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# Modeling elastic wave velocities and attenuation in rocks saturated with heavy oil

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## ABSTRACT

Although properties of bulk heavy oil can be approximated by an appropriate viscoelastic model, only a few attempts to model properties of rocks saturated with heavy oil have been reported. Rock-physics models used for rocks saturated with conventional fluids are inapplicable to those saturated with heavy oil because its viscoelastic rheology invalidates the main assumptions of the Gassmann and Biot theories. We estimate viscoelastic properties of mixtures of rock and heavy oil by considering (1) a system of layers of a solid and a viscoelastic medium and (2) by computing Hashin-Shtrikman (HS) bounds for this system. These two methods give approximate bounds for the frequency- and temperature-dependent velocities and attenuation coefficients in rocks saturated with heavy oil. We also propose a method to compute a realistic estimate of these properties that lie between those bounds. This estimate is based on a self-consistent equivalent-medium approach known as coherent-potential approximation. In a more general form, this approximation can be used for approximate fluid substitution for heavy oil. This approach gives frequency-dependent velocities and attenuation values that are qualitatively consistent with experimental observations.

## INTRODUCTION

Heavy oils are important hydrocarbon reserves that often are exploited by using thermal-recovery processes. As with conventional oil and gas, the seismic method is the primary method used for reservoir characterization and for production monitoring. To this end, rock-physics relationships are required to link seismic parameters (velocities and attenuation coefficients) to the properties of oil as a function of frequency and pressure, volume, and temperature (PVT) conditions. In recent years, some laboratory measurements of elastic properties of heavy oils and of rocks saturated with heavy oil have been reported (Nur et al., 1984; Eastwood, 1993; Schmitt, 1999; Batzle et al., 2006). According to these measurements, heavy oils exhibit viscoelastic properties such that they behave like liquids at low frequencies, whereas they behave almost like solids at high frequencies. At intermediate frequencies, the elastic moduli are complex, exhibiting strong attenuation and velocity dispersion. The characteristic frequency of this viscoelastic transition is strongly dependent on temperature. Oil that behaves as a nearly elastic solid at room temperature (over a wide range of frequencies) can exhibit Newtonian fluid behavior at temperatures above 200°C.

The properties of bulk heavy oil can be approximated by an appropriate viscoelastic model, but very few attempts to model the properties of rocks saturated with heavy oil have been reported (Eastwood, 1993; Leurer and Dvorkin, 2006). The rock physics of rocks saturated with heavy oil is different from that of rocks saturated with conventional fluids because the viscoelastic rheology of heavy oil makes the Gassmann and Biot theories and all their extensions invalid. Indeed, Gassmann theory assumes that fluid pressure is equilibrated throughout the pore space of a rock. If the medium is saturated with a Newtonian fluid, this is ensured by Pascal's law, which is valid in the static limit (in the absence of body forces). However, heavy oils are viscoelastic and have finite shear moduli even at seismic frequencies; therefore, Pascal's law does not apply. Similarly, the Biot theory assumes that shear stresses in a fluid are negligible compared with shear stresses in a solid matrix, an assumption that does not hold for viscoelastic media. Of course, both Gassmann and Biot theories might be valid at sufficiently low frequencies, but these frequencies can be many orders of magnitude lower than seismic frequencies.

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In this paper, we propose methods to estimate the properties of mixtures of rock and heavy oil by considering (1) a system of layers of a solid and a viscoelastic medium and (2) by computing Hashin-Shtrikman (HS) bounds for this system. These two approaches give approximate bounds for the frequency- and temperature-dependent properties of these rocks. We also propose a method to compute realistic estimates of these properties that lie between these bounds. This estimate is based on an equivalent-medium approach known as coherent potential approximation (CPA) (Berryman, 1980), which can be used in a general form for approximate fluid substitution for heavy oil.

This study focuses on the effect of temperature on the frequency-dependent shear modulus of oil. The effects of bulk viscosity are also important but lie outside the scope of this paper for two reasons: (1) We are not aware of any experimental data on bulk rheology of heavy oils, and (2) the effect of bulk viscosity on bulk modulus is smaller than the effect of shear viscosity on shear modulus.

## PROPERTIES OF BULK HEAVY OIL

### Shear-wave dispersion

Figure 1 shows the storage modulus (the real part of the shear modulus) of heavy oil (extracted from a rock sample from the Uvalde field, Texas) for a range of temperatures and frequencies, as measured by Batzle et al. (2006). The properties of heavy oil show viscoelastic behavior so that for a given temperature, its storage modulus increases with frequency. The simplest model of a viscoelastic medium is the Maxwell model, which results in the following dependency of the complex shear modulus $\mu_f$ on frequency $\omega$,

$$\mu_f(\omega) = \frac{\mu_\infty}{\dfrac{1}{-i\omega\tau} + 1}, \tag{1}$$

where $\mu_\infty$ is the (real) shear modulus of the medium at high frequencies (or quick deformation), $\tau = \eta/\mu_\infty$ is the so-called relaxation time (inverse of relaxation frequency $\omega_0$), $i = \sqrt{-1}$ is the imaginary unit, and $\eta$ is the dynamic shear viscosity of the same medium at low frequencies (or slow deformation). At high frequencies ($\omega\tau \gg 1$), the complex shear modulus of the medium approaches the real value $\mu_\infty$. Conversely, at low frequencies, ($\omega\tau \ll 1$), $\mu_f \cong -i\omega\eta$. In the time domain, this means that for very slow deformation, the shear stress is proportional to the time derivative (rate of change) of the shear deformation, which is the behavior characteristic of Newtonian fluids. Batzle et al. (2006) and Behura et al. (2007) note that the frequency dependency described by the Maxwell model is stronger than can be observed in experimental data. This is also evident in Figure 1, where the best-fit Maxwell model for a temperature of 20°C (dash-dotted line) is plotted alongside the experimental data.

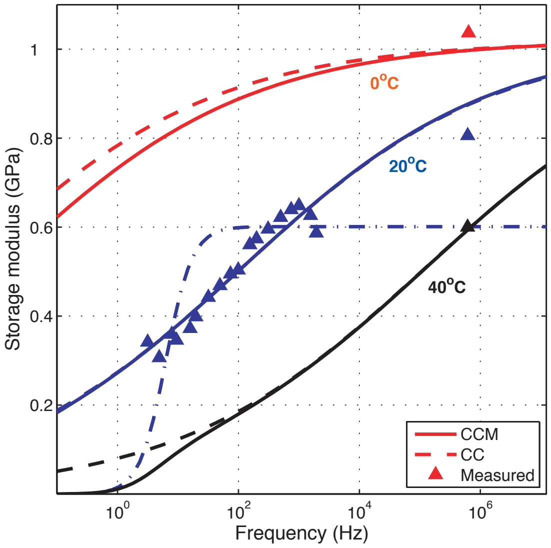

Figure 1. Storage modulus of Uvalde heavy oil as a function of frequency for temperatures as measured by Batzle et al. (2006) (triangles) and predicted using best fit of the combined Cole-Cole and Maxwell model (solid lines), the Cole-Cole model (dashed lines), and the Maxwell model (dash-dotted line, for 20°C only).

To model a more gradual variation of elastic properties with frequency, a memory function with more than one relaxation time is required. To achieve this, Batzle et al. (2006) use a model with the continuous-relaxation time spectrum proposed by Cole and Cole (1941),

$$\mu_f = \mu_0 + \frac{\mu_\infty - \mu_0}{\dfrac{1}{(-i\omega\tau)^\beta} + 1}, \tag{2}$$

where $\mu_0$ and $\mu_\infty$ are the (real) shear moduli of the medium in the low- and high-frequency limits, respectively, and the exponent $\beta < 1$ is an adjustable parameter. For appropriate parameters, the relationship given by equation 2 fits the measurements reasonably well (Batzle et al., 2006). However, according to this model, the complex shear modulus at low frequencies is

$$\mu_f \cong \mu_0 + (\mu_\infty - \mu_0)(-i\omega\tau)^\beta. \tag{3}$$

Thus, in the low-frequency limit, the complex shear modulus approaches a real value $\mu_0$, and the model predicts elastic behavior in the low- and high-frequency limits. This contradicts the widely assumed notion that oil behaves at low frequencies more like a Newtonian liquid. This is a common observation for many viscoelastic materials such as polymers and synthetic oils (Barlow and Lamb, 1959; Ferguson and Hudson, 1994). If we assume that heavy oil is Newtonian at sufficiently low frequencies (or large times), we have to set $\mu_0 = 0$. However, with this assumption in the low-frequency limit, we have

$$\mu_f \cong \mu_\infty(-i\omega\tau)^\beta = \mu_\infty^{1-\beta}(-i\omega\eta)^\beta. \tag{4}$$

Thus, at low frequencies, the absolute value of the complex shear modulus is proportional to $\omega^\beta$, not $\omega^1$, as it should be for Newtonian fluids. Note that the very conception of viscosity is problematic in this case.

To ensure that the behavior of oil is Newtonian in the low-frequency limit, we propose the following model, combining the relaxation spectra of the Cole-Cole and Maxwell models (we call it the

CCM model):

$$\mu_f = \frac{\mu_\infty}{\dfrac{1}{(-i\omega\tau)} + \dfrac{1}{(-i\omega\tau_1)^\beta} + 1}, \tag{5}$$

where $\tau = \eta/\mu_\infty$ and $\tau_1 \geq \tau$ are two characteristic points of the continuous-relaxation spectrum. In the low-frequency limit, $\mu_f \simeq -i\omega\eta$, whereas for high frequencies, $\mu_f \simeq \rightarrow \mu_\infty$. Furthermore, if the spectrum is sufficiently wide, $\tau/\tau_1 \gg 1$. Then $|\mu_f| \propto \omega^\beta$ for $\omega_1 \ll \omega \ll \omega_2$, where $\omega_1 = (\tau_1^\beta \tau^{-1})^{1/(1-\beta)}$ and $\omega_2 = \tau_1^{-1}$. Note also that for $\tau/\tau_1 \gg 1$ and $\omega \gg \omega_1$, the predictions of equation 5 are close to those of the Cole-Cole model (equation 2). Conversely, for $\tau/\tau_1 \rightarrow 0$, we recover the Maxwell model (equation 1).

This is illustrated in Figure 2, where we compare the relaxation spectrum $\partial(\mathrm{Re}\,\mu_f)/(\partial \ln \omega)$ corresponding to the CCM model (equation 5) with those of the Maxwell and Cole-Cole models. We see that the CCM and Cole-Cole models give much broader relaxation spectra than the spectrum of the Maxwell model. This is because typical heavy oil consists of molecules of vastly different sizes, resulting in a broad relaxation spectrum. However, at very low frequencies, the CCM spectrum decreases more rapidly with decreasing frequencies than the Cole-Cole spectrum, which is consistent with Newtonian fluid behavior.

### Temperature dependency

Elastic properties of heavy oils are known to be strongly dependent on temperature, so that they behave almost like a solid at room temperature but like a liquid when heated to, say, 200°C. Such behavior is not unique to heavy oils but is typical for many viscoelastic materials such as polymers and synthetic oils. The dependency of viscoelastic properties of such materials on frequency and temperature can be simplified using the so-called temperature-frequency superposition principle, which states that dispersion curves for different temperatures are the same if frequency is normalized by some temperature-dependent parameter (Williams et al., 1955). For our study, this means we can use dispersion equation 5 for all temperatures by assuming an appropriate temperature dependence of the relaxation time $\tau$ or viscosity $\eta$.

Batzle et al. (2006) review known viscosity-temperature relationships. We approximate these curves by the following empirical relationship:

$$\ln(\tau/\tau_\infty) = A \exp(-T/T_0), \tag{6}$$

where $\tau_\infty = \eta_\infty \mu_\infty^{-1}$, $T$ is Celsius temperature and $\eta_\infty$, $A$, and $T_0$ are adjustable parameters. The exponential term in the right-hand side of equation 6 ensures that at high temperatures, the viscosity $\eta = \tau\mu_\infty$ does not reduce below a set value $\eta_\infty$.

Figure 1 shows the dependency of the storage modulus Re $\mu_f$ of heavy oil as a function of frequency for temperatures as predicted by the Maxwell model, the Cole-Cole model, and the CCM. The parameters used in equations 1, 2, and 5 were obtained by setting the minimum viscosity at $\eta_\infty = 10^{-3}$ Pa·s and the ratio $\tau/\tau_1$ at 10 and by fitting the storage modulus to the data. The best-fit values for equation 5 are $A = 38$, $T_0 = 74°\mathrm{C}$, $\mu_\infty = 1.02$ GPa, and $\beta = 0.20$. There is a good fit of the CCM and Cole-Cole models with the experimental data. We also see that in the low-frequency limit, the predicted storage modulus decreases more rapidly with decreasing frequency.

## MODELING PROPERTIES OF ROCK-OIL MIXTURES

### Rock as a system of solid and oil layers

When pore fluid is Newtonian, low-frequency elastic moduli of a rock saturated with that fluid can be computed from the properties of the dry rock and the fluid compressibility by using the Gassmann equation. The corresponding dynamic moduli can be obtained from Biot's equations of poroelasticity. However, neither the Gassmann equation nor Biot's theory is applicable if the pore-filling material is viscoelastic. That is because the Gassmann equation is based on Pascal's law, which states that in the absence of body forces, fluid pressure is the same throughout the pore space. This law does not apply to solids or to any medium whose shear modulus has a finite component. Biot's theory is an extension of the Gassmann theory to finite frequencies and is also inapplicable to viscoelastic media.

To gauge the effect of viscoelasticity of the pore-filling material on overall rock properties, the first model we consider is a simple periodic system of elastic and viscoelastic layers (the "layered cake" of Figure 3). This simplistic approach to modeling elastic properties of fluid-saturated rocks was used by Schoenberg (1984), Schoenberg and Sen (1986), Molotkov and Bakulin (1996), Gurevich (1999, 2002), and Gurevich and Ciz (2006). The advantage of using this simple periodic system is that exact dispersion equations are known

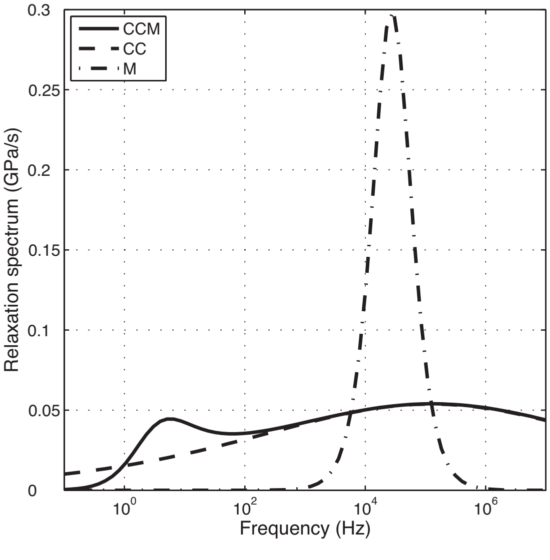

Figure 2. Frequency representation $\partial(\mathrm{Re}\,\mu_f)/(\partial \ln\omega)$ of the relaxation spectra for the viscoelastic combined Cole-Cole and Maxwell model (solid line), the Cole-Cole model (dashed line), and the Maxwell model (dash-dotted line). Relaxation spectra correspond to the fit of each model to Uvalde oil data (Figure 1) using temperature dependencies given by equation 6. The spectra shown correspond to a temperature of 40°C.

(Rytov, 1956; Brekhovskikh, 1981). The method is applicable to any rheology and does not have any requirements with respect to size of pores or properties of layers.

Let us denote the properties of elastic layers with a subscript $_s$ and those of viscoelastic (“fluid”) layers with a subscript $_f$. For shear waves propagating along the layers and polarized parallel to the layers, the exact dispersion equation is (Rytov, 1956; Brekhovskikh, 1981)

$$p\left[\tan^2\frac{\beta_s h_s}{2}+\tan^2\frac{\beta_f h_f}{2}\right]+(1+p^2)\tan\frac{\beta_s h_s}{2}\tan\frac{\beta_f h_f}{2} = 0. \tag{7}$$

Here, $\beta_s^2 = \omega^2(1/b_s^2 - 1/b^2)$ and $\beta_f^2 = \omega^2(1/b_f^2 - 1/b^2)$, where $b_s = (\mu_s/\rho_s)^{1/2}$ and $b_f = (\mu_f/\rho_f)^{1/2}$ are shear velocities in the materials $_s$ and $_f$, respectively; $p = \mu_f\beta_f/\mu_s\beta_s$; $\rho_f$ and $\rho_s$ are layer densities; $h_f$ and $h_s$ are layer thicknesses; and $b$ denotes the unknown complex velocity of the SH-wave. The real part of the complex velocity is the phase velocity of the wave, and the ratio of the imaginary part to the real part of the slowness yields the dimensionless attenuation (inverse quality factor)

$$Q^{-1} = 2\frac{\operatorname{Im} b^{-1}}{\operatorname{Re} b^{-1}}. \tag{8}$$

To simulate the properties of rocks, the model should include fluid layers of thickness corresponding to pore size of the rock, and solid layers of thickness corresponding to grain size of the rock. The dispersion equation 7 does not have an analytical solution but can be solved numerically by iteration.

The results of this solution for the phase velocity and the dimensionless attenuation are shown in Figure 4a and b. The calculations were performed for a system of alternating layers of a solid material with the moduli $K_s = 58$ GPa, $\mu_s = 5.7$ GPa, density $\rho_s = 2.54 \mathrm{g \cdot cm^3}$, and thickness $h_s = 15$ μm and with Uvalde heavy oil with bulk modulus $K_f = 2.03$ GPa, density $\rho_f = 0.9$ g·cm³, thickness $h_f = 5$ μm, and frequency- and temperature-dependent shear modulus as discussed in the previous section. Predictions of an anisotropic variant of Biot’s (1956) theory of poroelasticity, with dynamic-permeability function adjusted to flat slabs, also are shown in Figure 4b (Bedford, 1986; Gurevich and Ciz, 2006). We see that for low temperatures, the S-wave dispersion is consistent with viscoelastic behavior of the bulk oil, whereas at high temperatures, it begins to exhibit small Biot dispersion. The viscoelastic attenuation is much higher than Biot attenuation.

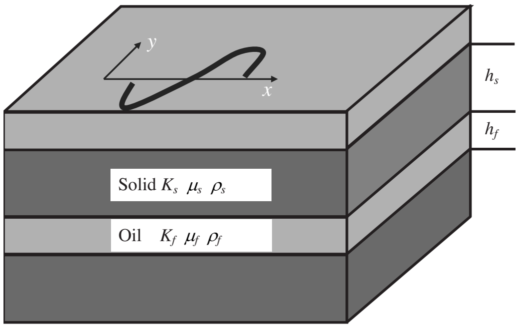

Figure 3. A periodic system of alternating solid and viscoelastic “fluid” layers (“layered cake”).

Also shown in Figure 4 are velocities and attenuation factors for the wave propagating perpendicular to the model layers. The corresponding exact dispersion equation given by Rytov (1956) and by Brekhovskikh (1981) is similar to equation 7 and is not repeated here. Clearly, the waves propagating across layers exhibit much higher dispersion.

Figure 5 shows our corresponding results for compressional waves. The dispersion of P-waves along the layers is of the same order of magnitude as that for S-waves propagating in the same direction. However, the dispersion of P-waves propagating perpendicular to layers is weaker than that for corresponding S-waves. This is because the shear modulus of the “fluid” layers at low frequencies

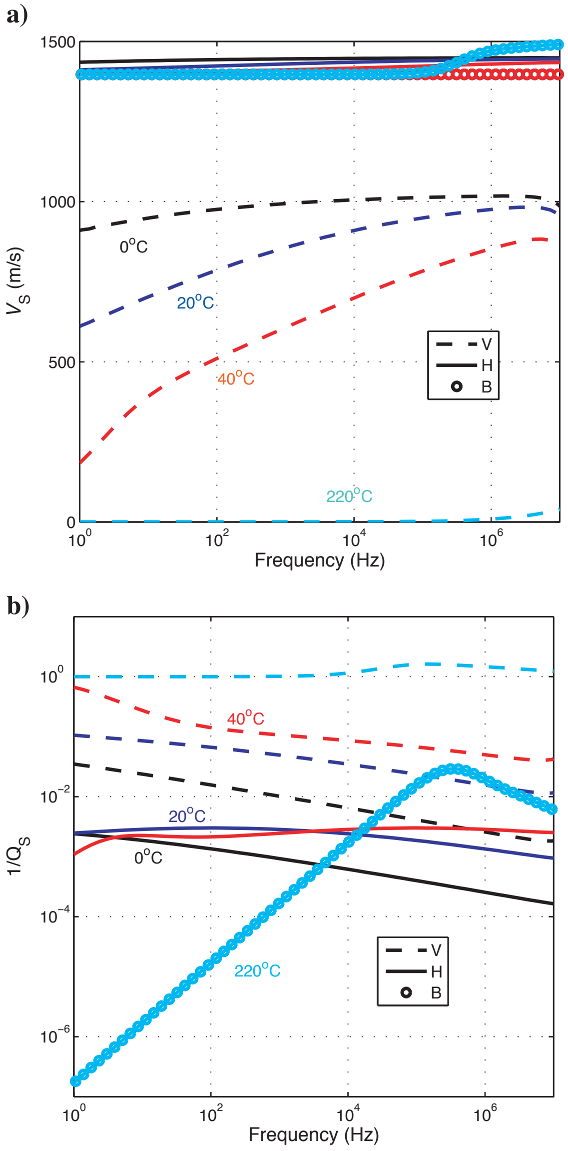

Figure 4. SH-waves in the oil-solid mixture of the “layered-cake” model: (a) Velocity and (b) attenuation versus frequency and temperature for SH-waves propagating parallel to layers (solid lines) and perpendicular to layers (dashed lines). Circles show predictions of the anisotropic Biot theory for SH-waves propagating parallel to layers.

tends to zero, whereas the P-wave modulus reduces to the bulk modulus of the fluid, which is finite. Qualitatively, the dispersion resembles that observed by Batzle et al. (2006) and by Behura et al. (2007). The characteristics of dispersion and attenuation that we obtained for waves parallel and perpendicular to layers can serve as bounds for the behavior of real rocks. Although models of periodic systems of layers such as ours are unrealistic, they provide an exact solution that is an important limiting case for approximate effective-medium models.

## Hashin-Shtrikman bounds

To obtain realistic estimates of the properties of a rock saturated with heavy oil, we computed Hashin-Shtrikman bounds for a mixture of elastic and viscoelastic media. The limitation of using these bounds is that they cannot simulate high-frequency (Biot) effects because they are designed intrinsically for static moduli (and the corresponding representative structure corresponds to isolated spherical pores or grains). However, the advantage of these bounds is that they are constrained by an additional requirement of isotropy and thus correspond to a more realistic geometric structure of the rock.

The original HS bounds are rigorous and exact bounds for static bulk and shear moduli of an isotropic composite consisting of two isotropic elastic constituents (see, e.g., Christensen, 1979). They are also valid if one of the constituents is fluid, in which case its shear modulus is simply set to zero. We use HS bounds to compute frequency-dependent moduli of a mixture of an elastic solid and a viscoelastic fluid by first computing the complex shear modulus of the "fluid" by using equation 5 and then using it as a static shear modulus. As a result, we obtain estimates of the bulk and shear moduli corresponding to lower and upper HS bounds. We note that the moduli obtained are no longer rigorous bounds because they are now complex. The conception of a value lying between two bounds is undefined for complex numbers. For the limiting cases of low temperature (elastic solid pore fill) and high temperature (inviscid fluid pore fill), these estimates provide rigorous realizable bounds. For intermediate cases, they provide exact expressions for realistic geometric configurations of a solid and a viscoelastic medium (Hashin, 1970) in the quasi-static limit. Rigorous bounds for viscoelastic media denote regions in the complex plane and are much more difficult to obtain (Milton and Berryman, 1997).

The results for S-waves are shown in Figure 6. We see a very similar behavior to the layered cake for S-waves — weak dispersion for the upper bound and much stronger dispersion for the lower bound. Similar behavior is observed for P-waves (Figure 7).

## Coherent potential approximation

The results for the layered cake (Figure 3) and the HS bounds give upper and lower estimates of the rock properties. To obtain a realistic middle estimate, we propose to use one of the popular mixing laws of the theory of composite materials, namely, coherent potential approximation (CPA). We choose CPA because it has the property that the more abundant constituent is the load-bearing one. Thus, for example, a solid-fluid mixture is modeled as a solid with spheroidal fluid inclusions when fluid concentration is low and as a suspension of solid particles in the fluid when solid concentration is low. This is an attractive property because it is consistent with the concepts of percolation and critical porosity and allows one to model both sandstones and unconsolidated sand. The application of an "elastic" mixing law to viscoelastic media is justified by the use of the elastic-viscoelastic correspondence principle (Hashin, 1970; Mase and Mase, 1999).

CPA, which originally was proposed in quantum field theory, is essentially a self-consistent version of the average T-matrix approximation of Küster and Toksöz (1974). CPA is computed by solving a system of two equations for bulk $K_*$ and shear $\mu_*$ moduli:

$$\phi(K_f - K_*)P^{*f} + (1-\phi)(K_s - K_*)P^{*s} = 0, \qquad (9)$$

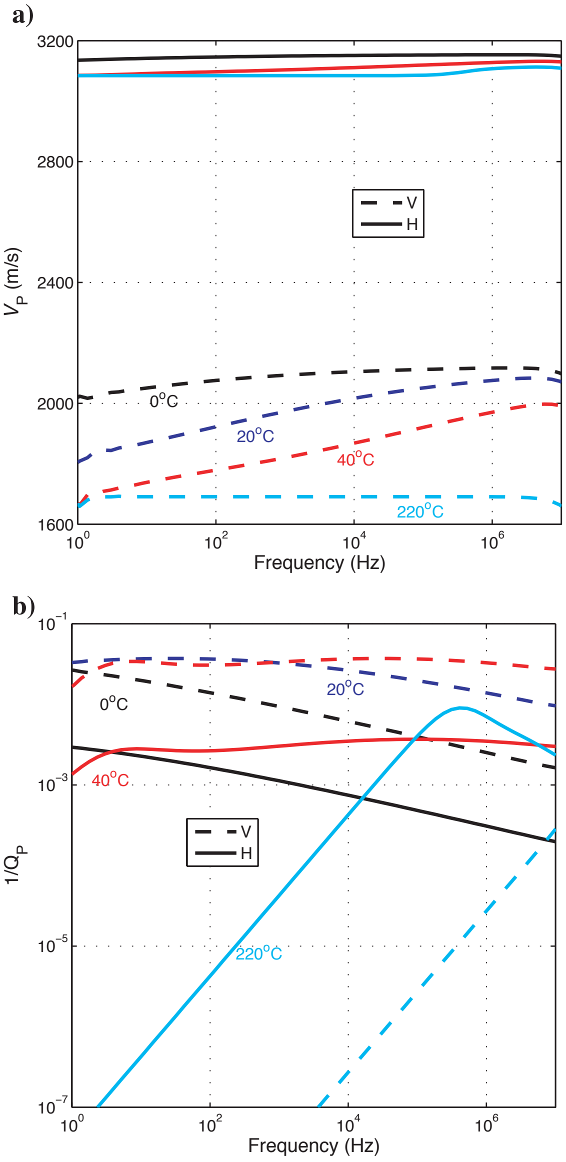

Figure 5. P-waves in the oil-solid mixture of the "layered-cake" model: (a) Velocity and (b) attenuation versus frequency and temperature for P-waves propagating parallel to layers (solid lines) and perpendicular to layers (dashed lines).

$$\phi(\mu_f - \mu_*)Q^{*f} + (1-\phi)(\mu_s - \mu_*)Q^{*s} = 0, \tag{10}$$

where $\phi$ is porosity, $K_f$ and $\mu_f$ are bulk and shear moduli of the pore fill, $K_s$ and $\mu_s$ are bulk and shear moduli of the matrix (grain) material, and $P$ and $Q$ are invariants of the so-called Wu tensor. The components of this tensor depend on the aspect ratio of the pores, the bulk and shear moduli of the pore fill, the matrix material, and the as of yet unknown effective moduli $K_*$ and $\mu_*$. Berryman (1980) gives the explicit expressions for the components of the Wu tensor. For spherical inclusions, they have a simple form:

$$P^{*i} = \frac{K_* + 4\mu_*/3}{K_i + 4\mu_*/3}, \tag{11}$$

$$Q^{*i} = \frac{\mu_* + F_*}{\mu_i + F_*}, \tag{12}$$

where $F_* = (\mu_*/6)(9K_* + 8\mu_*)/(K_* + 8\mu_*)$ and $i = f,s$. The coupled equations 9 and 10 can be solved by iteration.

Figure 7a and b shows the CPA results for spheres. As expected, they lie between the lower and upper HS bounds. Figure 8a and b shows the comparison of CPA velocities with those computed by using the Gassmann equation (with dry bulk and shear moduli computed by CPA with empty pores). We see that the CPA results are approximately Gassmann consistent when the fluid is Newtonian (i.e., for low frequencies or high temperatures). We note that the CPA for spheres is known to overestimate typical sandstone bulk and shear moduli, simply because typical pores in sands and sandstones are not

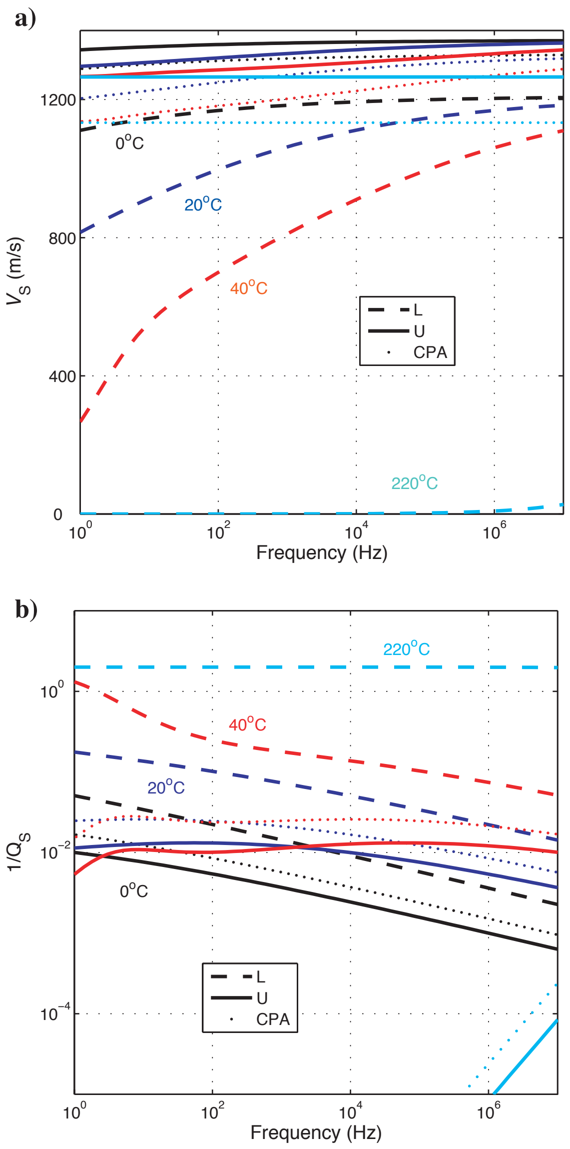

Figure 6. S-waves in the mixture of heavy oil and solid: (a) Velocity and (b) attenuation versus frequency and temperature for S-waves, estimated using upper (solid lines) and lower (dashed lines) Hashin-Shtrikman bounds and CPA for spherical pores (dotted lines).

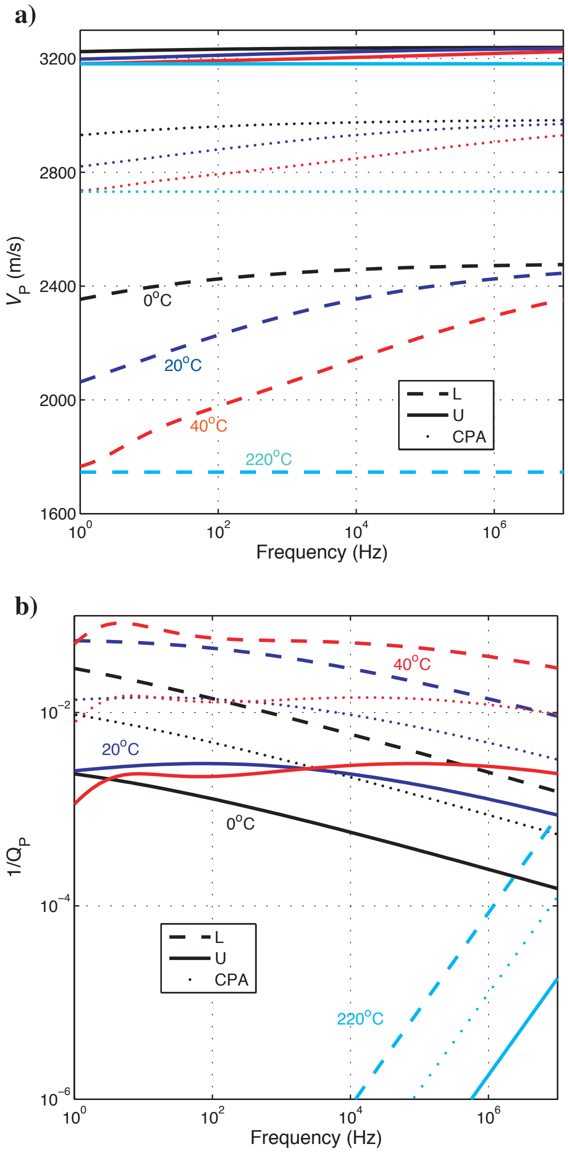

Figure 7. P-waves in the mixture of heavy oil and solid: (a) Velocity and (b) attenuation versus frequency and temperature for P-waves, estimated using upper (solid lines) and lower (dashed lines) Hashin-Shtrikman bounds and CPA (dotted lines).

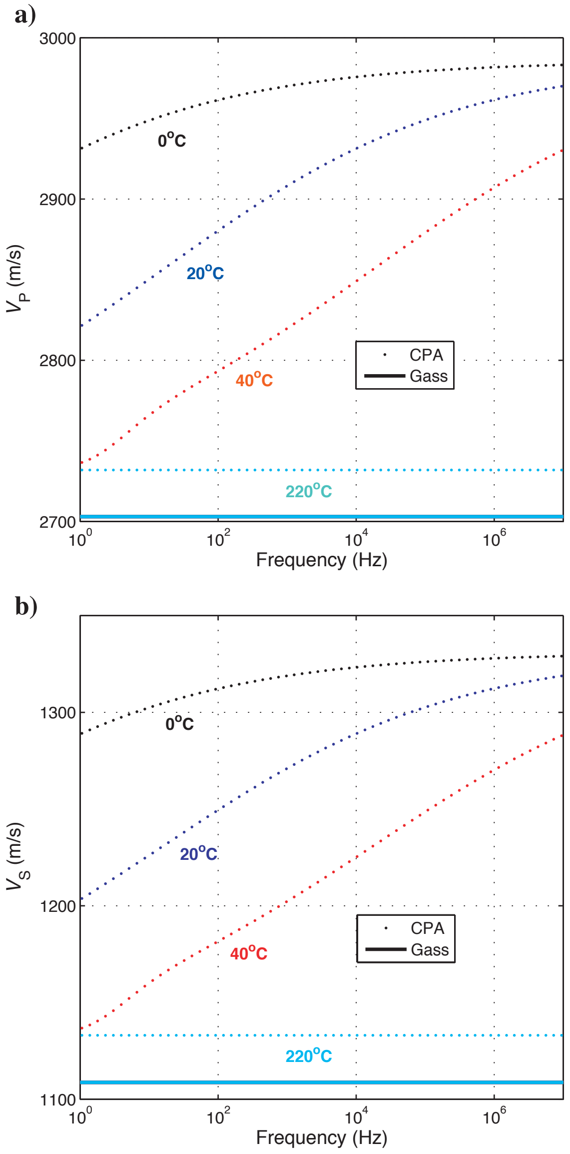

Figure 8. Oil-solid mixture: (a) P-wave and (b) S-wave velocity versus frequency and temperature computed using CPA for spherical pores (dotted lines) and the Gassmann equation (solid line).

spherical. More realistic estimates can be obtained by using CPA with the aspect ratio of pores and grains set to 0.3 or 0.2.

## CONCLUSIONS

We have shown how the effect of heavy oil in rock on elastic wave velocity and attenuation can be estimated by using simple theoretical constructs adopted from the theory of elastic composite materials. Our aim was not to predict precise experimental values, but to obtain estimates of frequency-dependent velocities and attenuation values that are qualitatively consistent with experimental observations. The results of our investigation can be used in the characterization of heavy-oil reservoirs by using seismic and sonic-log data. In particular, our approach can predict seismic-to-sonic dispersion and use it to tie seismic reflection data to well-log data in the presence of heavy oil or to develop attenuation-related seismic attributes for detection of heavy-oil reservoirs.

We note that the predicted P-wave dispersion was weaker in our calculations than that observed in the experiments. This might be because we ignored the bulk viscosity effect in our study. Alternatively, it might be attributed to squirt flow of heavy oil in and out of grain contacts.

This paper focused on the effect of temperature on attenuation and dispersion and ignored the important effects of pressure and steam saturation and the effect of oil properties on the properties of the matrix (which could be significant for loosely consolidated sediments such as tar sands). All these effects need to be analyzed to build a realistic rock-physics model for rocks saturated with heavy oil.

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