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Seismic characterization of reservoirs with multiple fracture sets using velocity and attenuation anisotropy data

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ABSTRACT

Knowledge about the spatial distribution of the fracture density and the azimuthal fracture orientation can greatly help in optimizing production from fractured reservoirs. Frequency-dependent seismic velocity and attenuation anisotropy data contain information about the fractures present in the reservoir. In this study, we use the measurements of velocity and attenuation anisotropy data corresponding to different seismic frequencies and azimuths to infer information about the multiple fracture sets present in the reservoir. We consider a reservoir model with two sets of vertical fractures characterized by unknown azimuthal fracture orientations and fracture densities. Frequency-dependent seismic velocity and attenuation anisotropy data is computed using the effective viscoelastic stiffness tensor and solving the Christoffel equation. A Bayesian inversion method is then applied to measurements of velocity and attenuation anisotropy data corresponding to different seismic frequencies and azimuth to estimate the azimuthal fracture orientations and the fracture densities, as well as their uncertainties. Our numerical examples suggest that velocity anisotropy data alone cannot recover the unknown fracture parameters. However, an improved estimation of the unknown fracture parameters can be obtained by joint inversion of velocity and attenuation anisotropy data.

1. Introduction

The successful management of fractured reservoirs depends upon improved characterization of fracture systems which often provide pathways for fluid flow during production. Alignment of these fracture systems to preferred orientations will lead to anisotropic wave characteristics and permeability in the reservoir. This suggests the use of seismic anisotropy to determine the orientation of fractures (Sayers, 2009). Knowledge about the spatial distribution of fracture density and azimuthal fracture orientation can greatly help in optimizing production from fractured reservoirs (Sayers, 2009). Frequency-dependence of seismic velocity and attenuation anisotropy data can potentially give important information about the fracture systems (Chapman, 2003, 2009; Gurevich et al., 2009; Liu et al., 2006, 2007a, 2007b; Maultzsch et al., 2007a, b).

Wave induced fluid flow and multiple scattering are believed to be the main driving mechanisms behind the attenuation of seismic waves. Scattering attenuation can be safely ignored in the long wavelength domain i.e. when fractures are much smaller than the seismic wavelength. This is due to the fact that the propagating seismic wave or flowing fluid only sees a homogenized structure and not the individual pores, micro-cracks or mesoscopic fractures. Wave induced fluid flow can occur at microscopic scale of pores and micro-cracks, the mesoscopic scale of fractures and the macroscopic scale of seismic wavelengths (Chapman, 2003; Gurevich et al., 2009). In particular, wave induced fluid flow caused by the pressure gradients at the microscopic or mesoscopic scale and in a direction potentially different from that of the wave propagation is known as squirt flow, whereas the wave induced fluid flow caused by the pressure gradients at the scale of the acoustic wavelength and in the direction of the wave propagation is known as global or Darcy flow.

The objective of this study is inferring fracture properties of reservoirs containing multiple sets using measurements of velocity and attenuation anisotropy data corresponding to different seismic frequencies and azimuths. This has been done by some authors before in the context of forward modelling (see Chapman, 2009; Liu et al., 2006, 2007a, 2007b). In this paper we study the inverse as well as the forward modelling.

We use the viscoelastic T-matrix approach of Jakobsen et al. (2003b) and Jakobsen and Chapman (2009), which is the most general model among the inclusion models, because it allows for non-dilute concentration of cavities characterized by different shapes, orientations and spatial distributions (see Gurevich et al., 2009; Müller et al., 2010). In addition to that the theory of Jakobsen and Chapman (2009) takes into account global and squirt flow in a consistent manner. We have also given attention to the discrimination of micro-cracks and mesoscopic fractures. The discrimination of micro-cracks and mesoscopic fractures is very important, because the analysis of seismic anisotropy data based upon static effective medium theories always assumes frequency-independence and

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cannot discriminate between them (Maultzsch et al., 2003). Numerical examples are presented about the inverse problem of estimating the fracture parameters (azimuthal fracture orientations and the fracture densities) from measurements of velocity and attenuation anisotropy data corresponding to different seismic frequencies and azimuths using Bayesian inversion where the posterior PDF is derived through Monte Carlo Markov chain (McMc) sampling.

2. The effective viscoelastic stiffness tensor

We depict a fractured reservoir as being composed of a solid matrix with a population of cavities. The population of cavities is divided into families, where members in each family have the same shape, orientation, scale-size and volume concentration $v^{(r)}$ labeled by $r=1,\ldots, R$. The different families of the cavities considered in this study are pores, randomly oriented micro-cracks and two sets of aligned mesoscopic fractures. Formally, randomly oriented micro-cracks mean infinitely many families or sets, but we perform an averaging over the different orientations (see Jakobsen et al., 2003a, b). The fracture volume concentration $v^{(r)}$ is related to the fracture density $\varepsilon^{(r)}$by $v^{(r)}=(4/3)\pi\varepsilon^{(r)}\alpha^{(r)}$, where $\alpha^{(r)}$ is aspect ratio for fractures of type r. The aspect ratio of a spheroidal cavity with long (short) axis $a^{(r)}$ ($c^{(r)}$) is given by $c^{(r)}/a^{(r)}$. The fracture density $\varepsilon^{(r)}$ is defined by $\varepsilon^{(r)}=N(a^{(r)})^3$, where N is the number density of fractures of type r within a representative volume element. The effective stiffness tensor $\mathbf{C}^*$ is given by (Jakobsen et al., 2003a, b)

$$\mathbf{C}^* = \mathbf{C}^{(0)} + \mathbf{C}_1 : \left(\mathbf{I}_4 + \mathbf{C}_1^{-1} : \mathbf{C}_2\right)^{-1}, \tag{1}$$

where

$$\mathbf{C}_1 = \sum_{r=1}^{N} v^{(r)}\mathbf{t}^{(r)}, \tag{2}$$

and

$$\mathbf{C}_2 = \sum_{r=1}^{N}\sum_{s=1}^{N} v^{(r)}\mathbf{t}^{(r)} : \mathbf{G}_d^{(rs)} : \mathbf{t}^{(s)}v^{(s)}. \tag{3}$$

Here, $\mathbf{C}^{(0)}$represents the elastic properties of the solid matrix, : denotes the double scalar product (see Auld, 1990), $\mathbf{I}_4$ is the (symmetric) identity for fourth-rank tensors and $\mathbf{G}_d^{(rs)}$ is given by the strain Green's function integrated over an ellipsoid having the same aspect ratio as $p^{(s|r)}(\mathbf{x}-\mathbf{x}')$, which in turn gives the probability density for finding an inclusion of type s at $\mathbf{x}'$, given that there is an inclusion of type r at point $\mathbf{x}$ (Jakobsen et al., 2003a, b). It is generally assumed that the correlation function has ellipsoidal or spherical symmetry represented by the choice of aspect ratios. In this study, we have also assumed the aspect ratio of the correlation function equal to 1 i.e. $\alpha_d=1$. This represents a uniform spatial distribution of fractures with spherically symmetric correlation function.

The t-matrix for a cavity of type r fully saturated with a homogenous fluid can be written as (Jakobsen et al., 2003b; Jakobsen and Chapman, 2009; Appendix-A)

$$\mathbf{t}^{(r)} = \mathbf{t}^{(r)}(\mathbf{v}, \Omega, \alpha, k_f, \eta_f, \mathbf{K}^*, \tau); \qquad r = (1, \ldots, R), \tag{4}$$

where $\mathbf{v} = \left(v^{(1)}, \ldots, v^{(n)}\right)$is a vector with the volume concentration for each cavity set, $\Omega=(\Omega^{(1)},\ldots, \Omega^{(n)})$ denotes the Euler's angles determining the orientation of each cavity set relative to the crystallographic axes of the material with properties given by $\mathbf{C}^{(0)}$, $\boldsymbol{\alpha}=(\alpha^{(1)},\ldots, \alpha^{(n)})$ is a vector with the aspect ratios for each cavity set, k_f is the bulk modulus of the saturating fluid, η_f is the viscosity of the fluid, $\mathbf{K}^*$is the effective permeability tensor and $\boldsymbol{\tau}=(\tau^{(1)},\ldots, \tau^{(n)})$ is a vector with the relaxation time constants for each cavity set.

For a reservoir model consisting of two aligned mesoscopic fracture sets with unknown azimuthal fracture orientations and fracture densities (as assumed in this study), we can write $\mathbf{t}^{(r)}$ as

$$\mathbf{t}^{(r)} = \mathbf{t}^{(r)}(\psi_1, \psi_2, \varepsilon_1, \varepsilon_2). \tag{5}$$

Here, $\psi_1$and ψ_2 represent the azimuthal fracture orientation of each fracture set and ε_1 and ε_2 represent the fracture density of each fracture set. The viscoelastic T-matrix approach of Jakobsen et al. (2003b) and Jakobsen and Chapman (2009) to cracked/fractured porous media with an improvement is given in Appendix-A. This improvement is related to relaxing on the assumption that the inclusions or cavities are of the same scale-size (see Appendix-A). The relaxation time of fractures τ_f can be calculated according to their size from the following equation (Agersborg et al., 2007; Chapman, 2003)

$$\tau_f = \frac{r}{\xi}\tau_m. \tag{6}$$

Here, r is the radius of fractures, ξ is the size of the grains and τ_m is the relaxation time for the micro-porosity (pores and randomly oriented micro-cracks). The theory of Jakobsen and Chapman (2009) predicts a frequency dependence of the seismic anisotropy by modelling the velocity dispersion and attenuation caused by squirt and global flow mechanisms for micro-porosity and mesoscopic fractures.

In general, $\mathbf{C}^*$depends on effective wave vector $\mathbf{k}^*$ and angular frequency ω. However, following Hudson et al., 1996; Pointer et al., 2000; Tod, 2001; Jakobsen et al., 2003b and Jakobsen and Chapman (2009), we eliminate the dependency of $\mathbf{C}^*$on the effective wave vector $\mathbf{k}^*$ by using the approximation $k^*=k\approx\omega/V^{(0)}$, where $V^{(0)}$is the speed of the wave mode under consideration in the solid matrix and k is the length of $\mathbf{k}$. In this approach of using an approximation for effective wave vector, the effective permeability tensor $\mathbf{K}^*$of the fractured reservoir is taken equal to the matrix permeability of the reservoir.

For the two mesoscopic fracture sets embedded in the solid matrix with different orientations, the symmetry of the rock is monoclinic and therefore characterized by 13 independent viscoelastic stiffness coefficients. The components of the effective viscoelastic stiffness tensor are a function of the fracture parameters, which is given by viscoelastic rock physics modelling as discussed above. The non-vanishing viscoelastic stiffness constants of a medium of monoclinic symmetry (see Appendix-B) in the usual two-index notation are c_{11}, c_{22}, c_{33}, $c_{12}=c_{21}$, $c_{13}=c_{31}$,$c_{23}=c_{32}$, c_{44}, c_{55}, c_{66}, $c_{16}=c_{61}$, $c_{26}=c_{62}$, $c_{36}=c_{63}$ and $c_{45}=c_{54}$. The presence of mesoscopic fractures present in a reservoir can produce significant dispersion and attenuation at seismic frequencies (Gurevich et al., 2009; Liu et al., 2007a, b; Maultzsch et al., 2003).

Figs. 1 and 2 show the real and imaginary parts of the 13 independent effective stiffness constants as a function of seismic frequency for three different combinations of azimuthal fracture orientations and fracture densities of each individual fracture set. Both the real and imaginary parts of independent effective stiffness constants show a high sensitivity to changes in azimuthal fracture orientations and fracture densities of both the fracture sets. We observe squirt flow characterized by positive dispersion (Fig. 1) and corresponding attenuation (Fig. 2) at seismic frequencies ($\leq 10^2$ Hz) for the effects associated with the presence of mesoscopic fracture sets, and at higher frequencies (between 10^3 to 10^5 Hz) for the effects associated with micro-porosity (pores and micro-cracks) for effective stiffness constants c_{11}, c_{22}, c_{33}, c_{12}, c_{13}, c_{23}, c_{66}. We only observe positive dispersion (Fig. 1) and corresponding attenuation (Fig. 2) associated with the effects of micro-porosity for the effective stiffness constants c_{44} and c_{55}. For the effective stiffness constants c_{16}, c_{26} and c_{36}, we observe both positive and negative dispersion (Fig. 1) and corresponding attenuation (Fig. 2) at seismic frequencies. No dispersion either positive or negative is observed for the effective stiffness constant