Heavy oils: Their shear story

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Summary

Heavy oils are important unconventional hydrocarbon resources with huge reserves. Seismic monitoring of thermal recovery processes makes study of their shear properties important. We measure, within the seismic band, the complex shear modulus (and thus also the attenuation) of a heavy-oil rock, and the oil extracted from it.

The modulus and quality factor (Q) of the heavy-oil saturated rock shows a moderate dependence on frequency, but is strongly influenced by temperature. At room temperatures, the extracted heavy oil supports a shear wave, but with increase in temperature, its shear modulus decreases rapidly, which translates to a rapid drop in the shear modulus of the rock as well. At these low to intermediate temperatures (30°C-100°C), an attenuation peak corresponding to the viscous relaxation of the heavy oil is encountered.

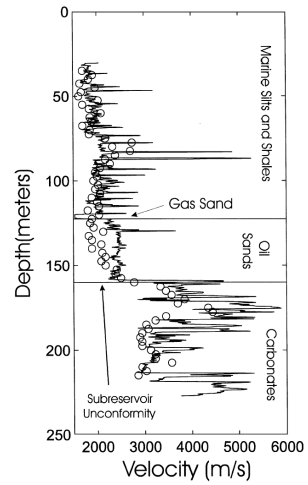

Fig. 1: Sonic log velocities (line) and VSP interval velocities (open circles) in a well through oil sands (Schmitt, 1999).

Introduction

High oil prices have focused new interest on heavy oil, considered as an 'unconventional' hydrocarbon source. These energy resources have reserves that are nearly triple the world reserves of conventional oil and gas (Curtis et al., 2002). The major challenge in exploiting heavy oil comes from its high viscosity, which makes production and transportation a costly affair. Steamflooding and production change physical properties, such as velocity, density, and attenuation, of the oil sand. Understanding such properties of these materials is essential to effective monitoring, since under some conditions the oil acts like a solid, while under other conditions, like a liquid. These changes can potentially be inferred from time-lapse studies, thereby helping in reservoir monitoring. Schmitt (1999) observed significant difference between the sonic log velocities and VSP interval velocities within a heavy oil sand reservoir (Figure 1).

Laboratory measurements are necessary to understand the physical changes that accompany heating of heavy oil rocks. Most laboratory acoustic studies, however, are in the ultrasonic range where the properties could be significantly different from the seismic range for these viscoelastic materials. To address this issue, we conduct torsional experiments in these rocks to decipher their shear moduli and shear attenuation under varying temperature and frequency in the seismic frequency band.

The experiment

Measurements are carried out using a shear rheometer. The rock sample is clamped at both ends, and measurements are conducted with the sample dry and under no lateral confining stress. A sinusoidal torsional strain is applied on one end, and the resulting stress is recorded on the other end, which is fixed. The experiment is schematically shown in Figure 2. When a viscoelastic material is subjected to a sinusoidally varying strain, a steady state will be reached when the resulting stress is also sinusoidal, with the same angular frequency, but with a phase lag of δ, which is a measure of attenuation of that body (O'Connell and Budiansky, 1978). For an elastic material, $\delta = 0$, and for a viscous fluid, δ can approach $\pi/2$, while δ for a viscoelastic body has a value between these two limits. Note that the minimum value for Q depends on how it is defined. For extremely lossy materials, Q derived from phase angle can approach 0 (O'Connell and Budiansky, 1978), which is different from the minimum value for Q, 2π, obtained from Futterman's formulation (1962).

The in-phase part of the stress, σ_0', gives the "real" or the "storage" modulus, G', and the out-of-phase part of the stress gives the "imaginary" or "loss" modulus, G'',

$$G' = \sigma_0'/\epsilon_0, \quad (1)$$

$$G'' = \sigma_0''/\epsilon_0. \quad (2)$$

The quality factor, Q, which is inversely proportional to the attenuation coefficient, is defined as (O'Connell and

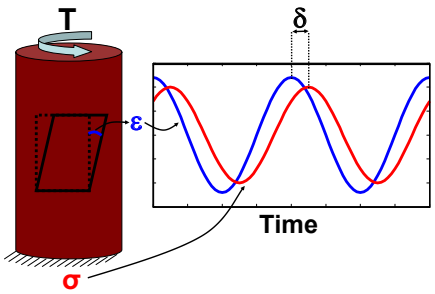

Fig. 2: Schematic diagram of a harmonic loading applied to a rock sample. T denotes the torque applied to one end of the sample. The resulting stress, σ (red) lags behind the strain, ϵ (blue) by a phase angle δ.

Budiansky, 1978)

$$Q \equiv \frac{1}{\tan\delta} = 2\pi\frac{W_{st}}{W_{dis}} = \frac{G'}{G''}. \quad (3)$$

where W_{st} is the maximum elastic stored energy during a cycle of loading at the frequency under consideration and W_{dis} is the energy dissipated per cycle. We will be using this definition of Q for our analysis.

Uvalde heavy-oil rock

The heavy-oil rock from Uvalde, Texas is a carbonate with a porosity of $\approx$ 25% and permeability of 550 mD. The rock is examined under temperatures ranging from 30°C to 350°C with increments of 10°C and for frequencies ranging from 0.01 to 80 Hz (with increments of 0.1 on the log scale). All measurements are made in the linear viscoelastic regime, under a strain of 8x10^{-5} which is an order of magnitude higher than strains encountered in seismology. This strain was selected after strain sweep experiments were used to make sure that all measurements were done within the linear viscoelastic regime.

G', and Q for the rock are shown in Figures 3a and 3b, respectively, while that for the extracted oil are shown in Figures 3c and 3d. The data has not been smoothed and is presented as it is without any processing; also none of the data, shown later, has been smoothed. G' increases with frequency for temperatures less than $\approx$150°C. At higher temperatures, however, the storage modulus has a weak dependence on frequency. The strong temperature dependence of G' can be clearly seen in Figure 3a. G' is highest ($\approx$10 GPa) at room temperature, decreases rapidly with increasing temperature, attaining a minimum value at around 150°C (this temperature-minimum changes with frequency). With further rise in temperature, G' increases marginally to approximately 1.8 GPa at 350°C. Note the moderately strong dependence of Q on frequency (Figures 3b). A relaxation mode (trough in Figures 3b) can be seen at temperatures less than 100°C. The same attenuation peak is better seen in Figure 4. Q is roughly 5 at room temperature within the seismic band

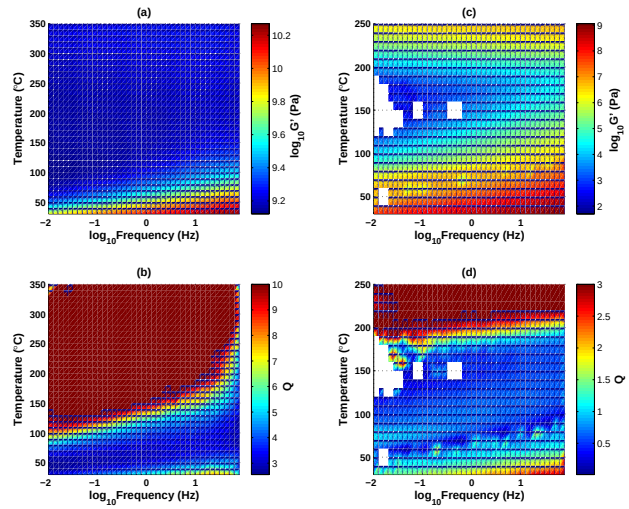

Fig. 3: The heavy-oil rock shear (a) storage modulus, (b) quality factor, and the extracted oil (c) storage modulus, and (d) quality factor. The color scales in (b) and (d) are modified to bring out the trends for Q. Measurements are done at increments of 10°C and frequency increments of 0.1 on the $\log_{10}$ scale.

and decreases with increasing temperature, attaining a value as low as 3. With yet further increase in temperature, Q increases, reaching $\approx$ 40 at 350°C (Figure 4). This is not seen in Figure 3b as the color scale has been modified to bring out the important trends in Q.

Extracted heavy oil

The trends observed for the mechanical properties of the rock are similar to those in the extracted oil. This supports that the behavior of the heavy oil within the rock dominates the mechanical response of the rock. The oil shows noticeable dispersion for temperatures less than $\approx$ 180°C (Figure 3c). At higher temperatures, however, the storage modulus is nearly constant with frequency. With increasing frequency, G' generally increases for all temperatures. The strong temperature dependence of G' for the oil can be clearly seen from Figure 3c. G' is highest ($\approx$ 1.0 GPa) at room temperature in the seismic band and decreases rapidly with increasing temperature, attaining a minimum value at around $\approx$ 180°C (as for the rock, the value of this minimum and the temperature of its occurrence changes with frequency). With further rise in temperature, G' increases to about 0.002 GPa at 250°C. Q of the oil shows a moderately strong dependence on frequency, with some general increases with frequency. A relaxation mechanism is seen in the temperature range of 50°C to 100°C, where Q initially decreases with frequency, reaches a trough, and then subsequently increases with further increase in frequency. The minimum Q in this region is close to 0. The position of this minimum shifts to higher frequencies with increasing temperature. Not surprisingly, Q changes

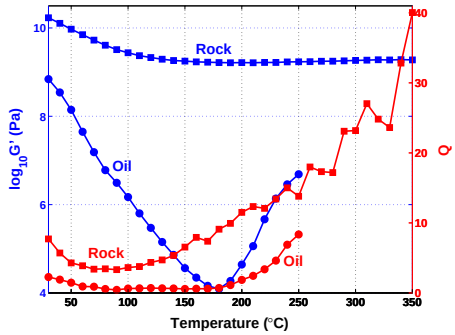

Fig. 4: G' (blue) and Q (red) of Uvalde heavy-oil rock (squares) and the extracted heavy oil (circles) measured at 12.6 Hz.

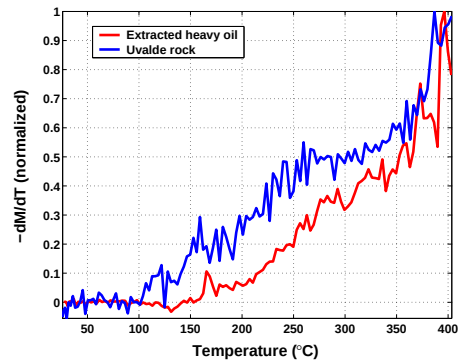

Fig. 5: Thermo-gravimetric analysis (TGA) of Uvalde heavy-oil rock (blue) and the oil extracted from it (red).

significantly with temperature. The quality factor of the oil is ≈ 2.5 at room temperature in the seismic band, and decreases with increase in temperature, attaining a value close to 0 as the oil goes through the relaxation mechanism. With yet further increase in temperature, Q initially increases and then drops before increasing again. This can be clearly seen at 0.01 Hz, where Q increases after the initial relaxation trough at 60°C (Figure 3d). At further higher temperatures, melting of the oil reduces Q, and it attains values as low as 0.2 at 140°C. Surprisingly, with further heating, Q rises again.

Mechanisms

The strong temperature dependence of the modulus and the attenuation comes from the melting of the heavy oil and its subsequent composition change at high temperatures. Nur et. al., (1984) suggested that this change in the heavy oil translates to a significant change in the mechanical response of the rock containing the heavy oil.

The increase in G' of the rock with frequency is consistent with the frequency dependence of G' of the heavy oil. Heavy oil is viscoelastic, and so at low frequencies, the molecules/chains in the viscoelastic material have time to slide relative to eachother, resulting in a low storage modulus. In contrast, at relatively higher frequencies the molecules/chains do not have sufficient time to slide as they are "locked", thereby making the material stiffer (high G'), as there is a more efficient transfer of mechanical energy between the molecules/chains. For intermediate frequencies, however, the molecules/chains have a maximum slip during a cycle of loading, leading to maximum frictional loss of energy.

The high frictional loss of energy manifests in a relaxation trough or attenuation peak, seen in Figure 3c. We believe this attenuation peak is caused by viscous relaxation of the heavy oil within the rock (Walsh, 1969). As described by O'Connell and Budiansky (1977), this relaxation occurs between the "saturated isolated" (at low frequencies the shear stresses in the fluid relax completely, but no fluid flows out of the pores/cracks) and "glued" cases (at high frequencies the viscosity of the fluid is high and the shear stresses in the fluid do not relax). The two relaxations in Figures 3b and 3d are taking place at identical temperatures and frequencies, thereby strongly implying that viscous relaxation of the heavy oil within the rock is responsible for the observed attenuation peak. The frequency dependence of Q rules out friction as the attenuation mechanish and the presence of a relaxation mechanism in the oil (Figure 3d) in the absence of a rock frame rules out "squirt flow" causing attenuation. The shift in the attenuation peak towards lower frequencies with decreasing temperature is because the effect of the decreasing temperature (increases viscosity) is counteracted by the effect of decreasing frequency (decreases viscosity), so as to sustain the viscous relaxation of the oil.

The rise in G' and Q for temperatures exceeding 150°C is probably caused by a compositional change in the heavy oil, wherein the lighter components are lost leaving the heavier asphaltenes behind. Asphaltenes are essentially solid particles that increase the modulus and Q of the oil. This compositional change can be corroborated from thermo-gravimetric analysis (Figure 5), which shows the mass of the heavy oil sample decreasing with increasing temperature. A significant drop in mass at ≈ 150°C corresponds to the loss of the lighter components, thereby making the heavy oil stiffer and less attenuative.

Modeling

In practice, velocity measurements do not exist for all temperatures and frequencies. This necessitates the use of modeling to provide us with the missing data, which can also help in uncertainty analysis. Laboratory data can be used to establish the right model. After extensive analysis, we found that Cole-Cole model (Cole and Cole, 1941) provides a good fit to the observed data. According to this model, the dynamic complex shear modulus, $\tilde{G}(\omega)$, is given by,

$$\tilde{G}(\omega) = G_\infty - \frac{G_\infty - G_0}{1 + (i\omega/\omega_r)^\alpha}, \quad (4)$$

where, G_0 and G_∞ are the shear moduli at zero and infinity frequencies, respectively. ω_r is the relaxation fre-

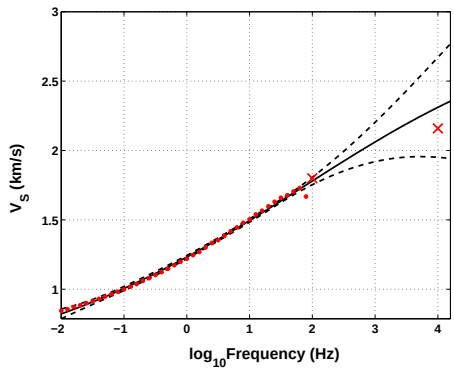

Fig. 6: The laboratory measured (red dots) shear velocity V_S of the Uvalde heavy-oil rock at 70°C with the Cole-cole fit (solid line) and 95% confidence intervals (dashed lines). The two velocities from Schmitt (1999) are shown by $\times$. The model parameters are $G_0 = 0.3 - i0.05$ GPa, $G_\infty = 19.37 + i0.87$ GPa, $\eta = 0.0026 + i0.0004$ GPa.s, and $\alpha = 0.225 + i0.0026$.

quency or the frequency at which the attenuation peak is observed and is given by

$$\omega_r = \frac{G_\infty - G_0}{\eta}, \tag{5}$$

where, η is the viscosity. As observed by Gautam et al. (2003), the complex composition of heavy oils might result in smearing of the relaxation peak, which is controlled by the parameter α. The result from Cole-Cole modeling of heavy-oil rock at 70°C is shown in Figure 6 along with their 95% confidence intervals. Usually, the modeling parameters are all assumed as real numbers, but our analysis shows that if these parameters are allowed to be complex, the fitting is even better, as seen in Figure 6. Complex G_0, G_∞, and η imply that all the elements in the Cole-Cole model are viscoelastic. Shear-wave velocities were computed from the P-wave velocities given in Schmitt (1999) by assuming a constant (with frequency) Poisson's ratio of 0.16. The two velocities, one computed from a VSP measurement (100 Hz) and the other a sonic log measurement (10 KHz), are shown in Figure 6. There is a good match between my laboratory measurements and field velocities. This emphasises that our laboratory measurements can potentially be directly applicable in seismic data analysis.

Discussion and conclusions

Unlike common fliuds (e.g. brine and light oil), heavy oils act as solids at room temperatures and fluids at higher temperatures. Thus, at room temperature, heavy oils support a shear wave, but not at higher temperatures where the shear modulus approaches zero. This makes study of shear properties of heavy-oils more attractive than bulk properties and emphasises the acquisition of multicomponent seismic data. Our shear wave measurements, as a function of temperature, should be representative of the conditions encountered during in-situ steamflooding of heavy oil reservoirs. Moreover, as our measurement window encompasses the seismic band, they should be close to the seismic properties of heavy oils in the field.

The marginal frequency dependence of the moduli and attenuation within the seismic bandwidth, for the heavy oils, makes exploitation of frequency-dependent analysis strictly from seismic data unlikely. Most of the existing methods for Q estimation from field data assume a constant Q within the seismic bandwidth, a resonable approximation as shown by our laboratory measurements. For heavy oils, however, there could be significant differences in properties between seismic, log, and ultrasonic frequencies.

The strong temperature dependence of the mechanical properties of heavy oils makes 4D-9C seismic analysis promising. Temperature has a dramatic influence on velocity as well as on attenuation, and thus on traveltimes and amplitudes of shear waves. For example, on heating a heavy oil reservoir, the shear-wave velocity might decrease by a factor of 3, while the quality factor can decrease by a factor of 10. Shear waves may provide additional information to discriminate among temperature, pressure, and fluid effects during steamflood.

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