Effects of fluid in reservoir on Q factor of P wave and S wave

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Physical logging has been widely used for many years to acquire physical properties of formations in the vicinity of borehole penetrating hydrocarbon reservoirs. Physical logging has several types of logging, for example, electric logging and sonic logging. In sonic logging, the estimation of the porosity of hydrocarbon reservoirs is mainly performed by the measurement of velocity. For acquiring physical properties of fluid in the formation, Biot physics or poroelastic analysis would be the best method. Among the available technologies, Q based on the Biot's equation could be used to estimate fluid viscosity from the matrix-fluid friction. Thus, the estimation of the fluid contact is possible by using Q which is a index of attenuation, we think.

In the present study, we investigate if we take the effect of the viscous attenuation from the acquired quality factor. Based of the result, we then try to estimate the locations of fluid contact using both compressional and shear attenuation factors. The results of our numerical simulations indicate the difference of these factors could be a good indicator of fluid contacts even in attenuating media.

1. INTRODUCTION

Physical logging, for example, sonic logging and electric logging, has been recognized as an porocity tool. Sonic logging tool, has sources and receivers, is amplified in a borehole and we mainly observe the full sonic waveform propagating along the borehole and estimate the porocity of rocks close to the boreholl from the travel time. Many studies about reservoirs by using sonic logging have been conducted (e.g. Randall et al., 1991 ; Cheng and Toksöz., 1981 ; Tsang and Rader., 1979).

The compressional wave causer the alteration of grain and pore in volume, therefore, is related to the boll modulus of pore fluids. On the other hand, shear wave does not causer the alteration of grain and pore in volume, therefore, is insulated from the influence of pore fluid. Q factor which is an index of attenuation is used for absorbing physical properties of hydrocarbon reservoirs. Biot’s equations, which can handle waves propagating in poroelastic medium which include pore fluid, are used to evaluate them. Biot’s equations, on the other hand, consider only viscous attenuation caused by the friction between rocks and pore fluid. However, not so many researches consider the solid friction caused by the heat which is internal friction of soil materials. If the calculated Q factor is different from the observed, there could be some difference in the estimation of pore fluid properties.

In this study, we use frequency-independent Q factor (constant-Q) as the solid friction and simulate elastic wave propagation using Biot’s equations. Then, when we add the solid friction, our goal is taking the effect of the viscous attenuation from the acquired Q factors which include viscous attenuation and solid friction, and then, estimation of the fluid contact (e.g. gas-oil contact and oil-water contact) on the basis of the result.

2. BIOT EQUATIONS

In this study, we study the poroelastic media including hydrocarbons. So we use Biot’s equations (Biot, 1956, 1962) that handle wave propagation in the poroelastic medium and the fluid in it. Biot’s equations are given by

\[ \rho_b \ddot{u} + \rho_f \ddot{w} = (\lambda_u + \mu) \nabla \nabla \cdot \ddot{u} + \mu \nabla^2 \ddot{u} + \alpha M \nabla \nabla \cdot \ddot{w}, \]  
\[ \rho_f \ddot{u} + \rho_n \ddot{w} = \alpha M \nabla \nabla \cdot \ddot{u} + M \nabla \nabla \cdot \ddot{w} - \delta \ddot{w}, \]  

where \( u \) is the displacement vector for the solid, \( w \) the displacement vector for the fluid relative to that for the solid, \( \rho_b \) the overall density of the saturated medium determined by \( \phi \rho_f + (1-\phi) \rho_s \), \( \rho_f \) and \( \rho_s \) the density of the fluid and the solid, \( \phi \) the porosity, \( \lambda_u \) the Lame constant of the dry saturated matrix, \( \mu \) the shear modulus of the dry porous matrix, \( \nu \) the tortuosity, \( \rho_n \) the effective fluid density defined by \( \nu \rho_f/\phi \), \( \eta \) the viscosity of the fluid, \( \kappa \) the permeability of the porous medium, \( b \) the mobility of the fluid defined by \( \eta/\kappa \), \( K \),
and $K_f$, the bulk moduli of the solid and the fluid respectively, $K_s$ bulk modulus of the dry porous matrix, $a$ the poroelastic coefficient of effective stress defined by $1 - K_f/K_s$, $M$ the coupling modulus between the solid and the fluid defined by $[(\phi/K_f + (\alpha - \phi)/K_s)^{-1}$.

We apply the velocity-stress formulation, which is an approach proposed for elastic-wave equations by Virieux (1986), to governing equations. Temporal discretization is based on a staggered-grid finite difference method.

### 3. CONSTANT Q

#### (1) Introduction of constant Q

We use frequency-independent quality factor (constant Q) to include intrinsic attenuation in our model. Starting with the frequency domain Green’s function for the 3D scalar wave equation

$$G(\omega, x, z) = \frac{e^{i\omega R}}{R},$$

where $\omega$ is the angular frequency, $R$ the radial distance, $V_0$ the velocity. We now introduce the complex velocity $V$ in terms of the quality factor $Q$,

$$V = V_0 e^{\frac{i\omega}{2Q} \text{sgn}(\omega)},$$

where $\text{sgn}$ is the signum or sign function defined by

$$\text{sgn}(\omega) = \begin{cases} +1 & (\omega > 0) \\ -1 & (\omega < 0) \end{cases}.$$  \hfill (5)

Introduction of complex velocity leads to the attenuation Green’s function given by

$$G(\omega, x, z) = \frac{e^{i\omega R}}{R} e^{-\frac{\omega}{2Q} \text{sgn}(\omega)},$$

and the attenuation coefficient is

$$\alpha = \frac{\omega \text{sgn}(\omega)}{2V_0 Q}.$$  \hfill (7)

We use the filter (Q-filter) of $e^{-\frac{\omega}{2Q} \text{sgn}(\omega)}$ and convolute it because we now perform the analysis in time domain.

#### (2) Minimum Phase

The zero phase Q-filter does not satisfy an causality because the zero phase Q-filter has an energy at negative time. So we make the zero phase filter into a minimum phase filter. Conversion to the minimum phase is shown below.

$$I(\omega) = \exp(H(\omega)\log(F(\omega))),$$

where $F(\omega)$ is $e^{-\alpha R}$, $H(\omega)$ the Hilbert transform, $I(\omega)$ the minimum phase of $e^{-\alpha R}$.

#### (3) Formulation of intrinsic attenuation

Q factor is defined by

$$Q = \frac{2\pi E}{\Delta E},$$

where $E$ is the peak strain energy stored in volume and $\Delta E$ is the energy lost due to imperfections in the elasticity of the material. Meanwhile, when a plane wave propagates in anelastic matrix the plane wave propagating along $x$ axis is expressed by the attenuation coefficient $\alpha(f)$ and the dispersion wave number $\kappa(f)$.

$$U(x, t) = U_0 \exp(-\alpha x) \exp(i(\omega t - \kappa x)), \quad (10)$$

where $U$ is the amplitude, $U_0$ the initial amplitude. The relationship between $Q$ and $\alpha(f)$ is shown in equation(12) because wave amplitude is proportional to $E^{\frac{1}{2}}$.

$$E = S U_1^2, \Delta E = S(U_1^2 - U_2^2), \quad (11)$$

$$Q = \frac{2\pi}{1 - \exp(2\alpha v(f)/f)}, \quad (12)$$

where $U_1$ and $U_2$ are amplitudes at receiver 1 and 2 respectively, $S$ is a proportional constant.

#### (4) Acquisition of Q

In this study, we use the amplitude spectral ratio (ASR) method to estimate the intrinsic attenuation from P head waves of full-waveform sonic logs. The method has the assumption that the velocity structure and the value of $Q$ are constant. The amplitude at a receiver is shown in equation(13):

$$U(x, t) = U_0 \exp(-\alpha x) \exp(i(\omega t - \kappa x)) G T,$$  \hfill (13)

where $G$ is the geometrical attenuation, $T$ is the scattering attenuation. In this study, $T$ is set to 1 because we do not consider scattering attenuation. Considering only the term of attenuation, equation (13) is described as:

$$\ln\left(\frac{U}{G}\right) = -\beta x + \ln(U_0).$$  \hfill (14)
And then, we get the $\beta$ and assign the $\beta$ to equation (15):

$$Q = \frac{2\pi}{1 - \exp(-2\beta V/f)}$$  \hfill (15)

4. NUMERICAL MODELING

We consider the numerical model shown in Figure 1 and 2. The model consists of $500 \times 500$ grids in the analysis model that has $8m \times 8m$. The layer thickness and saturated ratio are shown in Figs 1 and 2. The time interval is $4.0 \times 10^{-6}$ sec. We set the source at 1.28m from the top and the 37 receivers from 2.5m to the bottom with 0.16m intervals. The physical characters of solid and fluid phase are shown in Table 1, 2, and 3. At the part of fluid mixture, we apply the exponent law given by Brie et al.,1995 about the bulk modulus of the fluid. As the source function, we use a Ricker wavelet with a center frequency of 4 kHz. We set the absorbing boundaries at the model edges. We test two kinds of models. Model 1 has the Gas-Oil contact, i.e. the upper part of a reservoir. The parameters of the oil in model 1 is 'oil 1'. We add the solid friction of 40 in shale and 20 in sandstone. Model 2 has the Oil-Water contact, i.e. the lower part of a reservoir. In model 2, we try to use 'oil 1' and 'oil 2' in Table 3 as the parameters of oil. We add the solid friction of 20 in sandstone.

5. RESULTS

Q factors of compressional wave (red line) and shearwave (green line) calculated by ASR method for model 1 and model 2 are shown in Figure 3, 4, and 5, respectively. We also show the results subtracting the Q inverse of shear wave from that of compressional wave.

6. DISCUSSION

The value of Q inverse is almost constant at upper and lower part of model in Figs 3(a), 4(a) and 5(a), because each part is saturated with one kind of fluid. The apparent change in Q appears due to the effect of the reflection induced by the continuous velocity change at central part of model in Figs 3(a), 4(a) and 5(a).

$$Q^{-1} = \frac{1}{Q_{\text{fluid}}} + \frac{1}{Q_{\text{solid}}} + \frac{1}{Q_{\text{scat}}}$$  \hfill (16)

where $Q_{\text{fluid}}$ is the viscous attenuation, $Q_{\text{solid}}$ is the solid friction and $Q_{\text{scat}}$ is the scattering attenuation. In our study, since we don’t consider the scattering attenuation, equation(16) is described below:

$$Q^{-1} = \frac{1}{Q_{\text{fluid}}} + \frac{1}{Q_{\text{solid}}}$$  \hfill (17)

The shear wave is influenced only by the effect of solid friction whereas the compressional wave is influenced both by the effects of viscous attenuation and solid friction. Therefore, we get the effect of only viscous attenuation by subtracting the Q inverse of shear wave from the Q inverse of the compressional wave.

<table>
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<tr>
<th>Table 1: Physical characters of solid</th>
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<tbody>
<tr>
<td>sandstone</td>
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<tr>
<td>Bulk modulus of the solid grains $K_s [GPa]$</td>
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<tr>
<td>Bulk modulus of the dry frame $K_d [GPa]$</td>
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<tr>
<td>Shear modulus of the dry frame $\mu [GPa]$</td>
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<tr>
<td>Porosity $\phi$</td>
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<tr>
<td>Tortuosity $\nu$</td>
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<tr>
<td>Permeability $\kappa$</td>
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<tr>
<td>Density of the solid grains $\rho_s [kg/m^3]$</td>
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<th>Table 2: Physical characters of gas and water</th>
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<tr>
<td>gas</td>
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<tr>
<td>Bulk modulus of the fluid $K_f [GPa]$</td>
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<tr>
<td>Density of the fluid $\rho_f [kg/m^3]$</td>
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<tr>
<td>Viscosity of the fluid $\eta [Pa\cdot s]$</td>
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<th>Table 3: Physical characters of oil 1 and 2</th>
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<tr>
<td>oil 1</td>
</tr>
<tr>
<td>Bulk modulus of the fluid $K_f [GPa]$</td>
</tr>
<tr>
<td>Density of the fluid $\rho_f [kg/m^3]$</td>
</tr>
<tr>
<td>Viscosity of the fluid $\eta [Pa\cdot s]$</td>
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In Figure 3(b), the difference of inverse Q changes suddenly only at the upper part of the contact zone. This means that the difference of inverse Q between shear and compressional waves would be a indicator of the gas-oil contact. In Figure 4(b), on the other hand, it is difficult to identify the oil-water contact clearly because the difference between the Q inverse of oil layer (oil 1) and the Q inverse at only water layer is very small. In Figure 5(b), the boundary of oil-water contact become clearer than that in figure 4(b) because the shear wave in oil-saturated zone exhibits viscoelastic behavior due to the high viscosity of ‘oil 2’.

7. CONCLUSION
In the present study, we found it is possible to extract the effects of the viscous attenuation as predicted by Biot Physics by analyzing the Q factor in accord with the characteristics of the compressional and shear wave. We are then able to estimate the gas-oil contact and oil-water contact for heavy oil.

The results of our numerical simulations indicate the difference of these factors could be a good indicator of fluid contacts in attenuating media.

REFERENCES
6) Tsang, L. and Rader, D.,1979, Numerical evaluation of the transient acoustic waveform due to a point source in a fluid filled borehole : Geophysics ,VOL44, P.1706-1720