Velocity Measurements of Pore Fluids at Pressure and Temperature: Application to bitumen

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Summary

Time lapse geophysical imaging (e.g. 4D survey) of reservoirs require proper understanding of the saturating fluid's behavior at *in situ* conditions during hydrocarbon production. An adapted version of a pulse transmission technique for fluid is used to measure the ultrasonic velocity of highly viscous fluids. P-wave velocities in bitumen decrease 28% as the temperature rises from 10ºC (near virgin reservoir) to 130ºC. We apply these observed wave speeds and estimated fluid bulk moduli through Gassmann substitution in a porous dolomite to predict the changes in seismic reflectivity that would be observed with variations in temperature over a hypothetical bitumen saturated reservoir.

Introduction

Recovery of viscous hydrocarbons using methods such as SAGD or CSS from oil sands and/or carbonates necessitate that the reservoirs are heated to more than 100ºC in order to lower the viscosity of bitumen so that it can flow for production. Many workers (e.g., Eastwood (1993), Spencer (2013)) have observed significant drops in the P-wave velocities in bitumen saturated sands with increasing temperature at both high and low frequencies, respectively. In contrast, the S-wave velocity changes vary slightly. They both emphasize that drop in P-velocity is mostly due to the change in fluid bulk modulus with temperature. Recent ultrasonic measurements with bitumen saturated carbonate from the Grosmont formation of northern Alberta show that its P- and S-wave velocities decrease with temperature, and changes in the bitumen's properties are expected to be the dominating factor (Rabbani et al. 2015). However, to our knowledge, there are no publicly available reports in the literature on the seismic properties of highly viscous bitumen itself from the Grosmont formation under varying *in situ* conditions. This knowledge gap has motivated the development a laboratory protocol to provide appropriate measures of waves speeds and attenuation in bitumen over the temperature range from 10ºC to 130ºC and pressure up to 10 MPa. These developments were also necessitated because the standard pulse echo method does not provide satisfactory data through the highly attenuating fluid. Pore fluids in a geological formation are a combination of different compounds, therefore, a technique to measure the properties of saturated fluids with great accuracy is a valuable addition to understand the reservoirs overall seismic behavior. These measured properties can assist to the seismic monitoring of a geological formation (e.g. CO_2 sequestration site) (Njiekak et al. 2013).

In this contribution, we describe the experimental technique and provide some of our initial measurements through bitumen. We apply these measurements in a simple hypothetical synthetic seismic model that illustrates the changes in reflectivity associated solely with a temperature change in the fluid.

Theory and Method

The experimental configuration was constructed to measure the sound speed in fluids. With highly attenuating bitumen, a direct pulse transmission method is used with two independent receiver PZTs placed on both opposite sides of the middle transmitting PZT (**Fig. 1**). The receivers are glued with metal pieces and spaced at unequal distance in order to calculate attenuation using the spectral ratio method

(Molyneux and Schmitt, 2000). Bitumen is too attenuative to allow a pulse passing through the material twice as we have previously described in higher Q brines (Rabbani et al. 2014) and such a direct approach is necessary.

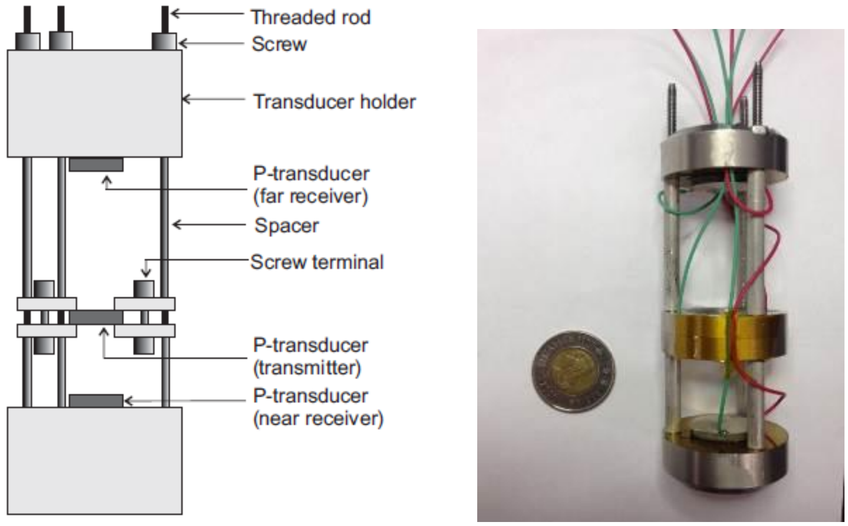


Figure 1: Pulse-transmission approach for highly attenuating fluids consisting of a central single transmitter and far and near receivers. Left - the schematic of the cell and right picture shows the actuall cell made with stainless steel.

Examples

Pressure and temperature effects

In **Fig. 2,** a set of ultrasonic waveforms in bitumen at 1 MPa pressure illustrates the effects of temperature on amplitude for near reciever. Here we have first computed RMS value of amplitude of a moving gate along a trace at each temperature. It is then plotted as background of the actual traces.

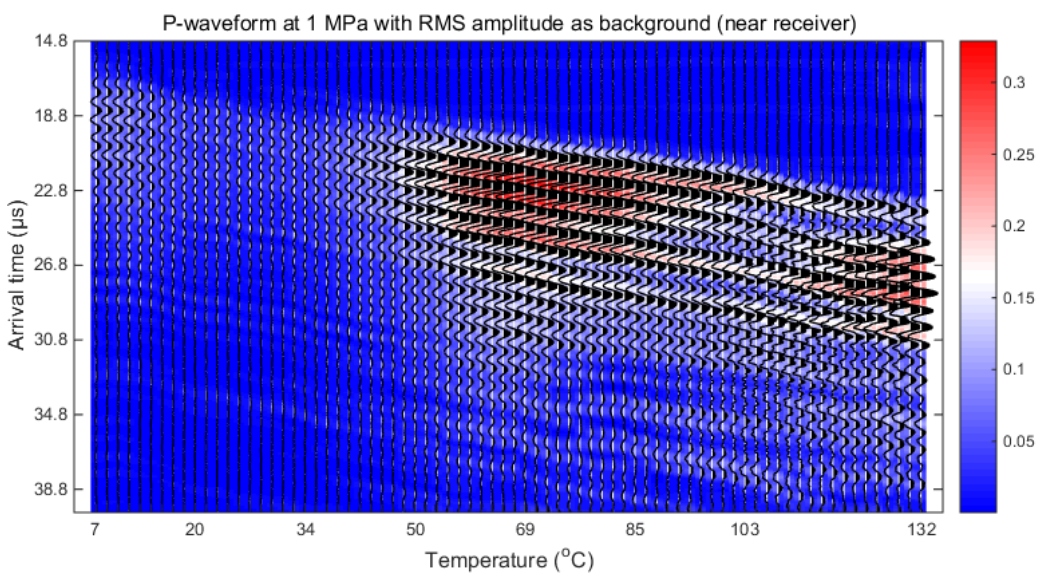


Figure 2: Amplitude variations in the signals in bitumen with increasing temperature at 1 MPa of pressure - for near reciever.

The measurements with bitumen at various pressure and temperature allow us to see the effects of attenuation on the waveforms. As the temperature increases bitumen’s viscosity decreases significantly compared to the drop in density and velocity to eventually lower the attenuation. Therefore, in **Fig 2**, the amplitudes get stronger with the increase in temperature. Larger RMS value of amplitude at higher temperature also indicate that highly viscous bitumen turns into liquid from it's quasi solid phase at low temperature. However, the traces undergo a change in their shape and amplitude at around 100ºC. Although not shown in here, the waveforms at all the other pressures with temperature indicate that bitumen phase starts changing (becoming liquid) from 40ºC and onward. At around 70ºC the amplitude is pretty much strongest for almost all the cases, which may tell that bitumen is completely liquid at that temperature. Unfortunately, we don't have data yet at high enough temperature for all the pressures except at 1 MPa to really explain the behavior at 90ºC and onwards.

Fig. 3 shows that P-wave velocities of bitumen drop significantly (~28%) with increase of temperature and maintain the expected trend of possessing larger value at higher pressure. The estimated three different slopes may indicate the possible phases of quasi solid, mostly liquid and liquid in bitumen (Han et al. 2008). Data shown here are only for the near receiver.

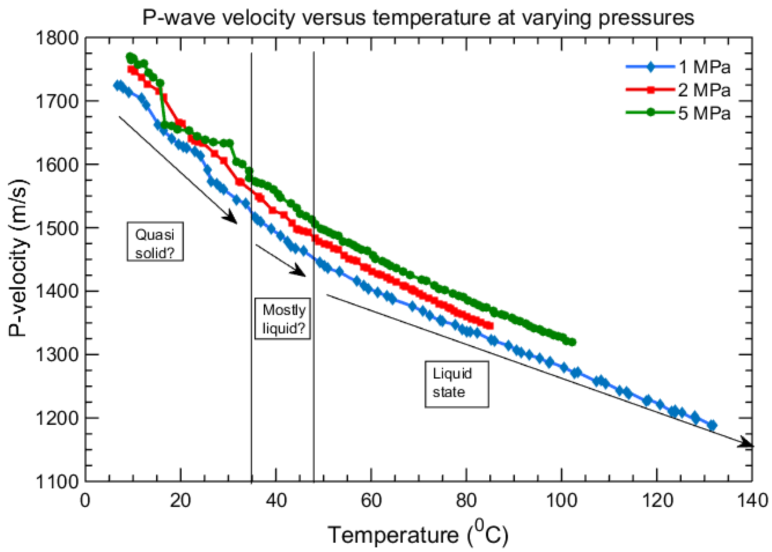
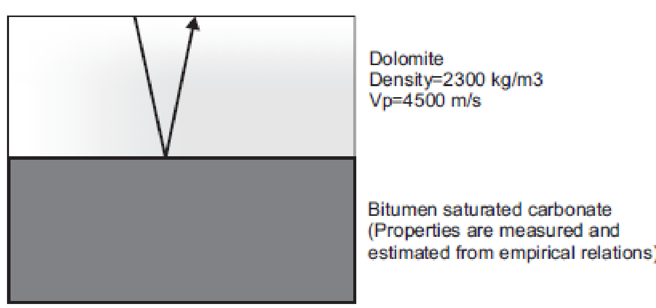


Figure 3: P-wave velocities of bitumen drop significantly as temperature increases. Velocities are also larger at higher pressure, as expected.

Implementation for time lapse (4-D) seismic survey

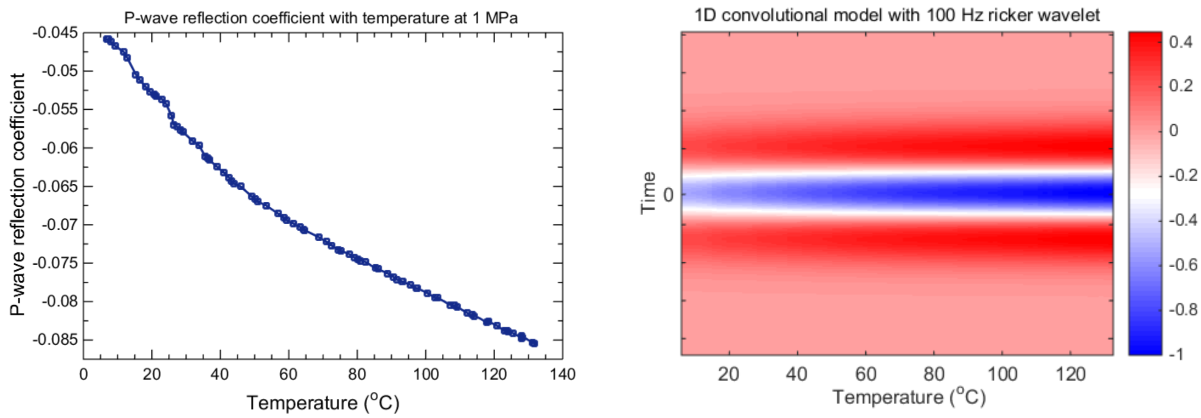
4-D seismology involves predicting the changes in repeating 3-D seismic surveys with time, where the changes in subsurface are produced due to the variations in the physical properties of fluid saturated rocks. The overall seismic responses can depend on various factors but are heavily influenced by the state of the fluid saturation within the rock. Time lapse (or 4-D) seismic monitoring can successfully assist imaging the changes in bitumen saturated oil sand reservoirs, due to the combined effects of increased temperature, pore pressure and effective stress changes, and the substitution of bitumen with water and steam during SAGD or CSS (Schmitt 1999; Zadeh et al. 2010). The ultrasonic measurements in this study show both the direct effects of pressure, and, more importantly temperature on bitumen.

Figure 4: Illustration of two layers - dolomite and bitumen saturated carbonate



The measured P-wave velocities with temperature and pressure can be implemented to demonstrate time lapse seismology for a simple layered 1-D world, where a pulse through a dolomite layer is reflected back from the underlying bitumen saturated layer (**Fig. 4**).

In this simplified model, we estimated the density of bitumen at pressure and temperature from the well using known empirical relations from Batzle and Wang, 1992. Unfortunately, the current design does not provide us the bitumen density. Initial density for bitumen at ambient condition was 1020 kg/m^3 in the empirical relation. The saturated rock density is then calculated by combining the matrix (dolomite) density (2795 kg/m^3) and rock's porosity (20%) with the estimated fluid density. The saturated bulk modulus is derived with Gassmann's model, ignoring here for purpose of illustration issues that may arise from substitution with a highly viscous liquid. In Gassmann relation, the frame and mineral moduli are set at 18 GPa and 94.9 GPa, respectively. The bulk modulus of the fluid is calculated from the measured P-wave velocities (e.g. **Fig. 3**) and the estimated density at pressure and temperature. The standard equation of compressional velocity with bulk and shear moduli (similar to dry shear modulus, 7.0 GPa), and density then yields saturated P-wave velocity of the saturated carbonate. Finally, the reflection coefficent from the interface between the dolmite and bitumen saturated carbonate is calculated from the corresponding impedances, seen in **Fig. 5-a.**



(a) (b)

Figure 5: a) P-wave reflection coefficient at 1 MPa pressure as a function of temperature and b) corresponding synthetic seismograms calculated by the convolutional model with normalized amplitude as a function of temperature.

We have seen in **Fig. 3** that temperature substantially affects the bitumen's velocities. Thererefore we try to carry out the reflection coefficient analysis with temperature variation. **Fig 5-a** shows that P-wave reflection coefficient at 1 MPa pressure strongly depends on the temperature, as it decreases with increase of temperature. Moreover, in a convolutional model in **Fig. 5-b**, where a ricker wavelet with 100 Hz central frequency is convolved with the reflection coefficients, shows that absolute value of the amplitude increases with temperature, where the amplitude peak is centered at zero time. The reflection coefficients were normalized with largest value in order to see the amplitude variation by -1 to 1 in the colorbar around the , **Fig. 5-b**. The sign in colorbar indicates the negative polarity of amplitude from the negative polarity signal.

This result demonstrates that studying the physical properties of bitumen at various conditions is necessary in order to properly interpret observed 4-D seismic responses.

Conclusions

Changes in seismic reflectivity due to thermal recovery processes from a bitumen saturated reservoir can be substantial due to the combined effects of increased temperature, pore pressure and effective stress changes, and the substitution of bitumen with water and steam. Therefore, these studies of bitumen's properties, which, in preliminary state showed a 28% decrease in the P-wave velocity with temperature would greatly contribute to the interpretation of 4D seismic surveys. Moreover rock-physics model for rocks saturated with highly viscous bitumen could be improved with the known properties of the pore fluid. Ongoing work seeks to better understand the role of attenuation, which we have ignored for now, and to look at additional laboratory techniques that could allow us to obtain additional physical properties of the bitumen under in situ conditions during our experiments.

Acknowledgements

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