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The Effects of Fluid Viscosity on Seismic Response: A Model Study

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Summary

Biot's mechanism and squirt flow are two major causes of attenuation. These effects are related and at seismic frequencies can be shown with simplified equations. Attenuation is affected by the viscosity of fluids. One order of magnitude change in viscosity is equivalent to one order of magnitude change in quality factor. The differences between elastic and viscoelastic responses of a simple geological model are shown.

Introduction

During the recovery of hydrocarbons from reservoir, fluid saturations and reservoir pressure are subject to change with time. Obviously, if thermal mechanisms are used, temperature changes are also added to the picture. These changes in the pressure-volume-temperature condition in the reservoir will change the phase, composition and viscosity of the fluids in situ. These changes in the reservoir and fluid conditions will change the seismic properties of pore fluids and hosting rocks (Batzle and Wang, 1992, Toksoz et al, 1976), making it possible to monitor the changes in the reservoir through changes in seismic attributes such as velocity, amplitude or phase.

There are several factors that affect the seismic amplitude, most important of which are reflection, refraction, diffraction, geometrical spreading, absorption and conversion. Absorption or attenuation of energy is due to non instantaneous response of a material to applied stresses which is called viscoelastic response (Carcione, 2007). In this current work, we examine the effects of viscosity of fluids on seismic Response through the Biot's theory and squirt flow mechanism.

BISQ Theory

A reservoir rock is generally formed of porous rock as the host and fluids in the pores. Biot (1962) explained the theory of propagation of stress waves in the medium for elastic porous frame filled with viscous fluid. Therefore in this theory, losses caused by solid framework are ignored (Wyllie et al, 1962). In the model, the fluid is forced to participate in an oscillatory motion by viscous forces and inertial coupling (Dvorkin and Nur, 1993). Biot's theory alone is not able to explain the high attenuations and velocity dispersions, observed during the monitoring of fluid viscosity using well logs or experimental laboratory velocity measurements (Dvorkin et al, 1994). Another phenomenon that affects the attenuation and velocity dispersion is the squirt flow mechanism. When pressure is applied, pores with lower aspect ratios undergo a bigger change in volume; therefore the fluid inside such cracks has to flow toward the pores with higher aspect ratios.

Dvorkin and Nur (1993) developed an integrated Biot plus squirt flow theory or BISQ. In this theory both mechanisms are considered simultaneously and the poroelastic behavior of rocks is related to measureable and macroscopic reservoir and fluid properties such as porosity, permeability, viscosity, compressibility, density, etc. Formulation of BISQ is based on uniaxial stresses and deformations, and explains the effect of reservoir parameters on P-wave attributes. These influences are all frequency dependent. Characteristic frequency separates the high and low frequency behaviors and is defined as

$$\omega_c = \frac{\mu\varphi}{k\rho_f} \tag{1}$$

where μ is fluid viscosity, φ is porosity, ρ_f is fluid density and k is permeability. Generally, seismic frequencies are much smaller than characteristic frequency. That means:

$$\frac{\omega}{\omega_c} \ll 1 \tag{2}$$

At such frequencies, the seismic attenuation, in terms of quality factor, is given by (Dvorkin et al, 1994):

$$Q = \frac{\mathrm{Re}\left(\sqrt{Y}\right)}{2\mathrm{Im}\left(\sqrt{Y}\right)} \tag{3}$$

where in the above

$$Y = \frac{\rho_m(1-\varphi)+\rho_f\varphi}{M+F_{sq}\frac{\alpha^2}{\varphi}} \tag{4}$$

$$F_{sq} = F\left[1-\frac{2J_1(\xi)}{\xi J_0(\xi)}\right] \tag{5}$$

$$\xi = \sqrt{i}\sqrt{\frac{R^2\mu\varphi\omega}{kF}} \tag{6}$$

$$F = \frac{\varphi}{\frac{\varphi}{K_f}+\frac{1-\varphi}{K_m}-\frac{K_d}{K_m^2}} \tag{7}$$

$$\alpha = 1-\frac{K_d}{K_m} \tag{8}$$

In these equations, J denotes a Bessel function with the type specified by the subscript, K_f, K_m and K_d are fluid, matrix and dry frame bulk modulus, respectively, ρ_m is matrix density and R is characteristic squirt flow length. It is assumed that R is a measureable rock property. It can be estimated by matching the real data and model calculations at well bore locations.

Attenuation and Viscosity

Figure 1 shows the relationship between quality factor and fluid viscosity. The parameters used for calculations are summarized in table 1.

Table 1: Rock and fluid properties

Matrix Bulk modulus	35 GPa	Fluid Density	1000 kg/m^3
Matrix Density	2650 kg/m^3	Fluid bulk modulus	20 MPa
Porosity	0.30	Fluid viscosity	Variable
Dry frame bulk modulus	1.7 GPa	Frequency	30 Hz
Dry frame shear modulus	1.855 Gpa	R	1 mm
Permeability	1 D	Saturation	1

The minimum ω_c in this case is 3×10^{10} Hz, so the condition given in (2) is well met and use of equations 3-8 is valid.

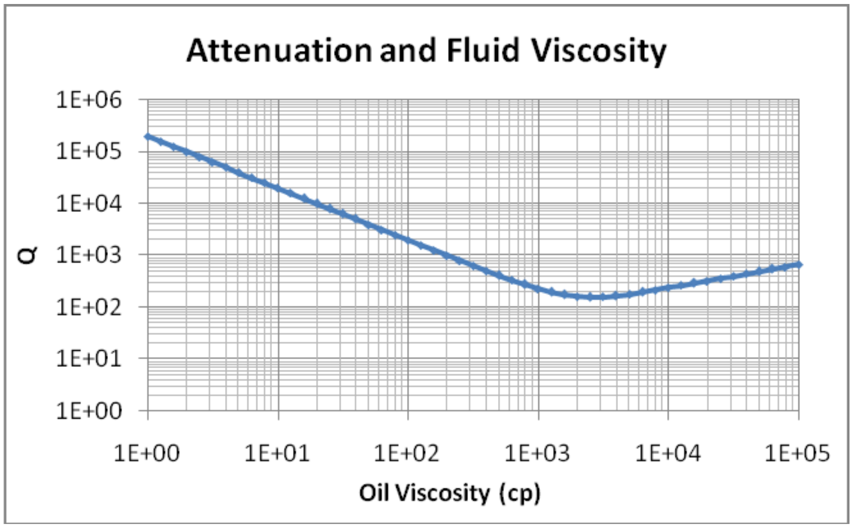


Figure 1: Change of attenuation with viscosity of fluid at frequency of 30 Hz.

This graph shows that Q decreases with viscosity to a minimum, then increases. A standard linear solid model known as Zener model shows the same behavior (Carcione, 2007). The figure shows that one order of magnitude change in viscosity will cause almost one order of magnitude change in quality factor.

Forward Modeling

To show the effect of viscosity on seismic response we use a simple geological model, shown in figure 2. The top and bottom layers are lossless formations. Therefore the elastic and viscoelastic propagation of waves in these layers are identical. The middle layer is fully saturated with a viscous fluid and the fluid viscosity is variable across the layer. Other fluid properties are fixed. This is an unrealistic case since changing the fluid viscosity without changing the other rock and fluid properties is almost impossible. However, the main purpose of this study is to quantify the seismic footprints of viscosity.

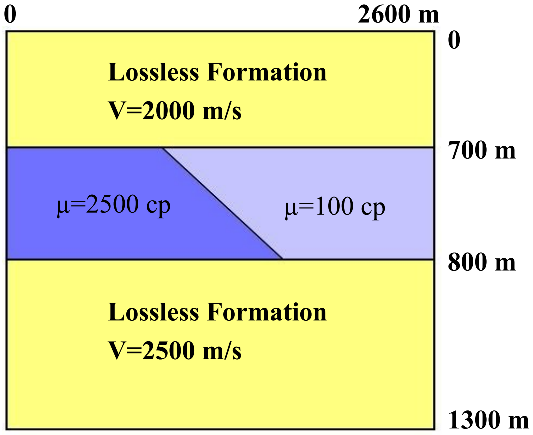
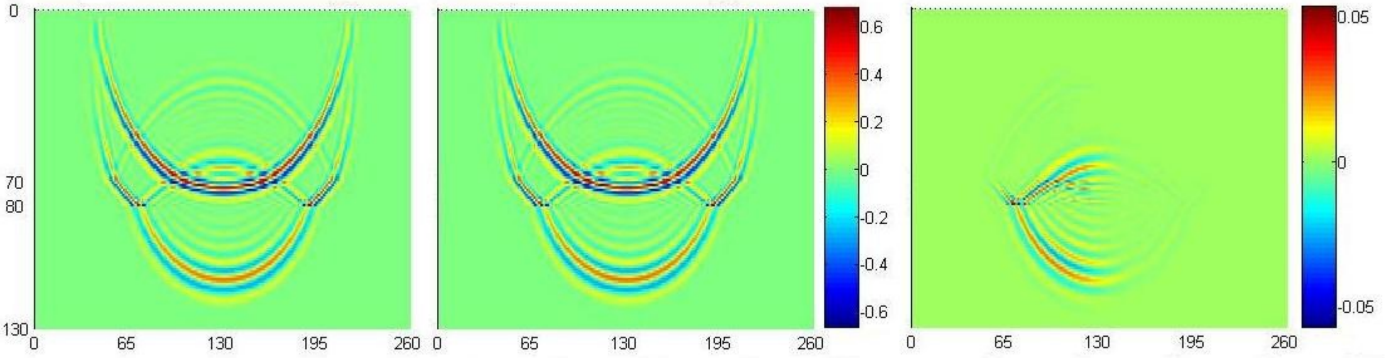


Figure 2: Geological model (schematic) used for forward modeling. The middle layer is saturated with the identical fluids except that viscosity is higher in the left part than in the right part.

Other rock and fluid properties for the middle layer are given in table 1. Figure 3 shows the elastic and viscoelastic responses of the model and the difference between these models. Snapshots are generated using finite difference forward modeling technique.

Snapshots of P wave Propagation



a) Visco-Elastic **b) Elastic** **c) Difference**

Figure 2: Snapshots of P-wave propagation generated using finite difference forward modeling technique for a) viscoelastic mode and b) elastic mode. Part c shows the difference between the modes.

Figure 3c shows that there is more difference on the left half of the model. This is due to the fact that the left half of the middle layer contains more viscous fluid, therefore from figure 1, has lower Q or causes higher attenuation. The synthetic model shows that, according to the theory of BISQ and for the properties given in table 1, there is around 4% change in the amplitude of the P-wave when viscosity changes from 2500 cp to 100 cp. Once again, this difference is only caused by change in viscosity, while in more realistic cases, the change in viscosity follows the changes in temperature or composition or both which are ignored in this study.

Conclusions

According to theory of BISQ, the quality factor first decreases and then increases with viscosity. This type of behavior is identical to standard linear solid model. A viscosity change of 2500 cp to 100 cp will cause 4% change in the amplitude of P-waves. For future work, we suggest that the effects of other parameters be included in the fluid substitution models, such as changes in temperature and composition of fluid which in turn will change the density and bulk modulus of fluid and saturated rock.

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