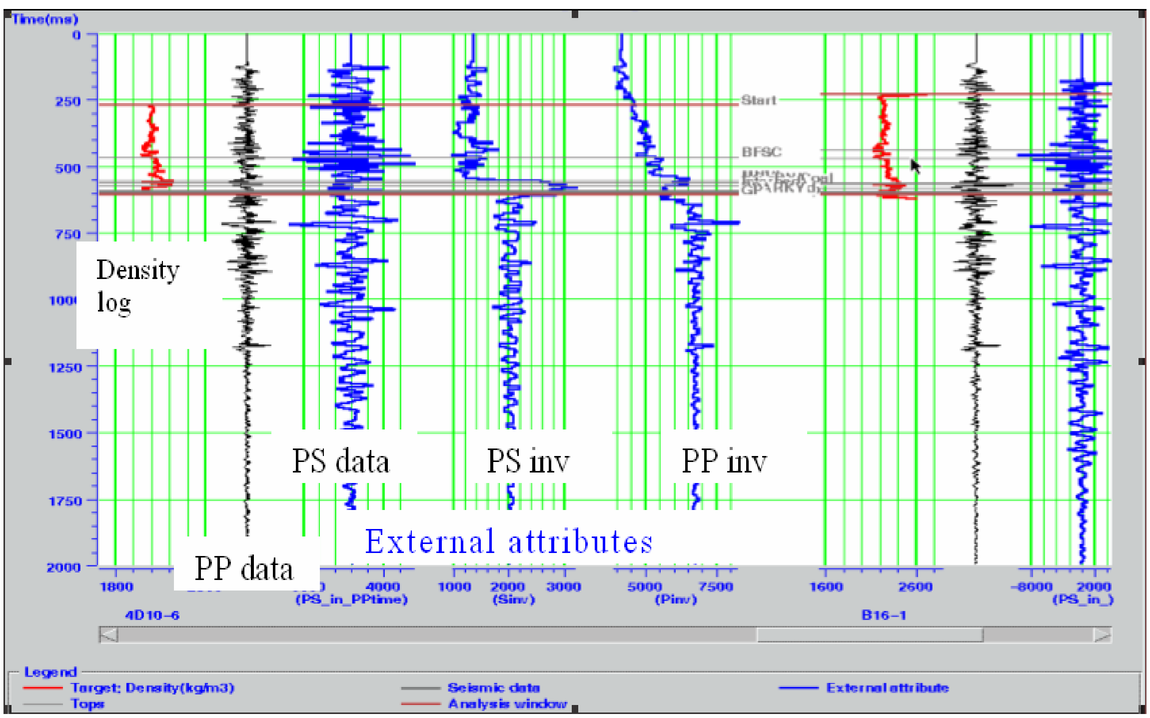


FIG. 13. Data window with density logs and seismic attributes (from the Emerge package).

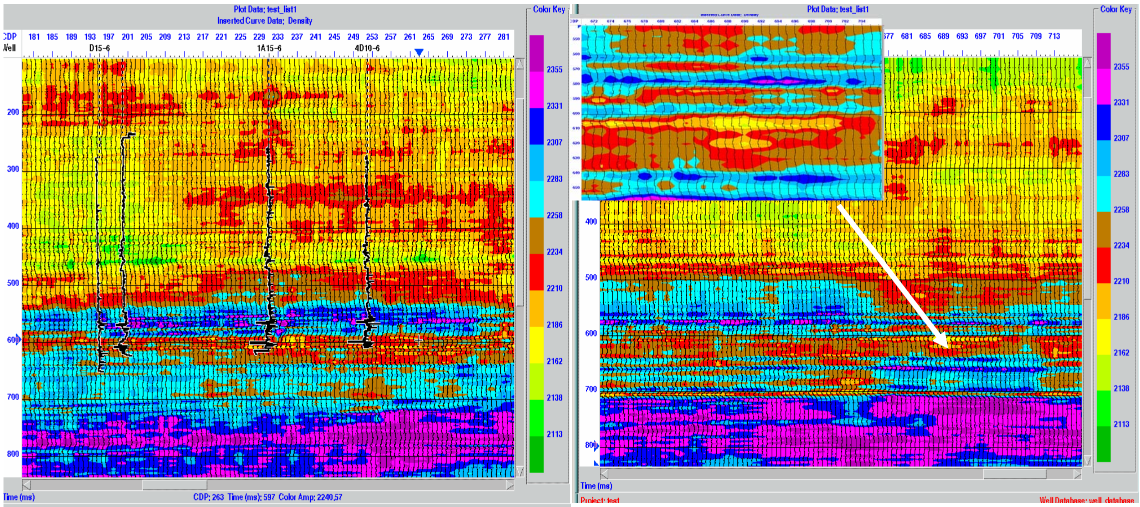
Table 2 shows the list of attributes selected by the step-wise regression as the best predictors of density. Each row includes all the attributes above. (Row 1 – best single

Target Final attribute Training Validation attribute, 2 – best pair, 3 – best triplet, etc.) The corresponding training error and validation error are given in kg/m^3.

Table 2. Multi Attribute list with corresponding error.

1	Density	Amplitude Weighted Cosine Phase (inversion)	70.75	71.38
2	Density	Derivative	69.01	70.60
3	Density	1/(Slowness)	67.04	69.52
4	Density	(inversion)**2	65.49	68.42
5	Density	Quadrature trace (inversion)	63.98	67.67
6	Density	Amplitude Weighted Frequency	62.75	67.02
7	Density	Integrate (inversion)	62.09	68.11
8	Density	Cosine Instantaneous Phase (inversion)	61.50	68.04

We are able to apply the best 6 attributes to the seismic data. Figure 13 shows the density, predicted along the seismic line. In this case, geostatistical methods help us to predict the density between the drilled wells. The productive zone here is seen as a density decrease at about 600 ms (red and yellow colors). If we assess the southern part of the line, a density anomaly is observed between CDPs 685 and 700. Also, this low density zone correlates with a low impedance anomaly on the PP impedance section. No wells have been drilled at this location. Geologically, this site could be prospective for oil accumulation as the predicted density here is noticeably lower than that for surrounding area.



CDP 180-282 **CDP 616-714**

FIG. 13. Predicted density section along the seismic line with enlarged zone of interest (CDP 685-700).

CONCLUSIONS

The integration of well logs and multicomponent seismic data has been described in this paper. In the Pikes Peak case, the productive zone has been delineated using Vp/Vs values from PP and PS seismic data, inversion, and geostatistics.

Calculated Vp/Vs values were helpful for sand and shale discrimination. The considerable Vp/Vs drop from 4.4 to 1.7 indicated the beginning of the productive zone (changing from shale to sand).

The PP and PS impedance sections have been created and analyzed. The top of the productive interval is interpreted as a PP impedance drop and PS increase. Inversion and other attributes have been used to predict the density along the seismic line**.** The productive zone has been characterized as a density decrease on logs and with geostatistical analysis (2.17 g/cc).

An interesting, and as yet undrilled, anomaly has been determined in the southern portion of the seismic line.

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