Characterizing the elastic properties and seismic signature of a heavy oil sand reservoir: 
Manitou Lake, Saskatchewan.
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Summary
A suite of well logs from the Manitou Lake heavy oil field in Saskatchewan was analyzed to study the effect of lithology and saturating fluid on density and P- and S-wave velocities in the sand reservoirs. The Vp values do not change significantly from shale to sand, but the shear-wave velocity increases significantly from 800 to 1300 m/s. A Vp/Vs value lower than 2.15 indicate sand reservoirs. Within the target zone, densities lower than 2250 kg/m$^3$ indicate sands. Modeling with the log response equation shows improvement in density estimations in comparison to using Gardner’s relation. PP and PS synthetics show an opposite seismic signature at the top of the reservoir, seen as a trough on the PP section and as a peak in the PS section, making registration between the two sections more complex. Bright spots are expected on the PS section where sand is present.

Introduction
The bulk density of a rock is a function of mineral composition, porosity, water saturation and hydrocarbon fluid type. In the case of oil sands or heavy oil developments, accurate estimates of density are necessary to determine the location of shales in the reservoirs, which may interfere with the steaming or recovery process (Gray et al., 2006). The Vp/Vs value has also been successfully used to differentiate lithologies and could be used to identify reservoir changes (Lines et al., 2005, Watson et al., 2002).

In this study, two wells (A11-17 and C07-16) from Manitou Lake, Saskatchewan, Canada, were used to evaluate the relations between different rock properties and the elastic parameters derived from the well logs. The logs used included gamma ray (GR), spontaneous potential (SP), density, neutron and density porosity, caliper, and resistivity, among others. P-wave and S-wave sonic logs were available for well A11-17.

The exploration targets in the area include the Colony and Sparky members of the Mannville Group. The Colony sand member consists of shales, siltstones, coals and sandstones. Deposition of this member occurred in an extensive complex of anastomosing channels sandstones, encased within siltstones, shales, coals and thin sheet sandstones (Putnam and Oliver, 1980). It is overlain by the marine shales of the Colorado and Belly River Groups. The Sparky member is informally grouped into the middle Mannville, which is dominated by sheet sandstone development, with narrow, channel sandstones and shales also present (Putnam, 1982). These units have been interpreted as a delta-front facies with associated tidal-flat, tidal-channel, and beach environments (Vigrass, 1977).

The log response equation was used to model the sonic and density logs, and the results compared to estimates using the mudrock line and Gardner’s equation. Synthetic seismograms were generated to evaluate the PP and PS response at the top of the reservoir. A simple band limited inversion of the PS data was used to estimate Vs, using the modeled logs as a constraint.

Rock Properties
Figure 1 shows the logs from well A11-17. Note the sharp decrease in the GR and SP logs at the top of the Colony sands, indicating the change from the shales of the Colorado Group to the predominantly sandy Mannville Group. At this interface the density log decreases, the P-wave shows almost no change and the S-wave velocity shows a very significant increase from 800 m/s in the shales to 1300 m/s in the sands. High resistivity values in the Colony and Sparky members indicate hydrocarbons, while the cross-over between the density and neutron porosity logs in the Colony sands suggests gas. Several coal beds can be interpreted in the area, based on the lower density values, between 1.6 and 1.7 g/cm$^3$.

Over the complete log interval, which ranges from 100 to 600 m, P-wave vs. density crossplots show overlap on the density values for shales and sands. However, within the target zone, density appear to be a good lithological indicator, with densities lower than 2250 kg/m$^3$ indicating sands, and higher values corresponding to shaly sands and shales (Figure 2). Across the whole depth interval, the Vp/Vs value appears to give the best differentiation with regards to lithology, with sands having a Vp/Vs value lower than 2.15 and shales having higher values. The sand reservoirs map within a very narrow range of shear wave velocity, between 1300 and 1500 m/s. The mudrock line that relates P- and S-wave velocities fits very closely to the least-squares fit from the data.

Log Response Equation
Density, P-wave sonic and S-wave sonic logs were modeled using the log response equation, defined by:

\[
\log = \phi_e \cdot S_w \cdot \log_{\text{water}} + \phi_e \cdot (1 - S_w) \cdot \log_{\text{hydro}} + (V_{sh} \cdot \log_{\text{shale}}) + ((1 - V_{sh}) \cdot \phi_e \cdot \log_{\text{matrix}}),
\]  

(1)
where $\phi_e$ is the effective porosity, corrected for shale volume, $S_w$ is the water saturation, and $log$ is the property value within each component. Within this approach the rock is modeled as having four major components that contribute to the log reading (e.g. water, hydrocarbon, shale and matrix). The first term corresponds to the water contribution, the second to the hydrocarbon, the third is shale contribution and the final term is the contribution from the rock matrix.

Shale volume was calculated from the GR log, effective porosity was calculated from the density-neutron crossplot method and corrected for shale volume. Log values for water, hydrocarbon and matrix were selected from the literature based on the known lithology and fluid properties (quartz matrix and 12° API oil $\approx 0.98 \text{ g/cm}^3$). Shale values were selected directly from the logs, as they can range significantly between different areas.

This model results in very good density estimates (Figure 3); however, it fails to reproduce the significant change in $V_s$ at the top of the reservoir. If shear logs modeled from the mudrock line are used to generate synthetic seismograms, the response at the top of the reservoir will not tie with the seismic section. Estimations of density using Gardner’s relationship with $V_p$ gives very poor results in the area, as density and $P$-wave velocity appear to be uncorrelated. Choosing different values of $a$ and $m$ for sands and shales improves the fit considerably.

**Synthetic Modeling**

PP and PS synthetic seismograms were generated for well A11-17 (Figure 4). The PP synthetic was generated using a Ricker wavelet with a dominant frequency of 60 Hz, while the PS synthetic used a 40 Hz Ricker wavelet, to account for the lower bandwidth of PS data. The PP signature at the top of the Colony corresponds to a trough, while on the PS section it corresponds to a peak. The Sparky B shows the same seismic signature.

This change in polarity between the two sections can affect significantly the registration process during the interpretation. Given the significant increase on the $S$-wave velocity at the top of the Colony, bright spots are expected in the PS section associated with sand intervals.
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Seismic Inversion

A band limited inversion using the BLIMP algorithm (Ferguson and Margrave, 1996) in Matlab was used to estimate shear wave velocities from the PS stacked data, using the density estimates from the log response equation. This algorithm uses an initial impedance estimate which is calculated from the well logs. The seismic trace is then integrated and exponentiated. The Fourier spectrum of the integrated trace is scaled to that of the estimated impedance, and a low-pass filtered impedance is added to the trace. The result is transformed to the time domain, and a new impedance estimate is obtained. In this case, the low- and high-cut frequencies were set to 10 and 100 Hz, respectively.

This algorithm is defined for zero-offset reflectivity, which in the case of a single PS trace is equal to zero. By using the PS stacked trace, an average of the PS reflectivity over the whole offset range is used instead. Stewart and Bland (1997) defined the following equation to convert PS reflectivity, \( R_{ps}(\theta) \), to an SS reflectivity at zero-offset (\( R_{ss} \)):

\[
R_{ss}(0) = \frac{\alpha}{4\beta} \csc \theta R_{ps}(\theta)
\]  

(2)

where \( \alpha \) and \( \beta \) are the P and S-wave velocities, \( \theta \) is the incidence angle. Applying this correction to the data results in an overall scaling of the amplitudes, but relative variations are not changed significantly. Since the algorithm scales the trace to the initial impedance estimate.

Figure 2: (a) Crossplot of P-wave velocity vs. density around target zone in well C07-16.

Figure 3: Log response modelling of P- and S-wave sonic, and density logs for well A11-17. Magenta indicates the original log, blue the modeled log, and green corresponds to the Vs and density estimates using the mudrock line and Gardner’s equation with the default parameters.
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from the log, applying this correction does not change the inverted impedance values.

Results from the inversion are shown in figure 5. Note that both the impedance and Vs estimates agree with the original logs, but with lower frequency content. Note that the sharp increase in S-wave velocity at the top of the Colony member is properly inverted from the PS data.

Conclusions

Shear-wave velocity is a very good lithological indicator in the area, showing a change of 500 m/s at the sand/shale interface, which results in significant changes in the PS section. Variations in density are more complex, as it is affected by the saturating fluid. Within the target zone, densities lower than 2250 kg/m³ corresponds to clean sands, while shaly sands and shales have densities between 2250 and 2600 kg/m³. Further work with fluid substitution will give more insight to the effect of changes in water saturation and fluid content on the elastic properties and the seismic response at the top of the reservoir. The use of the log response equation within a time-lapse inversion could lead to direct water saturation estimates.

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Figure 4: PP and PS synthetic seismograms for well A11-17. Note polarity reversal from the PP to the PS section at the top of the Colony and Sparky B members (Target reservoirs in the area).

Figure 5: Vs estimation from the impedance inversion of a PS stacked trace.