Forward modeling of fracture-induced sonic anisotropy using a combination of borehole image and sonic logs

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Summary

We develop a methodology to model and interpret borehole dipole sonic anisotropy related to the effect of geological fractures using a forward modeling approach. We use a classical excess-compliance fracture model that relies on the orientation of the individual fractures, the compliances of the fractures, and the compliances of the host rock. We extract the orientation of individual fractures from borehole image log analysis.

We validate the model using borehole resistivity image and sonic logs in a gas-sand reservoir over a 160-ft vertical interval of a well. We observe significant amounts of sonic anisotropy and numerous quasi-vertical fractures. The maximum horizontal stress direction, given by breakouts and drilling-induced fractures, is not aligned with the strike of natural fractures.

We show that using just two adjustable fracture compliance parameters, one for natural fractures and one for drilling-induced fractures, is an excellent first-order approximation to explain the fracture-induced anisotropy response. Given the presence of gas within the fractures, we assumed equal normal and tangential compliances.

The two inverted normal compliances are \( Z_N^{f_{SAT}} = 1.7 \times 10^{-12} \text{ Pa}^{-1} \) and \( Z_N^{f_{D1}} = 0.8 \times 10^{-12} \text{ Pa}^{-1} \). Predicted fast-shear azimuth matches measured fast-shear azimuth over 130 ft of the 160-ft studied interval. Predicted slowness anisotropy matches the overall variation and measured values of anisotropy for two of the three strong anisotropy zones. The medium is mostly a horizontal transverse isotropic medium (HTI) with small azimuthal variations of the symmetry axis. We also show that the measured sonic anisotropy is caused by the combination of stress and fracture effects where the predominance of one mechanism over the other is depth-dependent.

Introduction

The detection and characterization of natural fractures in the subsurface has a significant impact for the recovery in many hydrocarbon reservoirs. Surface seismic, borehole seismic, and borehole sonic techniques are commonly used to estimate effective anisotropic elastic properties. However, the interpretation of the measured anisotropy is often ambiguous due to different possible causes such as the intrinsic anisotropy of the rock, the presence of fractures, and the effect of nonequal principal stresses. Effective medium theories that are used to infer fracture properties from seismic or sonic data usually assume the cause of the anisotropy and a specific symmetry without necessarily taking into account the in situ geological complexity. In boreholes, the measurement of borehole images provide a very high-resolution (up to 5 mm) picture of the borehole wall subjected to in situ geological and geomechanical conditions. Here we address the problem of using geological fracture observations in boreholes to model and interpret fracture-induced dipole sonic anisotropy (Prioul et al. 2007). We apply a classical excess-compliance fracture model (Sayers and Kachanov 1995; Schoenberg and Sayers 1995) with only two adjustable parameters. Modeling results are compared with field data.

Fracture identification in boreholes

High resolution electrical or ultrasonic image logs are now routinely used for geological and geomechanical interpretations in boreholes. Image resolutions are typically of the order of 5 mm with a depth of investigation ranging from the borehole wall to several centimeters depending on the tool used. On the basis of the image morphology, different fracture types are discriminated and classified into natural fractures (e.g., open, partially healed, healed, lithologically bounded) and stress-induced fractures. Stress-induced fractures are due to the combination of far field nonequal principal stresses, near field stress concentration around the borehole and stress perturbation during drilling operation. Stress-induced fractures are generally classified using the mode of origin, shear and tensile failure modes, and the morphology (wide or narrow breakout, high-angle echelon, etc). The determination of the geometrical properties of the fractures includes the location and orientation of the ideal plane representation of the fractures (given as depth, \( z \), dip angle, \( \theta \), and dip azimuth, \( \phi \)). When systems of parallel natural fractures are observed, typical values of fracture intensity for very sparse sets are less than 0.75 m\(^{-1}\), and for tight sets more than 10 m\(^{-1}\).

Dipole sonic anisotropy in boreholes

Wireline sonic tools measure the dynamic elastic properties of the formation around the borehole using compressional and shear velocity measurements (Pistre et al. 2005). From the azimuthal anisotropy analysis of cross-dipole waveforms, fast-shear azimuths (\( \phi_{FA}^{meas} \)) are calculated using a method such as Alford rotation (Esmeroy et al. 1994), and fast- and slow-shear slownesses (\( DT_{s_{fast}} \) and \( DT_{s_{slow}} \)) are estimated from the zero-frequency limits of cross-dipole dispersions. Given a typi-
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cal dipole sonic frequency of 1–5 kHz and shear slownesses of 100–800 μs/ft, the shear sonic wavelengths are on the order of 0.25 ft to 10 ft (0.08 to 3.05 m).

Application of the compliance fracture model

When several planar fractures of various orientations are present and identified on image logs, they increase the effective elastic compliance of the medium and, consequently, increase the wave slownesses (i.e., decrease the wave velocities). When the average fracture spacing is much smaller than the wavelength, effective-medium models can be applied.

Sayers and Kachanov (1995) and Schoenberg and Sayers (1995) describe a simple displacement discontinuity method for including the effects of geologically realistic cracks and fractures on seismic propagation through rocks. They consider thin cracks of arbitrary shape and finite dimensions or sets of planar and parallel fractures for which the different cracks and fractures are noninteracting. The overall elastic compliance $s_{ijkl}$ is decomposed through a linear addition of the crack or fracture set compliances $s_{ijkl}^b$ and the compliance of the host medium $s_{ijkl}^h$:

$$s_{ijkl} = s_{ijkl}^h + s_{ijkl}^b. \quad (1)$$

When the cracks or fractures possess elastic axial symmetry, the excess compliance $s_{ijkl}^b$ to the host medium is written as

$$s_{ijkl}^b = \frac{1}{4} \left[ \delta_{ij} \alpha_{ij} + \delta_{ik} \alpha_{ik} + \delta_{jl} \alpha_{jl} + \beta_{ijkl} \right], \quad (2)$$

where $\delta_{ij}$ is the Kronecker symbol, $\alpha_{ij}$ is a second-rank tensor, and $\beta_{ijkl}$ is a fourth-rank tensor.

For individual cracks embedded in a representative volume $V$, Sayers and Kachanov (1995) defines $\alpha_{ij}$ and $\beta_{ijkl}$ as

$$\alpha_{ij} = \sum \left( Z_{ij}^{(r)} n_i^{(r)} n_j^{(r)} \right),$$

$$\beta_{ijkl} = \sum \left[ (Z_N^{(r)} - g_T^{(r)}) n_i^{(r)} n_j^{(r)} n_k^{(r)} n_l^{(r)} \right], \quad (3)$$

where $Z_N^{(r)} = B_N^{(r)} A^{(r)} / V$ and $Z_T^{(r)} = B_T^{(r)} A^{(r)} / V$ (units of 1/strain) are related to the normal $B_N^{(r)}$ and tangential $B_T^{(r)}$ compliances of the $r$th crack (units of length/strain), $n_i^{(r)}$ is the $i$th component of the normal to the crack, and $A^{(r)}$ is the area of the crack within $V$.

For borehole sonic conditions, the elastic medium probed between the sonic transmitter and receivers (given by the tool geometry) defines the volume over which the long-wavelength approximation must be satisfied. The compliances of the host rock $s_{ijkl}^h$ and that of the fractures $Z_N^{(r)}$ and $Z_T^{(r)}$ have to be specified. The compliances of the host medium $s_{ijkl}^h$ are related to the elastic properties of the medium (i.e., sonic slownesses) without the fractures. They are unknown in the well, but, a practical starting point is to consider the host medium as isotropic. Then, the two isotropic elastic constants are defined at every depth by the measured compressional slowness from the monopole, the lowest of the shear slownesses from the dipole (called the fast-wave), and the density. In the case of a forward modeling problem, the normal $Z_N^{(r)}$ and tangential $Z_T^{(r)}$ compliances are unknowns and can be different for each fracture. For dry or gas-filled fractures, $Z_N^{(r)} / Z_T^{(r)} \approx 1$ is a good approximation, but in general, for water- or oil-filled fractures, $Z_N^{(r)} / Z_T^{(r)} \ll 1$ (Sayers 2002). When normal and tangential compliances are equal (equal $Z_N^{(r)} / Z_T^{(r)} \approx 1$), the fourth-rank tensor $\beta_{ijkl}$ vanishes and the lowest possible symmetry of the elastic tensor is orthorhombic. Fracture compliances have the following orders of magnitude: $\sim 10^{-14} - 10^{-13}$ m/Pa from laboratory experiments, $\sim 10^{-13}$ m/Pa from VSP data (Vertical Seismic Profile), $\sim 10^{-12}$ m/Pa from borehole sonic logs and crosshole data, and $\sim 10^{-9}$ m/Pa from reflection seismic data (Lubbe and Worthington 2006).

Once the above parameters have been defined, fractures can be selected within a depth range corresponding to the transmitter-receiver position. Then, the solution of the Christoffel equation for arbitrary anisotropy is solved for the three modes of elastic wave propagation, one compressional $qP$-wave, and two shear $qS_f$- and $qS_2$-waves. Analysis of the azimuthal variation of shear-wave velocities in the plane orthogonal to the borehole provides the two properties commonly observed in sonic anisotropy: the fast-shear azimuth ($\varphi_{FS}^{PA}$), and the two fast- and slow-shear slownesses ($DT_{fast}^{pred}$ and $DT_{slow}^{pred}$). Note that in this approach, we do not assume any particular symmetry of the elastic medium.

Analysis of sonic and image log data

We analyze a vertical well from a tight sandstone gas reservoir (matrix porosity $\sim 10\%$) in the USA Rocky Mountains in which both resistivity image log and sonic log have been obtained over depths 9,600–10,300 ft (i.e., a 700-ft interval). All modes (monopole, dipole, and Stoneley) were recorded using 13 axial levels of eight azimuthal sensors each. The distance between the dipole transmitters and the 13 receivers varies between 9 and 15 ft for the upper dipole and 10-16 ft for the lower dipole (Pistre et al. 2005). Fast-shear azimuth ($\varphi_{FS}^{PA}$) and fast- and slow-shear slownesses ($DT_{fast}^{meas}$ and $DT_{slow}^{meas}$) are measured (Figure 1). Significant amount of anisotropy (2%-16% in slownesses) is observed at three intervals: 10,125–10,150 ft, 10,155–10,175 ft, and 10,195–10,230 ft. At those locations, the fast-shear azimuth is slowly oscillating between North -15° and North 45° (60° variation) independently of any tool rotation. The formation resistivity image log has been analyzed (Figure 1). The observed fractures are classified in two types: natural and stress-induced fractures. Natural formation fractures
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were divided into four subtypes as continuous open fractures (conductive; red circles), partially healed fractures (partially conductive; magenta diamonds), open lithologically bounded fractures (conductive; blue triangles), and healed fractures (resistive, light blue circles). The open fractures strike mainly North 5° and North 70°, with most of them dipping 70° to 90°. We computed an average fracture intensity of 1.24 to 2.5 fractures per foot (4.1 and 8.2 fractures per meter). Drilling-induced fractures have been divided into two subtypes as tensile (green squares) or shear-induced (green triangles) events. They strike mainly North 0°-20° and dip 80° to 90°. Thus, the maximum horizontal stress field direction given by drilling-induced fractures and borehole breakouts (North 0° to 20°) is not necessarily inline with the strike of natural, open fractures (North 5° to 70°).

Fig. 1: Data and forward modeling results: (track 1) Dip angle and azimuth of fractures (see text for symbol details); (track 2) predicted fast-shear azimuths $\phi_{\text{FSA}}^\text{pred}$ (yellow circles) versus measured ones $\phi_{\text{FSA}}$ (continuous black curve); (track 3) predicted fast-shear slowness $(DTs_{\text{slow}})_{\text{fast}}$ as red circles) and slow-shear slowness $(DTs_{\text{slow}})_{\text{slow}}$ as blue circles) versus measured ones $(DTs_{\text{meas}})_{\text{fast}}$ and $(DTs_{\text{meas}})_{\text{slow}}$, as red and blue curves), and compressional slowness (green); (track 4) difference between measured slownesses $(DTs_{\text{meas}} - DTs_{\text{meas}})$ as black curve, and the difference between predicted slownesses $(DTs_{\text{pred}} - DTs_{\text{pred}})$ as grey dots.

Comparison of predicted and real data

The exceed-compliance forward modeling described above has been applied over a 160-ft depth interval. Dipole shear wavelengths are on the order of ~3 to 10 ft (owing to the presence of a fast formation and low frequencies of dipole shear), and the average fracture spacing is between 0.4 to 0.8 ft. Therefore, the conditions of long-wavelength effective-medium are satisfied.

The overall response from natural and drilling-induced fractures was computed using the following observed fractures: continuous open fractures, partially healed fractures, open lithologically bounded fractures, and healed fractures, and the tensile and shear drilling-induced fractures. Drilling-induced fractures, observed at the borehole wall, are usually assumed to have a very limited extension within the formation as compared to natural fractures. This condition is translated in our model by allowing different compliance parameters for drilling-induced fractures and for natural fractures. Given the presence of gas, we assumed equal normal and tangential compliances $Z'_{\text{NAT}} = Z'_{\text{NAT}}^\text{NAT}$. Hence, the model uses only two parameters for all the fractures and for the entire section ($Z'_{\text{NAT}}^\text{NAT}$ and $Z'_{\text{D}}^\text{D}^\text{DI}$). The moving depth window (h) in which the fractures are selected was set at 10 ft, i.e., minimum transmitter-receiver spacing. Computations are performed every foot. The normal and tangential compliances of the fractures were inverted to be $Z'_{\text{NAT}}^\text{NAT} = 1.7 \times 10^{-12}$ Pa$^{-1}$ for the natural fractures and $Z'_{\text{DI}}^\text{DI} = 0.8 \times 10^{-12}$ Pa$^{-1}$ for the drilling-induced fractures. Root-mean-square functions $RMS_{\text{FSA}}$ and $RMS_{\text{DTs}}$ minimizing error functions $|\phi_{\text{FSA}}^\text{meas}(z) - \phi_{\text{FSA}}^\text{pred}(z)|$ and $(|\text{DTs}_{\text{fast}}^\text{meas}(z) - \text{DTs}_{\text{fast}}^\text{pred}(z)| - |\text{DTs}_{\text{slow}}^\text{meas}(z) - \text{DTs}_{\text{slow}}^\text{pred}(z)|)$ were computed on grid of $Z'_{\text{NAT}}^\text{NAT}$ and $Z'_{\text{DI}}^\text{DI}$ every 0.1 $\times 10^{-12}$ Inversion results are shown in Figure 2. Function $RMS_{\text{DTs}}$ has a clear global minimum with $Z'_{\text{NAT}}^\text{NAT} \neq Z'_{\text{DI}}^\text{DI}$. Function $RMS_{\text{FSA}}$ is not very sensitive to the compliances except for low values of $Z'_{\text{DI}}^\text{DI}$ indicating that the drilling-induced fractures cannot be ignored even though their compliance effect is small compared to one of the natural fractures.

The measured and predicted fast-shear azimuth ($\phi_{\text{FSA}}^\text{meas}$ and $\phi_{\text{FSA}}^\text{pred}$), and fast- and slow-shear slownesses $(DTs_{\text{meas}}^\text{fast}, DTs_{\text{meas}}^\text{slow}, DTs_{\text{pred}}^\text{fast}, DTs_{\text{pred}}^\text{slow})$ are displayed on Figure 1. For the interpretation of the fast-shear azimuth results, we define six depth zones: $z_1$ (10,111–10,160 ft), $z_2$ (10,160–10,190 ft), $z_3$ (10,190–10,204 ft), $z_4$ (10,204–10,242 ft), $z_5$ (10,242–10,258 ft), and $z_6$ (10,258–10,270 ft). The predicted fast-shear azimuth (yellow circles on Track 2 on Figure 1) reproduces the measured trend (continuous black curve) over 130 ft of the 160-ft studied interval, for zones $z_1$, $z_2$, $z_4$, and $z_6$, even though the measured azimuth shows up to 60° variations within 20 ft. The match between the measurement and the prediction is better than 15° in zones $z_2$, $z_4$, and $z_6$, and better than 25° for zone $z_1$. There-
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There are significant anisotropies in the elastic properties of the host rock, re-creating the overall trend and values of the measured sonic anisotropy, which is caused by a combination of stress and fracture effects. Figure 1 displays also the measured and predicted slow-nesses. The difference between measured slownesses is displayed as a black curve (\( DT^{\text{slow}} \) - \( DT^{\text{meas}} \)), and the difference between predicted slownesses, as a gray dotted curve (\( DT^{\text{pred}} \) - \( DT^{\text{meas}} \)). The predicted anisotropy reproduces the overall trend and values of the measured anisotropy for two of the three strong anisotropy zones, i.e., 10,155–10,175 ft and 10,195–10,235 ft. For those two zones, this result demonstrates that the use of two unique fracture compliance parameters, one for natural fractures \( Z_N^{\text{NAT}} \) and one for drilling-induced frac-tures \( Z_N^{\text{fDI}} \), is an excellent first-order modeling approximation. If drilling-induced fracture compliance parameters are chosen to be the same as the natural fracture ones \( Z_N^{\text{fDI}} = Z_N^{\text{NAT}} = 1.7 \times 10^{-12} \text{ Pa}^{-1} \), the slowness anisotropy is overestimated in several zones of small anisotropy (e.g., relative slowness error increase from 5% to 20% at depth 10,235 ft and from 10% to 25% at depth 10,155 ft).

Symmetries of the modeled anisotropic response

We also computed the relative distance between our computed elastic compliance tensor and the best-approximating isotropic, TI, and orthorhombic (ORT) tensors following (Dellinger 2005). Figure 3 shows that the medium is close to a transverse isotropic medium (see track 2 where the distance to the best TI tensor is only up to \( \sim5\% \)). We also note that the minimum cross-energy line (track 1) is not zero when the distance to the best TI is not zero, i.e., when the medium has lower symme-tries such as orthorhombic. The symmetry axis of the best TI medium (track 3) is horizontal with azimuthal variations consistent with the fast-shear azimuth, indicating that the medium is mostly a horizontal transverse isotropic medium (HTI). We also show the variations of the Thomsen’s parameters over the interval (track 4).

Response from individual fracture types

Because the excess compliance tensor \( s_{ijkl}^{\text{fDI}} \) is a linear addition of the individual fracture sets, each fracture type contribution can be analyzed separately as an isolated one. The analysis of each independent fracture type showed that the anisotropy is mainly driven by open, litholog-ically bounded, or partially healed fractures, but also consistent with stress-related, drilling-induced fractures in zones of small anisotropy. Therefore, the measured sonic anisotropy is caused by a combination of stress and fracture effects.

Conclusions

We have developed a methodology to model and interpret borehole dipole sonic anisotropy related to the effect of geological fractures using a forward modeling approach. We used a classical excess-compliance fracture model that relies on the orientation of the individual fractures, the elastic properties of the host rock, and the normal and tangential fracture compliance parameters. We showed that using just two fracture compliance parameters, one for natural fractures and one for drilling-induced fractures, was an excellent first-order approximation to explain the fracture-induced anisotropy response over a depth interval of 130-ft in a gas field. We showed that the predicted fast-shear azimuths matched measured ones over 130-ft of the 160-ft studied interval, and the predicted slowness anisotropy matched the overall variation and measured values over most of the interval. Furthermore, we showed the robustness of the measured fast-shear azimuth obtained by the Alford rotation as a measurement of fracture-induced anisotropy. In addition, computation of the best isotropic, transversely isotropic, and orthorhombic approximations of the modeled tensors provides a powerful way to identify the best symmetry of the elastic medium. Finally, we demonstrated that the measured sonic anisotropy is caused by the combination of fracture and stress effects where the predominance of one mechanism over the other is depth-dependent.
EDITED REFERENCES
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