Shear wave velocity dependence on fluid saturation

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Summary

Sets of aligned open fractures in a background porous rock may result in an effective medium that is anisotropic with respect to wave propagation. Using Brown and Korringa's fluid substitution theory we show that the velocities of vertically propagating shear waves in a fractured, anisotropic rock are dependent on fluid saturation. The shear-wave sensitivity to fluids originates from the effective symmetry of the fractured rock but it is influenced by the "isotropic" porosity, the mineralogy of the rock and the bulk modulus of the saturating fluid. Transversely isotropic (TI) and orthorhombic symmetry rocks will only show changes with saturation of near vertical propagating shear waves when the symmetry planes of the rock are tilted with respect to the vertical direction. Monoclinic and lower symmetry rocks in general will show shear wave velocity variations dependent on fluid saturation.

We characterize the changes in vertical shear-waves with saturation for two monoclinic symmetry models proposed by Bakulin et al. (2000) and Grechka and Tsvankin (2001). The first model is formed by one set of vertical, micro-corrugated fractures in an isotropic background. The second is formed by one set of dipping, rotationally invariant cracks in a transversely isotropic background with vertical symmetry axis. Our results indicate that the shear wave splitting parameter increases as the compressibility of the saturating fluid increases, which is consistent with recent observations that have been reported from multicomponent seismic data.

Introduction

It is well known that for isotropic rocks Gassmann's theory predicts that the bulk modulus (K) changes with saturation while the shear modulus (μ) remains fixed. Hence, the commonly accepted notion that P-waves are sensitive to pore fluids while, except for density effects, S-waves are not. However, multicomponent data acquired over a fractured reservoir at Natih field, Oman, have shown a decrease in slow shear velocity and an increase in shear-splitting when gas substitutes water or oil (Guest et al., 1998).

The apparent contradiction between these results and the notion that shear waves are insensitive to fluids results from the violation of Gassmann's isotropic rock assumption when aligned sets of fractures make the rock anisotropic. Using Brown and Korringa's (1975) anisotropic generalization of Gassman's equations we show that, under conditions of equilibrated pore pressures, fractured rocks with symmetry lower or equal to monoclinic present vertically propagating shear-waves that may be sensitive to fluid saturation.

Fluid Substitution Theory

Brown and Korringa's equation can be written as:

$$S_{ijkl}^{dry} - S_{ijkl}^{sat} = \frac{(S_{ij\alpha\alpha}^{dry} - S_{ij\alpha\alpha}^{0})(S_{kl\alpha\alpha}^{dry} - S_{kl\alpha\alpha}^{0})}{(C_{dry} - C_0) + (C_f - C_0)\phi}, \qquad (1)$$

where C_{dry}, C_0 and C_f are the compressibilities of the dry rock, mineral material and fluid respectively. S_{ijkl}^{sat} is the saturated rock compliance while S_{ijkl}^{dry} and S_{ijkl}^{0} are the compliances of the dry rock and mineral material.

Greater intuition into the meaning of Brown and Korringa's equation can be achieved by rewriting equation (1) in conventional 6x6 matrix notation. By doing this we see that the terms with contracted indices, $S_{ij\alpha\alpha}$, in the numerator of equation (1) represent sums of elements of the first three rows of the compliance matrix. Therefore, if we define V_K as the sum of the first three elements of the K-th column of the compliance matrix, as shown in Figure 1, we can rewrite B&K's equation as:

$$S_{IJ}^{dry} - S_{IJ}^{sat} = \frac{(V_I^{dry} - V_I^{0})(V_J^{dry} - V_J^{0})}{(C_{dry} - C_0) + (C_f - C_0)\phi}. \qquad (2)$$

Although it seems we have not improved much between equations (1) and (2), now it is easier to see when we may expect changes in vertical shear-wave velocities with saturation based on the symmetry of the rock. When the off-diagonal blocks of the compliance matrix are zero (e.g. isotropic rock), vertical shear-wave velocities depend only on the S_{44} and S_{55} compliances. Since in this case the sums V_4 and V_5 are zero (see Figure 1), from equation (2) we see that $S_{kk}^{dry} = S_{kk}^{sat}$ for $k = 4, 5$; indicating that the vertical shear-waves will not be sensitive to fluid saturation.

From the above explanation we immediately obtain Gassman's result that states that the shear modulus is not sensitive to fluids if the rock is isotropic. In the case of transverse isotropy and orthorhombic symmetry rocks whose symmetry planes are **not** tilted with respect to the vertical axis, the off-diagonal compliance blocks are also zero and the vertical shear waves are not sensitive to saturation (see Figure 1). This result has been described in a less explicit form by Brown and Korringa (1975).

If an anisotropic rock has a symmetry lower than orthorhombic (e.g. monoclinic) the sums V_4 or V_5 may be non-zero and the vertically propagating shear waves will be sensitive to the pore fluids. This will occur because S_{44} or S_{55} will be fluid sensitive and also because, for this

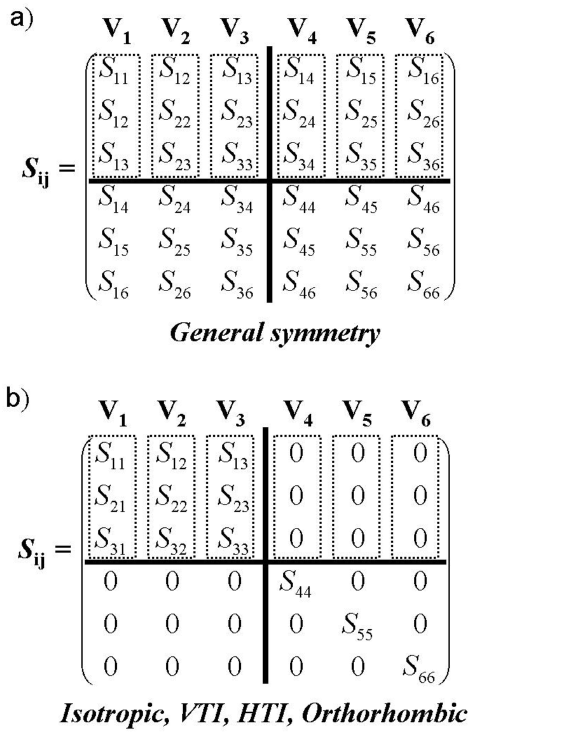

Fig. 1: The change with saturation of components S_{44}, S_{55} and S_{66} depends on the sum of the elements in columns V_4, V_5 and V_6. For isotropic and non-tilted TI and orthorhombic symmetries these columns are zero, which results in shear compliances that do not change with saturation. However, monoclinic and lower symmetry rocks will have fluid sensitive shear compliances.

low symmetry, the S-wave vertical velocities will depend on other compliances besides S_{44} and S_{55}.

One Set of Micro-corrugated Fractures in an Isotropic Background

Bakulin et al. (2000) have studied the anisotropy produced by one set of micro-corrugated fractures embedded in an isotropic background, with normals oriented in the X_1 direction (see Figure 2).

The compliance matrix of this effective medium can be written as the sum of the isotropic compliance of the background plus a fracture system compliance as indicated below.

$$S_{rock} = S_{iso} + \begin{pmatrix} Z_N & 0 & 0 & 0 & Z_{NV} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ Z_{NV} & 0 & 0 & 0 & Z_V & 0 \\ 0 & 0 & 0 & 0 & 0 & Z_H \end{pmatrix}. \quad (3)$$

Here Z_N is the normal compliance of the fractures that

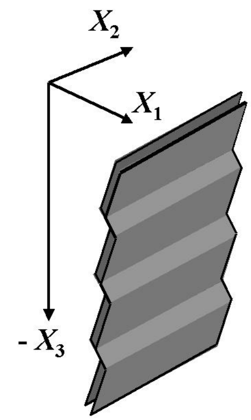

Fig. 2: Vertical fracture with rough structure in the X_3 direction that couples normal and tangential displacements.

relates the normal displacements to the normal stresses applied to the fracture in the X_1 direction. The Z_V and Z_H elements are the tangential compliances that relate tangential displacements and stresses in the X_2 and X_3 directions, respectively. The Z_{NV} compliance represents the coupling of normal displacements to tangential applied stresses, or conversely, the coupling of tangential displacements to applied normal stresses (see Figure 2).

From equations (2) and (3) we can prove that V_{S_1} will not change with saturation because S_{44} is not fluid sensitive. However, V_{S_2} will change with saturation because it depends on S_{55}, which is fluid sensitive. This means that the shear splitting at vertical incidence can provide information about the fluid content of the fracture network.

We use equation (2) to calculate the compliance matrix of a 100% brine saturated rock and then compare the dry and saturated shear-splitting (γ) calculated from:

$$\gamma \equiv \frac{V_{S_1}^2 - V_{S_2}^2}{2V_{S_2}^2}, \quad (4)$$

where V_{S_1} and V_{S_2} as a function of the stiffness components are given in Bakulin et al. (2000).

Figure 3 shows the dry-rock shear splitting parameter and the absolute and relative changes after saturation as a function of the dry coupling compliance Z_{NV}^{dry}. Our calculations show that the velocity of the S_2 wave is larger for the brine saturated rock than for the dry rock. Therefore, since the S_1 velocity is the same for the dry and saturated case, we find that the shear-wave splitting parameter is smaller for the brine saturated rock and larger for the dry rock. Although the relative changes in γ can be as large as 10% of the dry value, we see that the larger percent changes are due in part to the simultaneous decrease of γ^{dry} with increasing values of $(\gamma^{dry} - \gamma^{sat})$.

These calculations were done for an extreme case of fluid

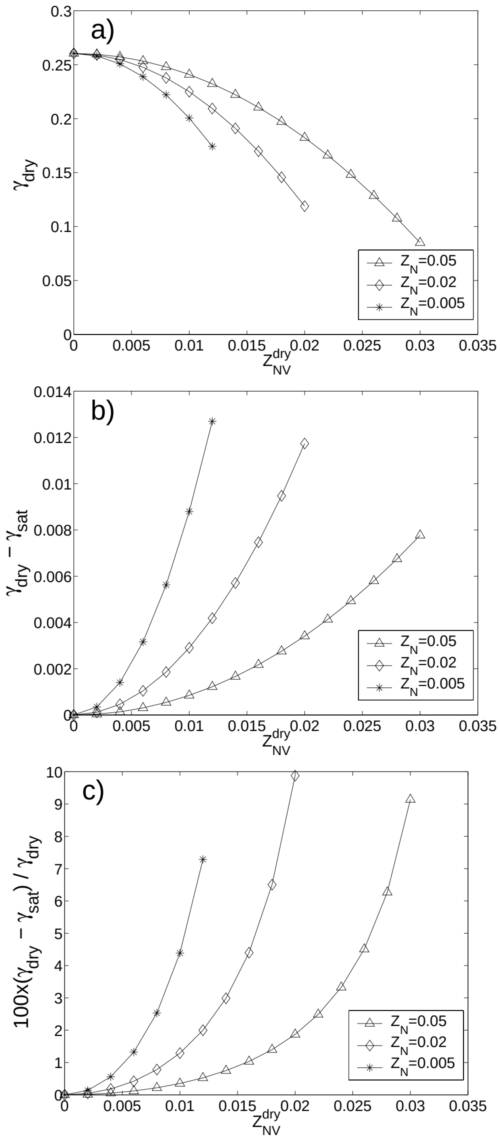

Fig. 3: Difference between dry and saturated values of the shear splitting parameter vs. Z_{NV}^{dry}. Top: shear splitting for the dry rock. Middle: absolute change in shear splitting between the dry and saturated rock. Bottom: percent increase for each of the points in the top plots. Calculations are done for a porous quartz matrix with a modeled porosity of 10% and a fixed value of $Z_V^{dry} = 0.02\ Gpa^{-1}$. The unit of Z_{NV}^{dry} in the X-axis is Gpa^{-1}.

substitution from a dry rock to a 100% brine saturated rock. The dry case, to all practical purposes, is close to saturating the rock with air at ambient conditions ($C_f \rightarrow \infty$) and brine is probably the stiffest fluid of interest that we will find in a rock ($C_f \rightarrow 0$). In field experiments changes in the fluid compressibility will always be smaller and we should expect that the changes in shear splitting should be correspondingly smaller.

Our calculations suggest that vertical shear-wave splitting should increase when the compressibility of the saturating fluid increases (e.g. gas at low differential pressures that displaces oil or water). This result is qualitatively consistent with the findings of Guest et al. (1998) in which the shear splitting parameter increased due to a decrease in the S_2-wave velocity in areas believed to be saturated with highly compressible gas. This observation was made from interpretation of a single multicomponent survey in which the increase in γ was very well correlated with the known gas cap of the reservoir.

One set of dipping, rotationally invariant Cracks in a VTI Background

Grechka et al. (2001) proved that a single set of dipping, rotationally invariant fractures embedded in a VTI background results in a monoclinic rock with vertical symmetry axis. Figure 4 illustrates the model in which the rotationally invariant cracks, originally with their normals in the X_1 direction, are rotated by an angle θ about the X_2 axis. After rotation the crack planes are no longer aligned with the VTI axis, the medium becomes monoclinic and the compliance of the rock has the following nonzero terms,

$$S_{rock} = \begin{pmatrix} S_{11} & S_{12} & S_{13} & 0 & S_{15} & 0 \\ S_{12} & S_{22} & S_{23} & 0 & 0 & 0 \\ S_{13} & S_{23} & S_{33} & 0 & S_{35} & 0 \\ 0 & 0 & 0 & S_{44} & 0 & S_{46} \\ S_{15} & 0 & S_{35} & 0 & S_{55} & 0 \\ 0 & 0 & 0 & S_{46} & 0 & S_{66} \end{pmatrix}. \quad (5)$$

From equation (5), we see that the effective compliance will have non-zero elements in the off-diagonal blocks and by the same arguments used above we can expect that the shear compliances will be sensitive to fluid saturation.

To model the dry rock we use VTI parameters measured on 18% porosity Berea sandstone for the background (Sarkar and Kranz, personal communication) and values of Z_N and Z_T that are consistent with Hudson's theory of penny-shaped cracks. The parameters of the background rock are: $\epsilon = 0.07$, $\delta = 0.04$, $\gamma = 0.09$, $Vp_0 = 2.3\ Km/s$ and $Vs_0 = 1.62\ Km/s$. For the crack compliances we take $Z_N \approx Z_T$ with $0 \leq Z_N \leq 0.02$.

In Figure 5 we see that the changes in γ with saturation are larger with increasing crack dip angle. If the dip angle is zero the effective symmetry of the rock becomes orthorhombic and, since the off-diagonal block elements are zero, there is no change in shear splitting with saturation. Also, when Z_N and $Z_T \rightarrow 0$ (no cracks limit) the

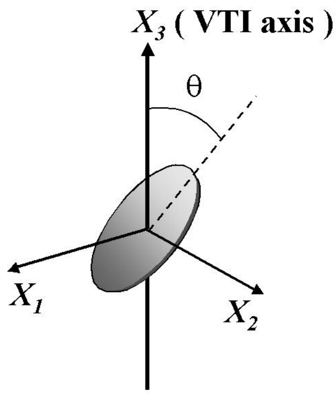

Fig. 4: Representation of a dipping, rotationally invariant crack in a VTI background.

medium has the VTI symmetry of the background and no changes in γ are seen. We also note that the changes are larger when the normal compliance of the cracks increases, which indicates that we should expect larger S-wave sensitivity to fluids with increasing crack density.

Our results indicate that for this sandstone the change in γ can be as large as 15% when the cracks are dipping 45°. However, in general we should expect that these changes will depend on the strength of the VTI anisotropy of the background rock. In this case we arrive to the same conclusion obtained for the micro-corrugated fractures, in which the shear-wave splitting parameter increases as the compressibility of the saturating fluid increases.

Conclusions

Using two different models of fractured rocks with monoclinic symmetry, we have shown that the splitting of vertically propagating S-waves increases with increasing compressibility of the pore fluids. We may expect to observe these variations after gas injection into water or oil saturated portions of a reservoir, or after water encroachment due to production in a zone originally saturated with highly compressible gas.

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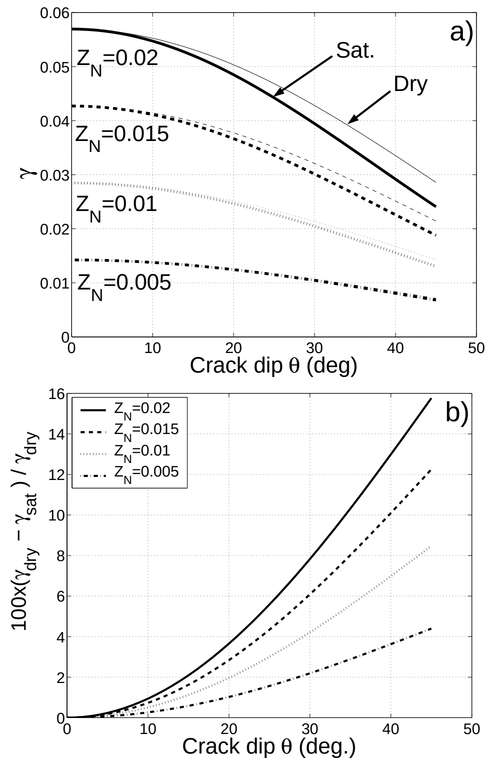

Fig. 5: Shear splitting change with saturation vs. dip angle of the fractures. Top: shear splitting for dry (thin lines) and saturated (thick lines) cases. Note that for all values of the normal compliance $\gamma^{dry} > \gamma^{sat}$. Bottom: Percent change in shear splitting with saturation vs. crack dip angle. Z_N is expressed in Gpa^{-1}.

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