Q-05 Low frequency attenuation in a saturated rock

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Introduction

High porosity zones bearing reservoir fluids are often interbedded with relatively impermeable lithologies. Fluids in the pores and fractures in the reservoir significantly affect the acoustic bulk characteristics, which are delineated from surface seismics, vertical seismic profiling, cross-well tomography, and sonic logging. The detected waves contain information about the rock along the wave path and the objective of all techniques is to extract this information in terms of geological structures and rock/fluid properties.

Rock and fluid properties are accessible only around the well vicinity from log and core measurements. In order to reduce the uncertainties during the exploration, development, and production phase of a hydrocarbon reservoir, there are needs to extract more information from seismic data, especially for reservoir modeling and time lapse interpretation. In general, only structural images with acoustic migration and elastic parameters with AVA analysis are recovered from 3D seismic data. Therefore during seismic data processing, the earth is, in particular, assumed to be nonporous. Poroelastic modeling of wave propagation at seismic frequencies is of major importance, since the governing rock and fluid parameters that cause this energy loss might then be extracted from the amplitude decay of the recorded waves.

Biot (1956) developed a fundamental theory for the propagation of elastic waves through a macroscopically homogeneous fluid saturated porous medium. However, Biot's theory doesn't predict the level of attenuation in the real earth. In Fig. 1, the purely viscosity-based damping model of the Biot theory underestimates the field data of Sams et al. (1997). Recently, Pride et al. (2004) matched the data with a 'double-porosity' model with a strong contrast between the frame bulk moduli of the two porous phases saturated by a single fluid. The research presented here shows that the concept of White et al. (1975), in which a single porous skeleton fully saturated with two immiscible fluids, is capable to explain the observed level of attenuation in the field data of Sams et al. (1997).

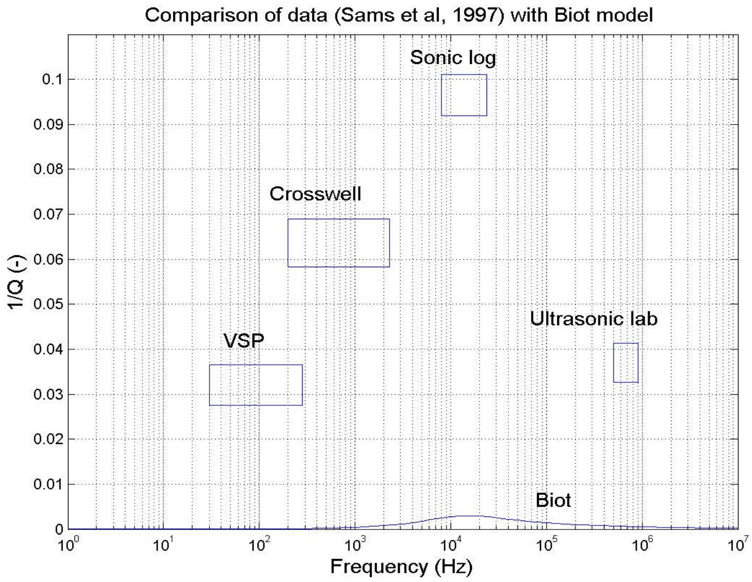

Fig. 1 Specific attenuation as a function of frequency. Comparison between the field data (boxes) of Sams et al. (1997) and modelled data (curve) based on the Biot theory (1956).

Periodically layered fluid distribution

Biot's poroelasticity equations have been applied to the particular problem of compressional wave propagation through a periodically horizontally layered medium (see Fig. 2). This problem is chosen, because it is the simplest possible heterogeneous medium for which White's model can be deduced from first principles. The specific attenuation Q^{-1} is defined by the imaginary over the real component of the fast compressional wavenumber:

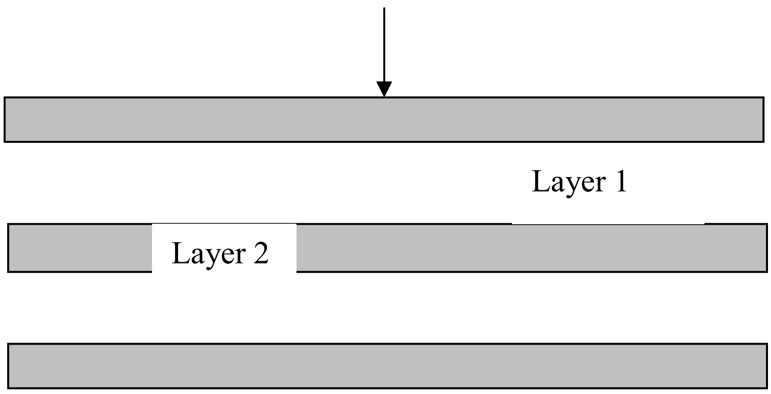

Fig. 2. Wave propagation through a periodically layered porous medium. Layers 1 and 2 have pore fluids with different properties.

$$Q^{-1} = \frac{2\,\mathrm{Im}\{k\}}{\mathrm{Re}\{k\}} = \frac{2\,\mathrm{Im}\left\{\omega\sqrt{\rho/H^*}\right\}}{\mathrm{Re}\left\{\omega\sqrt{\rho/H^*}\right\}}, \qquad (1)$$

where ω is frequency, ρ is density, and H^* is the complex plane wave modulus, defined as the ratio of an effective pressure p and a resulting strain ε. In the original paper by White et al.

(1975), this strain was separated into a part that is due to a fast compressional wave obeying the wave equation and a slow compressional wave obeying the diffusion equation.

The effective strain caused by the fast compressional wave is

$$\varepsilon_e = - p/H_e \; , \tag{2}$$

where H_e is the effective plane wave modulus of the layered medium (see Fig. 2):

$$H_e = \left(\frac{1}{H_1}\frac{L_1}{L} + \frac{1}{H_2}\frac{L_2}{L} \right)^{-1} , \tag{3}$$

in which L is the sum of the half thicknesses of both layers. The elastic modulus $H_{l\,=\,1,\,2}$ is the Gassmann constant of layer l, which is in terms of Biot's phenomenological parameters

$$H_l = P_l + R_l + 2Q_l \, . \tag{4}$$

The solution of the diffusion equation

$$\frac{\partial p}{\partial t} = \frac{{Q_l}^2 - P_l R_l}{b_l H_l} \nabla^2 p \, , \tag{5}$$

is the complex wavenumber of the slow compressional wave q_l in layer l with

$${q_l}^2 = -i\omega \frac{b_l H_l}{{Q_l}^2 - P_l R_l} \, , \tag{6}$$

where the viscous damping factor b_l is defined by Chandler and Johnson (1981). The wavenumber q_l is used to calculate the acoustic impedance Z_l looking into layer l from the boundary by Darcy's law

$$\left.\frac{p_l}{w}\right|_{L_l} = \frac{\eta_l}{\kappa q_l} \cot q_l L_l = Z_l \, , \tag{7}$$

where p_l is the pore fluid pressure in layer l, and η_l and κ are the viscosity and permeability. The velocity of the fluid relative to the solid skeleton is

$$w = \frac{B_2 - B_1}{Z_1 + Z_2} p \, , \tag{8}$$

where B_l is Skempton's coefficient of layer l, which is defined as

$$B_l = \frac{p_l}{p} = \frac{Q_l + R_l}{H_l \phi} \, , \tag{9}$$

in which ϕ is the porosity. At low frequencies the total displacement is related to the relative fluid velocity by the difference in Skempton's coefficients of both layers

$$u_1 + u_2 = \frac{B_2 - B_1}{i\omega} w \, . \tag{10}$$

With the expression (8) we find for the strain due to fluid flow

$$\varepsilon_{flow} = \frac{u_1 + u_2}{L_1 + L_2} = \frac{(B_2 - B_1)^2}{i\omega (Z_1 + Z_2)} \frac{p}{L} \, . \tag{11}$$

Finally, with expression (2) the complex plane wave modulus derived by White et al. is

$$H^* = H_e\left[1 - \frac{H_e(B_2 - B_1)^2}{i\omega(Z_1 + Z_2)L}\right]^{-1}. \tag{12}$$

From the numerical models is concluded that for layers that are alternately saturated with water and gas, fluid flow across the boundaries results in substantial attenuation of the low frequency compressional waves, see Fig. 3.

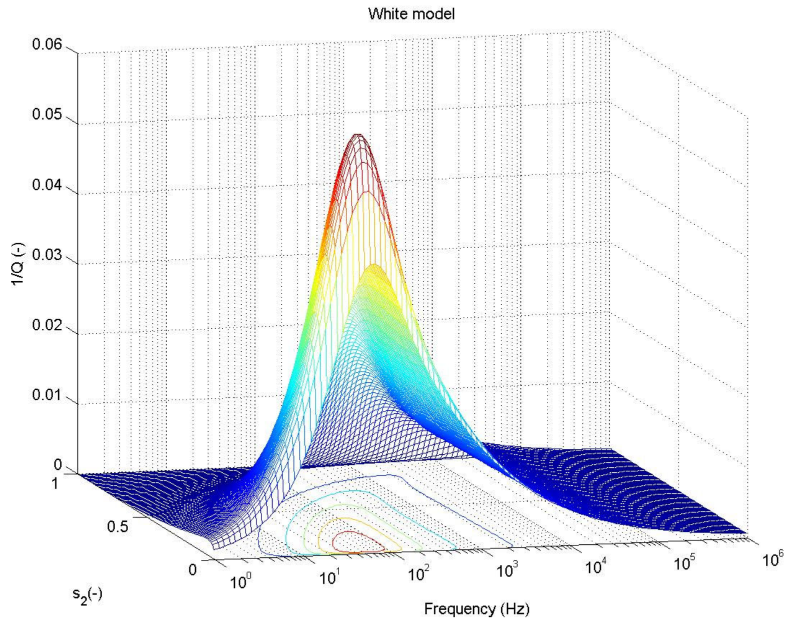

Fig. 3 Specific attenuation as a function of frequency and the gas fraction s_2 according to a White model to represent a periodically layered fluid distribution of water and gas.

Conclusions

It is shown that White's local flow model predicts considerably higher levels of attenuation than the original Biot model. Although the rate of attenuation is associated with several factors, its dependence on three aspects is presented here, namely frequency, the degree of saturation and the fluid content. First, there is a maximum attenuation at some specific frequency. Second, there is a maximum attenuation at some specific percentage of gas, while an increasing gas fraction shifts the attenuation peak towards higher frequencies. If this model is extended to the higher frequency regime following the Dutta-Odé approach, it is able to predict the levels of attenuation in the data by Sams et al.

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