Modeling studies of heavy oil—in between solid and fluid properties

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Rocks filled with heavy oil do not comply with established theories for porous media. Heavy oils demonstrate a blend of both purely viscous and purely elastic properties, also referred to as viscoelasticity. They have a non-negligible shear modulus that allows them to support shear-wave propagation depending on frequency and temperature. These oils behave as solids at high frequencies and low temperatures, and as fluids at low frequencies and high temperatures. The solid-like properties of heavy oils violate Gassmann's equation, the most common and widely used fluid-substitution technique in the industry.

Few instances of elastic property modeling for heavy oil-saturated rocks have been reported. Most previously reported work has involved modeling without comparison with measured data, or modeled results on simple grain-fluid aggregates with comparison to measured ultrasonic data. We have modeled the viscoelastic properties of heavy oil-saturated rock samples using the Hashin-Shtrikman (HS) bounds and the frequency-dependent complex shear modulus of the heavy oil. The two studied rock samples are very different in terms of lithology and consolidation state. In our exercise, we have extended the HS bounds to incorporate complexities like intragranular porosity and the contribution of heavy oil to rock matrix properties. By considering the complex shear modulus of the heavy oil in our HS calculations, we have been able to estimate attenuation. We also tested the applicability of Ciz and Shapiro's (2007) form of the generalized Gassmann's equations in predicting the saturated bulk and shear moduli of the heavy oil-saturated rock samples.

Comparison of modeled results with measured data shows a good agreement between the two over a wide range of frequencies spanning the seismic and ultrasonic band.

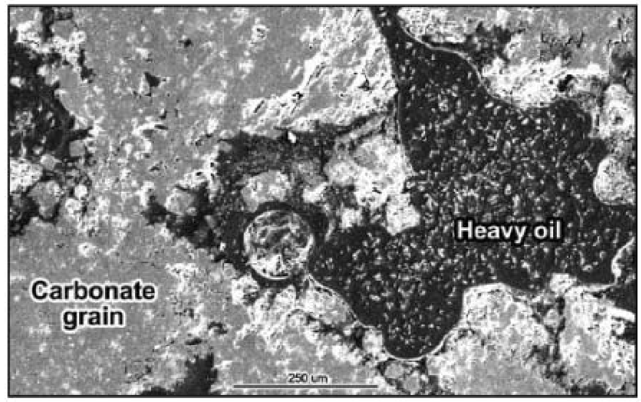

Figure 1. SEM photograph of the Uvalde heavy-oil rock. (From Batzle et al., 2006.)

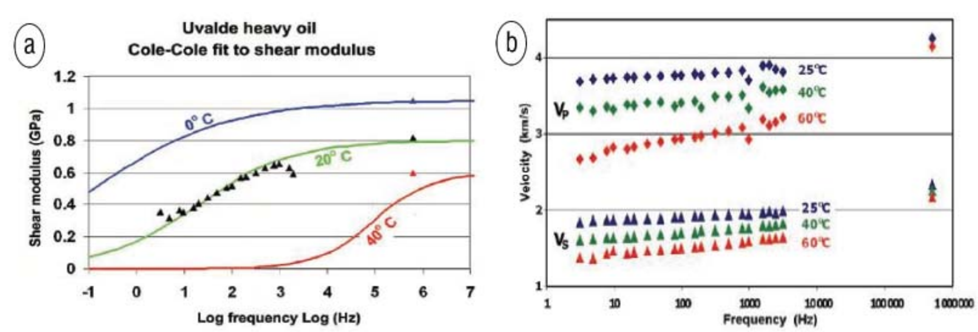

Figure 2. Measured elastic and acoustic properties of the Uvalde heavy-oil rock and the extracted heavy oil. (a) Measured shear modulus with Cole-Cole fit. (b) Frequency and temperature dependence of velocities. (From Batzle et al.)

Uvalde heavy-oil rock and the Canadian tar sands

The studied rock samples are: (1) Uvalde rock from Texas and (2) tar sands from Canada. The two samples exhibit different lithologies and consolidation states. The Uvalde is a carbonate consisting of consolidated calcite grains with heavy oil in the pore spaces. It has a porosity of approximately 25% and permeability of 550 mD. The heavy oil has an API density of -5 (~1.12 gm/cc) and an extremely high viscosity that is highly dependent on temperature. A scanning electron microscope (SEM) image of the Uvalde heavy-oil rock (Figure

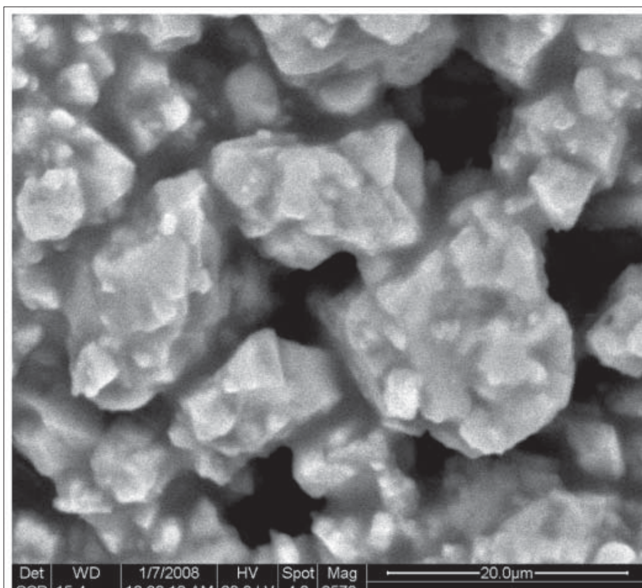

Figure 3. SEM photograph of the Canadian tar sands. The quartz grains are light and the intermediate black regions are the heavy oil.

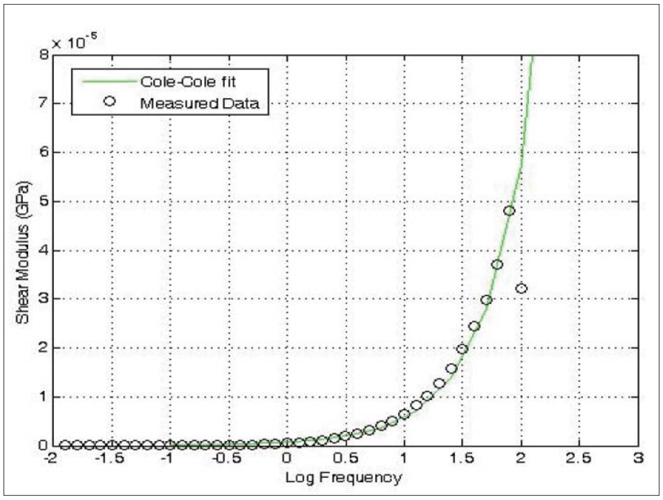

Figure 4. *Measured elastic and acoustic properties of the Canadian tar sand sample and the extracted heavy oil. Real part of measured shear modulus at 20°C (from Hinkle, 2007) with Cole-Cole fit.*

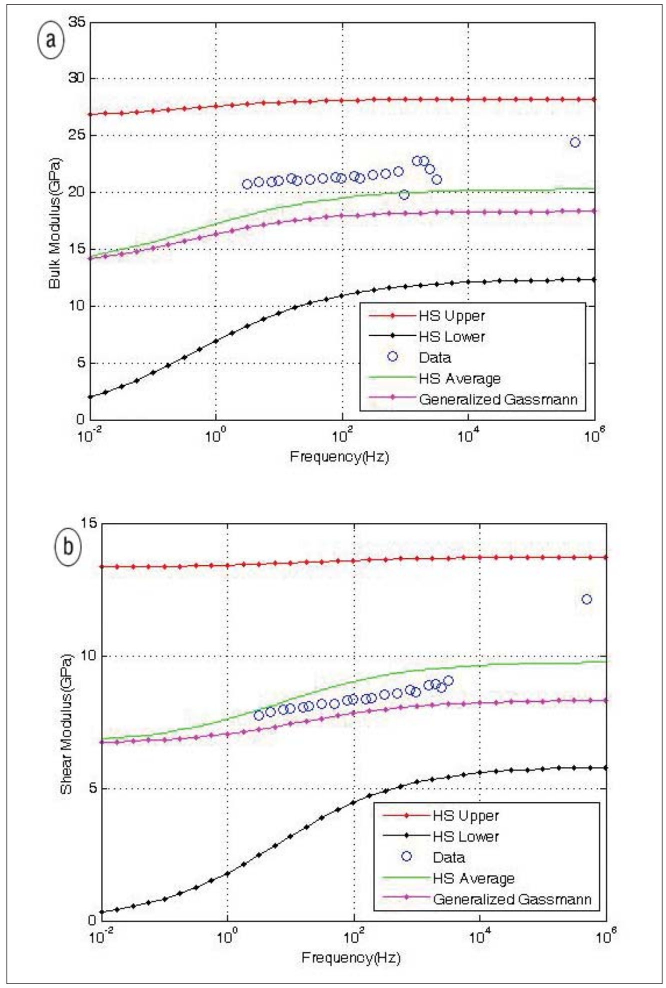

Figure 5. *Hashin-Shtrikman bounds for (a) bulk and (b) shear moduli as a function of frequency for a system of porous calcite grains and heavy oil. Heavy oil is not considered part of the matrix. The blue circles represent measured data at 20°C from Batzle et al. The green line represents average Hashin-Shtrikman properties.*

1) shows that the carbonate grains themselves are porous, and hence, the total rock porosity can be divided into intragranular porosity (the porosity within the grains) and intergranular porosity (the porosity between adjacent grains). The frequency dependence of the shear modulus of the Uvalde heavy oil can be approximated using a Cole-Cole type distribution, essentially an empirical relationship between the complex shear modulus, the "static" and "infinite frequency" shear moduli, angular frequency, and relaxation time. Figure 2a shows the Cole-Cole approximations to the shear modulus of the Uvalde heavy oil at different temperatures as a function of frequency, along with measured shear modulus data at 20°C. The black triangles represent the measured data, and the solid lines represent the Cole-Cole approximations. Figure 2b shows the temperature and frequency dependence of the velocity measured on the Uvalde heavy oil-saturated rock. We used measured velocities at 20°C for comparison with modeled results. The Canadian tar sands are unconsolidated quartz grains held together by viscous heavy oil (Figure 3). They typically have very high porosities in the range of 36–40%. Figure 4 shows measured shear modulus of the heavy oil extracted from a Canadian tar sand sample as function of frequency and Cole-Cole fit to the data. The blue circles represent the measured data, and the green line represents the Cole-Cole fit to the data. We used the Cole-Cole fit for our modeling.

Elastic property estimation using Hashin-Shtrikman (HS) bounds

The Hashin-Shtrikman bounds give ranges for the effective bulk and shear moduli of isotropic two-phase composites as a function of the volume fraction of the constituents. They can be extended to include multiple phases in which case the bounds have to be computed more than once, two phases at a time. The bounds can be used for viscoelastic material by using the complex modulus in the HS expressions in place of the real modulus. Bounds of bulk and shear moduli of viscoelastic materials using HS expressions have been calculated by others (Torquato et al., 1998; Hashin, 1970; Gabiansky and Lakes, 1997). However, such calculations and estimates have been done for materials like cellular solids (honeycomb structures) and sand-epoxy mixtures, and the method needs to be tested for actual rock-oil systems by comparing with measured data.

We used the HS bounds and complex shear modulus of heavy oil to calculate bounds for the complex effective bulk ($K^* = K' + iK''$) and shear modulus ($G^* = G' + iG''$) for the Uvalde rock and the Canadian tar sands. This has also enabled us to calculate the P- and S-wave attenuation, Q_P^{-1} and Q_S^{-1} by taking a ratio between the real and imaginary parts, as follows:

$$Q_p^{-1} = \frac{K''}{K'}; Q_s^{-1} = \frac{G''}{G'} \quad (1)$$

HS modeling of the Uvalde heavy-oil rock

The SEM picture of the rock (Figure 1) shows the presence of intragranular porosity in the calcite grains. This would cause the grains to have bulk and shear moduli less than that

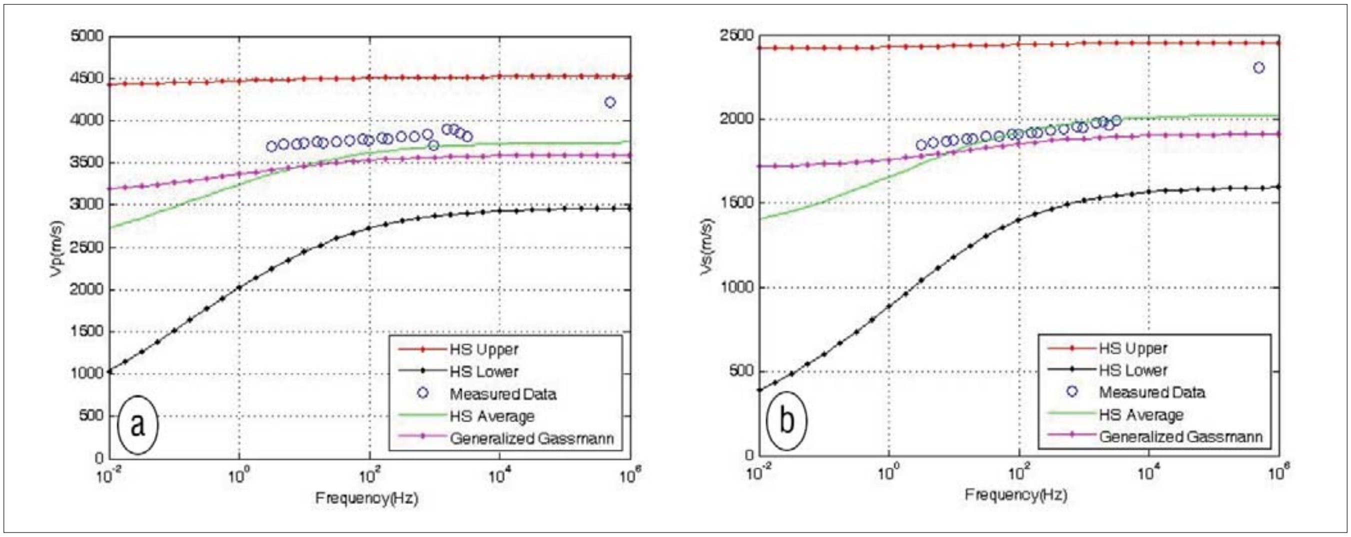

Figure 6. *Hashin-Shtrikman bounds for (a) V_P and (b) V_S as a function of frequency for a system of porous calcite grains and heavy oil. Heavy oil is not considered part of the matrix. The blue circles represent measured data at 20°C from Batzle et al. The green line represents average Hashin-Shtrikman properties.*

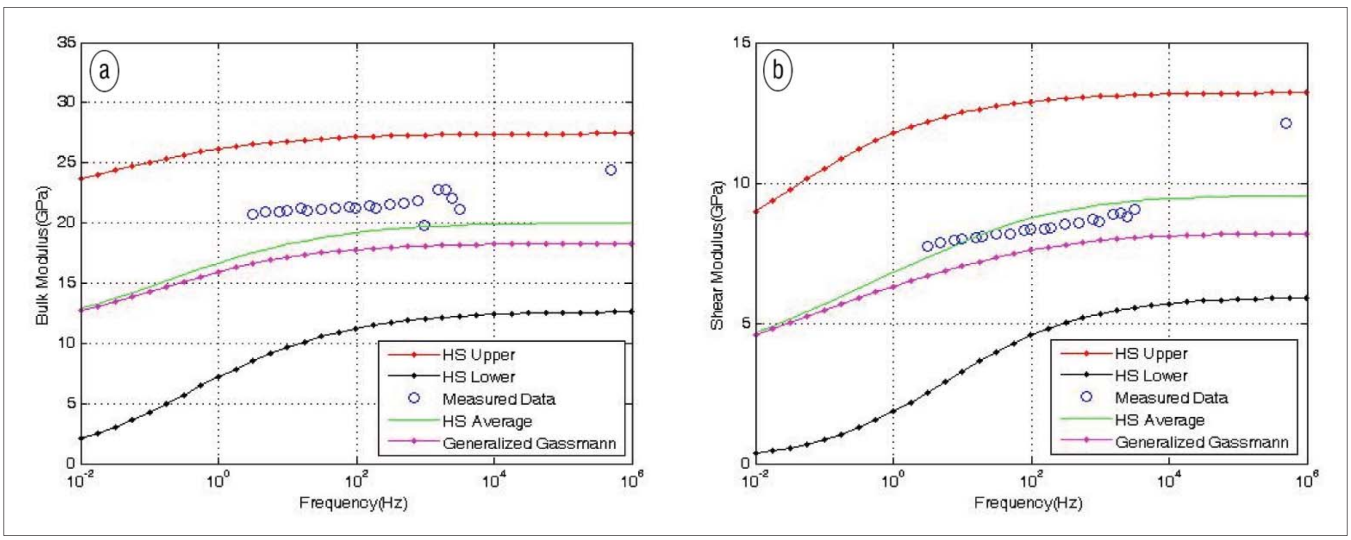

Figure 7. *Hashin-Shtrikman bounds for (a) bulk and (b) shear moduli as a function of frequency for a system of porous calcite grains and heavy oil, and considering part of the heavy oil as contributing matrix properties. The blue circles represent measured data at 20°C from Batzle et al. The green line represents average Hashin-Shtrikman properties.*

of pure calcite. We calculated the bulk and shear moduli of the grains separately using the HS bounds, assuming an intragranular porosity of 5% and considering the intragranular spaces to be dry. Because the porosity is built inside the grains, the stiffer calcite mineral encloses the softer pore spaces, and so the effective modulus of the grains would be closer to the upper bound. Hence, we took values that were 70% of the upper bounds and not average properties. In order to compute the bulk modulus of the fluid saturating the intergranular pore space, we considered a two-component fluid phase, heavy oil and air (with heavy-oil saturation, S_{HO}, of 0.9) and used the upper HS bounds. The Ruess bound, commonly used to calculate effective bulk modulus of fluid mixtures, was not used in this case because the Uvalde heavy oil at 20°C is a solid, and fluid-like behavior is observed only at high temperatures. We used the fluid shear modulus as predicted by the Cole-Cole fit to measured data from Batzle et al. (2006). The obtained solid and fluid moduli were used to compute the effective modulus of the aggregate. Figure 5 compares the modeled bulk and shear modulus with actual data measured at 20°C and 1000 psi (~7 MPa) differential pressure. Differential pressure is the difference between confining pressure and pore pressure. The measured data closely follow the average HS line. Figure 6 compares the modeled and measured velocities.

So far we have considered the heavy oil only as a pore-filling fluid. However, we could also consider it part of the matrix—i.e., as a coating on the grains and acting as a viscous cementing material and therefore contributing to matrix properties. To simulate this situation, we calculated the bulk and shear moduli of the matrix (grains and heavy oil) and the fluid phase separately. We computed the matrix properties using the average HS bounds and 5% cement saturation. Cement saturation denotes the fraction of the intergranu-

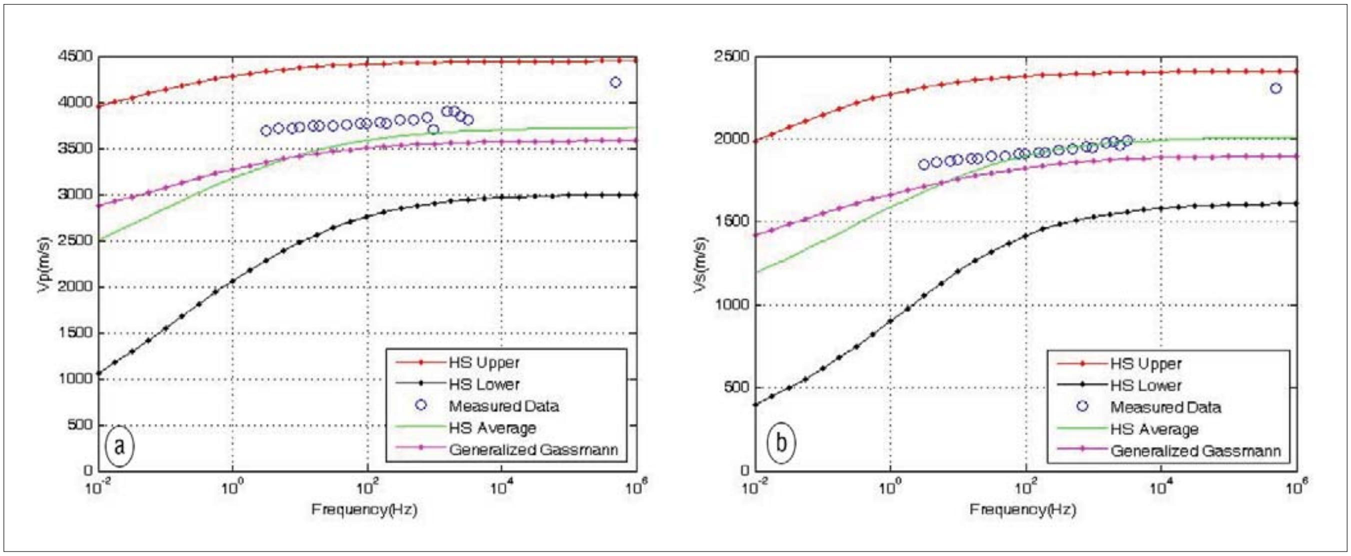

Figure 8. Hashin-Shtrikman bounds for (a) V_P and (b) V_S as a function of frequency for a system of porous calcite grains and heavy oil and considering part of the heavy oil as contributing to matrix properties. The blue circles represent measured data at 20°C from Batzle et al. The green line represents average Hashin-Shtrikman properties.

lar pore space occupied by heavy oil acting as cement and contributing to the matrix properties. Figure 7 compares the modeled and measured data. The predicted values in this case are slightly lower than when heavy oil is not considered part of the matrix. This is because the introduction of heavy oil as a matrix component lowers the bulk and shear moduli of the matrix. Another observation is that the modeled bulk and shear moduli are significantly lower at low frequencies, compared to the previous case. This is because, at low frequencies, the heavy oil behaves more like a fluid, which means it has a much lower shear modulus. The low shear modulus then contributes toward significant lowering of the effective bulk and shear moduli of the matrix and, hence, that of the rock. Figure 8 compares the modeled and measured velocities. It can be observed that, in this case and the previous one, the differences between predicted and measured values are smaller for velocities than moduli.

We calculated shear attenuation from the computed complex effective shear modulus of the rock using Equation 1. Figure 9 shows the estimated and measured shear-wave attenuation for the two scenarios discussed above. The estimated attenuation values are higher than actual measurements.

Generalized Gassmann's equations for a solid infill of the pore space

We also calculated the saturated bulk and shear moduli of the Uvalde heavy-oil sample using the generalized Gassmann's equations given by Ciz and Shapiro. The advantage of using this set of equations is that they can account for the non-negligible shear modulus of the heavy oil filling the pore spaces. The saturated shear modulus computed with these equations is, unlike Gassmann's equation, significantly different from the dry case.

The generalized Gassmann's equations for the saturated bulk and shear modulus as given by Ciz and Shapiro are:

$$K_{sat}^{*-1} = K_{dry}^{-1} - \frac{\left(K_{dry}^{-1} - K_{gr}^{-1}\right)^2}{\phi\left(K_{if}^{-1} - K_{\phi}^{-1}\right) + \left(K_{dry}^{-1} - K_{gr}^{-1}\right)} \quad (2)$$

$$\mu_{sat}^{*-1} = \mu_{dry}^{-1} - \frac{\left(\mu_{dry}^{-1} - \mu_{gr}^{-1}\right)^2}{\phi\left(\mu_{if}^{-1} - \mu_{\phi}^{-1}\right) + \left(\mu_{dry}^{-1} - \mu_{gr}^{-1}\right)} \quad (3)$$

where K^*_{sat} and μ^*_{sat} are the saturated bulk and shear moduli; K_{dry} and μ_{dry} are the dry frame bulk and shear moduli; K_{gr} and μ_{gr} are the bulk and shear moduli of the grain material of the frame; K_ϕ and μ_ϕ are the bulk and shear moduli associated with the pore space; and K_{if} and μ_{if} are the bulk and shear moduli of the solid infill of the pore space. For a monominerallic homogeneous porous frame $K_\phi = K_{gr}$ and $\mu_\phi = \mu_{gr}$. K_{dry} and μ_{dry} were obtained from average Hashin-Shtrikman properties for a solid-air composite. We considered two cases, one with no heavy oil in the matrix and the other with some heavy oil in the matrix and contributing to the solid properties. The saturated bulk and shear moduli calculated from Equations 2 and 3 compare very well with average Hashin-Shtrikman properties (Figures 5-8).

Hashin-Shtrikman modeling of Canadian tar sand

It is relatively simple to compute the Hashin-Shtrikman bounds for the Canadian tar sands by modeling it as a homogeneous isotropic mixture of quartz grains and viscous heavy oil. We considered the tar-sand aggregate to be quartz grains and heavy oil with an overall porosity of 36%. In order to compute the bulk modulus of the heavy oil, we considered a two-component fluid phase, heavy oil and air (with S_{HO} of 0.9) and used the upper HS bounds. We used the heavy oil shear modulus as predicted by the Cole-Cole fit to mea-

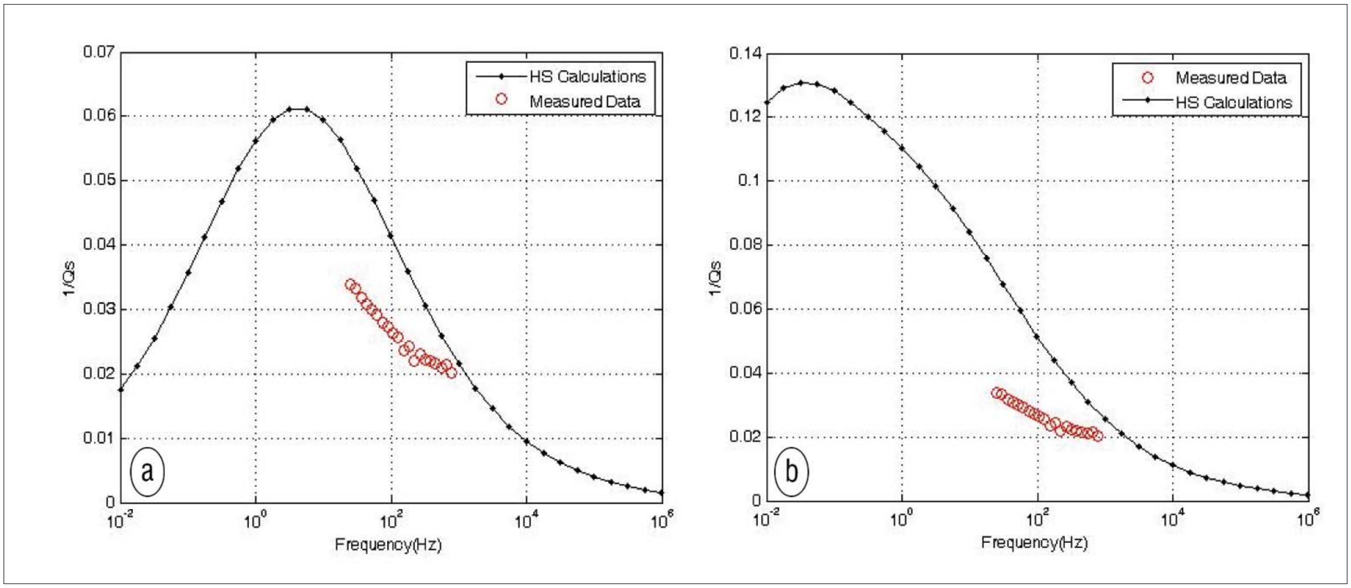

Figure 9. Attenuation estimation as a function of frequency from Hashin-Shtrikman calculations for a system of porous calcite grains and heavy oil. The red circles represent measured data at 20°C from Kumar et al. (a) Shear-wave attenuation from HS calculations. Heavy oil is not considered a part of the matrix. (b) Shear-wave attenuation from HS calculations. Heavy oil is considered a part of the matrix. Cement saturation is 5%.

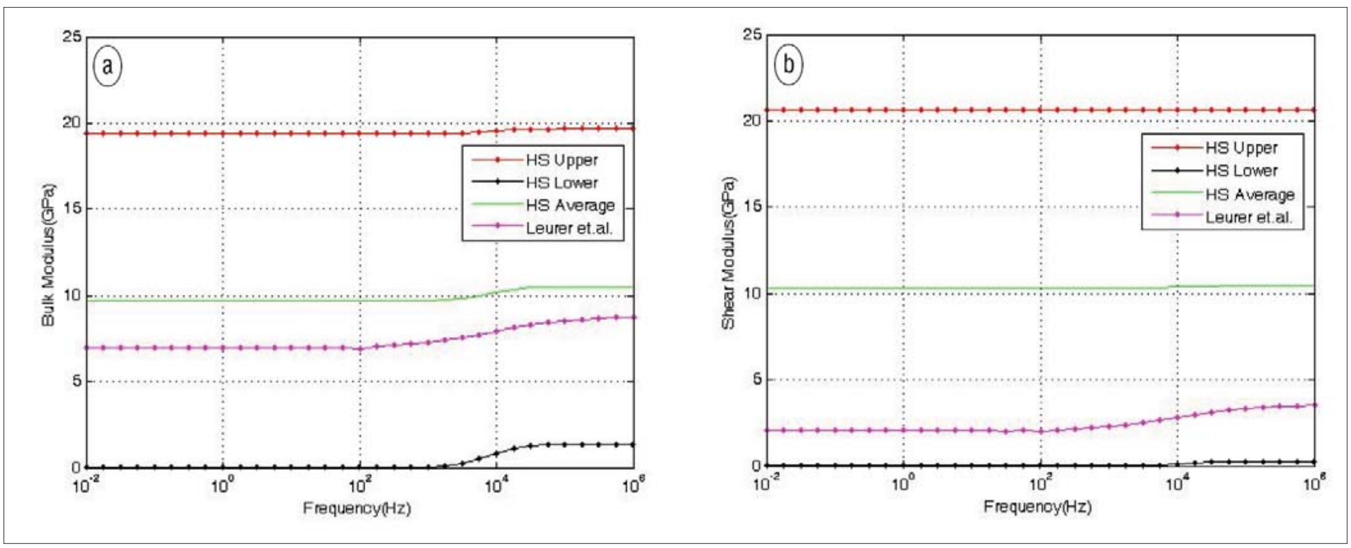

Figure 10. Hashin-Shtrikman bounds for (a) bulk and (b) shear moduli as a function of frequency for a system of quartz grains and heavy oil. Heavy oil is not considered part of the matrix. The blue circles represent measured data at 20°C. The green line represents average Hashin-Shtrikman properties.

sured data from Hinkle (2007). We also calculated moduli and velocities of the tar sands using Leurer and Dvorkin's (2006) viscoelastic model for unconsolidated sediments with viscous cement. Figure 10 shows a comparison between the two models. The moduli values calculated by Leurer and Dvorkin's viscoelastic model are lower than the Hashin-Shtrikman average and lay closer to the lower HS bounds implying that the aggregate behaves more like a system of sand grains covered with heavy oil and hence is very soft. Figure 11 shows a comparison of the velocities.

Conclusions

We have been able to use the Hashin-Shtrikman bounds to estimate the elastic and acoustic properties of two very different rock types in terms of lithology and physical properties. In this exercise we have been able to account for complexities such as intra- and intergranular porosities of the grains and complex frequency dependent shear modulus of the saturating heavy oil. The comparison between measured and predicted data is good. We also tested the applicability Ciz and Shapiro's form of the generalized Gassmann's equations for predicting saturated moduli and velocities and got a reasonably good match with measured data.

Suggested reading. "Heavy oils-seismic properties" by Batzle et al. (*TLE*, 2006). "Generalization of Gassmann equations for po-

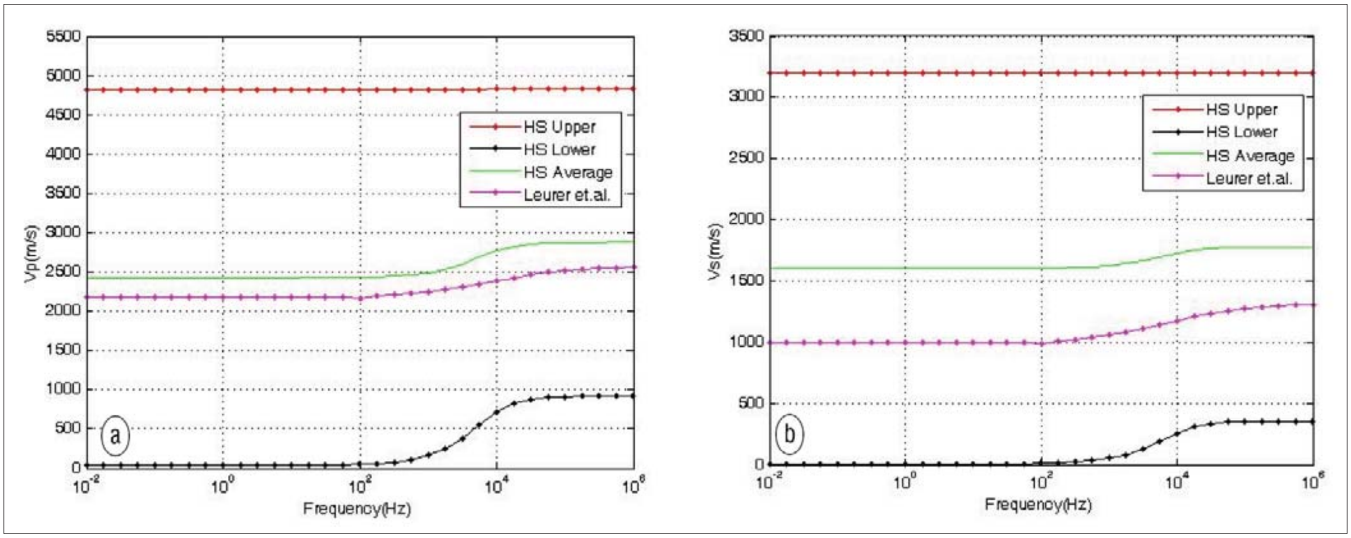

Figure 11. *Hashin-Shtrikman bounds for (a) V_p and (b) V_S as a function of frequency for a system of quartz grains and heavy oil. Heavy oil is not considered part of the matrix. The blue circles represent measured data at 20°C. The green line represents average Hashin-Shtrikman properties.*

rous media saturated with a solid material" by Ciz and Shapiro (Geophysics, 2007). "Temperature-dependent propagation of P- and S-waves in Cold Lake oil sands: Comparison of theory and experiment" by Eastwood (Geophysics, 1993). "Bounds on the complex bulk and shear moduli of a two-dimensional two-phase viscolastic composite" by Gibiansky and Lakes (*Mechanics of Materials*, 1997). "Viscoelastic modeling of rocks saturated with heavy oil" by Gurevich et al. (SEG 2007 *Expanded Abstracts*). "Complex moduli of viscoelastic composites-1: General theory and application to particulate composites" by Hashin (*International Journal of Solids and Structures*, 1970). Relating Chemical and Physical Properties of Heavy Oils by Hinkle (master's thesis, Colorado School of Mines, 2007). "Effects of fluids on attenuation of elastic waves" by Kumar et al. (SEG 2003 *Expanded Abstracts*). "Viscoelasticity of precompacted sand with viscous cement" by Leurer and Dvorkin (Geophysics, 2006). "Effective mechanical and transport properties of cellular solids" by Torquato et al. (*International Journal of Mechanical Sciences*, 1998).

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