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Frequency-dependent attenuation of compressional wave and seismic effects in porous reservoirs saturated with multi-phase fluids

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ABSTRACT

Varying fluid types and saturations in porous media cause attenuation of compressional seismic waves and thus contribute to frequency-dependent reflections. We analyze the frequency-dependent attenuation and the corresponding seismic reflection behavior by taking into account the effects of the multi-phase fluid on the wave-induced fluid flow in porous reservoir. Fluid viscosity, the property that largely controls pore-fluid mobility, is proportional to the relaxation time, which in turn influences the frequency-dependent velocities. Here, we describe the variation of effective viscosity varies with saturation for a sandstone reservoir saturated for different multi-phase fluid mixtures using the Refutas equation. Then we explore the frequency-dependent velocity and inverse quality factors under different fluid saturation cases by employing equivalent-medium theory of Chapman's model. Next, we present a frequency-dependent phase-shift wavefield extrapolation method to simulate frequency-dependent seismic wavefield on 4-layer models. Comparative analyses indicate that the frequency-dependent attenuation and the seismic behaviors are functions of fluid viscosity associated with hydrocarbon saturations. Hydrocarbon saturations in fluid mixture strongly affect attenuation and characteristic frequencies. The frequency-dependent attenuation within the seismic frequency range can be increased due to the presence of hydrocarbons in multi-phase fluids. Synthetic seismic records indicate that the frequency-dependent attenuation of compressional wave and seismic reflection signatures are significantly dependent on hydrocarbon saturation, in terms of amplitude, waveform and traveltime of the reflection located at the base of the saturated reservoir and the underlying shale layer.

1. Introduction

Attenuation is of great importance for the detection of hydrocarbons on surface seismic data. It is demonstrated that the intrinsic frequency-dependent attenuation of compressional wave occurs when the seismic wave travel through rocks partially saturated with hydrocarbons (Castagna et al., 2003; Chapman et al., 2003; Korneev et al., 2004; Batzle et al., 2006; Chen et al., 2009; Quintal et al., 2011; Quintal, 2012; Chen et al., 2013). When fluids are contained in the pore space of rocks, one mechanism that causes attenuation is known as wave-induced fluid flow (WIFF) (Pride et al., 2004; Korneev et al., 2004; Brown, 2009; Müller et al., 2010; Rubino et al., 2012). Wave-induced flow of viscous pore fluids on the mesoscopic scale is a major cause of P-wave attenuation in partially saturated porous rocks at seismic frequencies (Pride et al., 2004; Müller et al., 2010). Even low fluid mobility (i.e. permeability to viscosity ratio) can produce strong attenuation associated with significant velocity dispersion within the seismic frequency range (Batzle et al., 2006).

The fluid viscosity associated with saturation largely controls pore-fluid flow in porous rocks and plays an important role in determining the characteristics of frequency-dependent complex velocities (Batzle et al., 2006; Chapman et al., 2003; Gurevich, 2002; Chen et al., 2014). Some authors discuss the relationship between viscosity and P-wave velocity. The transition from the viscosity-dominated regime to the inertial regime is often modeled using the dynamic permeability model of Johnson et al. (1987). Johnson (2001) developed a theory for the acoustic response of patchy saturation within the context of the low-frequency Biot theory (Biot, 1956). The work of Pride et al. (2004) showed that mesoscopic flow is a significant mechanism of fluid-related attenuation in the seismic exploration frequency-band by

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using fluid-saturated porous grain models to derive three different P-wave attenuation behaviors using a single theoretical framework. Gurevich (2002) investigated attenuation and dispersion of elastic waves in Periodic solid and viscous fluid layered systems at low frequencies. The effect of pore fluid viscosity on effective elastic properties considered with several attenuation regimes are numerically simulated using digitized rocks by Saenger et al. (2011).

In general, the blending of different phase fluid components impacts the density, bulk modulus and effective viscosity of the pore fluid mixture. Therefore, these physical effects can be taken into account in exploring the mechanism of frequency-dependent attenuation and seismic effects in multi-phase fluid-bearing rocks. In this paper, we numerically and analytically calculated the frequency-dependent attenuation of P-wave in porous rocks saturated with multi-phase fluids. The effects resulting from changes in saturation on seismic responses in partially hydrocarbon saturated rocks are studied. Firstly, using the equivalent-medium theory of Chapman's model (Chapman et al., 2003), we explore the frequency-dependent inverse quality factors under different fluid saturation cases. Then we study the frequency-dependence of the seismic wavefield using a 4-layer model for various cases of fluid mixtures using a frequency-dependent phase-shift wavefield extrapolation method.

2. Theory and method

2.1. Background of the Chapman (2003) theory

We use the dynamic equivalent-medium theory proposed by Chapman (2003) to obtain the frequency-dependent elastic modulus. The theory, based on a squirt flow mechanism in fractured porous rock, considers the frequency-dependent seismic anisotropy in reservoirs through the knowledge of rock porosity, permeability, fracture density and orientation and pore fluid properties such as viscosity, bulk modulus and density. The poroelastic model of Chapman (2003) is consistent with the work of Brown and Korringa (1975) and Hudson (1981) in the low- and high-frequency ranges. It can be used to reproduce velocity dispersion and attenuation results in the low- and high-frequency limits, i.e. at any frequency (Chapman, 2003; Mavko et al., 2009).

The element of the effective stiffness tensor C_{ijkl}, given by Chapman (2003), is of the form:

$$C_{ijkl} = C^0_{ijkl} - \phi_p C^1_{ijkl} - \varepsilon_c C^2_{ijkl} - \varepsilon_f C^3_{ijkl} \tag{1}$$

where C° is the isotropic elastic tensor of the stiffness matrix with Lamé parameters λ and μ. The corrections C^1, C^2 and C^3, multiplied by porosity ϕ_p, micro-crack density ε_c and fracture density ε_f, respectively, are function of the Lamé parameters, fluid and fracture properties, frequency, and relaxation time τ that is related to the squirt flow time delay. The relaxation time is an extremely important parameter giving an implied relationship between the fluid mobility and the frequency-dependent velocities. The corrections are related to contributions from fluid-filled pores, micro-crack and fractures, respectively.

To make Chapman's (2003) model more applicable to real data, the Lamé parameters λ_0 and μ_0 obtained from P- and S-wave velocities ($v_p{}^\circ$ and $v_s{}^\circ$) and the density (ρ) of the unfractured rock, are adopted in our derivations. We also employ $C^\circ(\Lambda,\mathrm{M})$ to indicate that the velocities are obtained at a certain frequency f_0. This allows the model to have the Lamé parameters taken from laboratory measurements for direct calibration of the model. Subsequently, we have the frequency independent reference constants:

$$\Lambda = \lambda_0 + \phi_p\left(\lambda_0, \mu_0, \omega_0, \tau_0\right) + \varepsilon_c\left(\lambda_0, \mu_0, \omega_0, \tau_0\right),$$
$$M = \mu_0 + \phi_p\left(\lambda_0, \mu_0, \omega_0, \tau_0\right) + \varepsilon_c\left(\lambda_0, \mu_0, \omega_0, \tau_0\right) \tag{2}$$

where the last two terms in the right-hand side of the equations refer to correction to the elastic tensor with $\lambda_0 = \rho\left(v_p^0\right)^2 - 2\mu_0$; $\mu_0 = \rho\left(v_s^0\right)^2$; $\omega_0 = 2\pi f_0$. Then we can calculate the frequency-dependent, anisotropic, elastic tensor as:

$$C_{ijkl}(\omega) = C^0_{ijkl}\left(\Lambda, M, \omega\right) - \phi_p C^1_{ijkl}\left(\lambda_0, \mu_0, \omega, \tau\right) - \varepsilon_c C^2_{ijkl}\left(\lambda_0, \mu_0, \omega, \tau\right) - \varepsilon_f C^3_{ijkl}\left(\lambda_0, \mu_0, \omega, \tau\right) \tag{3}$$

The correction terms in Eq. (3) associated with pores, micro-cracks and fractures that are responsible for the frequency-dependent nature and anisotropy of rocks, can be obtained from laboratory measurements (Maultzsch et al., 2003).

The model considers that the fluid flow effects occur on two scales (Maultzsch et al., 2003); the grain scale associated with the microcracks and pores, and the fracture scale. This leads to the existence of two characteristic frequencies and associated relaxation time. The relaxation time τ_m associated with the grain-scale fluid flow corresponds to the traditional squirt-flow frequency while the fluid flows in and out of fracture result in a lower characteristic frequency (larger relaxation time τ_m) related to the size of fractures. The two relaxation times are related to each other through

$$\tau_f = \left(\frac{a_f}{\varsigma}\right)\tau_m \tag{4}$$

where a_f denotes the fracture radius and ζ is the grain size. Since it is extremely difficult to know τ_m exactly, Chapman et al. (2002) gave an approximation that is valid for the small aspect ratio such that:

$$\tau_m \approx \frac{4a^3(1-\sigma)}{9\kappa\varsigma\mu}\eta \tag{5}$$

where a is the crack radius, σ denotes the Poisson ratio, κ is the rock permeability, μ is the shear modulus and η is the fluid viscosity. This equation is particularly interesting, since it shows the significant influence of viscosity on the position of the attenuation peak on the frequency axis, and how the seismic response of a given hydrocarbon saturated sandstone reservoir is affected.

2.2. Calculation of frequency-dependent velocity and attenuation

The matrix representation of the frequency-dependent elastic stiffness calculated from Chapman's (2003) model has the following form:

$$\begin{pmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix}, \quad C_{66} = \frac{1}{2}\left(C_{11} - C_{12}\right) \tag{6}$$

The complex-valued and frequency-dependent elastic stiffness tensor then allows to obtain the corresponding frequency-dependent complex compressional velocity $V(\omega)$ (Mavko et al., 2009):

$$V(\omega) = \left(C_{11}\sin^2\theta + C_{33}\cos^2\theta + C_{44} + \sqrt{M}\right)^{1/2}(2\rho)^{-1/2} \tag{7}$$

where