Laboratory experiments and numerical simulation on Bitumen Saturated Carbonates: A Rock Physics Study for 4D Seismology

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SUMMARY

The change in seismic reflectivity from a reservoir — during in situ bitumen recovery processes such as SAGD — 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. These physical property changes can be observed with time lapse seismic monitoring e.g. 4D seismology. The proper interpretation of geophysical observations, however, requires a solid understanding of the saturated reservoir rock's behavior and pore fluid's properties under changing conditions. Our first suite of ultrasonic measurements with bitumen saturated carbonate show the P- and S-wave velocities decrease by ~11.5 % and ~8.5 % for a temperature increase from 10ºC to 102ºC, respectively at a constant effective pressure of 5 MPa. In the next effort, direct measurements with bitumen show ~29% decrease of P-wave velocity for 10ºC to 130ºC change in temperature. Different slopes in velocity versus temperature plot may also indicate the possible states of quasi solid and liquid in bitumen. The change in fluid bulk modulus with temperature drives the drop in the P-wave velocities. We may also infer that the decline in S-velocity in core sample is due to greatly lowered viscosity of the fluid with temperature.

We also attempt to simulate numerically the ultrasonic pulse-transmission through rock saturated with viscous fluid, which exhibits similar trends of P-wave velocity drop with temperature. However, the decrease in velocity is not quite large as experimental studies with bitumen saturated carbonates; may be due to the difference in pore structure and fluid properties. In addition, the dynamic moduli of saturated rocks at seismic frequencies on core scale using the strain-stress method indicate its strong dependency on viscosity of pore fluid and (or) the frequency.

Key words: Rock Physics, Bitumen, Carbonates, 4D Seismology.

INTRODUCTION

Bitumen is a type of heavy oil – API (American Petroleum Institute) value less than 10 – with quite high density (>1 g/cm^3) and viscosity (~10^7 cP) at in situ condition. In spite of recent advances in the production of hydrocarbons from tight formations, large reserves of bitumen exist globally and these still remain attractive economic targets. Most of the reserve, for example in Canada, lies in oil sands deposits but a large fraction resides in nearly untouched carbonate reservoirs. Of this, the carbonate Grosmont Formation in north-eastern Alberta may hold in excess of 64.5 billion m3 of (406 billion barrels) initial volume of bitumen in place. The vast scale of the available resource makes the Grosmont formation a still largely untapped resource and motivates further study.

The recovery of such highly viscous bitumen necessitates that the viscosity be reduced so that it can flow for production. In many cases this means that the reservoir will be sufficiently heated to more than 100ºC as has now long been carried out in the oil sands using cyclic steam stimulation (CSS) or steam assisted gravity drainage (SAGD) although electrical technologies may play a role in heating or even initial in-situ upgrading. The variations in elastic moduli of subsurface formations, particularly due to elevated pressure and temperature of injected steam during in situ bitumen recovery processes such as SAGD lead to changes in seismic wave speeds and attenuation (Kato et al. 2008; Schmitt 1999). The overall seismic responses can depend on various factors but are heavily influenced by the state of the fluid saturation within the rock. The proper interpretation of geophysical observations (e.g. 4D seismology), therefore, requires a solid understanding of the saturated reservoir rock's behaviour and pore fluid's properties under changing conditions of saturation, temperature, and pressure.

Eastwood (1993) carried out ultrasonic P- and S-wave velocities measurements in Cold Lake oil sands and observed a good agreement with theoretical predictions of the velocities. While the S-wave velocity remains almost constant, the P velocity in the oil sands is dropped by 15% over a temperature change of 22ºC to 125ºC. In more recent studies, Uvalde bitumen saturated carbonate rock exhibits shear relaxation at room temperature and Uvalde bitumen acts as solid at low temperature but transforms into liquid with zero shear modulus at higher temperatures (Batzle et al. 2006; Behura et al. 2007). Strong temperature dependence of the bulk and shear moduli of unidentified extra heavy oil are also recently observed with ultrasonic measurements (Han et al. 2008). Most recently, Spencer (2013) conducted low frequency measurements on samples of an Ells River oil sand and rheometer measurements on its produced bitumen. The saturated P-modulus and shear modulus in the bitumen sand drops by 30% and 6%, respectively with temperature change from 5°C to 49°C.

In this study, our main objective is to study rock physics properties of bitumen saturated carbonates and raw bitumen over a wide range of pressure, temperature and frequency. Then, we will employ these data to quantify the effects that are due to the changes from fluid itself and not from fluid-rock interactions. These observations would assist interpreting 4D seismic surveys of a bitumen saturated carbonate reservoir.

METHOD AND RESULTS

Bitumen Saturated Carbonates

In first suits of ultrasonic measurements with pulse transmission method in bitumen saturated carbonate core sample (10 % porosity), we observed the P- and S-wave velocities dropped by ~11.5 % and ~8.5 %, in figure 1, for a temperature increase from 10 °C to 102 °C, respectively at a constant effective pressure of 5 MPa (Rabbani et al. 2014).

In their studies, Eastwood (1993) and Spencer (2013) both emphasize that drop in P-velocity in bitumen saturated sands is mostly due to the change in fluid bulk modulus with temperature. Therefore, we would like to study fluids properties under different conditions.

Fluid Properties: Bitumen

Bitumen is too attenuative to allow a pulse passing through the material twice; therefore a direct pulse transmission method is used with two independent receiver PZTs placed on both opposite sides of the middle transmitting PZT. The receivers are glued with metal pieces and spaced at unequal distance in order to calculate attenuation using the spectral ratio method.

In figure 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.

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 figure 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 may indicate that bitumen starts changing its phase (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 liquid at that temperature — although it can't be confirmed with the current means. Changing properties of the transducer itself at higher temperatures (>80ºC) may also have a little effect on the results but we believe the behaviour is an intrinsic property of the bitumen.

The associated 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 presence of different states in bitumen such as quasi solid at low temperature and liquid as temperature increases may be indicated from the velocity gradient (Han et al. 2008).

In the next effort, we used an adapted version of the pulse-echo technique to simultaneously measure the seismic velocities, density, attenuation, shear, and bulk viscosity of fluids at ultrasonic frequency. The technique involves two buffers — one for a P-wave and other for an S-wave transducers — to calculate relative reflection coefficients and also flight time of propagating signal. The signals passing through the buffers reflect back from the solid-nitrogen or solid-fluid boundary, as shown in figure 3(a) for shear wave and the corresponding reflection coefficient eventually assist measuring the density and viscosity of the fluid of interest. Viscosity in bitumen in Figure 3(b), for example, drops by more than 95% from 2.5×10^5 cP to 4×10^3 cP for a 10ºC to 50ºC temperature change at 2 MPa pressure. This measured dynamic viscosity is very consistent with related published data (Zhao and Machel, 2012)

Rock Physics Model

We carried out rock physics modeling at both high (ultrasonic) and low (seismic) frequencies, aiming to provide an insight for heavy oil exploration and thermal recovery (such cyclic steam stimulation, steam assisted gravity drainage) in Grosmont carbonate reservoirs. The modeling at high frequency simulates the pulse transmission method in the lab, while the modeling at low frequency simulates the stress-strain method. The geometrical models of these modelings are based on the rock digital images (thin section, SEM, CT, etc.), which can be referred to Wang et al. (2015) for detailed information. Here we mainly show the modeling results.

High frequency results

We modeled the elastic wave propagation in a vuggy sample (porosity=13%) at high frequency. The pore fluid is bitumen. The temperature ranges from -5℃ to75℃, and the viscosity ranges from 10^7 to 15Pas. The modeling results are shown in figure 4.

If we do not consider the viscosity change with temperature, the change of density and velocity of bitumen with temperature lead to some velocity changes (blue points in Fig.1). In our modeling, the P-wave velocity change from -5℃ to 75℃ is about 100m/s (relatively 1.79%). However, waveforms show visible difference even when we do not consider the viscosity change with temperature. At the same frequency, the P-wave velocity of which the viscosity of bitumen is considered is higher than that of no viscosity. And the higher the viscosity, the faster the P-wave propagates. When the frequency is 1 MHz, our modeling results is consistent with the predictions of self-consistent model, which indicates that our modeling results at high frequency is reliable.

Low frequency results

In order to investigate the effects of fluid viscosity, frequency, and pore structure on the viscoelastic properties, we designed and carried out 5 series of numerical modelings, the results are shown in figure 5.

Based on the modeling results at low frequencies, it would be safe to conclude that the viscoelastic properties of a viscous fluid-saturated rock are dependent on the frequency, the fluid viscosity, and the rock frame stiffness. The frequency and the viscosity are related because the storage modulus of a viscous fluid is dispersive. The pore structure parameters, such as porosity, pore aspect ratio, and pore size affects the rock frame stiffness and results in different viscoelastic behavior of the saturated rocks. However, the viscoelastic properties (the storage moduli and the phase angle) are more sensitive to the pore aspect ratio.

CONCLUSIONS

The overall seismic responses can depend on various factors but are heavily influenced by the state of the fluid saturation within the rock. The studies of bitumen properties showed a 28% decrease in the P-wave velocity and 95% drop in viscosity with the increase of temperature. Numerical model of the ultrasonic pulse-transmission through rock saturated with viscous fluid exhibits similar trends of P-wave velocity drop with increasing temperature. However, the decrease in velocity is not quite as large as experimental studies of bitumen saturated carbonates. This may be due to the difference in pore structure and fluid properties. However, the dynamic moduli of saturated rocks at low frequencies on core scale using the strain-stress method indicate its strong dependency on viscosity of pore fluid and / or the frequency.

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REFERENCES

Batzle, M. L., D. H. Han, R. Hofmann. 2006. Fluid mobility and frequency-dependent seismic velocity - Direct measurements (in Geophysics 71 (1): N1-N9.

Behura, Jyoti, Mike Batzle, Ronny Hofmann et al. 2007. Heavy oils: Their shear story (in Geophysics 72 (5): E175-E183.

Eastwood, J. 1993. Temperature-Dependent Propagation of P-Waves and S-Waves in Cold Lake Oil Sands -Comparison of Theory and Experiment Geophysics 58 (6): 863-872.

Han, De-hua, Jiajin Liu, Michael Baztle. 2008. Seismic properties of heavy oils—measured data (in The Leading Edge 27 (9): 1108-1115.

Kato, Ayato, Shigenobu Onozuka, Toru Nakayama. 2008. Elastic property changes in a bitumen reservoir during steam injection (The Leading Edge 27 (9): 1124-1131

Rabbani A., Douglas R. Schmitt, and Randolf Kofman. 2014. A laboratory procedure of measuring ultrasonic properties of CO2 saturated fluids, GeoConvention:FOCUS, Calgary, AB (extended abstract)

Schmitt, D. R. 1999. Seismic attributes for monitoring of a shallow heated heavy oil reservoir: A case study (in English). Geophysics 64 (2): 368-377.

Spencer, J. W. 2013. Viscoelasticity of Ells River bitumen sand and 4D monitoring of thermal enhanced oil recovery processes (in English). Geophysics 78 (6): D419-D428.

Wang, Z. Z., R. H. Wang, R. J. Weger, T. Y. Li, and F. F. Wang, 2015, Pore-scale modeling of elastic wave propagation in carbonate rocks: Geophysics, 80, no. 1, D51–D63.

Zhao Y., Machel H. (2012) Viscosity and other rheological properties of bitumen from the upper devonian Grosmont reservoir, Alberta, Canada, AAPG Bulletin. 96, 1, 133–153

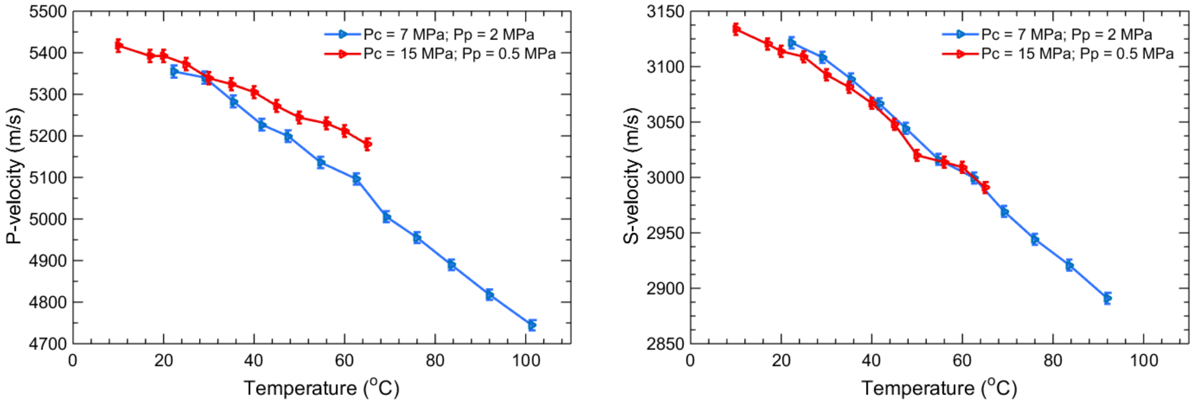


Figure 1: Effects of temperature change on P- and S-wave velocities, on their ratios, and on Q-factor. A significant decrease in both P- and S- velocities with temperature change from 21ºC to 102ºC at 5 MPa differential pressure and from 10ºC to 70ºC at 14.5 MPa differential pressure

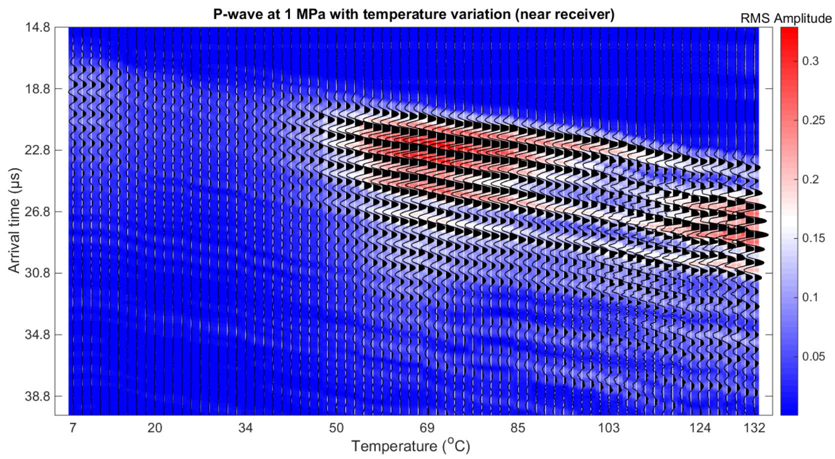
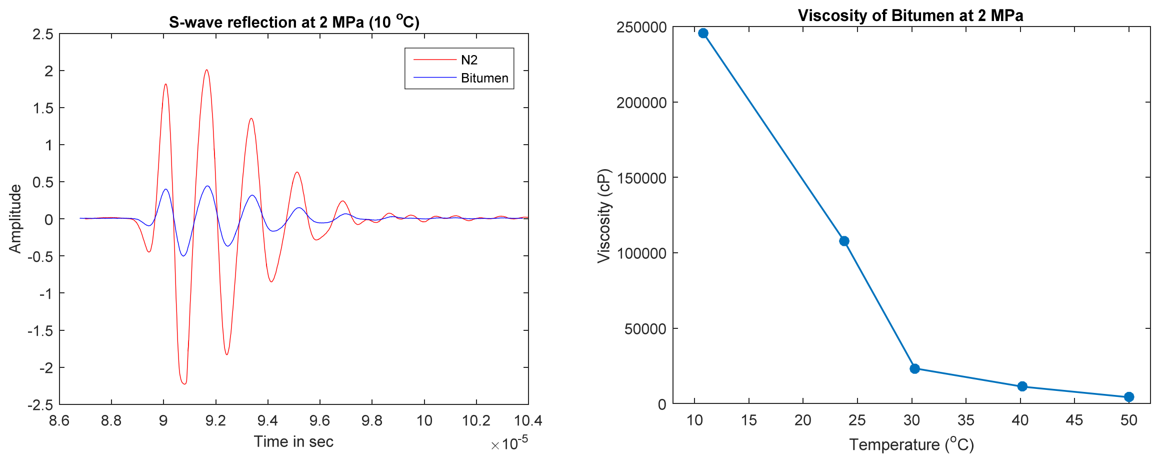


Figure 2: Amplitude variations in the signals in bitumen with increasing temperature at 1 MPa of pressure - for near reciever



(a) (b)

Figure 3: Shear wave reflection from the solid to nitrogen and bitumen (b) Viscosity of bitumen calculated from the reflection coefficients as the function temperature at 2 MPa pressure.

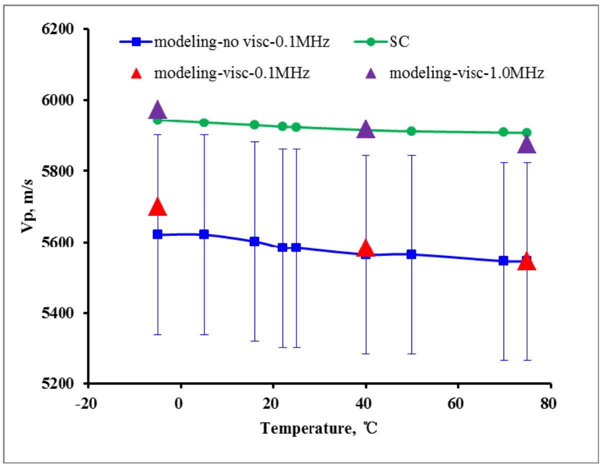


Figure 4: P-wave velocity from numerical modeling at high frequencies (>105Hz), and the comparison between modeling results with predictions of the self-consistent model. The error bar is 5%.

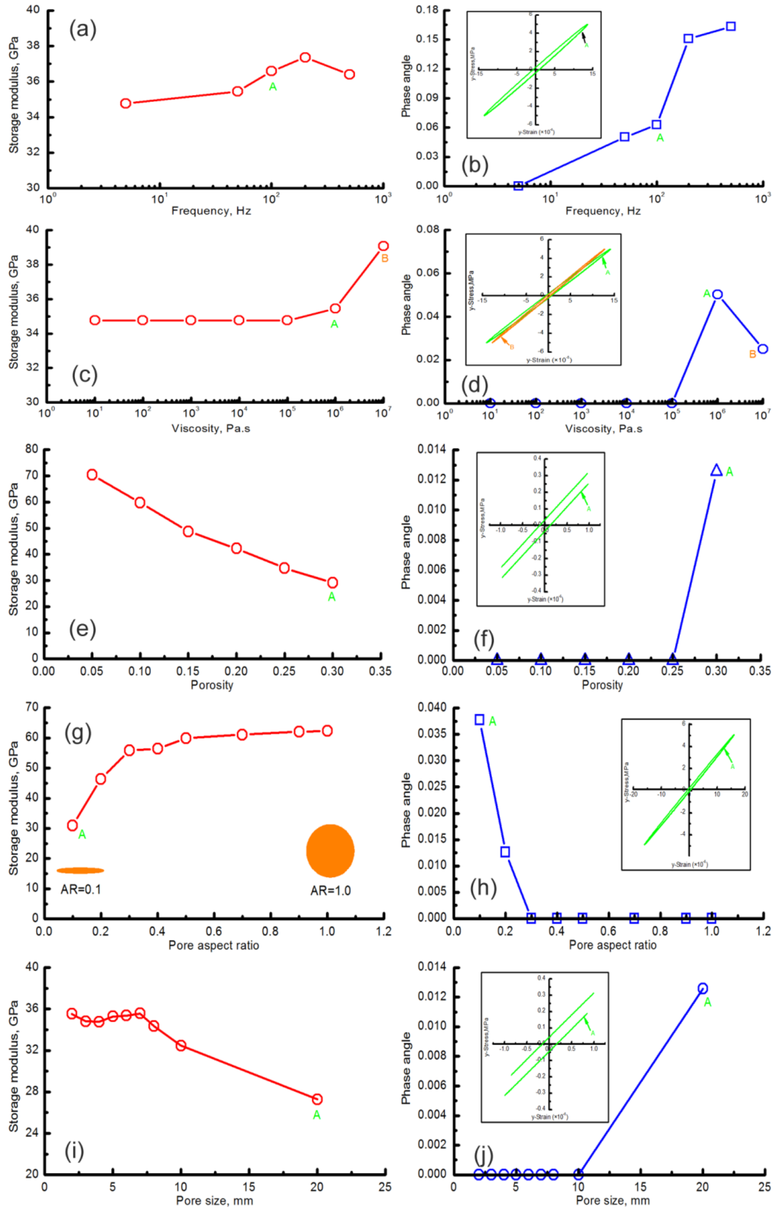


Figure 5: The effects of frequency (a and b), fluid viscosity (c and d), porosity (e and f), pore aspect ratio (g and h), and pore size (i and j) on the viscoelastic properties (storage modulus at the left column, phase angle at the right column)