Heavy oils—seismic properties

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Heavy-oil seismic properties are strongly dependent on composition and temperature. In biodegraded oils, straight chain alkanes are destroyed and complex heavy compounds dominate. As a result, the simple empirical trends developed for light oils for fluid properties such as viscosities, densities, gas-oil ratios, and bubble points may not apply well to heavy oils.

For very heavy oils, the viscosity is high and the material can act like a solid. This semisolid or glass-like behavior results in the ability of the material to have an effective shear modulus and propagate a shear wave. Velocities and moduli become strongly temperature- and frequency-dependent. As a result, for these heavy oils, properties measured in the ultrasonic (10^5–10^6 Hz), sonic logging (10^4 Hz), and seismic (10–100 Hz) frequency bands can have completely different values. Extrapolating from measurements made in the ultrasonic range to seismic frequencies is very difficult, particularly if temperatures vary over the extremes encountered during thermal recovery processes.

Background. Heavy oils are defined as having high densities and extremely high viscosities. *Heavy oils* usually mean oils with API gravities below 20, and *very heavy oils* mean an API less than 10 (density greater than 1 g/cc). These are an abundant resource, particularly in Canada (Figure 1), Venezuela, and Alaska.

By some estimates, heavy oils represent as much as 6.3 trillion barrels of oil in place. This matches available quantities of conventional oil. More than 50% of Canada's oil production is now from heavy oil.

Seismic monitoring of heavy-oil production can improve the effectiveness of the recovery program. However, seismic monitoring still remains only qualitative due to incomplete calibration and poorly understood aspects of the oil and the influence of the recovery process. The situation is complicated because many heavy oils act like solids and their prop-

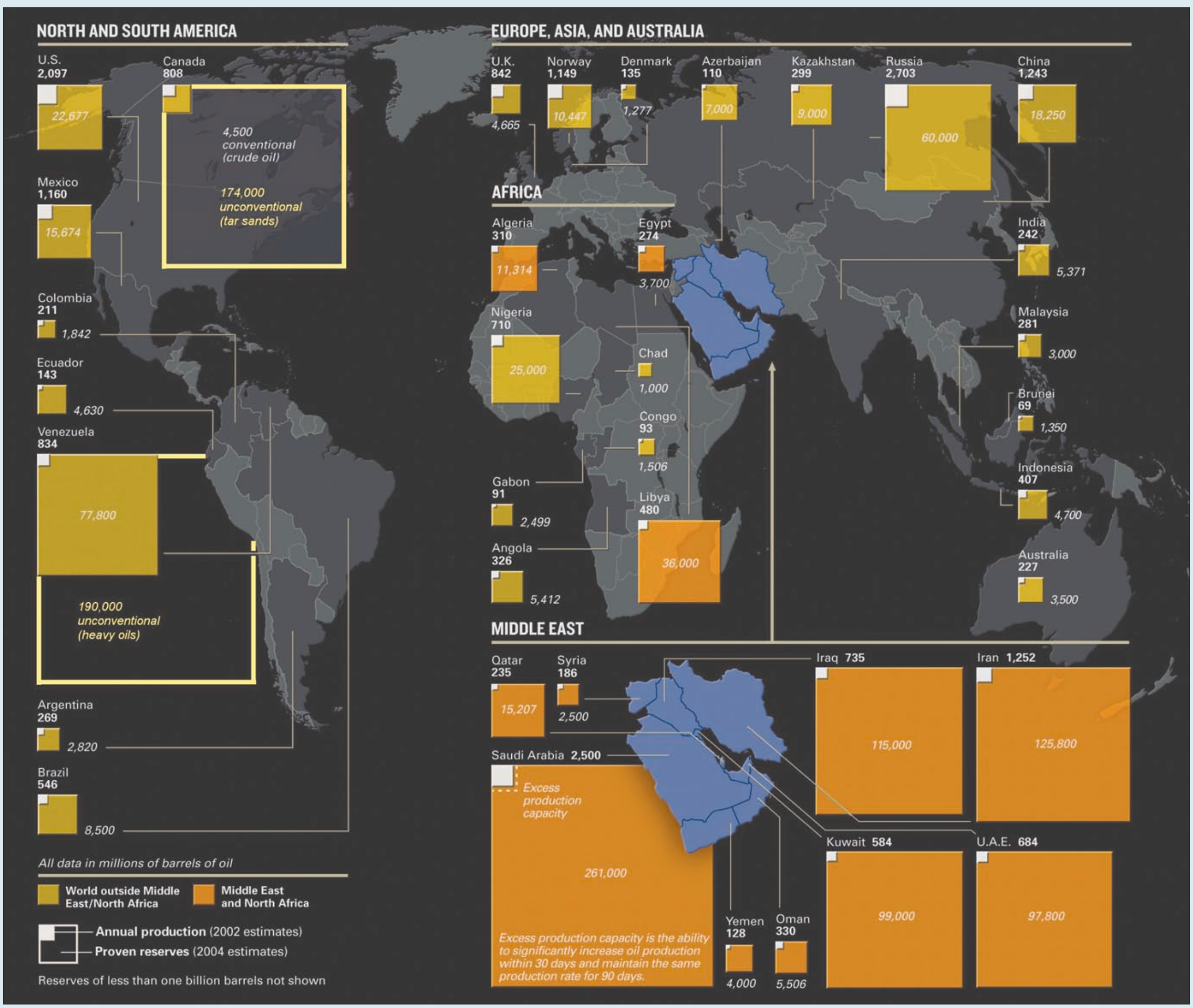

Figure 1. Heavy oils are an enormous resource. If we include heavy oils (yellow outlines), Canadian reserves almost match the conventional reserves of Saudi Arabia; and Venezuela takes the lead in total reserves (modified from Appenzeller, 2004, 5W Infographic/National Geographic Image Collection).

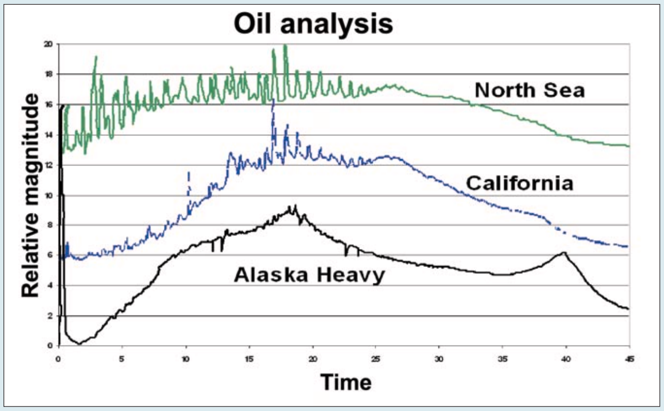

Figure 2. Oil compositions from HPLC (high-pressure liquid chromatography) analyses on some of our tested samples. The straight alkanes (pentane, hexane, etc.) are represented by spikes in the North Sea crude. As biodegradation occurs, the alkanes are consumed, leaving a background of complex organic compounds, as with the Alaska heavy-oil sample.

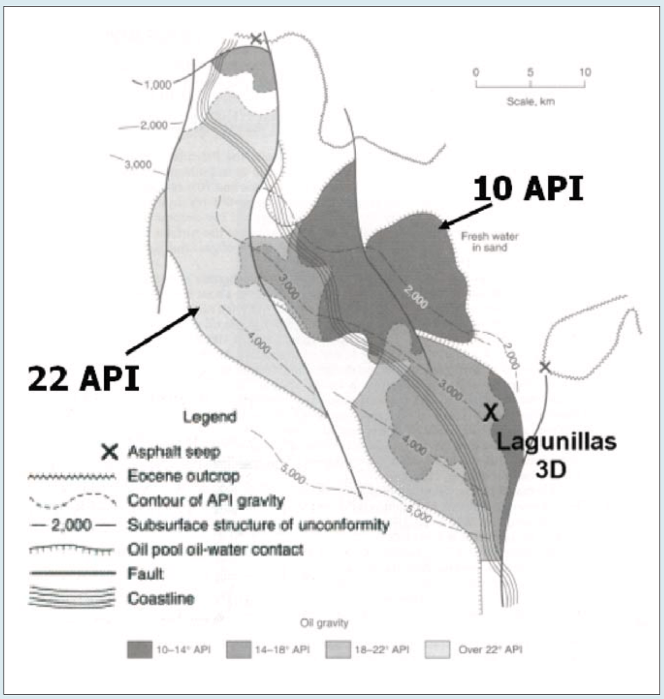

Figure 3. Distribution of oil weights in the Lagunillas Field, Venezuela. At shallow depths, circulating groundwater allows the biodegradation of the oil, lowering the API to the point where the heavy oil serves as a seal (from Hunt, 1996).

erties have strong frequency dependence.

Heavy oils themselves are often fundamentally different chemical mixtures from more typical crude oils due to such processes as biodegradation. In this case, straight alkane chains tend to be consumed by bacteria, leaving a mixture of complex organic compounds (Figure 2). These processes require relatively low temperatures and can be a result of both aerobic and anaerobic activity. Heavier compounds include asphaltenes, bitumens, pyrobitumens, resins, etc. These complex compounds are often rather operationally defined. For example, asphaltenes are usually defined as the component of crude oils not soluble in heated heptane. Although this is useful in assessing if solids will form in production pipes, it gives little insight into their seismic properties.

Biodegradation is complex and can be happening at different levels of activity in different portions of a single reservoir. An example of the complexities possible is shown in

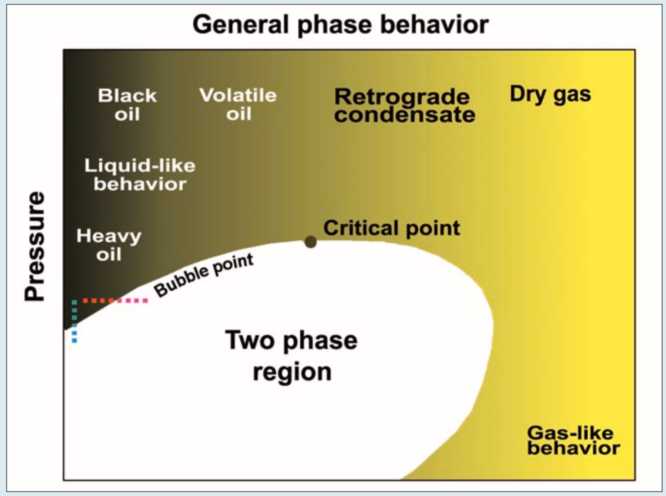

Figure 4. Schematic phase behavior for hydrocarbon mixtures showing the relative position of heavy oils. The bubble-point line can be crossed by changing either pressure (vertical dashed blue line) or temperature (horizontal dashed red line).

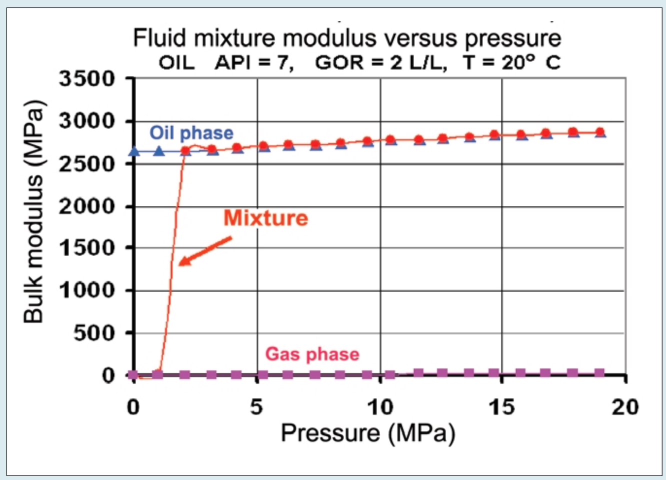

Figure 5. Heavy oil bulk modulus (mixture) as a function of pressure. Decreasing the pressure causes the oil to cross the bubble point, lowering the modulus substantially.

Lagunillas Field in Figure 3. Here, lighter oils (API 22) are found at depth. Nearer the surface, groundwater circulation promotes bacterial attack of the oils, leaving behind the heavy tar zone, dropping the oil to around 10 API. This heavy oil can be so viscous that it becomes effectively immobile. In some cases, such as with Lagunillas, this heavy oil or tar can then form the seal for the lower reservoir. By some estimates, even most light oils are actually biodegraded to some extent.

Heavy oils can also be produced from other mechanisms. For example, an influx of gas at pressure can alter the equilibrium of a hydrocarbon system. A light-oil reservoir could be invaded by gas at high pressure. Such situations often occur when deeper, high-pressure gas migrates up through the geologic section. Light gases are incompatible with the heavier oil components. As the light-gas content increases, heavy molecules drop out of solution. Alternatively, as oils migrate up to regions of lower pressure, asphatines become less soluble and drop out of solution (Wilhelms and Larter, 1993). Thus, a heavy coating or "tar mat" can form, usually at the base of an otherwise light oil or even gas reservoir. These processes can happen where biodegradation is not pronounced. These tar mats often cause drilling and production problems. Because the processes forming these mats are completely different, we expect the chemical makeup to be sub-

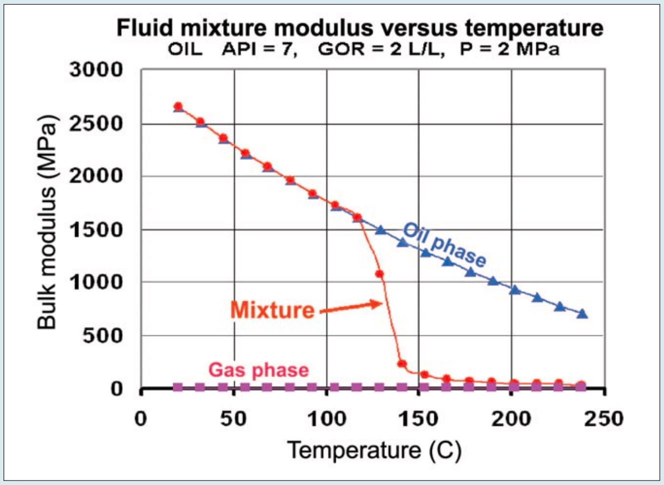

Figure 6. Heavy oil bulk modulus (mixture) as a function of temperature. Increasing the temperature will also cause the oil to cross the bubble point.

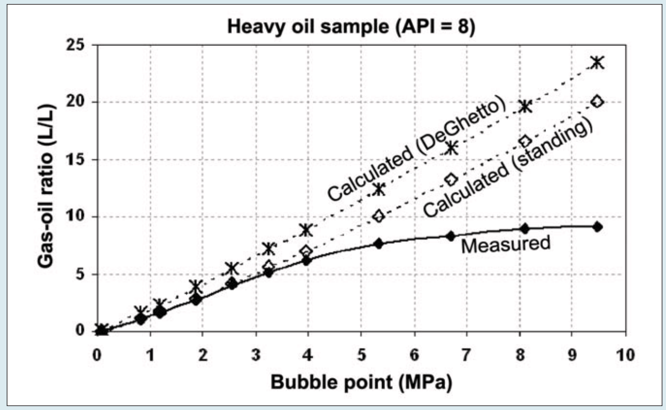

Figure 7. Bubble points over a range of gas-oil ratios. Even though the GORs are very low for this heavy oil, they are systematically shifted to higher pressures than predicted by the relations of Standing (1962), or the modified equation for heavy oils from De Ghetto et al. (1995).

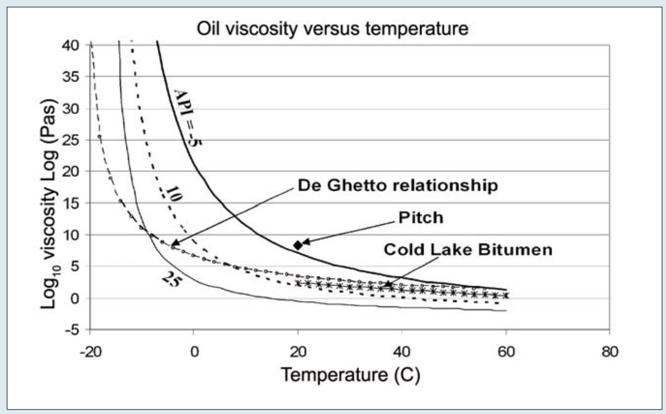

Figure 8. Viscosity versus temperature for oils from Beggs and Robinson (1975). The relation produces a singularity at low temperatures. Also plotted are the data of Eastwood (1992) and Edgeworth et al. (1984) and the heavy oil relation from De Ghetto et al. (1995).

stantially different than biodegraded oils. At this moment, however, research is still under way to see if this means there will be a substantial difference in their seismic properties.

As a further complication, heavy-oil *sands* often behave almost like sand grains floating in an oil matrix. As temperatures change, grain contacts change along with the background oil properties. Velocities and attenuations become strongly temperature-dependent, even within the seismic band. In addition, even very small amounts of gas can have an enormous effect on seismic data. As a result of pressure changes during the recovery process, pore pressure can cross the bubble-point line in either direction (Figure 4). The primary seismic signature of, say, a steam flood, may be the result of crossing the bubble point and not the thermal or even steam phase effects (see for example, Jenkins et al., 1997). Hence, the resulting signature will be a complex combination of fluid, rock, and recovery process characteristics.

Let us first examine the response of crossing the boundary by dropping the pressure or raising the temperature—both common occurrences in heavy oil production. As an example, the calculated fluid bulk modulus for an oil of API 7 is plotted in Figure 5 as a function of pressure (from the Han and Batzle relations). Even with a low gas-oil ratio (GOR) of 2 L/L, we cross the bubble point at about 2 MPa. Above the bubble point, the bulk modulus of the homogeneous mixture is very high: 2600–2800 MPa. This is close to the bulk modulus of water. However, after crossing the bubble-point line, gas comes out of solution, and the modulus drops to near zero. The same effect is seen with the density, although to a smaller degree. Hence, the seismic properties will be strongly dependent on the reservoir conditions and production history. Even if the local engineering analysis indicates that the amount of gas in solution is "inconsequential," that may be true only for reservoir engineering purposes.

Temperature also has a large influence. The phase boundary can also be crossed by changing temperature (Figure 4). In Figure 6, the calculated modulus is plotted as a function of temperature. Crossing the bubble point occurs at about 120° C and the drop in modulus is as substantial as changing the pressure. Obviously, with such dramatic modulus fluctuations, we need a good understanding of the properties and phase behaviors of these heavy oils for seismic monitoring.

Bubble point. As we have seen, even with small amounts of gas in solution, we can still cross the bubble-point line by changing pressure or temperature. At this "heavy" end of the bubble-point line, the seismic data is extremely sensitive to the phase boundary, even with very low gas-oil ratios. Thus, having a good grasp of the bubble-point relations is important.

We can test published bubble-point relations by measuring bubble points directly. In these experiments, we monitor live fluid volumes as pressure is decreased. These are not the classic types of bubble-point measurements where an optical cell is used to directly observe bubble formation. However, with accurate volume measurements, these two methods should give comparable results. We can compare our measured bubble points with calculated values from published relationships.

The bubble points for a heavy oil (API 8.8) are seen in Figure 7. Notice that these bubble-point values are at much lower pressures and gas contents than are typical for the lighter oils. Under the same pressure and temperature conditions, heavy oils can contain far less gas. The discrepancy between the observed and calculated bubble point is obvious. Most relationships overestimate the amount of gas that will go into solution or underestimate the bubble-point pressure. Because of the significance of crossing the phase boundary on seismic data, we need to use a precise bubble-point relation.

Viscosity. One of the most important properties of heavy oils for both engineering and geophysical purposes is viscosity. Viscosity is often the limiting factor in heavy oil production. As we shall see, it also has a strong influence on the seismic properties. Although viscosity is influenced by pressure and gas content, it is primarily a function of oil gravity and temperature. Beggs and Robinson (1975) developed one of the typical empirical relations.

$$Log_{10}(\eta+1) = 0.505y(17.8+T)^{-1.163}$$
where (1)
$$Log_{10}(y) = 5.693 - 2.863 / \rho_0$$

Here, η is viscosity (in centipoise, cp), T is temperature (degrees C), and ρ_0 is the oil density (at STP). Results of this equation and other relationships are shown in Figure 8. (Note that the figure is plotted in Pascal seconds, 1 Pa s = 1000 cp). The low-temperature limit is fixed by the "17.8" in equation 1. Thus at temperatures below about 0° C, these relations are questionable. The viscosity of bitumen (API = 10.3) from the Cold Lake Field reported by Eastwood (1993) is also plotted. To gain insight for the viscosity of very heavy oil, a data point is available from Edgeworth et al. (1984) where they timed the drops coming out of a funnel filled with "pitch" or very heavy oil. Figure 9 shows this experiment, where on average, one drop falls every eight years.

Heavy-oil velocity. As we expect, the compressional velocity (V_P) of our heavy oils will be a function of composition, pressure, and temperature. As an example, the P-waveforms collected on a sample of very heavy oil (ρ_0 = 1.12, API = -5) is shown in Figure 10. Waves are plotted for temperatures of -12.5° C and +49.3° C. The increase in transit time (decrease in velocity) with increasing temperature is obvious. Also apparent is the change in waveform. Amplitudes and frequency content are lower at higher temperature. Hence, large changes in attenuation and relaxation mechanisms are coming into play. At low temperatures, heavy oils will cross their "glass point" resulting in a nonlinear dependence of velocity on temperature.

An example of the nonlinear dependence of velocity of heavy oil on temperature is shown in Figure 11. This is a gas-free oil with a gravity of API = 7. Note that there is little pressure dependence, but strong temperature dependence. Going from 20° C to 150° C results in a 25% velocity drop. Above about 90° C, the oil velocity drops linearly with increasing temperature, as is common in lighter oils. However, below 70° C, the departure from linearity is obvious. At low temperatures, this oil approaches its glass point and begins to act like a solid. Thus, the change in velocity seen in Figure 12 is not only due to an increase in the bulk modulus, but also the appearance of a shear component, the topic of the next section.

Heavy oil shear properties. As a fluid mixture approaches the glass point, the viscosity becomes so high (Figure 8), that it effectively has a nonnegligible shear modulus. This transition can be tested by propagating a shear wave through the fluid. The shear wave results for the very heavy oil sample (API = -5) are shown in Figure 12. At low temperatures (-12.5° C) a sharp shear arrival is apparent. Thus, by many definitions, because this oil has a shear modulus, it is a solid, or glass. Increasing the temperature not only decreases the shear velocity, but also dramatically reduces the shear-wave amplitude. At this point, this oil is only marginally solid. If we do presume this oil is solid, we can derive the effective bulk and shear moduli for this heavy oil (Figure 13). Both moduli decrease approximately linearly with increasing temperature. However, the shear modulus approaches zero at about 80° C. Similar types of behavior are seen in plastic polymers as a function of temperature.

As we have seen, very viscous fluids can propagate a shear wave. Not only will temperature play a major role, but there also will be a strong modulus or velocity dependence on frequency. Because frequency dispersion and attenuation are coupled, such dispersion requires substantial seismic attenuation within the fluid phase itself. We might describe heavy-oil behavior using the viscoelastic model of Maxwell. The shear impedance, Z, can then be expressed as a function of viscosity η, fluid density ρ, the effective high-frequency shear modulus G_{oo}, and frequency ω.

$$Z = \left(\frac{i\eta\omega\rho}{1 + i\eta\omega / G_\infty}\right)^{1/2} \quad (2)$$

If we define a relaxation time, τ, as the ratio of the viscosity to shear modulus

$$\tau = \frac{\eta}{G} \quad (3)$$

then

$$Z = \left(\frac{iG\rho\omega\tau}{1 + i\omega\tau}\right)^{1/2} \quad (4)$$

The shear velocity, V_S, can then be derived from the general relation

$$Vs = |Z^*| / \rho \quad (5)$$

The low-frequency shear modulus of very heavy oils can be measured directly using a stress-strain technique (Batzle et al., 2006). Although the Maxwell model gives the proper trends, dispersion curves are too steep. Another form that is often used to describe a relaxation process was developed by Cole and Cole (1941) and applied to attenuation measurements by Spencer (1981). The Cole-Cole relationship involves the same characteristic relaxation time, τ, for the attenuation mechanism as well as a spread factor, β, which determines the distribution of relaxation times. The real and imaginary components, M' and M'', of a general modulus, $M = M' + iM''$, are

$$M' = M_0 + \tfrac{1}{2}(M_\infty - M_0)\left\{1 + \frac{\sinh(1-\beta)y}{\cosh(1-\beta)y + \sin(\pi\beta/2)}\right\} \quad (6)$$

and

$$M'' = \frac{\tfrac{1}{2}(M_\infty - M_0)\cos(\pi\beta/2)}{\cosh(1-\beta)y + \sin(\pi\beta/2)} \quad (7)$$

where $y = ln(\omega\tau)$, M_0 and M_∞ are the zero and infinite frequency moduli.

This would lead to a general attenuation of

$$\frac{1}{Q} = \frac{M''}{M'} \quad (8)$$

The results of using the high-frequency (ultrasonic) shear modulus shown in Figure 13 and the viscosities from Figure 8 in the Cole-Cole relation are shown in Figure 14. Notice the strong temperature and frequency dependence of the shear properties. At low temperatures (0° C), this oil acts like a solid. However, by +20° C, the shear properties are in transition. At high frequencies, such as with our laboratory ultrasonics, this material is still effectively a solid. At seismic frequencies, however, the material can go through shear relaxation and acts like a liquid, with no shear modulus. For this oil at 40° C, ultrasonics are in a completely different viscoelastic regime and will not give results representative of properties at seismic frequencies. Logging frequencies can be in this transition region

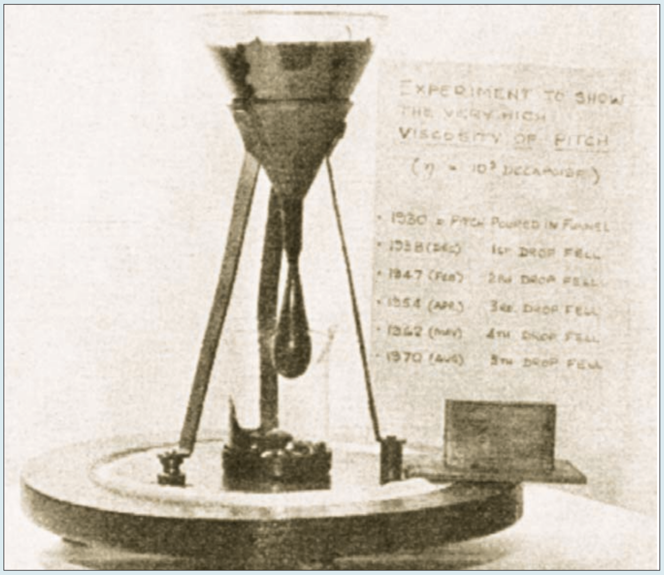

Figure 9. The heavy oil or "pitch" drop experiment described by Edgeworth et al. (1984). The background record says:

1930	*Pitch poured in funnel*
1938 (DEC)	*1st drop fell*
1947 (FEB)	*2nd drop fell*
1954 (APR)	*3rd drop fell*
1962 (MAY)	*4th drop fell*
1970 (AUG)	*5th drop fell*

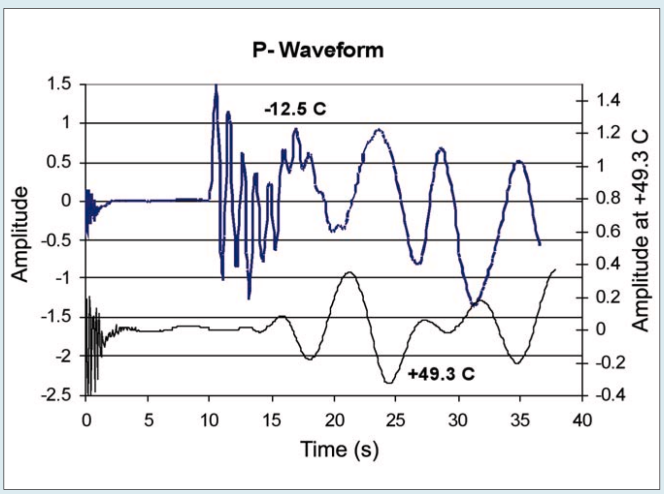

Figure 10. *Ultrasonic compressional waveforms for a very heavy oil (API = -5). Strong arrivals are seen at low temperatures. At higher temperatures, not only is the arrival delayed, but the wave is attenuated.*

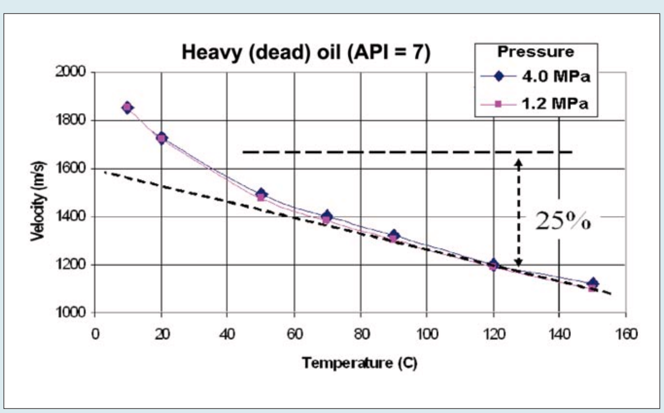

Figure 11. *This heavy-oil velocity also drops substantially with increasing temperature. At temperatures below about 70° C, the temperature-velocity relation becomes strongly nonlinear.*

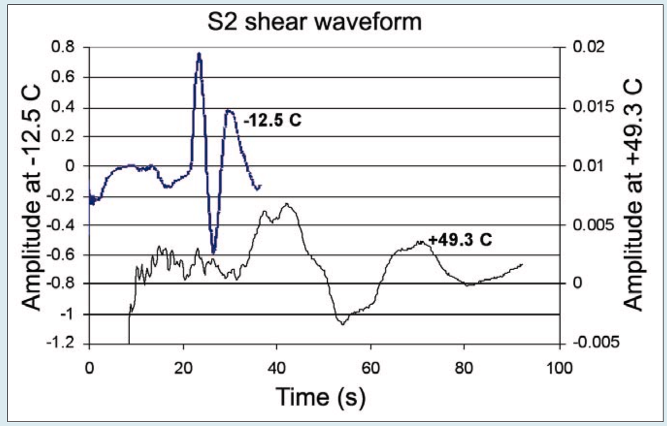

Figure 12. *Ultrasonic shear waveforms in very heavy oil at -12.5° C and 49.3° C. The sharp arrival at low temperature is delayed and dramatically decreased in amplitude at higher temperature.*

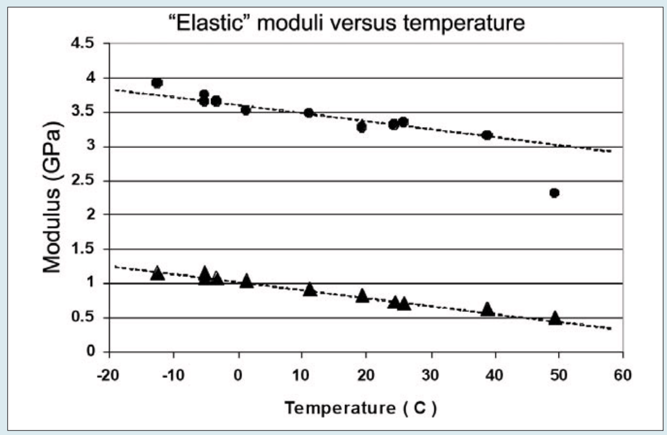

Figure 13. *Elastic moduli of the heavy oil from ultrasonic data. The effective shear modulus (triangles) drops toward zero as temperatures approach 80° C.*

and yield some intermediate value between seismic and ultrasonic frequencies.

Heavy oils in rocks. As an example of the influence of heavy oils on the seismic properties of rocks, we can examine the results for a carbonate from south Texas saturated with the very heavy oil seen in the previous figure. A scanning electron microscope image of the rock is shown in Figure 15. The heavy oil fills the pore space with a semisolid material. As a result, we expect the velocities to be both strongly temperature and frequency dependent. Figure 16 shows that at ultrasonic frequencies, the velocities remain high, even at elevated temperatures. However, at low seismic frequencies, the velocity is more temperature sensitive. In the graph, strong velocity dispersion can be seen, even within the seismic band. A similar amount of dispersion can be observed in the data collected by Schmitt (1999). Sonic velocities in the heavy oil zone are much higher than seismic frequency velocities collected by VSP (Figure 17). For these heavy oils, disagreements of more than 20% between seismic and logging frequencies can be expected. Note that in any synthetic modeling of these reservoirs, the reflections of the heavy oil sands based on standard sonic logs would be completely different than the low-frequency seismic response.

Conclusions. The geophysical properties of heavy oils are controlled by factors such as density (API), composition, temperature, pressure, gas-oil ratio (GOR), and bubble point. Although relatively little gas can be in solution, the transition from a free-gas phase to gas in solution can produce the dom-

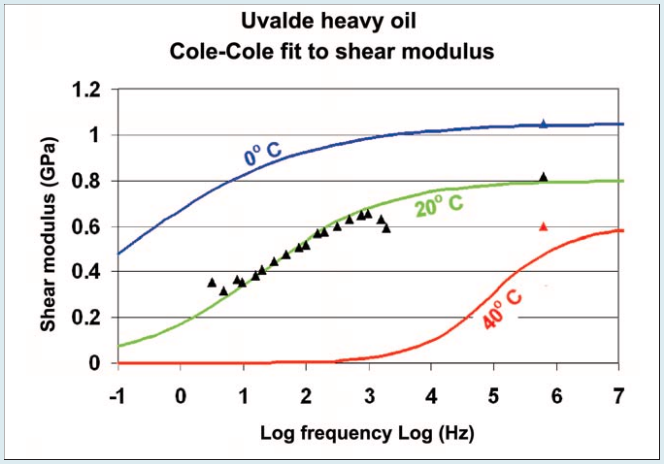

Figure 14. *Measured (triangles) and calculated (lines) shear modulus,* G, *in Uvalde heavy oil (API = -5) using a viscoelastic liquid (Cole-Cole) model. High-frequency shear modulus comes from ultrasonic data (Figure 13). Viscosities were derived from Figure 8. Low-frequency data were measured using a low-amplitude stress-strain technique.*

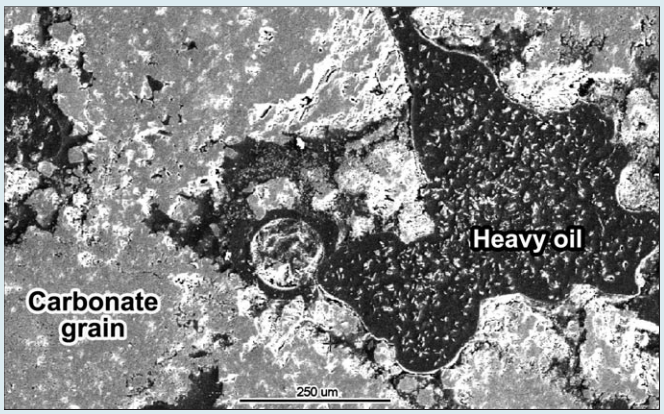

Figure 15. *Scanning electron microscope image of the Uvalde carbonate saturated with heavy oil.*

inant time-lapse seismic response. Heavy oils can also have such high viscosities that they act more like a solid than a liquid. As a result, these oils have an effective shear modulus and propagate a shear wave. However, this shear behavior is strongly frequency- and temperature-dependent. With heavy oils saturating rocks (or sands), they will impart a similar strong frequency and temperature behavior to the reservoir. Thus, data collected in the seismic frequency band will not equal those collected in the sonic logging band or with ultrasonic measurements.

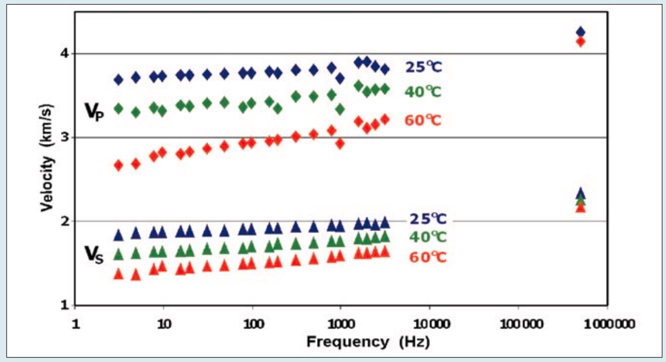

Figure 16. *Frequency dependence of the Uvalde heavy-oil-saturated sample. As expected, velocity decreases with increasing temperature. Also, dispersion becomes significant within the seismic band as temperature increases (from Kumar, 2003).*

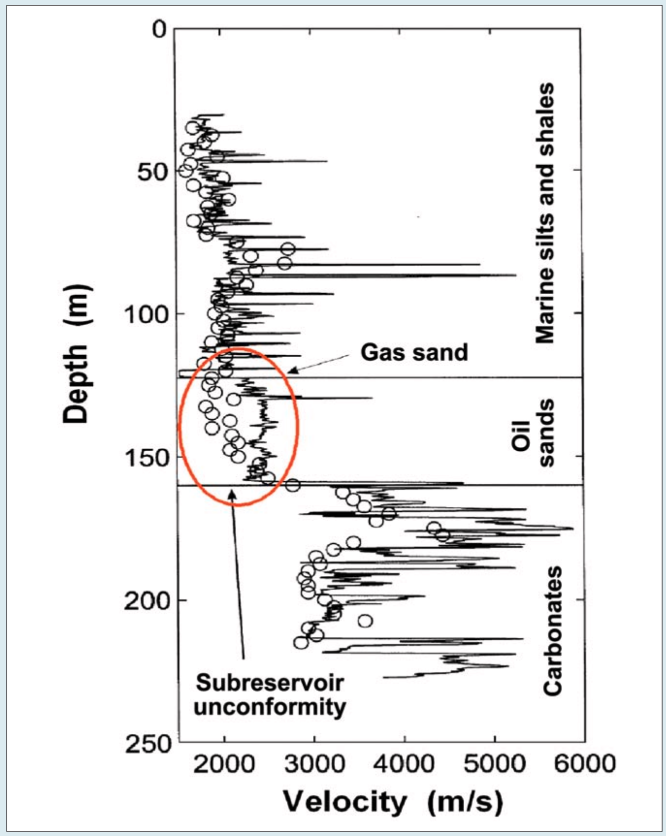

Figure 17. *Pikes Peak Field, Canada sonic log versus VSP. Significant dispersion was detected by Doug Schmitt (1999) in the heavy-oil zone.*

Suggested reading. "The end of cheap oil" by T. Appenzeller (*National Geographic*, 2004). "Fluid mobility and frequency dependent seismic velocity—Direct measurements" by Batzle et al. (GEOPHYSICS, 2006). "Estimating the viscosity of crude oil systems" by Beggs and Robinson (*Journal of Petroleum Technology*, 1975). "Dispersion and absorption in dielectrics" by K. S. Cole and R. H. Cole (*Journal of Chemical Physics*, 1941). "Pressure-Volume-Temperature correlations for heavy oils and extra heavy oils" by De Ghetto et al. (SPE 30316, 1995). "Temperature-dependent propagation of P- and S-waves in Cold Lake oil sands: Comparison of theory and experiment" by Eastwood (GEOPHYSICS, 1993). "The pitch drop experiment" by Edgeworth et al. (*European Journal of Physics*, 1984). "Steamflood delineation using attenuation at Husky's Pikes Peak project" by Hedlin et al. (SEG 2001 *Expanded Abstracts*). *Petroleum Geochemistry and Geology, Second Edition* by J. M. Hunt (W. H. Freeman and Co., 1996). "Time-lapse monitoring of the Duri steamflood: A pilot and case study" by Jenkins et al. (*TLE*, 1997). "Fluid effects on attenuation and dispersion of elastic waves" by G. Kumar (MS thesis, Colorado School of Mines, 2003). "Oil systems correlations" by M. B. Standing (*Petroleum Production Handbook, volume 2*, edited by Frick, McGraw-Hill, 1962). "Seismic attributes for monitoring of a shallow heated heavy oil reservoir: A case study" (GEOPHYSICS, 1999). "Origin of tar mats in petroleum reservoirs. Part II: formation mechanisms for tar mats" by Wilhelms and Larter (*Marine and Petroleum Geology*, 1994). TLE

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