Thermal damage on velocities of heavy oil sands

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Summary

Understanding thermal effects on seismic properties of heavy oil sands is important for seismic reservoir monitoring with thermal process. Velocities of heavy oil sands as a function of temperature are revealed as mainly controlled by properties of heavy oil (Han et al., 2007). However, newly measured data suggest that the thermal damage of sand frame also plays a significant rule to reduce velocity. Thermal damage of sand frame is a quasi-static processing, and mainly deteriorates the heavy oil contribution to strength sand frame. We should count the thermal damage effect on sand frame when modeling velocity-temperature trend of heavy oil sands.

Introduction

Heavy oil is amorphous material. Acoustic velocity behavior of heavy oil depends on oil phase (Han et. al, 2006). As shown in Figure 1, heavy oil in the liquid phase at a higher temperature, S-wave velocity is negligible and P-wave velocity shows negligible frequency dependent, similar as conventional liquid oil. As heavy oil in the glass solid phase (viscosity> 10^{15} cp) at low temperature, both P- and S-wave velocities have negligible dispersion, similar as an elastic solid. There is transition zone of the quasi-solid phase with a high threshold of temperature to separate with liquid phase zone. This threshold temperature is called the liquid point. The liquid point is empirically defined from ultrasonic velocity measurement. In this phase, S-wave velocity is measurable and increases with decreasing temperature. P-wave velocity deviated to high value from the liquid trend as shown in Figure 1. Both P-and S-wave velocities of the heavy oil become frequency dependent: high at ultrasonic, but low at sonic and seismic (Han et. al., 2005).

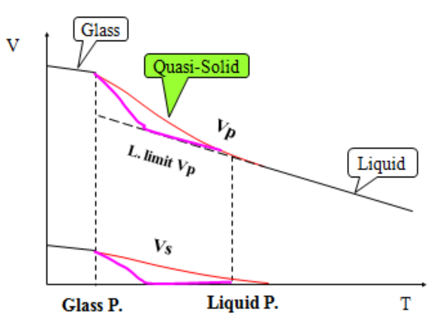

Figure 1: Schematic of velocity trend for heavy oil.

We have measured velocities on heavy oil saturated sands from Alberta, Canada. Oil has API gravity of ~8. These heavy oil sand samples are unconsolidated with high porosity of ~35% from shallow depth of ~400 m. We have measured velocities as function of temperature on these heavy oil sand samples. Figure 2 shows measured dry and heavy oil saturated velocities on a sample. We examined how Gassmann's equation works to model measured velocity-temperature trend. Using measured dry velocity data and measured oil properties in the calculation, the Gassmann's equation can predict the velocity-temperature trend well as long as the heavy oil in the liquid phase as shown in Figure 2. We have found that properties of heavy oil sands are mainly controlled by the properties of heavy oil (Han et al., 2007).

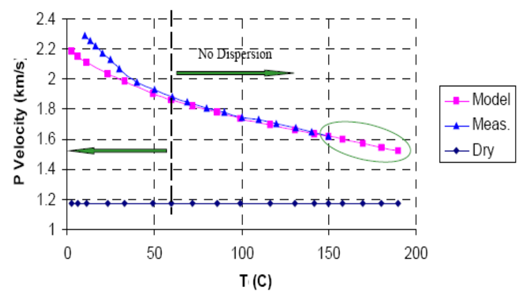

Figure 2: Measure P-wave velocities on oil saturated and dry samples with model prediction with the Gassmann's equation.

At temperature lower than the liquid point, oil in the quasi-solid phase, the model deviates and underestimates from data trend. We are not sure what the cause is. Although we have found other factors such as grain sorting, oil saturation also conjunction with thermal effects (Han, et al., 2007), our knowledge of interaction among them is limited.

With more measurement on heavy oil sand samples from different reservoirs, we have found that velocity-temperature data on heavy oil sands are much more complicated, which deserve a new effort to further investigate.

Thermal pressure of heavy oil

Most popular way to produce in situ heavy oil is to reduce its viscosity with a thermal processing. When oil is heated, its volume expands significantly, an order higher than that of sands, which is negligible. If we assume oil is confined in pores (sand frame), pressure of heated oil increases. Figure 3 show thermal pressure generated with increasing

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temperature as oil volume (density) remains as a constant. With 10 °C increment of temperature, thermal pressure on oil can be much greater than overburden pressure, typically less than 10 MPa for shallow heavy oil reservoirs.

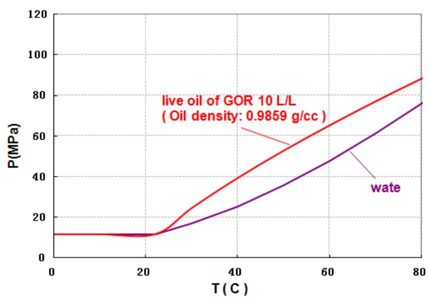

Figure 3: Thermal pressure of heavy oil and water with constant density assumption.

Thermal damage as heavy oil in the quasi-solid phase

Thermal damage is caused mainly by confined pore fluid. Without fluid saturation, such as dry rock, there is negligible thermal damage on rock frame. In the laboratory, samples are settled in pressure vessel and typically heated and confined with pressure fluid. Pore pressure is controlled by a pump through input line on the top of the sample. However, at low temperature such as 10 °C, a typical value at in situ of a shallow reservoir in Alberta Canada, heavy oil with API gravity of 8 has viscosity in an order of millions cp and behaves as a solid. If so, heated oil will pressurize, overcome the overburden pressure (confining pressure at lab), pump up the rock frame, and alter the grain contact. However, oil is not solid, pressurized oil can relax through pores to low pressure area. Relaxation time depends mainly on oil viscosity. At lab, if heavy oil in pores cannot fully relax due to high viscosity, thermal pressure increases and pore pressure is un-controllable. Grain contact can be altered (damaged) by the thermal pressure. Therefore, potential of thermal damage is high at low temperature. With increasing temperature, thermal damage potential reduced and eventually stopped with no more thermal pressure can be generated (or pore pressure is fully controlled at lab). Velocity data shown in Figure 2 suggest that there is negligible thermal damage on sand frame as heavy oil in the liquid phase. Dry properties of dry sand remain as constant with temperature increase from 60º to 150 ºC. However, at temperature lower than 60 C, heavy oil is in quasi-solid phase, there is thermal damage in sand frame. Low estimation of Gassmann's model may caused by using wrong dry rock properties.

Dry velocity data

We test the oil saturated sample with temperature up-to 150 °C, then clean oil out to get the dry sample. We measured velocities of dry sample with temperature up-to 150 °C. Dry velocity as shown in Figure 2 remains as a constant. There is no thermal damage on the dry sample as expected. However, the dry sample has marked with all the thermal damage occurred in the first temperature cycling test with oil saturation. It means that early thermal damage at temperature lower than the liquid point cannot be preserved. Therefore, measured dry velocity data at low temperature than the liquid point is a low estimation, which cannot be used in the Gassmann's model.

General velocity-temperature trend

We have assumed that thermal damage is limited as temperature higher than the liquid point. With more data available, we can see more evidence of that thermal damage reduced with increasing temperature, but not limited at the liquid point. As shown in Figure 4, velocities are measured on a dry sample in which heavy oil has been cleaned out after initial temperature test. Then, we measured velocities on the sample saturated with water. We apply Gassmann's model with measure dry data and water property. Model predicts water saturated velocities perfectly. We expect that Gassmann's model may also predict velocity-temperature trend well for this sample.

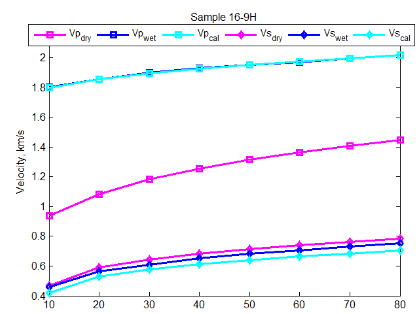

Figure 4: Measure dry and water saturated velocities and matched model using the Gassmann's equation.

As shown in Figure 5, the Gassmann's model underestimates P-wave velocities of oil sands even at temperature much higher than the liquid point. For the same sample, why the Gassmann's model works well for water saturated case, but not well for velocity-temperature trend on heavy oil sands? For the case of water saturation, we used correct dry velocity data with correct water properties without worry any thermal damage occurred during measurement processing. However, for model of

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velocity-temperature trend on heavy oil sands, velocities used in oil saturated case have less thermal damage than the dry velocities, which is measured on more damaged sample by previous temperature test. Therefore, the mismatch between Gassmann's modeling and measured data is not a problem with the Gassmann's equation. It is caused by using wrong data.

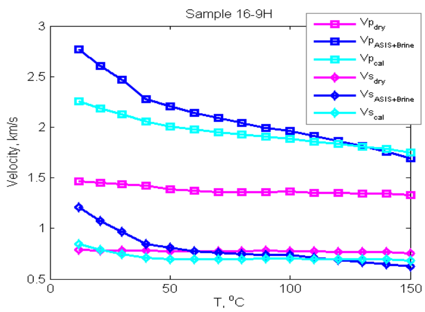

Figure 5: Measure velocity-temperature trend on a heavy oil sands. Gassmann's model did not match data well.

Complexity of velocity-temperature trend

Although all the oil sand samples are unconsolidated with similar porosity and oil saturation from same reservoir, they show very different velocities and velocity-temperature trends. Figure 6 show P-wave velocities as function of temperature measured on a group of samples from Alberta, Canada. At in situ condition of 10 ºC, velocities are featured with a wide scatter from low as 2.2 km/s to high as 2.8 km/s and large velocity reduction gradient. At temperature higher than 50 ºC, velocity reduction gradient approach to a constant but varies in wide range from ~5 m/s/°C to 2.7 m/s/°C. Low velocity data with low gradient appear as a low limit for other samples. At high temperature of 150 °C data scatter reaches the minimum. It seems suggest the thermal damage for all the samples reach to a limit. It also means that Gassmann's model match all the data well at 150 °C.

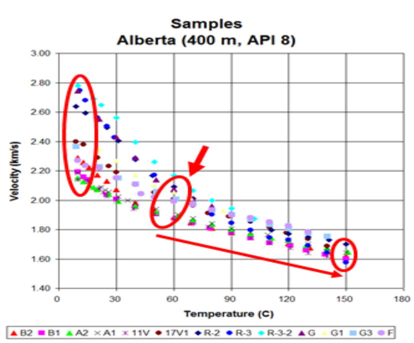

Figure 6: Measured velocity-temperature trend on Alberta heavy oil sands from Canada.

As we assumed, if properties of heavy oil dominates velocity-temperature trend of heavy oil sands, the velocity gradient should be more or less similar. But data suggest otherwise. Gassmann's calculation matches the data with the low velocity and low gradient trend. It suggests that thermal damage effect is eliminated for low velocity samples. In consequences, dry properties of sample can remain unchanged. Other samples with high velocity and velocity reduction gradient appear to continue the processing of the thermal damage with increase temperature similar as data shown in the Figure 5. If we use proper dry properties, Gassmann's model should be predict well all the velocity-temperature trend. Unfortunately, we may not be able to preserve less damaged rock frame after clean the oil out of the sand frame.

Different velocity-temperature trend

Figure 7 shows newly measured velocity-temperature trend for heavy oil samples from the Ugnu formation of the North Slope of Alaska. The Ugnu formation at depth of ~ 1,200 meters and temperature of 20 °C, consists of heavy oil saturated unconsolidated sands with porosity of ~35% and oil API gravity of 12. In general, data show similar pattern of velocity-temperature trend as that from Alberta, Canada (Figure 6), but with different features.

1. Less scatter of velocities
2. Less temperature effects on velocities
3. Significantly high velocities at 150 C.

With relatively light oil at relatively high temperature, the Ugnu oil is almost in a liquid phase as shown in Figure 8.

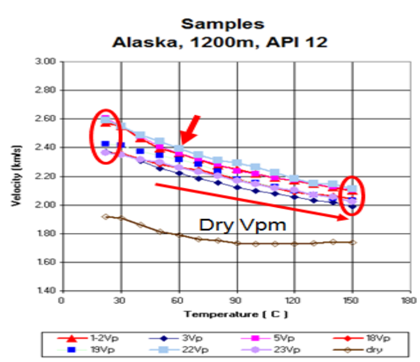

Figure 7: Measured velocity-temperature trend on Ugnu heavy oil sands from Alaska.

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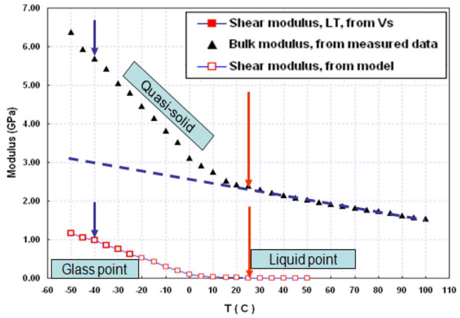

Figure 8: Measured bulk and shear modulus on Ugnu heavy oil samples.

The oil has less contribution to enhance strength of the sand frame. Pore fluid-sand structure is relatively simple and homogenous. Velocity data at 20 °C have much less scattering. We have observed thermal damage effect but eliminated at temperature of 60 °C. We invert dry velocity from oil saturated data with a low bound of velocity as shown in Figure 7. Dry velocity decreases as temperature increase from 20 to 60 °C, then, remains as a constant at temperature higher than 60 °C.

Data of the Ugnu heavy oil sands also show significantly higher velocity (>2 km/s) than those (low as 1.6 km/s) of the Alberta heavy oil sands (figure 5) at 150 °C. The Ugnu oil is lighter than that of Alberta oil and will contribute less to increase velocity. Therefore, higher velocities of the Ugnu sands are mainly caused by deeper depth and better compaction. The Ugnu data were measured at effective pressure of ~13.8 MPa, much higher than 3 MPa used for the Alberta data. But such pressure effect on velocity is not enough to cause more than 10% velocity increase. Although both sands have similar porosity the Ugnu sands is better compacted and preserved with less thermal damage with lighter oil to enhance higher velocities.

Conclusion and Discussion

Measured velocity-temperature trend on heavy oil sands suggests that the thermal damage of sand frame is caused by thermal pressure of heavy oil and mainly deteriorates the heavy oil contribution to strength sand frame and reduce velocities. It is a quasi-static processing and not counted as frequency dependent. Thermal damage mainly occurs at low temperature and reduces with increasing temperature. Addition to heavy oil effect, threshold of the thermal damage is limited by rock texture and degree of compaction.

Analysis of measured data suggests that Gassmann's model work well for heavy oil sands at temperature higher than the liquid point. We should count the thermal damage effect on sand frame when modeling velocity-temperature trend of heavy oil sands. With frequency depended oil properties we can predict frequency depended heavy oil sand properties with the Gassmann' model.

We tend to conclude that the Gassmann's calculation also works at the temperature lower than the liquid point as heavy oil in a quasi-solid state, if we count all frequency effect on properties of heavy oil and count frame properties to include static contribution from heavy oil effect. Unfortunately, we cannot test our hypothesis because we cannot preserve the heavy oil contribution to the sand frame as we intend to move oil out from frame, except the oil contribution has been eliminated such as at high temperature of 150 °C.

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