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Frequency-dependent attenuation as a potential indicator of oil saturation

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ABSTRACT

At seismic frequencies, wave-induced fluid flow is a major cause of P-wave attenuation in partially saturated porous rocks. Attenuation is of great importance for the oil industry in the interpretation of seismic field data. Here, the effects on P-wave attenuation resulting from changes in oil saturation are studied for media with coexisting water, oil, and gas. For that, creep experiments are numerically simulated by solving Biot's equations for consolidation of poroelastic media with the finite-element method. The experiments yield time-dependent stress–strain relations that are used to calculate the complex P-wave modulus from which frequency-dependent P-wave attenuation is determined. The models are layered media with periodically alternating triplets of layers. Models consisting of triplets of layers having randomly varying layer thicknesses are also considered. The layers in each triplet are fully saturated with water, oil, and gas. The layer saturated with water has lower porosity and permeability than the layers saturated with oil and gas. These models represent hydrocarbon reservoirs in which water is the wetting fluid preferentially saturating regions of lower porosity. The results from the numerical experiments showed that increasing oil saturation, connected to a decrease in gas saturation, resulted in a significant increase of attenuation at low frequencies (lower than 2 Hz). Furthermore, replacing the oil with water resulted in a distinguishable behavior of the frequency-dependent attenuation. These results imply that, according to the physical mechanism of wave-induced fluid flow, frequency-dependent attenuation in media saturated with water, oil, and gas is a potential indicator of oil saturation.

1. Introduction

Frequency-dependent attenuation and/or reflectivity in seismic data have often been observed associated with hydrocarbons (Castagna et al., 2003; Chapman et al., 2006; Dasgupta and Clark, 1998; Goloshubin et al., 2006; Korneev et al., 2004; Odebeatu et al., 2006; Rapoport et al., 2004; Taner et al., 1979; Wang, 2007). Odebeatu et al. (2006) applied spectral decomposition techniques to seismic reflection data and observed sharp changes in the spectral behavior associated with hydrocarbon saturation. Rapoport et al. (2004) conducted extensive experimental research, using well and surface data, and measured abnormally high attenuation and velocity dispersion of seismic waves in oil and gas fields. Other authors also observed that hydrocarbon reservoirs exhibit high seismic attenuation (e.g., Dasgupta and Clark, 1998), particularly at low seismic frequencies, as Chapman et al. (2006) remarked. Korneev et al. (2004) used laboratory and field data to show that attenuation can be related to an increase in reflectivity at low frequencies. Quintal et al. (2011a) explained the laboratory data of Korneev et al. (2004) using the theory of wave-induced fluid flow, which is a physically-based mechanism for attenuation. Goloshubin et al. (2006) showed three examples of field data in which oil-rich reservoirs exhibit increased reflectivity at low seismic frequencies. They suggested that using low-frequency imaging has a strong potential for predicting hydrocarbon content in reservoirs.

At seismic frequencies, wave-induced fluid flow between mesoscopic-scale heterogeneities is a major cause of P-wave attenuation and the associated velocity dispersion in a partially saturated porous rock (e.g., Müller et al., 2010; Pride et al., 2004). The mesoscopic scale is the scale much larger than the pore size but much smaller than the wavelength. Flow of the pore fluid is generated by fluid pressure differences between regions with different petrophysical properties (due to different fluid content, porosity, solid frame compressibility etc.). In White's model (White, 1975; White et al., 1975), a partially saturated rock is approximated by a poroelastic medium with regions fully saturated by one fluid and other regions fully saturated by another fluid. This is frequently referred to as patchy saturation. White (1975) introduced a three-dimensional (3D) model of a water-saturated medium with spherical gas-saturated inclusions, and White et al. (1975) introduced a one-dimensional (1D) layered model referred to as the interlayer-flow model. Dutta and Odé (1979a, 1979b) showed that wave-induced fluid flow can be modelled using Biot's equations of poroelasticity (Biot, 1962) with spatially varying petrophysical parameters on the mesoscopic scale.

The main objective of this study is to investigate the effects on P-wave attenuation resulting from changes in oil saturation in media with coexisting water, oil, and gas. In these media, P-wave attenuation is due to interlayer fluid flow. In the first part of the study, the models consist of periodically alternating pairs of layers with

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different solid frame properties and different fluid saturation. One pair of layers in this periodic model is referred to as the Representative Elementary Volume (REV). In the second part of the study, the periodic REV consists of a triplet of layers, where only one layer has a different solid frame, but each layer is fully saturated with a different fluid (water, oil, and gas). In the last part of the study, a model consisting of one hundred triplets of layers with randomly varying thicknesses is considered. In each triplet, one layer has a different solid frame than the other two, and each layer is fully saturated with a different fluid (water, oil, and gas), equivalently to the case with periodic triplets. Assuming that water is the wetting fluid, these models represent hydrocarbon reservoirs, with water saturating the layers with lower porosity, and hydrocarbon (gas and/or oil) saturating the layers with higher porosity and permeability. This is based on the fact that the wetting fluid preferentially saturates regions of small pores due to capillary effects (Goertz and Knight, 1998).

To study P-wave attenuation in a model whose periodic REV consists of a pair of layers, the analytical solution of the interlayer-flow model (Carcione and Picotti, 2006; Quintal et al., 2009; White et al. 1975) is used. For a model whose periodic REV consists of a triplet of layers, or a model consisting of many triplets of layers with randomly varying thicknesses, no analytical solution is available, and in these cases the P-wave attenuation is calculated numerically using the algorithm described by Quintal et al. (2011b).

2. Theory of the interlayer-flow model

In the 1D version of White's model (Carcione and Picotti, 2006; Norris, 1993; Quintal et al., 2009; White et al., 1975), here referred to as interlayer-flow model, a rock with mesoscopic-scale heterogeneities is represented by a layered poroelastic medium consisting of two periodically alternating layers of media 1 and 2. The layers can differ in the properties of the pore fluid and/or of the solid frame. A partially saturated rock is approximated by such a medium when each of the layers is fully saturated with a different fluid. The analytical solution of the interlayer-flow model (Appendix A) yields the complex and frequency-dependent P-wave modulus, E, as a function of several petrophysical parameters and the thicknesses of the two alternating layers. Once E is computed, the frequency-dependent, complex P-wave velocity can be obtained with

$$V = \sqrt{\frac{E}{\rho}}, \quad (1)$$

where ρ is the bulk density of the layered medium. The frequency-dependent phase velocity is

$$V_p = \left(\mathrm{Re}\left(\frac{1}{V}\right)\right)^{-1}, \quad (2)$$

and frequency-dependent attenuation is given by

$$\frac{1}{Q} = \frac{\mathrm{Im}(E)}{\mathrm{Re}(E)} \quad (3)$$

(e.g., Carcione, 2007), where Re and Im denote real and imaginary parts, respectively, and Q is the quality factor. Attenuation is due to fluid flow caused by fluid pressure differences between layers. In the analytical solution of the interlayer-flow model (Appendix A), dynamic effects were not taken into account, and attenuation, $1/Q$, has always a maximum, $1/Q_{\min}$ ($Q_{\min}$ is the minimum value of Q), at a certain frequency referred to as transition frequency, f_{tr}. Not accounting for dynamic effects is appropriate for this study because the aim is to better understand the behavior of intrinsic attenuation caused by fluid flow at low seismic frequencies. An analytical solution combining dynamic effects and intrinsic attenuation caused by interlayer flow is given by Gelinsky and Shapiro (1997).

As shown in Appendix A, $1/Q$ (Eq. (3)) can be expressed as a complicated function of two petrophysical parameter groups, g and s, and the angular frequency ω (Eq. (A4)). The parameter g (Eq. (A5)) consists of elastic moduli, porosity, and relative thickness of layers (related to the saturation ratio), and the parameter s (Eq. (A8)) is dominated by the absolute thickness of the layers and the flow parameters, i.e., viscosity and permeability. For better understanding the dependence of $1/Q$ of the interlayer-flow model on the basic petrophysical parameters, some approximations may be used, which are mathematically much simpler than the full solution, such as approximations for the value of f_{tr} (Dutta and Seriff, 1979) and for the maximum value of attenuation, $1/Q_{\min}$ (Quintal et al., 2009, 2011a). The approximations derived by Dutta and Seriff (1979) and Quintal et al. (2009) are limited to media with a homogeneous solid frame and layers characterized only by different fluid saturation, with one fluid much more compressible than the other. Quintal et al. (2011a) derived new approximations for $1/Q_{\min}$ and f_{tr} which are valid for media with heterogeneities characterized by any two sets of petrophysical properties, i.e., different solid frame properties and/or different pore fluids. Their approximation for $1/Q_{\min}$ is a function of only the group of parameters g (Eq. (A5)), being independent of the flow parameters and of the absolute thickness of the layers.

3. Heterogeneous media saturated with two fluids

To further understand the influence of the rock and fluid parameters on attenuation, $1/Q$, the analytical solution of the interlayer-flow model (Appendix A) is used for media having heterogeneous porous frame saturated with one or two fluids. These media consist of two periodically alternating layers with different sets of solid frame properties S1 and S2. The layer with solid frame S1 is 10-cm thick and is always saturated with water. The layer with solid frame S2 is 20-cm thick and is saturated either with water, gas, or oil. The REV of each medium for these three saturation profiles is illustrated in Fig. 1, cases 1, 5, and 6. Table 1 shows the definitions of symbols used for the basic petrophysical parameters describing the properties of the solid frame, given in Table 2, and the properties of the fluids, given in Table 3.

In Table 2, all the petrophysical parameters for the solid frame S1 are fixed. For the solid frame S2, only the density and bulk modulus of the grains, ρ_s and K_s, respectively, have fixed values, while the other parameters are systematically varied. The bulk modulus of the dry

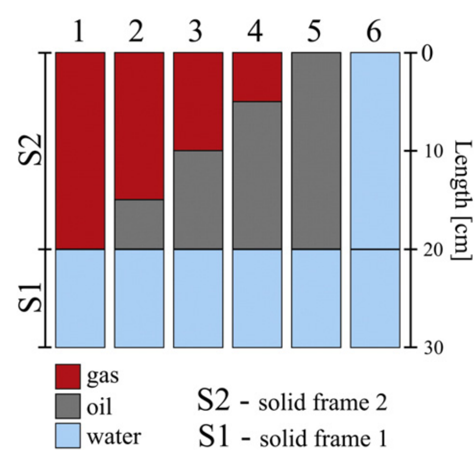

Fig. 1. Sketch of the REV for six different saturation cases. In all the cases, the REV has two different sets of solid frame properties, S1 and S2 (Table 2). The lower part of the REV, 10-cm thick, with solid frame S1, is saturated with water. The upper part of the REV, 20-cm thick, with solid frame S2, is saturated with gas in case 1, with gas and oil in cases 2 to 4, with oil in case 5, and with water in case 6. The properties of the fluids are given in Table 3.