Seismic properties of heavy oils—measured data

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Seismic techniques hold great potential for characterization and recovery monitoring of heavy oil reservoirs. However, to be more effective, we must understand the seismic properties of the heavy oils and the heavy oil sands because this knowledge of in-situ properties is key to linking the seismic response to reservoir properties and changes. In this article, we examine the seismic properties of heavy oils in detail.

Heavy oil and bitumen

Definitions of heavy oils differ widely. The USGS defines heavy oil as a dense and viscous oil that is chemically characterized by its content of asphaltenes. API gravity of heavy oil has been defined from 22 to less than 10 (ultraheavy oil or bitumen).

High-density heavy oils can be formed by several mechanisms. Heavy "tar mats" can occur in deep reservoirs by chemical precipitation, and tend to accumulate at the base of the reservoir. More commonly, heavy oils are formed in shallow deposits by biodegradation of lighter oils; alkane chains and lighter hydrocarbons are consumed by bacteria, leaving a mixture of complex organic compounds (see, for example, Hunt, 1996). This requires contact with circulating fresh water. Although this mechanism can be different than that forming tar mats, the heavy components may be similar.

Typically, heavy crude oils are classified into four types—saturates, aromatics, resins, and asphaltenes—based on solubility classes (SARA analysis). Heavy oils contain more resins and asphaltenes with high molecular weight. As described by Batzle et al. (2006), due to complex heavy compounds in heavy oil, the simple empirical trends developed to estimate fluid properties of light oil may not be appropriate for heavy oils.

Liquids, solids, glasses

In terms of molecular dynamics, the phase transition between liquids and solids can be very complicated. On the molecular level, fluid, solid, and glass have different structures:

1) Liquids: molecules are disordered and not rigidly bound.
2) Crystalline solids: molecules are ordered in a regular lattice.
3) Glassy solid: molecules are disordered but rigidly bound (amorphous solid) due to high viscosity. Glass point is often defined as when liquid viscosity equals 10^{15} centipoise (cp). A fluid with viscosity higher than the glass point is glassy solid. Dropping below the glass point temperature, Tg, occurs when viscosity exceeds 10^{15} cp.
4) Quasi-solid: a transition phase between a glassy solid and liquid phase for viscous materials.

A crystalline solid has a melting point (temperature), at which the solid absorbs (fusion) heat, and transforms into a fluid phase. A glassy solid has no distinct melting point; instead there is a temperature transition zone called the quasi-solid phase. With increasing temperature, glass gradually softens and eventually liquidizes and transforms into a liquid phase.

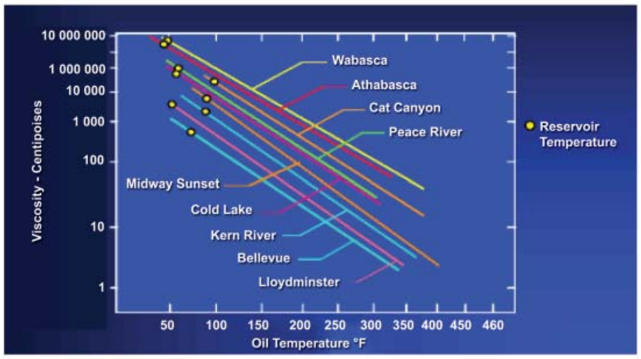

Figure 1. *Viscosity temperature trends for various heavy oils (from Dusseault, 2006).*

Viscosity is the key controlling heavy-oil production and, as we shall see, it also has a strong influence on seismic properties. Viscosity is a measure of the fluid resistance to flow. Temperature, composition, and density (API gravity) are dominant influences on the properties, including viscosity, of heavy oil.

Viscosity of oil has been carefully studied because it controls the economics of oil production and transportation. However, currently, there is no definitive model for viscosity of heavy oils.

Measured data demonstrate that composition is also a dominant factor controlling viscosity. Although viscosity data show large variations in magnitude, they have similar temperature-dependence (Figure 1). In general, viscosity shows increased temperature-dependence at low API gravity (high density). Generally, we can calibrate viscosity with empirical relations over a local area where variations in composition are restricted.

We have conducted numerous density measurements using the constant mass method. The density data are fitted quite well using linear temperature dependence. This is similar to the behavior of light oils. Gas in solution has a small effect for most shallow heavy oils and may be negligible due to the small amount of gas that can go into solution (low GOR).

Velocity model for light oil. The P-wave velocities of light oils (API gravity > 22) are independent of frequencies and have no measurable shear velocities. The velocity of light oil is basically controlled by pressure-temperature conditions and velocity-pseudodensity, which is derived from API gravity, GOR, and gas gravity. For light oil, both velocity and viscosity increase with decreasing temperature. We can correlate ve-

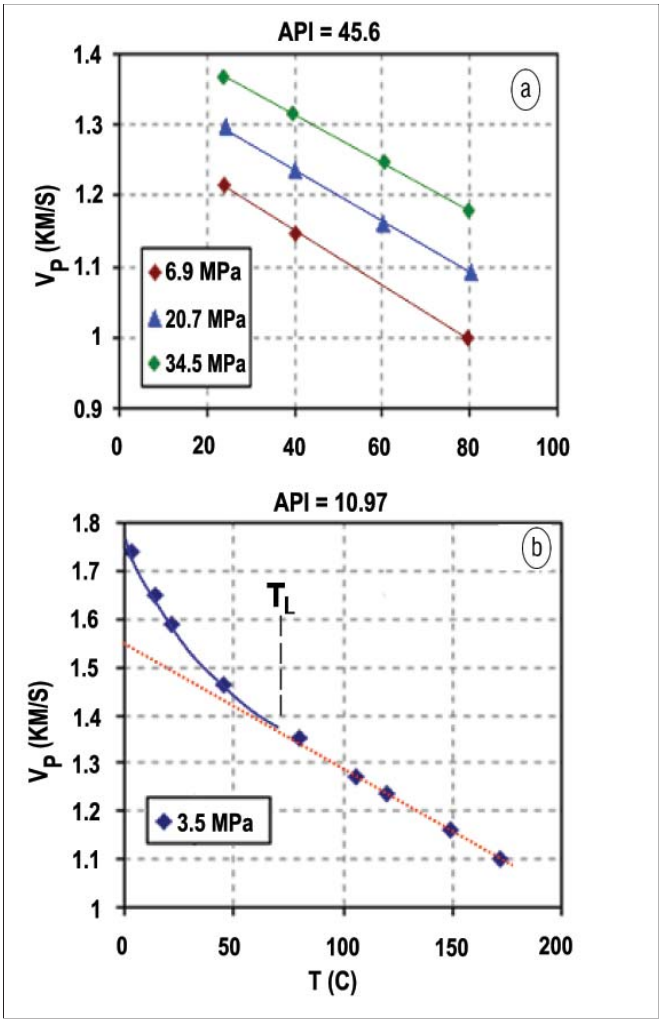

Figure 2. *(a) Velocity-temperature measurements for a light oil at different pressures. Note that the* V_P*–temperature trends can be fit very well by straight lines. (b) Velocity-temperature measurements for a heavy oil at different pressures. At low temperatures, the* V_P*–temperature data show a strong non linear trend. The temperature where this departure begins we call the liquid point,* T_L

locity to temperature linearly (Figure 2a). No viscosity effect on the velocity of light oil has been observed.

The suite of velocity data used to develop this model includes heavy oil samples at high temperatures. This suggests that heavy oils at high temperatures are similar to light oils. However, at low temperatures, viscosity of heavy oils drastically increases and heavy oils transform into a viscoelastic state.

Velocities of heavy oil. We have measured P-wave velocities of heavy oil samples as functions of temperature, pressure, and gas-oil ratio (GOR). Using the pulse transmission method, the velocity can be calculated as

$$V = L/t \qquad (1)$$

where L is the length of the sample and t is traveltime of the P-wave. We can control sample pressure and temperature generally within sensor accuracy (less than 0.5%). With calibration using distilled water, the accuracy of the P-wave velocity is better than 0.5%.

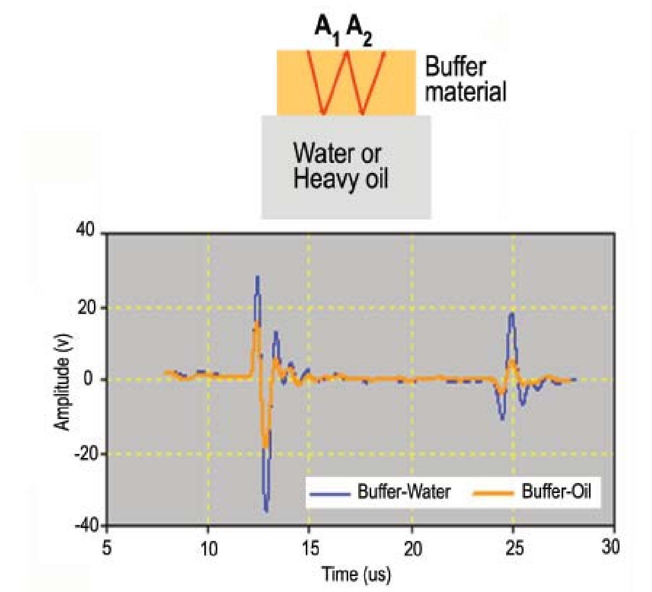

Figure 3. *Shear-wave measurements using the reflection of a shear wave off a solid-liquid interface. Calibration is performed using water (shear modulus = 0).*

We found that both amplitude and frequency of the P-wave signals of heavy oil are very sensitive to temperature. The signal-to-noise ratio decreases significantly at low temperature. For 3-MHz transducers, the P-wave signal of heavy oil is attenuated with decreasing temperature. This amplitude behavior indicates we are approaching a viscous relaxation effect within the heavy oils at lower temperatures.

The behavior of heavy oils is distinctly different from light oils at low temperatures. As can be seen in Figure 2b, below about 50°C, the trend becomes nonlinear. This stronger temperature dependence in P-wave velocity indicates that we are beginning to be influenced by the viscous shear properties of the fluid, i.e., it begins to act like a solid.

As mentioned, heavy oils in the quasi-solid phase possess shear rigidity. Several methods are available to obtain these shear rigidities (Behura et al., 2007). We measured shear velocity in heavy oil in the glass state with conventional ultrasonic wave-transmission methods. However, with increasing temperature, heavy oil transitions into a more classical fluid, and the transmitted shear signal becomes very noisy and attenuated. Consequently, we developed an alternative method: Measure the reflected shear wave off a fluid-solid interface, derive the reflection coefficient, then derive the shear impedance and shear velocity for the viscous liquid (Han et al., 2005). This allows measurement of shear velocity of lighter fluids as a function of API gravity, temperature, GOR, and pressure. Basically, we use reflected amplitude from a buffer-water interface to calibrate the amplitude measured from a buffer-oil interface under the same conditions (Figure 3). If buffer impedance and oil density are known, we can derive shear velocity. The typical error in shear velocity is around 5%. The main sources of errors are from stability of coupling between transducer and buffer and electronics. In general, relative error will increase to 20% at shear velocity less than 100 m/s.

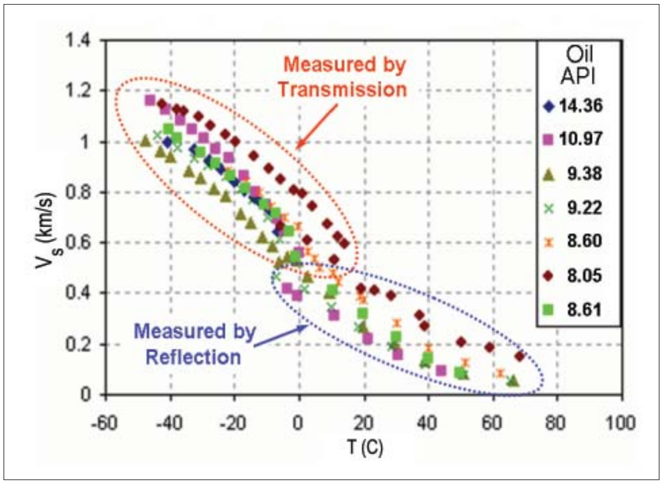

Figure 4. *Shear velocity versus temperature for several heavy oils (dead). Two measurement techniques were used: pulse transmission and reflection amplitude.*

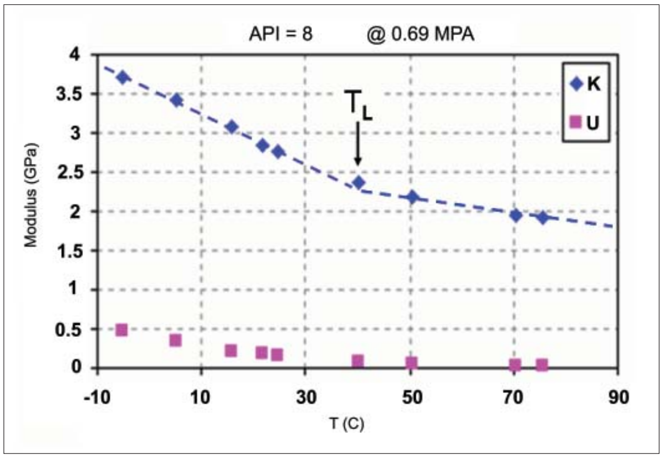

Figure 5. *Bulk modulus (diamonds) and shear modulus (squares) for an API 8 gravity heavy oil. At a liquid point temperature (T_L) of 40° C, a shear modulus appears and the bulk modulus—temperature trend changes slope.*

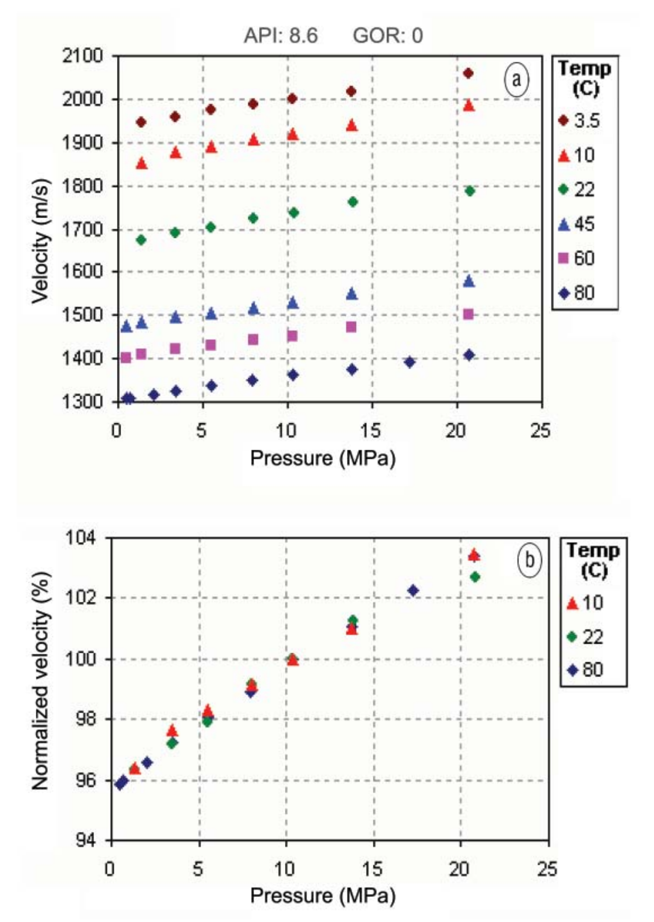

Figure 6. *(a) The effect of pressure on the P-wave velocity of an 8.6 API heavy oil at several temperatures. The pressure trend is very consistent that relations for lighter oils may be used. (b) If velocities for each temperature are normalized to the velocity at 10 MPa, the trends collapse to a single curve.*

We can now examine the influence of API gravity and temperature on shear velocity. Figure 4 shows the shear velocities measured on several heavy oil samples with API gravity ranging from 14.36 to 8.05. Most shear velocities were measured at room pressure. There is a general increase in shear velocity with decreasing API gravity (increasing density). However, there is considerable variation and factors other than simple density, such as specifics of the composition, influence the velocity.

Using the measured densities, P- and S-wave velocities, we can extract the bulk (K) and shear (μ) moduli of the heavy oils. Figure 5 shows the moduli of a sample with API = 8 at pressure of 0.69 MPa (100 psi). These data show that the bulk modulus decreases rapidly from 3.7 GPa at -8°C to 2.2 GPa at 50°C, then continues decreasing to 1.9 GPa at 76°C with a much lower gradient. The data show clearly that, whenever the shear rigidity of heavy oil is negligible, the bulk modulus shows a linear trend with increasing temperature. Similarly to the case of velocities, we can define the liquid point (T_L) as the temperature at which the shear rigidity vanishes, and the slope of the bulk modulus-temperature trend changes.

Factors influencing velocity

The velocity of shallow heavy oils is a function of temperature, API gravity (density), viscosity, and wave frequency. From the point of view of petroleum engineers and geochemists, the API gravity (density) of oil may have no unique relation to velocity or viscosity because oils with same density may have very different chemical composition. However, from the data we examined from both light and heavy oil samples, API is still a dominant influence on velocities and velocity dispersion at temperatures lower than the liquid point. We observed that heavy oils with similar API gravities show systematic differences in velocity, but usually these differences are less than 10%. The compositional dependence is outside the scope of this paper (see Hinkle et al., 2008).

Pressure effect. Similar to light oil, the P-wave velocity of heavy oil increases with increasing pressure and decreases with increasing temperature. Here, we focus on the pressure effect. Figure 6a shows velocity data for a dead oil sample with API gravity of 8.6. The P-wave velocity was measured at increasing pressure from 0 to 20.7 MPa (3000 psi) and temperature from 3.5 to 80°C. For each temperature, velocity tends to increase linearly with pressure. With increasing temperature, the velocity gradient with respect to pressure seems to decrease slightly. It is of interest that heavy oil with high velocity shows a slightly higher velocity gradient with respect to pressure. Figure 6b shows relative velocities—i.e., all temperature curves are normalized to the velocity at 10 MPa. The increase of the relative velocity with pressure seems to be constant, but slightly less than 0.4% per MPa. Overall, the pressure effect on single-phase heavy oil is small for a low-pressure heavy oil reservoir. The model developed to predict the pressure effect on light oil can be used for heavy oil without correction.

Gas effect. There are two conditions we need to examine to determine the influence of gas on heavy oil: in solution and as a free gas. For completely dissolved gas, there is only one "live" liquid phase. We measured this dissolved gas effect on velocity for several heavy oils. Figure 7 shows measured velocity on a heavy oil sample (API gravity = 11) with GOR near 0 (dead oil), 2, and 37. The data show velocity as a function of temperature at 3.45 MPa (500 psi) for dead and GOR = 2, and at 24.2 MPa (3500 psi) for GOR = 37. The velocity of the dead oil is almost the same as that of the live oil with GOR of 2 and a few percent higher than the live oil with GOR of 37. Gas dissolved in heavy oil does reduce oil velocity—the higher the GOR, the lower the velocity. However, the low capacity to dissolve gas in heavy oils and low-pressure environment of most heavy oil reservoirs generally results in a very low GOR. Thus, although gas in solution has an effect on velocity, we usually need not worry about it.

In contrast, small amounts of free gas in heavy oil reservoirs are very important. During production, pressures often drop below the bubble point. Under these conditions, gas exsolution can generate foamy oil (gas bubbles in heavy oil). It is also possible to cross the bubble point by raising temperature. Figure 8 shows the effect of crossing the bubble point with increasing temperature. Small amounts of gas bubbles can drop the velocity below even that of the free-gas phase itself (this is a density effect). Note that this assumes pressure equilibrium. If heavy oils have viscosity over 10^6 cp, the gas effect on seismic velocity of heavy oils may be reduced because local pressure in the oil may not reach equilibrium with that of gas.

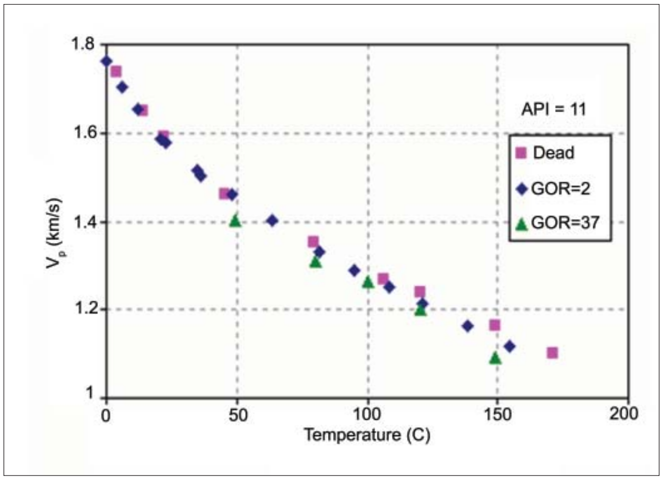

***Figure 7**. Gas in solution (no free-gas phase) lowers the velocity of heavy oils. However, the effect is small and can often be ignored*

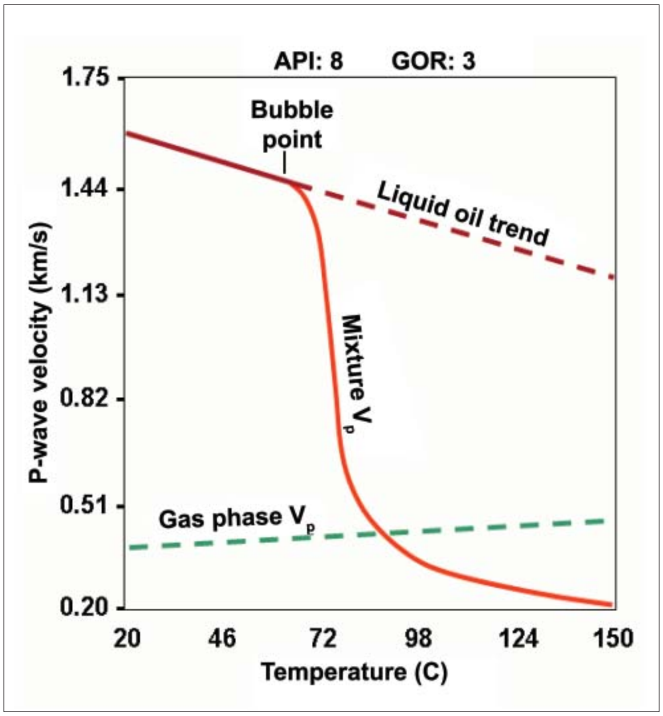

***Figure 8**. Gas coming out of solution has a dramatic influence on the velocity of the heavy oil-gas mixture. Even for this low GOR (3), as we raise temperature past the bubble point, velocity drops to a fraction of the value for the single phase liquid.*

Temperature effect. Probably the most important parameter for heavy oil is viscosity. As discussed, viscosity of heavy oil depends largely on API gravity (density) and temperature. API gravity roughly represents the amount of heavy compounds (such as resins and asphaltines) in heavy oils. API gravity is the basis of most published viscosity models. In contrast, temperature is an environmental condition. In a shallow, low-temperature environment, heavy oil is in the quasi-solid phase. Heavy molecules tend to interact to resist any relative movement. Increasing temperature lowers the coherent force between heavy molecules and reduces viscosity and velocity. Figure 9 shows measured P-wave velocities of heavy oil samples with different densities in a range of 0.897 to 1.014 gm/cc (API gravity from 8 to 26) at low pressures, less than 6.9 MPa (1000 psi). The velocity trends fall into several domains:

1) When temperature is higher than the liquid point (T_L), heavy oil properties are similar to that of light oil; the velocity gradient with temperature is nearly a constant (~3.0 m/s/°C) and slightly decreases for heavier oils. Velocity of heavy oil with temperature greater than the liquid point (T_L) can be expressed as:

$$V = V\,(API, T, (\eta\ (API, T)^{*}\ f))\ldots)$$

$$\sim= V_0\,(\mathrm{API}) + B\,(\mathrm{API}) * \Delta T \quad (T > T_L) \tag{2}$$

At high temperature, viscosity is low and its influence on velocities is negligible. The term B (API) is a function of API gravity for the oil. The pressure and GOR effect on velocity are less important. Velocity relates to temperature linearly.

2) When temperature is lower than the liquid point (T_L), heavy oil is in the quasi-solid phase. Viscosity increases rapidly and the viscosity-frequency effect can no longer be ignored. Velocity deviates from the simple trend in the liquid phase as shown in Figure 9. The velocity gradient with respect to temperature is no longer constant. These data were measured at a frequency of ~1 MHz. With decreasing temperature, the velocity gradient of heavy oil in the quasi-solid phase increases from that of liquid phase, and decreases toward to that of glass-solid phase. This velocity gradient reaches its highest value within the transition zone.

We have observed cases where the viscosity does not conform to a simple API relationship, but velocity does. As an example, a waxy oil, with API = 26.25 (density = 0.897 g/cc) is categorized as "light oil." Physically, the oil appears solidified and cannot flow at room temperature. With such a high apparent viscosity, we expected a high velocity gradient with respect to temperature near room temperature. However, the measured data show similar behavior as that of a typical light oil. One possible interpretation is that the viscosity of the waxy oil is apparently not really high and room temperature is still not lower than the liquid point (T_L). This suggests that, in general, heavy oil velocity is largely controlled by API gravity. However, for a particular reservoir or region, the composition of the heavy oil may effect velocity.

Liquid point. The nonlinear P-wave velocity of heavy oil can be explained by this viscosity threshold characterized by (T_L). We can generalize by reexamining the data in terms of a normalized temperature, T_{nor} for the various oils defined as

$$T_{nor} = \frac{T_w - T}{T_w - T_g} \tag{3}$$

where T_w and T_g represent the temperature when oil viscosity is equal to 1 cp (water) and 10^{15} cp (glass point), respectively. Currently, we apply a viscosity model (Beggs and Robinson, 1975) to calculate normalized temperature. We assume that the normalized temperature is representative for different heavy oils, which will simplify our analysis of heavy-oil velocity data.

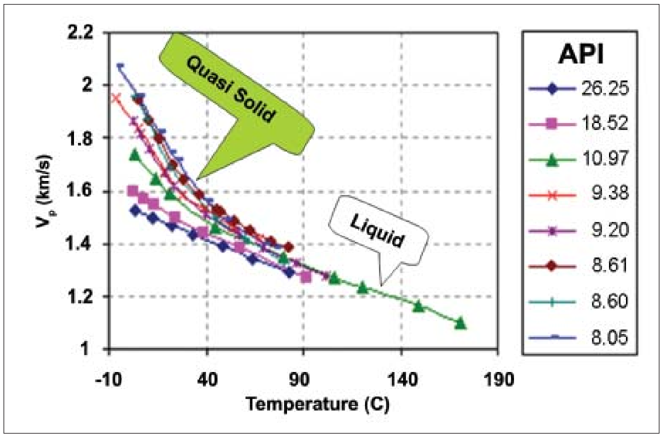

***Figure 9**. P-wave velocities of numerous oils as a function of temperature. The lighter oils (API 26) continue to act like liquids even at low temperature. Heavy oils enter the quasi-solid phase at low temperatures.*

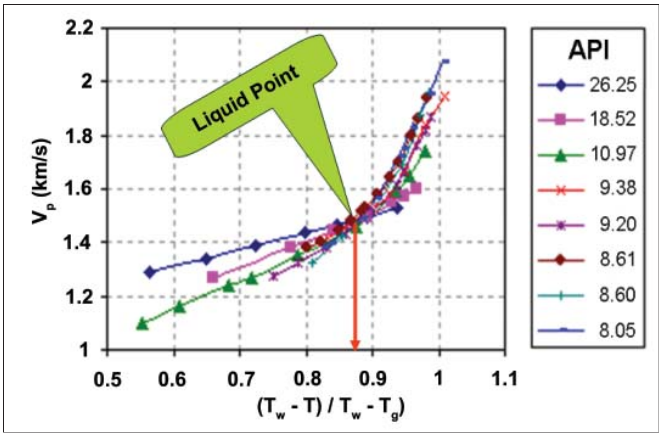

***Figure 10**. P-wave velocities plotted in terms of normalized temperature. This wide variety of oils have velocities which all cross at the liquid point (T_L) which is a function of viscosity.*

Figure 10 shows the P-wave velocity of the eight heavy-oil samples in Figure 9 but now as a function of T_{nor}. With this normalized temperature (based on viscosity), the data for different oils all cross near a single point (P-wave velocity ~1.5 km/s and T_{nor} ~0.89). If $T_{nor} < 0.89$, velocities show a linear relationship to the normalized temperature. If $T_{nor} > 0.89$, velocities deviate up from the linear trend. We define this point ($T_L = 0.89$) as the liquid point; it corresponds to velocity ~1.5 km/s and viscosity ~900 cp

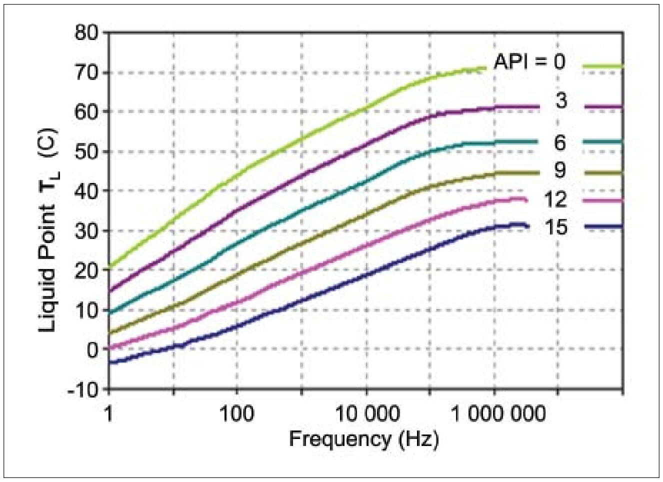

Figure 11*. Expected behavior of the liquid point (T_L) as a function of the density of the oil (API) and the measurement frequency.*

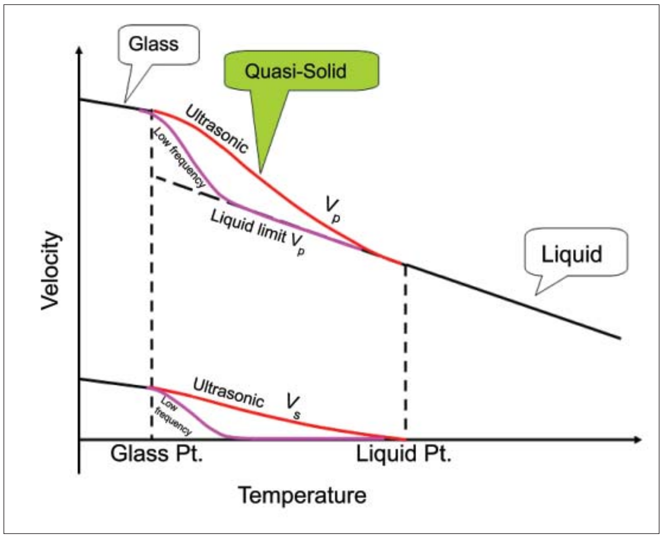

Figure 12*. P-wave velocities plotted in terms of normalized temperature. This wide variety of oils have velocities which all cross at the liquid point (T_L) which is a function of viscosity..*

based on the viscosity model from Beggs and Robinson. This is the threshold between the linear and the deviated velocity-temperature trends. Liquid points are different for different API gravity oils. However, our velocity data reveal that the various oils all have a liquid point corresponding to this one viscosity value. Thus, the liquid point as defined by our velocity data represents a phase transition threshold.

Frequency effect. The frequency dependence of velocity occurs when oils are in a quasi-solid phase in between the glass and liquid points. In practice, heavy oils in the glass phase are considered elastic because viscosity is too high (> 10^{15} cp), and molecules in such glassy solids are fixed in location and the material is considered rigid, similar to a crystalline solid. Heavy oils in the liquid phase are also elastic because the viscosity effect on velocity is negligible. Thus, the frequency effect on velocity is coupled to viscosity (see Batzle et al.). Therefore, the liquid point temperature and viscosity depends on wave frequencies. This is a relaxation phenomenon where the effective stiffness will depend on the rate or frequency of deformation. From our data at 1 MHz, viscosity of the liquid point is slightly less than 1000 cp. For a seismic wave with a frequency of 30 Hz, viscosity of the liquid point should be much higher (= lower temperature) since molecules have a much longer time to move relative to one another. The expected behavior for liquid point as a function of oil API gravity (density) and frequency is shown in Figure 11.

Most viscoelastic materials have a correspondence between viscosity and frequency. For moduli, raising the frequency has the same effect as increasing viscosity. This principle allows building a relationship for the velocity of heavy oil expressed now as function of API, temperature, and a coupled function of viscosity-frequency as shown in Equation 4.

$$V = V\,(API, T, (\eta\,(API, T)^{*}\,f))\ldots)$$

$$\sim= V_0\,(\rho) + B\,(API, T, (\eta\,(API, T)^{*}f)\,)\ ^{*}\ \Delta T\quad (T < T_L)\qquad (4)$$

This relationship shows why we should expect discrepancies among velocity measurements made at widely different frequencies, for example laboratory ultrasonics versus field seismic.

Summary

Most heavy oils are biodegraded and found in shallow, relatively low-temperature environments (<1000 m depth). Pressure on heavy oil is normally low (<10 MPa). Pressure and GOR dependence for velocity are similar to those of light oils.

Based on the data presented in this article, we conclude that, in general, heavy-oil velocity is largely controlled by API gravity similar to the case with light oils. However, after comparing a wide variety of distinct reservoirs, we find the composition of heavy oil can effect velocity, but this need to be evaluated and calibrated locally.

The temperature effect on velocity is of critical importance for heavy oils. This temperature dependence can be divided into three parts: as seen in Figure 12.

1) When temperature higher than the liquid point (T_L), velocity decreases linearly with increasing temperature, as is the case with light oils.
2) When temperature is in between liquid and glass points (Tg), heavy oil is in a quasi-solid phase. The velocity gradient with temperature of quasi-solid oil increases from that of fluid phase, reaches a maximum, then decreases to approach that of glass phase.
3) When temperature drops below the glass point, heavy oil more like a solid. With decreasing temperature, both P- and S-wave velocity will continue to increase, but with a low temperature gradient.

Finally, the velocity data reported here were measured at ultrasonic frequencies (MHz range). The velocities of heavy oils in quasi-solid phase are strongly frequency-dependent, as is the liquid point (T_L). Therefore, both measurement and modeling are required to explore velocities of heavy oil in seismic and sonic logging frequencies.

Suggested reading. "Highlighting heavy oil" by Brown et al. (*Oilfield Review,* 2006). "Heavy oils, seismic properties" by Batzle et al. (*TLE*, 2006). "Estimating the viscosity of crude oil systems" by Beggs and Robinson (*JPT,* 1975). "Heavy oils: Their shear story" by Behura et al. (Geophysics, 2007). "Don't forget viscosity" by Bergman (2nd Annual Reservoir Engineering Symposium, 2004). "Pressure-volume-temperature correlations for heavy oils and extra heavy oils" by De Ghetto et al. (SPE paper 30316, 1995). *Mechanics of Heavy Oil* by Dusseault (2006 short course, US Society of Rock Mechanics). "Velocity, density, and modulus of hydrocarbon fluids: Empirical modeling" by Han and Batzle (SEG 2000 *Expanded Abstracts*). "Measurement of shear-wave velocity of heavy oil" by Han et al. (SEG 2005 *Expanded Abstracts)*. "Acoustic property of heavy oil—measured data" by Han et al. (SEG 2006 *Expanded Abstracts*). "Heavy oils: a worldwide overview" by Hinkle and Batzle (*TLE*, 2006). "Correlating the chemical and physical properties of a set of heavy oils from around the world" by Hinkle et al. (*Fuel,* in press). *Petroleum Geochemistry and Geology* by Hunt (Freeman, 1996). "Seismic attributes for monitoring of a shallow heated heavy oil reservoir: A case study" by Schmitt (Geophysics, 1999). "Rock physics of heavy oil deposits" by Schmitt (CSEG 2004 *Expanded Abstracts*).

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