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Constructing a discrete fracture network using seismic inversion to predict elastic and seismic properties plus fluid-flow anisotropy

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Summary

Rock fractures are of great practical importance to petroleum reservoir engineering because they provide pathways for fluid flow, especially in reservoirs with low matrix permeability, where they constitute the primary flow conduits. In such reservoirs, understanding the spatial distribution of natural fracture networks is key to optimizing production. Fortunately, the presence of fractures can be inferred from variations in reflection amplitude as a function of azimuth and incidence angle. We present the application of a method for constructing a geologically realistic discrete fracture network (DFN), constrained by seismic amplitude variation with offset and azimuth data. Application is made to a fractured carbonate reservoir. The DFN realization is upscaled to compute the anisotropic permeability tensor, which is then compared with fluid flow anisotropy results.

Introduction

Rock fractures are fundamentally important in petroleum reservoir engineering as they provide pathways for fluid flow. This is especially true in reservoirs with low matrix permeability, where fractures constitute the primary flow conduits. Understanding the spatial distribution of natural fracture networks is thus key to optimizing production. The impact of fracture systems on fluid flow patterns can be predicted using discrete fracture network (DFN) models, which allow estimating not only the six independent components of the second-rank permeability tensor, but also the 21 independent components of the fully anisotropic fourth-rank elastic stiffness tensor, from which both the elastic and seismic properties of the fractured rock medium can be predicted (Sayers and den Boer, 2012). As they are stochastically generated, DFN realizations are inherently nonunique. It is, thus, important to constrain their construction, to reduce their range of variability and, hence, the uncertainty in fractured rock properties derived from them. A fast and efficient algorithm is presented for constructing a geologically realistic DFN, constrained by seismic amplitude variation with offset and azimuth (AVAz) data. Potential applications of this method are numerous, including predicting fluid flow, plus elastic and seismic properties of fractured reservoirs, model-based inversion of seismic AVAz data, and the optimal placement and orientation of infill wells to maximize production. An example application illustrates how the method can be used to predict fluid flow anisotropy in a fractured carbonate reservoir.

Theory

Owing to their preferred orientations, fractures create significant permeability anisotropy in reservoirs. Thus, for optimum drainage, it is important that producers be more closely spaced along the direction of minimum permeability than along the direction of maximum permeability. Because fractures also affect elastic wave propagation, seismic data can be used to characterize naturally fractured reservoirs in sedimentary basins. Oriented sets of fractures lead to variations in elastic rock properties with direction, and hence to variations in seismic reflection amplitude with azimuth. Compared to seismic velocities derived from normal moveout (NMO) analysis or kinematic inversion, inversion of reflection amplitudes yields greater vertical resolution and sensitivity to reservoir properties (Nichols, 2012). Accordingly, the use of seismic reflection amplitude inversion to characterize fractured reservoirs has received much attention (Mallick and Frazer, 1991;

Lefeuvre and Desegaulx, 1993; Chang and Gardner, 1993; Lynn *et al*., 1994, 1995; Mallick *et al*., 1996; Ikelle, 1996, 1997; Rüger, 1997, 1998; Sayers and Rickett, 1997).

Fractures can be characterized by means of orthotropic inversion of AVAz data, using prestack depth-migrated (PSDM) gathers as input (Bachrach *et al*., 2013). This approach is based on the PP-reflection coefficient derived by Pšencík and Martins (2001) for arbitrary elastic symmetry, assuming weak impedance contrasts and small anisotropy. For orthotropic symmetry, the PP-reflection coefficient can be written in the form:

$$R_{PP}(\theta,\phi) = R_{PP}^{iso}(\theta) + \frac{1}{2}\Delta\varepsilon_z + \frac{1}{2}\left[\left(\Delta\delta_{\mathrm{x}} - 8\frac{\bar{\beta}^2}{\bar{\alpha}^2}\Delta\gamma_{\mathrm{x}}\right)\cos^2\phi + \left(\Delta\delta_{\mathrm{y}} - 8\frac{\bar{\beta}^2}{\bar{\alpha}^2}\Delta\gamma_{\mathrm{y}}\right)\sin^2\phi + \right.$$
$$\left. +2\left(\Delta\chi_z - 4\frac{\bar{\beta}^2}{\bar{\alpha}^2}\Delta\varepsilon_{45}\right)\cos\phi\sin\phi - \Delta\varepsilon_z\right]\sin^2\theta + \frac{1}{2}\left[\Delta\varepsilon_{\mathrm{x}}\cos^4\phi + \Delta\varepsilon_{\mathrm{y}}\sin^4\phi + \right.$$
$$\left. +\Delta\delta_{\mathrm{z}}\cos^2\phi\sin^2\phi + 2\left(\Delta\varepsilon_{16}\cos^2\phi + \Delta\varepsilon_{26}\sin^2\phi\right)\cos\phi\sin\phi\right]\sin^2\theta\tan^2\theta.$$

Here $R_{PP}^{iso}(\theta)$ is the weak contrast PP-reflection coefficient for isotropic media, given by

$$R_{PP}^{iso}(\theta) = \frac{1}{2}\frac{\Delta I_P}{\bar{I}_P} + \frac{1}{2}\left[\frac{\Delta\alpha}{\bar{\alpha}} - 4\frac{\bar{\beta}^2}{\bar{\alpha}^2}\frac{\Delta\mu}{\bar{\mu}}\right]\sin^2\theta + \frac{1}{2}\frac{\Delta\alpha}{\bar{\alpha}}\sin^2\theta\tan^2\theta.$$

In these equations, Δ denotes the property contrast between reservoir (Medium 2) and overburden (Medium 1). For example, $\Delta I_P = \left(I_P^{(2)} - I_P^{(1)}\right)$, $\Delta\alpha = \left(\alpha^{(2)} - \alpha^{(1)}\right)$, and $\Delta\mu = \left(\mu^{(2)} - \mu^{(1)}\right)$ are the contrasts in acoustic impedance $I_P = \rho\alpha$, P-wave velocity α, and shear modulus $\mu = \rho\beta^2$ between the reservoir and the overburden, where ρ denotes density and β denotes S-wave velocity. A bar over a symbol denotes an average, e.g. $\bar{I}_P = \left(I_P^{(1)} + I_P^{(2)}\right)/2$.

Assuming that fractures are sub-vertical, and that normal and shear fracture compliance are approximately equal, perturbation parameters ε_{x}, ε_{y}, ε_{z}, ε_{16}, ε_{26}, δ_{x}, δ_{y}, δ_{z}, χ_{z}, γ_{x}, γ_{y}, and ε_{26} are given by (Sayers, 2009):

$$\varepsilon_{\mathrm{z}} = -\frac{\lambda^2(\alpha_{11}+\alpha_{22})}{2(\lambda+2\mu)},\ \varepsilon_{\mathrm{x}} = \varepsilon_z - \frac{2\mu(\lambda+\mu)\alpha_{11}}{(\lambda+2\mu)},\ \varepsilon_{\mathrm{y}} = \varepsilon_z - \frac{2\mu(\lambda+\mu)\alpha_{22}}{(\lambda+2\mu)},$$
$$\delta_{\mathrm{x}} = \varepsilon_{\mathrm{x}} + \varepsilon_z,\ \delta_{\mathrm{y}} = \varepsilon_{\mathrm{y}} + \varepsilon_z,\ \delta_{\mathrm{z}} = \varepsilon_{\mathrm{x}} + \varepsilon_y,$$
$$\chi_z = \varepsilon_{16} = \varepsilon_{26} = -\frac{2\mu(\lambda+\mu)\alpha_{12}}{(\lambda+2\mu)},\ \gamma_x = -\frac{\mu\alpha_{11}}{2},\ \gamma_y = -\frac{\mu\alpha_{22}}{2},\ \varepsilon_{45} = -\mu\alpha_{12},$$

where λ and μ are second-order elastic constants of the unfractured reservoir rock, and all parameters are linearized in the components of the second-rank tensor α_{ij}, defined by Kachanov (1980) and Sayers and Kachanov (1995) as:

$$\alpha_{ij} = \frac{1}{V}\sum_{r=1}^{N} B_T^{(r)} n_i^{(r)} n_j^{(r)} A^{(r)}$$

where summation is over all *N* fractures in volume *V*, $B_N^{(r)}$, and $B_T^{(r)}$ are the normal and tangential (shear) compliance of the r^{th} fracture in volume *V*, $n_i^{(r)}$ is the i^{th} component of the unit normal to the r^{th} fracture, and $A^{(r)}$ is the area of the r^{th} fracture. These equations allow constructing a multiscale DFN from inverted AVAz data, using the algorithm described by den Boer and Sayers (2018), and illustrated in Figure 1.

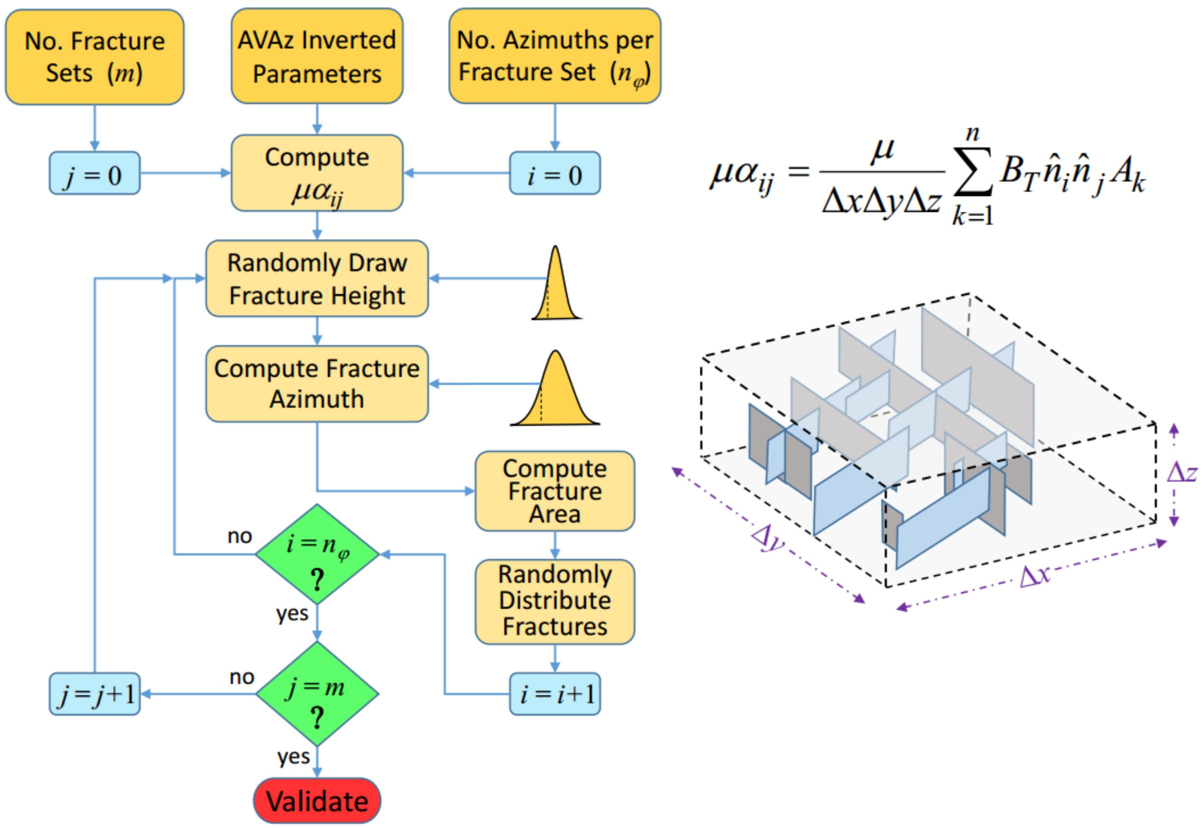

Figure 1: Algorithm for constructing a DFN from inverted AVAz data (den Boer and Sayers, 2018).

Example

An example will show applying the method to AVAz inversion of seismic data from a fractured carbonate reservoir.

Conclusions

We present a multiscale algorithm for constructing a geologically realistic DFN constrained by seismic AVAz data. Although the present implementation assumes that normal and shear fracture compliances are approximately equal so that the fourth-rank compliance tensor may be neglected, this assumption implies no loss of generality because the underlying approach can readily be extended to include this term (den Boer and Sayers, 2018). The constrained multiscale DFN thus derived agrees not only with the input inverted AVAz data and assumed a priori geologic constraints, by construction, but also exhibits fractal properties, consistent with fracture networks observed in actual geology, and is consistent with fluid flow patterns inferred from production data. The potential applications of this method for modeling fracture networks include predicting not only fluid-flow, but also the elastic and seismic properties of fractured reservoirs, model-based inversion of seismic AVAz data, and optimal placement and orientation of infill wells to maximize production.

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