Simple Models for the Stress-Dependence of Anisotropic Seismic Velocities in Fractured Rock*

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Abstract

Time-lapse seismic methods offer strong potential for monitoring fluid movements in complex geologic media such as carbonates. Seismic detection and characterization of fracturing in such materials will be of particular interest, since fractures can control fluid flow in cases where they provide the primary conduits through which fluids move through a low permeability rock matrix. Reliable seismic reservoir characterization requires reliable models that relate fracturing and seismic velocities, but these results are complicated by several factors. For example, fractures often cause the rock to display seismic anisotropy (Pointer et al., 2000; Tod, 2001; Bakulin et al., 2002; Sayers, 2002; Guéguen and Sarout, 2009), which should be taken into account in any seismic modeling or imaging applications. Furthermore, the influence of these fractures will depend on changes in stress in the reservoir during fluid movement, and the magnitude of the seismic anisotropy may vary as a result. Reliable inversions or other analyses of field data thus require a model relating various fracture sets to the resulting seismic properties as both fluid saturations and stress distributions change during hydrocarbon production. While a number of analytic solutions for the effective seismic properties of fractured media have been proposed, there are few that consider the effects of stress variations (e.g., Pointer et al, 2000; Tod, 2001; Maultzsch et al., 2003).

Introduction

In this paper, we will present results based on a recently developed phenomenological model for the effective velocities of fractured media that aims to address this problem and to provide a solution that facilitates straightforward simulations using with field-scale reservoir models. This model combines two general approaches (Gao and Gibson, 2011). First, the stress-dependence of normal and tangential compliances of individual fractures is quantified in terms of increasing contact area of rough surfaces with a distribution of asperities. Second, these compliances are used in the general theoretical framework outlined by Sayers and Kachanov (1995) (see also Sayers, 2010), which expresses the effective seismic velocities of fractured rock in terms of these fracture compliances. This approach also makes it straightforward to develop expressions for arbitrary combinations of multiple aligned fracture sets, an important and useful result for applications to fractured, carbonate reservoirs. Below we first outline the model for the seismic velocities, and then present examples of inversions of laboratory velocity measurements, both isotropic and anisotropic, using this model. The presentation will also include simulations of seismic reflections from anisotropic reservoirs with stress changes.

Method

The starting point for the stress-dependent model of seismic velocity in the fractured rock is to assume that the effective compliance is simply the sum of the compliance of the unfractured host rock S_0 and the additional compliance introduced by fractures, ΔS (Sayers and Kachanov, 1995):

$$S = S_0 + \Delta S \tag{1}$$

In the simplest case, where fractures are randomly oriented, the material is effectively isotropic, and there are only two unique terms in the compliance tensor (Sayers and
Kachanov, 1995):

$$S_{11} = S_{11}^0 + \alpha_{11} + \beta_{1111} \tag{2}$$

$$S_{44} = S_{44}^0 + 2\alpha_{11} + \frac{4}{3}\beta_{1111} \tag{3}$$

Here α_{11} and β_{1111} are components of second and fourth-rank crack density tensors and the required components are:

$$\alpha_{11} = \frac{1}{3}B_T\gamma \tag{4}$$

$$\beta_{1111} = \frac{1}{5}(B_N - B_T)\gamma \tag{5}$$

In these expressions, γ is related to the density of fracturing, and we refer to it as the maximum crack porosity, while B_N and B_T are the normal and tangential compliances of the fracture.

Incorporation of stress-dependence into the model is accomplished by utilizing values of the two compliances that are functions of confining pressure P. Specifically, we apply an asperity deformation model that represents the rough surface of the fractures in terms of a phenomenological model that includes a set of cylindrical rods representing asperities. Gangi (1978, 1981) developed an expression for the decreased compliance B_N of the fracture as pressure increases, which is a result of the increasing number of cylindrical rods in contact. In other words, the fracture surface area in contact is larger at higher pressures, and the fracture is less compliant. Gao and Gibson (2011) developed an analogous expression for the tangential compliance B_T, and both solutions assume a power law distribution of asperity heights on the rough-surfaced fracture. The expressions for these two compliances are:

$$B_N(P) = \frac{1}{n(P + P_i)}\left(\frac{P + P_i}{P_r}\right)^{1/n} \tag{6}$$

$$B_T(P) = b_r\left[1 - \left(\frac{P + P_i}{P_r}\right)^{1/n}\right]\left(\frac{P + P_i}{P_r}\right)^{\frac{1}{n}-1} \tag{7}$$

Here P_i is a pressure parameter describing the initial state of rock, or the surface area in contact, when applied pressure P=0. The exponent in the power law distribution of asperity heights is n, and P_r and b_r are both constants related to material properties.

Combining these various results into the expressions for the compliance terms (eqs. 2 and 3) and performing some algebraic simplifications produces the following expressions for the compressional and shear velocities of the isotropic rock:

$$V_p(P) = \left(\frac{4V_{s0}^2}{3 + A\rho V_{s0}^2} + \frac{3V_{p0}^2 - 4V_{s0}^2}{3 + B\rho(3V_{p0}^2 - 4V_{s0}^2)}\right)^{1/2} \tag{8}$$

$$V_s(P) = \left(\frac{3V_{s0}^2}{3 + A\rho V_{s0}^2}\right)^{1/2} \tag{9}$$

where

$$A = \frac{2}{15}\left(2B_N(P) + 3B_T(P)\right)\gamma \tag{10}$$

$$B = B_N(P)\gamma \tag{11}$$

and V_{p0} and V_{s0} are the velocities of the rock matrix.

Because the influence of a set of aligned fractures is included by adding their contributions to the total compliance using eq. 1, analogous results for the effective properties of anisotropic models is accomplished by simply adding the appropriate compliances for each fracture set. The relevant components depend on the orientation of the fractures. Though the resulting expressions are relatively long and complicated, the approach outlined above can therefore produce stress-dependent models of velocity in anisotropic rock with multiple combinations of fracture sets.

Inversion of Laboratory Data

Isotropic velocities

Laboratory measurements of seismic velocity in rock samples subjected to isotropic confining pressure provide a useful demonstration of the ability of the model to calculate pressure-dependent velocities in rock. Coyner (1984) acquired high quality velocity data in a variety of rock types under pressures ranging from 0 to about 100 MPa. Here we consider fits to drained (dry) rock samples. Extensions to the solutions outlined above allow the considerations of fluids. For example, a simple approach is to utilize eqs. 8 and 9 to represent the properties of the drained rock (the "skeleton") and to use Gassmann theory to predict fluid effects (Smith, 2003). We also have developed methods for adjusting compliances to take fluids into account.

Figure 1 compares the laboratory data for a sample of Bedford Limestone to the theoretical fit obtained by applying standard linearized least squares inversion techniques using eqs. 8 to 11. The model clearly fits the data with negligible error.

Anisotropic velocities

Benson et al. (2005) acquired velocity measurements from the Crab Orchard Sandstone (COS), which displays seismic anisotropy. Carbonates will display similar behavior. The rock is a relatively low porosity sandstone (about 4.5%). The velocities measured by Benson et al. (2005) show that the sandstone is almost transversely isotropic, and a common seismic approach would be to represent it as a medium with a single set of aligned fractures. However, in this case, the relevant model equations derived using the compliance approach predict a value for one elastic modulus that implies that the corresponding shear wave velocity is pressure-independent. The data show that this is not true; indicating that a model with a single fracture set is inadequate. We therefore derived velocity equations for the combination of a single fracture set perpendicular to the axis of symmetry observed in the COS and a set of isotropic, randomly oriented fractures. The combination of these two sets matches pressure-dependent data quite well (Figure 2).

Field Scale Reservoir Models

We will present results of computing synthetic seismograms for fracture models with pressure-dependent effective seismic velocities similar to those shown in Figure 1 and Figure 2. The fracture model facilitates such simulations by providing relatively simple expressions for general, anisotropic distributions of fractures that require the specification of comparatively few parameters in the model volume. We note also that it is possible to integrate results with the discrete fracture network models often used in geologic characterization of reservoirs (e.g., Shekhar and Gibson, 2011).

An important application is to use the models to determine estimate how reliably seismic data can measure changes in fluid saturations or stress in the subsurface. An increase in effective stress during hydrocarbon production will reduce the compliance of fractures, and the fractures are thus expected to have less influence on seismic reflection amplitudes as stress increases (eq. 1). In addition, seismic anisotropy caused by the presence of aligned fractures will also decrease with increased stress. Test calculations using the compliance model clearly demonstrate this behavior. Seismic modeling will show how this affects potential seismic investigations of reservoir conditions during hydrocarbon production.

Conclusions

Effective characterization of complex carbonate reservoirs where fractures have a strong influence on fluid movement requires reliable methods for relating fracture distributions to changes in seismic reflection amplitudes. Here we outline a method that expresses the stress-dependence of fracture compliances to increasing contact area of rough-surfaced fractures. This in turn allows a simple model for the effective seismic velocities in media with isotropic or aligned fracture sets, and the resulting solution can easily represent the changes in seismic anisotropy caused by variations in stress fields. Inversions of laboratory data measuring isotropic and anisotropic seismic velocity variations demonstrate the model can easily reproduce such measurements, and it is easily incorporated into field scale models since a relatively small number of parameters is required.

References

Angerer, E., S. Crampin, X. Li, and T. Davis, 2002, Processing, modelling and predicting time-lapse effects of overpressured fluid-injection in a fractured reservoir: Geophysical Journal International, v. 149, p. 267–280.

Bakulin, A., V. Grechka and I. Tsvankin, 2002, Seismic inversion for the parameters of two orthogonal fracture sets in a VTI background medium: Geophysics, v. 67, p. 292–299.

Benson, P., P. Meredith, E. Platzman, and R. White, 2005, Pore fabric shape anisotropy in porous sandstones and its relation to elastic wave velocity and permeability anisotropy under hydrostatic pressure: International Journal of Rock Mechanics and Mining Sciences, v. 42, p. 890–899.

Coyner, K.B., 1984, Effects of stress, pore pressure, and pore fluids on bulk strain, velocity, and permeability in rocks: PhD thesis, Massachusetts Institute of Technology.

Crampin, S., and S. Zatsepin, 1997, Modelling the compliance of crustal rock - ii. response to temporal changes before earthquakes: Geophysical Journal International, v. 129, p. 495–506.

Gangi, A.F., 1981, The variation of mechanical and transport properties of cracked rock with pressure: Proceedings of U.S. Symposium on Rock Mechanics, v. 22, p. 85–89.

Gangi, A.F., 1978, Variation of whole and fractured porous rock permeability with confining pressure: International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, v. 15, p. 249–257.

Gao, K., and R.L. Gibson, Jr., 2011, Pressure-dependent seismic velocities based on unified asperity-deformation model: SEG Technical Program Expanded Abstracts, v. 30, p. 2231–2235.

Guéguen, Y., and J. Sarout, 2009, Crack-induced anisotropy in crustal rocks: predicted dry and fluid-saturated Thomsen's parameters: Phys. Earth planet. Inter., v. 172, p. 116-124.

Maultzsch, S., M. Chapman, E. Liu, and X.Y. Li, 2003, Modelling frequency-dependent seismic anisotropy in fluid-saturated rock with aligned fractures: implication of fracture size estimation from anisotropic measurements: Geophys. Prospect., v. 51, p. 381–392.

Pointer, T., E. Liu, and J.A. Hudson, 2000, Seismic wave propagation in cracked porous media: Geophysical Journal International, v. 142, p. 199–231.

Sayers, C.M., 2010, Geophysics under stress: geomechanical applications of seismic and borehole acoustic waves: Society of Exploration Geophysicists and European Association of Geoscientists and Engineers: 2010 Distinguished Instructor Short Course, No. 13.

Sayers, C.M., 2002, Stress-dependent elastic anisotropy of sandstones: Geophysical Prospecting, v. 50, p. 85–95.

Sayers, C.M., and M. Kachanov, 1995, Microcrack-induced elastic wave anisotropy of brittle rocks: Journal of Geophysical Research, v. 100, p. 4149–4156.

Shekhar, R., and R.L. Gibson, Jr., 2011, Generation of spatially correlated fracture models for seismic simulations: Geophysical Journal International, v. 185, p. 341-351.

Smith, T.M., C.H. Sondergeld, and C.S. Rai, 2003, Gassmann fluid substitutions: A tutorial: Geophysics, v. 68, p. 430–440.

Tod, S.R., 2001, The effects on seismic waves of interconnected nearly aligned cracks: Geophysical Journal International, v. 146, p. 249–263.

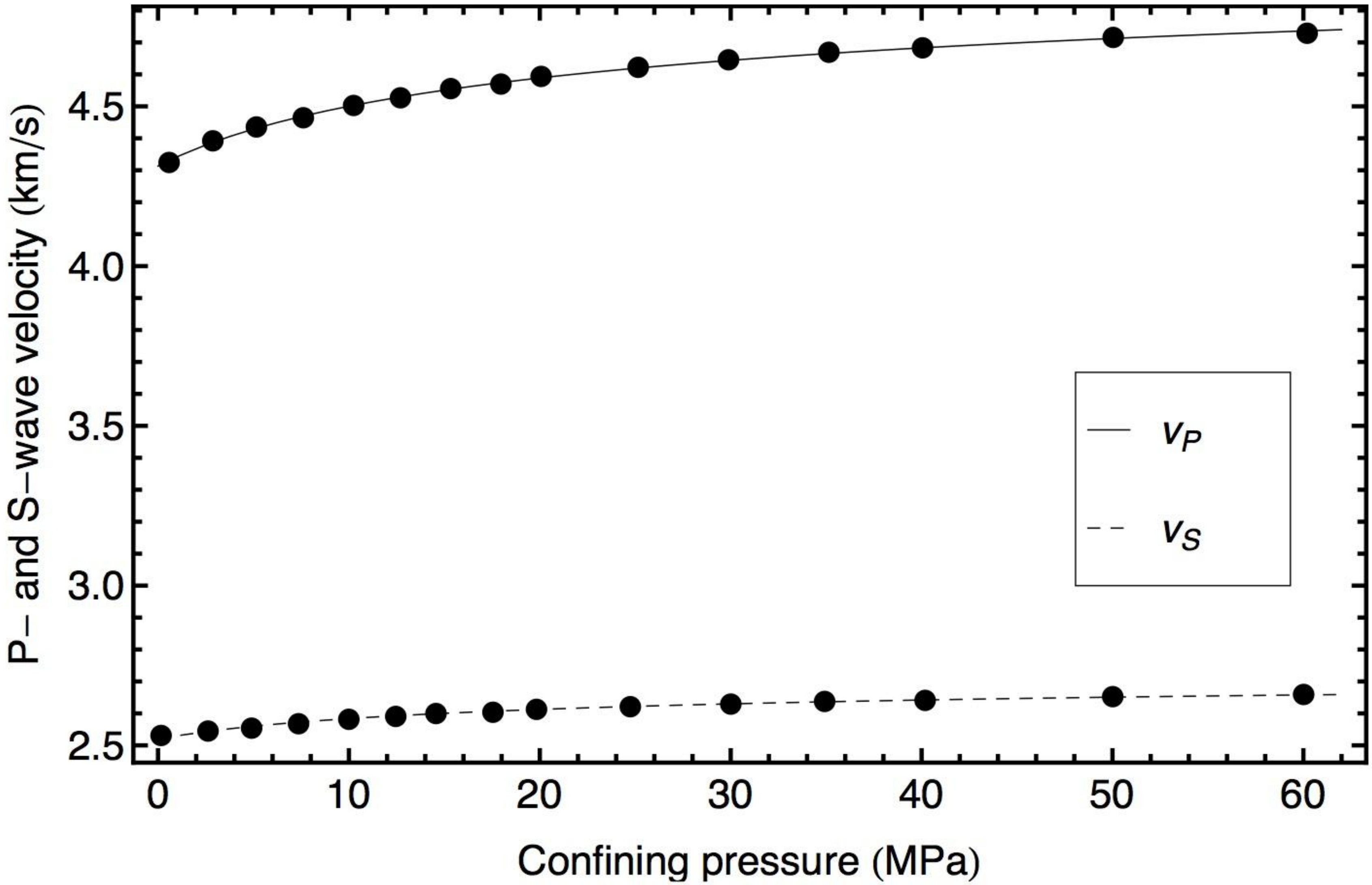

Figure 1. Comparison of laboratory measurements of P- and S-wave data in Bedford Limestone by Coyner (1984) (symbols) and least squares inversion solution using eqs. 8 to 11 (lines).

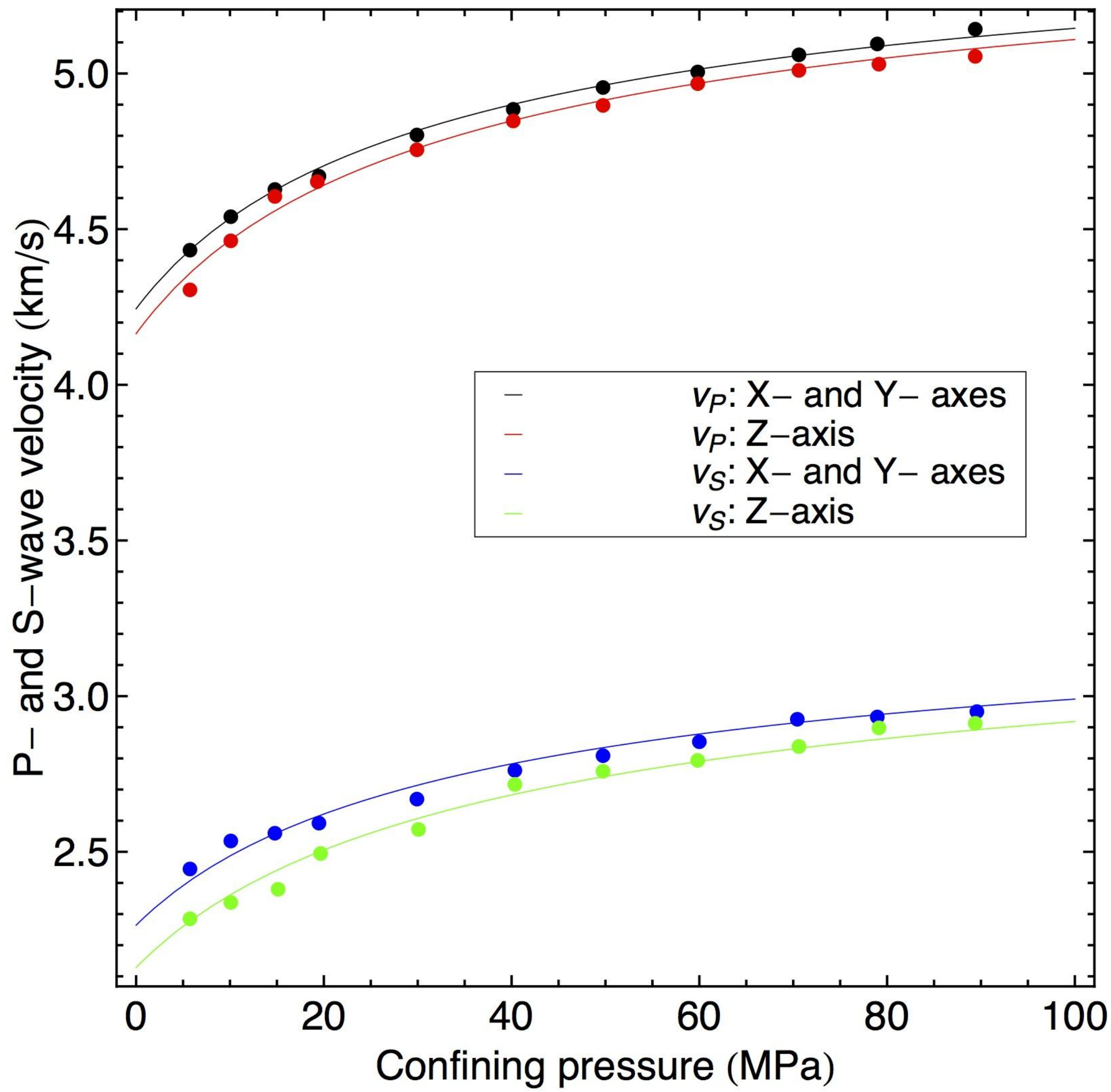

Figure 2. Comparison of laboratory measurements of anisotropic P- and S-wave velocities in Crab Orchard Sandstone (Benson et al., 2005) (symbols) with least squares inversion results for the stress-dependent fracture model combining an aligned fracture set with a set of randomly oriented, isotropic fractures. The velocities in the horizontal plane are nearly constant, but the value is significantly different in the vertical (z) direction.