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Multiscale rock-physics templates for gas detection in carbonate reservoirs

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ABSTRACT

The heterogeneous distribution of fluids in patchy-saturated rocks generates significant velocity dispersion and attenuation of seismic waves. The mesoscopic Biot–Rayleigh theory is used to investigate the relations between wave responses and reservoir fluids. Multiscale theoretical modeling of rock physics is performed for gas/water saturated carbonate reservoirs. Comparisons with laboratory measurements, log and seismic data validate the rock physics template. Using post-stack and pre-stack seismic inversion, direct estimates of rock porosity and gas saturation of reservoirs are obtained, which are in good agreement with oil production tests of the wells.

1. Introduction

Recently, major targets of seismic exploration for oil/gas resources have been gradually shifted to highly heterogeneous reservoirs in complex geological environments. The combined analysis of multiscale wave data, which includes surface seismic data (10^{1-2} Hz), vertical seismic profile data (10^{1-3} Hz), sonic logs (10^{3-4} Hz) and laboratory measurements (10^{1-6} Hz), is useful for the detection of gas in complex heterogeneous reservoirs, since information at different spatial and frequency scales is available.

The mechanism of wave-induced local fluid flow, which is closely related to the mesoscopic heterogeneity of pore structures and fluid distributions in reservoirs, is known to induce significant velocity dispersion and attenuation of seismic waves (Ba et al., 2008a, 2011; Müller and Gurevich, 2005; Müller et al., 2010). Actually, the compressional wave velocity, which is obtained from measurements at different scales (Sams et al., 1997), is frequency-dependent as predicted by this mechanism.

Wave propagation in patchy-saturated media plays an important role in the study of multiscale wave data of gas reservoirs. Frequency-dependent P-wave velocity and attenuation can be predicted and related to the mineral and fluid properties (Dutta and Seriff, 1979; Johnson, 2001; Müller and Sahay, 2011; White, 1975). Therefore, application of the patchy-saturation theory to heterogeneous gas reservoirs has the potential of improving the use of multiscale wave data to improve the performance of hydrocarbon detection. However, mesoscopic wave theories still need further experimental validation and tests for practical applications.

Rock-physics models have been applied by Xu and White (1995), Goodway (2001) and Avseth et al. (2005) to sandstone reservoirs. Xu and Payne (2009) extended the Xu–White model, which was originally designed for clastic rocks, to carbonate rocks and their predictions are in good agreement with measurements. Generally, there are three steps in traditional rock-physics modeling: (1) Obtain the properties of grain minerals with mixing laws or effective medium theories; (2) Use of effective-medium theories, empirical relations or experimental measurements to estimate the elastic properties of the dry-rock matrix; (3) Fluid substitution. The latter is mostly treated with the Wood law and Gassmann's equations. Since the Gassmann–Wood method neglects patchy heterogeneities, a non-dispersive frequency-independent P-wave velocity is modeled. Consequently, a single rock-physics template is available at all frequencies.

In this study, the Biot–Rayleigh (BR) theory of patchy-saturated rocks (Ba et al., 2011) is used for fluid substitution. Firstly, the BR theory is compared with White's and Johnson's theories for carbonates. Regarding the in-situ petrology properties of carbonate reservoirs in Metajan district of the Right Bank Block of the Amu Darya, a multiscale rock-physics template is designed and then compared with laboratory measurements, sonic logs and surface seismic data. Based on post-stack and pre-stack inversion of surface seismic data, the template is used to estimate the porosity and gas saturation of reservoir rocks. Finally, the characteristics of the multiscale rock-physics template are summarized.

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2. Wave propagation theory for patchy-saturated rocks

2.1. Biot–Rayleigh theory

The double-porosity theory has been extended to describe wave propagation in patchy-saturated rocks by Pride et al. (2004), in which a branching function is used to connect the exact low- and high-frequency limits of wave dispersion and attenuation (Müller et al., 2010). Ba et al. (2011) extended the Rayleigh's (1917) formula to describe the oscillation of local fluid flow and derived dynamic equations for wave propagation in a double-porosity medium saturated with a single fluid (see Fig. 1A), which can be expressed as

$$N\nabla^2\mathbf{u} + (A+N)\nabla e + Q_1\nabla\left(\xi^{(1)} + \phi_2\varsigma\right) + Q_2\nabla\left(\xi^{(2)} - \phi_1\varsigma\right) = \rho_{11}\ddot{\mathbf{u}} + \rho_{12}\ddot{\mathbf{U}}^{(1)} + \rho_{13}\ddot{\mathbf{U}}^{(2)} + b_1\left(\dot{\mathbf{u}} - \dot{\mathbf{U}}^{(1)}\right) + b_2\left(\dot{\mathbf{u}} - \dot{\mathbf{U}}^{(2)}\right), \quad (1a)$$

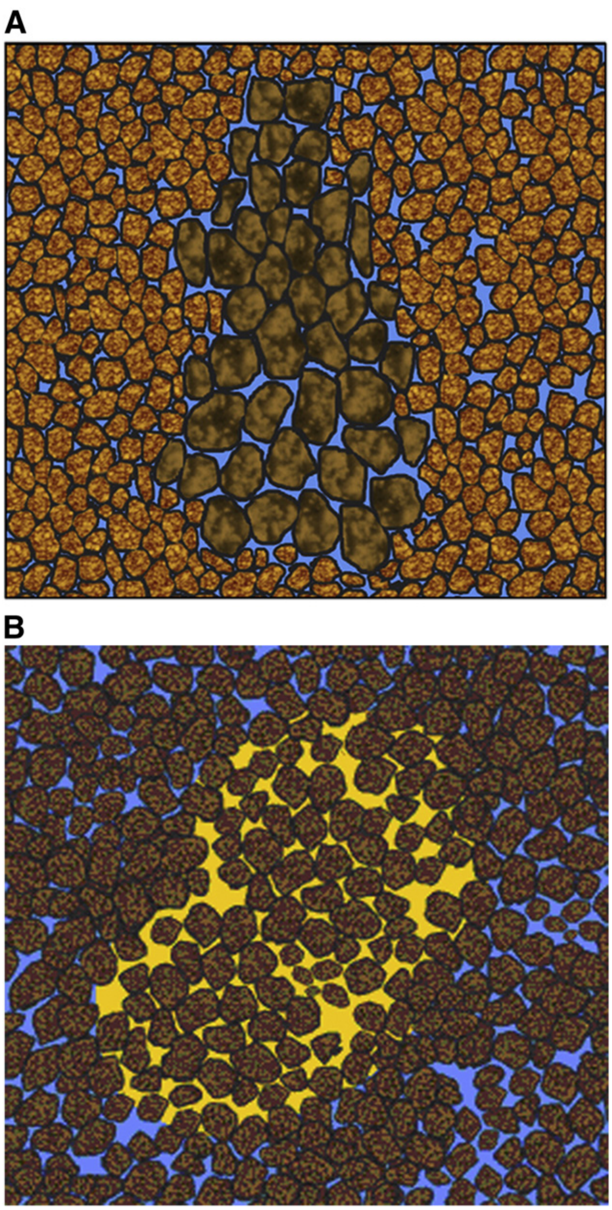

Fig. 1. Synoptic diagram for two types of mesoscopic heterogeneity in rocks. (A) A double-porosity matrix saturated with one fluid. (B) A single-porosity matrix saturated with two immiscible fluids.

$$Q_1\nabla e + R_1\nabla\left(\xi^{(1)} + \phi_2\varsigma\right) = \rho_{12}\ddot{\mathbf{u}} + \rho_{22}\ddot{\mathbf{U}}^{(1)} - b_1\left(\dot{\mathbf{u}} - \dot{\mathbf{U}}^{(1)}\right), \quad (1b)$$

$$Q_2\nabla e + R_2\nabla\left(\xi^{(2)} - \phi_1\varsigma\right) = \rho_{13}\ddot{\mathbf{u}} + \rho_{33}\ddot{\mathbf{U}}^{(2)} - b_2\left(\dot{\mathbf{u}} - \dot{\mathbf{U}}^{(2)}\right), \quad (1c)$$

$$\phi_2\left(Q_1 e + R_1\left(\xi^{(1)} + \phi_2\varsigma\right)\right) - \phi_1\left(Q_2 e + R_2\left(\xi^{(2)} - \phi_1\varsigma\right)\right) = \frac{1}{3}\rho_f^{(1)}\ddot{\varsigma}R_0^2\frac{\phi_1^2\phi_2\phi_{20}}{\phi_{10}} + \frac{1}{3}\frac{\eta_1\phi_1^2\phi_2\phi_{20}}{\kappa_{10}}\dot{\varsigma}R_0^2, \quad (1d)$$

where $\mathbf{u}$, $\mathbf{U}^{(1)}$ and $\mathbf{U}^{(2)}$ are the average particle displacements of the solid frame, fluid phase 1 (the fluid in the host medium) and fluid phase 2 (the fluid in the inclusions) respectively, and e, $\xi^{(1)}$ and $\xi^{(2)}$ are the corresponding displacement divergence fields of the three phases. The scalar ς represents fluid variation in local fluid flow. ϕ_{10} and ϕ_{20} are the porosities of the host medium and inclusions, respectively. ϕ_1 and ϕ_2 are the absolute porosities of the host and inclusions ($\phi_1 = \nu_1\phi_{10}$ and $\phi_2 = \nu_2\phi_{20}$, where ν_1 and ν_2 are the volume ratios of host medium and inclusion and $\nu_1 + \nu_2 = 1$. $\phi = \phi_1 + \phi_2$ is the porosity of the whole matrix). κ_{10} is the permeability of the host medium. η_1 and $\rho_f^{(1)}$ are the fluid viscosity and density of the host medium, respectively. R_0 is the inclusion radius. b_1 and b_2 are Biot's dissipation coefficients.

The theory has been reformulated for patchy-saturated rocks by Ba et al. (2012), where a single-porosity medium is saturated with two fluids (see Fig. 1B). In this case Eq. (1) is still available, but the host medium and inclusions have the same frame ($\phi_{10} = \phi_{20} = \phi$) and are saturated with different fluids. ϕ_1 and ϕ_2 are the relative porosities of the two types of pores which are saturated with different fluids; ν_1 (ν_2) indicates saturation and R_0 is the radius of gas pockets. The reformulated elastic constants for a patchy-saturated rock can be expressed as (Ba et al., 2012; Sun et al., submitted for publication)

$$A = (1-\phi)k_s - \frac{2}{3}N - \frac{\phi_1(1-\phi-k_b/k_s)k_s^2/k_f^{(1)}}{1-\phi-k_b/k_s+\phi k_s/k_f^{(1)}} - \frac{\phi_2(1-\phi-k_b/k_s)k_s^2/k_f^{(2)}}{1-\phi-k_b/k_s+\phi k_s/k_f^{(2)}}, \quad (2a)$$

$$Q_1 = \frac{(1-\phi-k_b/k_s)\phi_1 k_s}{1-\phi-k_b/k_s+\phi k_s/k_f^{(1)}}, \quad (2b)$$

$$Q_2 = \frac{(1-\phi-k_b/k_s)\phi_2 k_s}{1-\phi-k_b/k_s+\phi k_s/k_f^{(2)}}, \quad (2c)$$

$$R_1 = \frac{\phi\phi_1 k_s}{1-\phi-k_b/k_s+\phi k_s/k_f^{(1)}}, \quad (2d)$$

$$R_2 = \frac{\phi\phi_2 k_s}{1-\phi-k_b/k_s+\phi k_s/k_f^{(2)}}, \quad (2e)$$

$$N = \mu_b, \quad (2f)$$

where k_s, k_b, $k_f^{(1)}$ and $k_f^{(2)}$ are the bulk moduli of the solid grain, dry rock skeleton, fluid in the host medium and fluid in the inclusions, respectively; μ_b is the dry-rock shear modulus. The density coefficients are

$$(1-\phi_1-\phi_2)\rho_s = \rho_{11} + \rho_{12} + \rho_{13}, \quad (3a)$$

$$\phi_1\rho_f^{(1)} = \rho_{12} + \rho_{22}, \quad (3b)$$

$$\phi_2\rho_f^{(2)} = \rho_{13} + \rho_{33}, \quad (3c)$$

$$\rho_{22} = \alpha\phi_1\rho_f^{(1)}, \quad (3d)$$

$$\rho_{33} = \alpha\phi_2\rho_f^{(2)}, \quad (3e)$$