Statistical AVO intercept-gradient analysis of direct S-waves: A methodology for quantitative fracture characterization

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Abstract

Identification and characterization of subsurface fractures is important to understand preferential pathways for fluid flow in unconventional reservoirs and to optimize water flooding and EOR operations in fractured formations. This study focuses on understanding the effects of fractures on the elastic properties of a rock and illustrates the value of direct S-wave modes (like S-P and S-S) for quantitative fracture characterization. This study employs statistical rock physics and Amplitude Variation with Offset (AVO) analyses and discovers that AVO attributes of direct S wave modes might be more useful for interpreting fracture properties like fracture-orientation, fracture-density and fracture-fill than is a P-P wave mode. AVO modeling suggests that fracture orientation information can be obtained from AVO gradients of the S-S wave mode. Modeling results also demonstrate that in angle and azimuth space, the AVO intercept of a slow S-S wave mode in the plane parallel to fractures is sensitive to the crack density (γ) parameter of a rock formation. As a result, an Intercept-Anisotropy (IA) attribute is derived from S-wave AVO intercepts, which quantitatively estimates subsurface fracture density. AVO modelling also suggests that the AVO gradient of a slow S-S wave mode in a direction normal to fracture-orientation is sensitive to the type of fluid fill in fractures. Consequently, S-wave gradients are used to design a Gradient-Anisotropy (GA) attribute that can estimate fracture fill. These attributes may be used to depict the lateral variation in fracture-density and fracture- fill in subsurface. Because direct S-wave AVO attributes are less affected by subsurface uncertainty compared to P-wave attributes, they significantly reduce ambiguity in estimating fracture properties. This workflow can also be applied to direct S-waves produced by vertical force sources and provide a robust and cost-effective way for employing multicomponent seismic technology to characterize subsurface fractures.

Introduction

Direct S-wave modes have proved to be effective in detecting azimuthal anisotropy (Martin and Davis, 1987). Traditionally, use of direct S-wave for fracture characterization is limited to shear-wave splitting analysis, travel-time analysis, and post-stack amplitude analysis. Studies concerning pre-stack amplitude analysis for fracture characterization are rare for direct S-waves. Using pre-stack methods like AVO can be useful in delineating thin fractured reservoirs and can provide localized geological information with higher vertical resolution than travel-time methods (Tsvankin et al., 2010). AVO methods have already proved useful for delineating fractures in P-wave and converted S-wave seismic data (Shen et. al, 2002; Perez et. al, 1999; Lynn et. al, 1995) and can provide more quantitative information about fractures if applied to direct S-wave modes as well.

In this study, we establish a statistical rock physics model for elastic constants that incorporates uncertainty in lithology, porosity, shape, and spatial density of fractures. This statistical model is then used to understand what P-wave and S-wave AVO attributes would be optimal for observing variations in elastic constants caused by fracture-orientation, spatial density, and fluid fill of fractures. The results of this study show that S-wave AVO provides quantitative estimates of fracture-orientation, fracture-density and fracture-fill with significantly less ambiguity than do P-waves. We demonstrate that fracture-orientation information lies in non-normal S-waves incidence angles in azimuths both parallel and perpendicular to fractures, fracture density information lies in near-normal slow S-wave incidence angles in fracture-parallel azimuths, and fracture-fill information lies in non-normal, pre-critical slow S-waves incidence angles in fracture-perpendicular azimuths. This study also highlights the importance and advantages of S-wave AVO analysis over P-wave AVO analysis for quantitative fracture characterization and provides the necessary background and motivation to study S-wave AVO in detail.

Data and Methodology

For this study, we use well log and core data from Well-32 in Wellington field located in south-central Kansas, USA as shown in Figure-1. Wellington field is a part of sub-crop play with Mississippian cherty, dolomitic reservoirs preserved in structural blocks bounded by NE and NW trending lineaments in Sumner County, Kansas, USA. The stratigraphic units that are of immediate interest to this study are Ordovician age carbonates in the Arbuckle formation. The Arbuckle is fractured and heavily dolomitized and brine saturated is being considered for CO2 storage.

Rock physics study of Upper Arbuckle formation

First we build an isotropic carbonate background that closely resembles the upper Arbuckle formation in terms of porosity distribution and pore-shapes. This construction is done using the isotropic DEM model (Norris, 1985). This model assumes that the inclusions are dry ellipsoid pores that are randomly oriented in an isotropic and homogeneous dolomitized carbonate background. The background elastics constants obtained from the DEM model act as an input for the second stage, where a single set of aligned fractures are modeled using Hudson's model for HTI media (Hudson, 1981). Hudson's theory assumes isolated cracks or inclusions and simulates high-frequency wave propagation behavior. In order to understand effects of fluids in these cracks at seismic wavelengths, low-frequency relations given by Brown and Korringa (1975) were used to calculate stiffness matrix of the fluid saturated rock. This stiffness matrix is used to calculate seismic velocities and Thomsen parameters because these directly affect seismic amplitudes.

AVO modeling and intercept-gradient analysis

P-P and S-S AVO modelling was done for the top of the Arbuckle formation in planes parallel to fractures (isotropy plane) and planes orthogonal to fractures (symmetry plane). For S-S wave modes, two polarizations have been considered corresponding to the fast and slow directions. Mathematical formulations proposed by Ruger (2001) for HTI media have been used to model these wave modes. Also, intercept and gradient attributes for all reflectivity modes were calculated and cross plotted to understand their dependence on different rock and fracture properties.

Uncertainty

Due to assumptions required to reduce mathematical and computational complexities and our inability to create the actual rock texture in a rock physics model, there is uncertainty in the model's prediction response. This problem can be partly solved by incorporating uncertainty in the input parameters (porosity, crack density, aspect ratio, and fluid) used by a rock physics model, propagate those uncertainties through the model, and observe the effect on the model response. This approach indicates not only the sensitivities of different rock properties, but also helps explain the observed data. Variations in Arbuckle's crack density and crack aspect ratio as well as variations in the elastic parameters of the shale layer above the Arbuckle formation have been considered in the AVO model.

Results

Our rock physics model provides estimates of seismic velocities and anisotropic parameters like ε, δ and γ described by Thomsen (1986). Figure-2 shows the porosity dependence of slow P-wave and S-wave velocities and the Thomsen parameters ($\varepsilon^{(v)}$, $\delta^{(v)}$ and γ) defined with respect to vertical in an HTI media. Figure-2 is plotted for both dry and brine-saturated Arbuckle formation. Vp, Vs and γ in figure 2(a), 2(b), and 2(c) are color coded with the crack density parameter. γ shows a direct relationship with crack density i.e. a higher value of γ corresponds to high crack density and vice versa. Filled black circles shown on the γ plot are S-wave velocity anisotropy data from borehole measurements in upper Arbuckle formation and are in agreement with the model. This model suggests that crack density in the upper Arbuckle formation near well bore is less than 5%. $\varepsilon^{(v)}$, $\delta^{(v)}$ and ($\Delta\delta^{(v)} - \Delta\varepsilon^{(v)}$) plots in figure 2(d), 2(e), and 2(f) are color coded with the fracture-content to show the behavior of dry and brine-saturated Arbuckle carbonates. These plots show that $\delta^{(v)}$ is insensitive to fracture-fill but $\varepsilon^{(v)}$ is higher for brine as compare to dry rock. Similar dependence of $\varepsilon^{(v)}$ on fracture-fill has also been discussed in Sava et al. (2001). The behavior of ($\Delta\delta^{(v)} - \Delta\varepsilon^{(v)}$) plot in Figure-2(f) shows a clear separation between two fracture-fills, implying its application as a proxy for fracture-fill.

Figure-3 shows the AVO behavior of P- waves, fast and slow S-waves in isotropy and symmetry planes when the top of Arbuckle is saturated with brine. It is important to note that differences between P wave intercept and gradient for isotropy and symmetry planes lie within the uncertainty of the aspect ratio and crack density, and hence is not distinguishable. S-waves are more sensitive to fracture-direction and hence have significant advantage over P-waves for determining fracture-orientations. Figure-4 is the intercept-gradient cross plot for AVO responses in Figure-3 color coded with crack density and crack aspect ratio. Here filled circles represent the isotropy plane and open circles denote the symmetry plane. Direct correlation between slow S-wave intercept (S2-S2 AVO intercept) and crack density implies that a zone with higher fracture-densities will be seen as a dim spot on a slow shear seismic section in the direction parallel to the fracture-orientation. Figure-5 shows the AVO behavior of P and S wave modes for different pore fluid type in the symmetry plane. There is a shift in the P-wave AVO intercepts for the different fluid type as shown in Figure-5(a). According to our model, change in the intercept for P-waves is mainly due to change in the matrix porosity and not due to fluid in fractures. Figure-5(c) shows change in gradients of AVO curves for different fluid fill. This gradient change is a direct consequence of dependence of $\Delta\delta^{(v)} - \Delta\varepsilon^{(v)}$ parameter on fluids. Our model suggests that, the gradient of slow S-wave in symmetry plane gives information of the fluid present in the fractures. This AVO information gets translated in the intercept gradient cross plots in Figure-6. With a careful decoupling process, Gradient-Anisotropy (GA) attribute (Figure-7b) that is sensitive to $\Delta\delta^{(v)} - \Delta\varepsilon^{(v)}$ can be extracted from the S-wave AVO gradients to get information regarding fluid in fractures. Similarly, an Intercept-Anisotropy (IA) attribute is derived from S-wave AVO intercepts, which quantitatively estimates subsurface fracture density as shown in Figure-7(a).

Conclusions

This study suggests that S-waves are more sensitive to the orientation of fractures compared to P-waves. S-wave AVO analysis shows a large variations in AVO gradients with respect to the direction of fractures, implying its application to determine the average fracture-orientation in subsurface. For the P-P mode, azimuthal variations in AVO gradients are less than the uncertainty of lithology and fracture-density and hence will not be an optimal attribute to determine fracture-orientation. We demonstrate that, in angle and azimuth space, the slow-S-wave AVO intercept attribute in the isotropy plane or Intercept Anisotropy attribute, quantitatively estimates the $\boldsymbol{\gamma}$ (crack density) of a rock formation whereas P-P azimuthal AVO attributes do not correlate well with crack density. Also, results suggest that, $\Delta\boldsymbol{\varepsilon}^{(v)} - \Delta\boldsymbol{\delta}^{(v)}$ as great potential to discriminate fluids in the fractures. Because $\Delta\boldsymbol{\varepsilon}^{(v)} - \Delta\boldsymbol{\delta}^{(v)}$ governs the AVO behavior of S-waves in the symmetry plane, we conclude that slow S-wave AVO gradient in direction normal to fracture-orientation or Gradient Anisotropy attribute can act as a potential seismic attribute for discriminating fluid fill in fractures. Conclusively, adding S-wave AVO analysis to our current fracture characterization workflows can significantly reduce ambiguity in quantitatively estimating fracture properties. Attributes derived from S-waves are less affected by the subsurface uncertainty as compared to attributes derived from P-waves and thus are more reliable for fracture characterization.

Acknowledgments

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Figures:

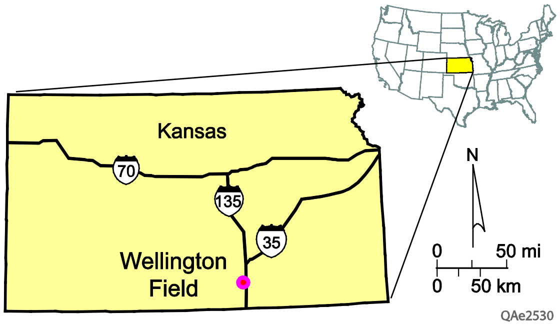

Figure-1: Dataset comes from Wellington field, situated in south central Kansas, United States

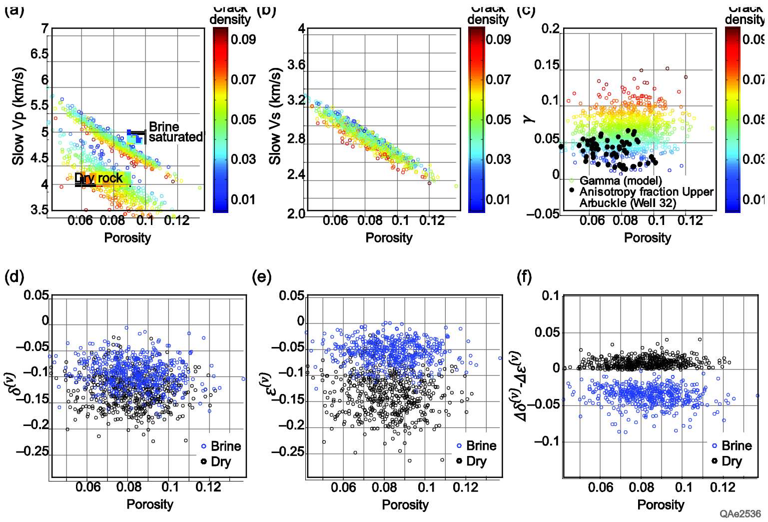

Figure-2: Porosity dependence of elastic parameters color coded with crack density (a, b and c) and fracture fill (d, e and f). Modeled gamma is consistent with the well measurements. Also note that gamma is directly correlated to crack density. $\Delta\varepsilon^{(v)} - \Delta\delta^{(v)}$ is sensitive to the fracture fill i.e. dry (black) and brine (blue)

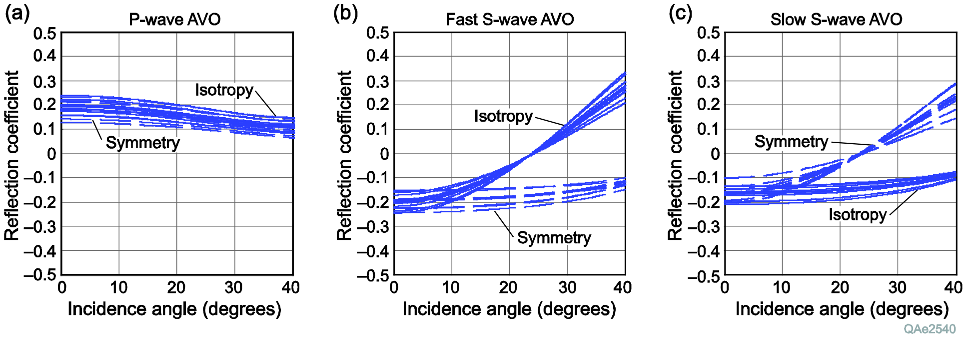

Figure-3: Reflectivity vs. offset plot for brine-saturated rock in isotropy (solid) and symmetry (dashed) planes. Note the overlap of isotropy and symmetry plane reflectivities for P-waves (a) and significant differences in reflectivity at higher incidence angles for both fast (b) and slow S-waves (c), underscoring their value in fracture identification.

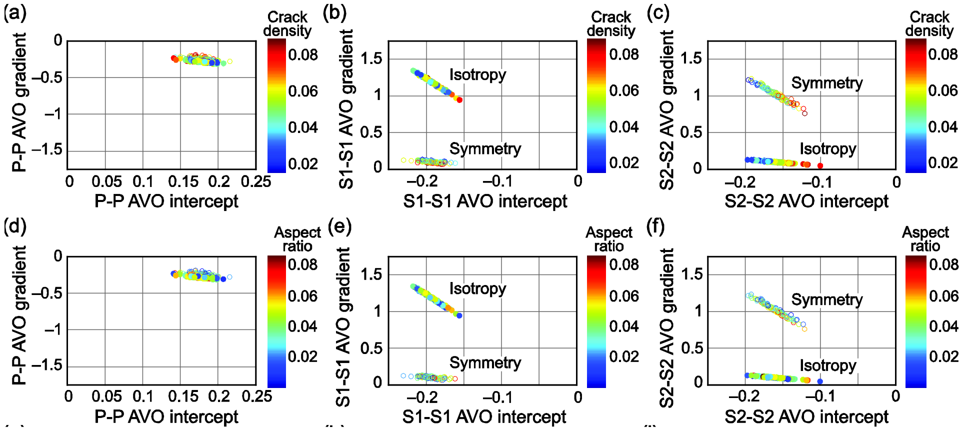

Figure-4: Intercept-gradient cross plots for P-wave (a and d), fast S-wave (b and e) and slow S-wave (c and f) in isotropy (filled circles) and symmetry (open circles) planes, color coded with crack density (a, b, and c) and crack aspect ratio (d, e, and f). Note difference in AVO gradient distributions in isotropy and symmetry planes for fast and slow S-waves (e and f), Also note the systematic change in slow S-wave AVO intercept and gradient with changing crack density (c).

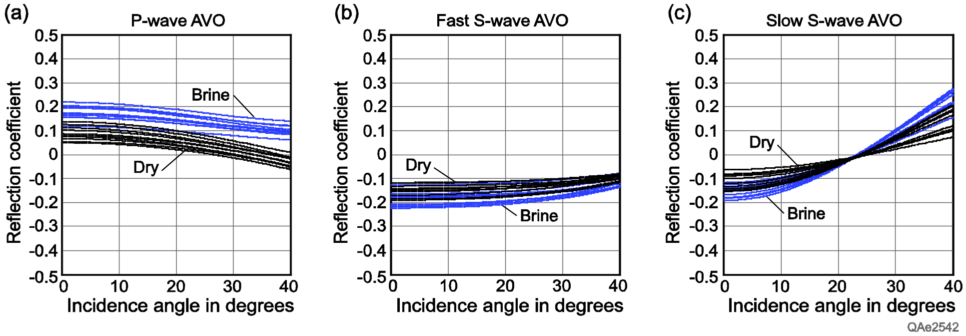

Figure-5: Reflectivity vs. offset plot in symmetry planes for dry (black) and brine (blue) saturated fractures. Note difference in P-wave reflectivity for different pore fill (a) and change in slow S-wave AVO gradient for different fracture fills (c).

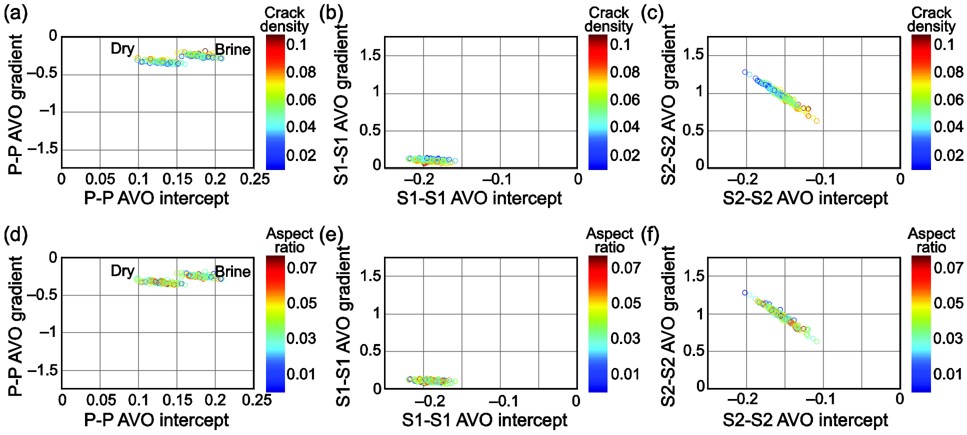

Figure-6: Intercept-gradient cross plots for P-wave (a and d), fast S-wave (b and e) and slow S-wave (c and f) in symmetry plane for dry and brine saturated fractures, color coded with crack density (a, b, and c) and crack aspect ratio (d, e, and f). Note the difference in P-wave AVO intercept distribution for different pore fill (d), Also note the systematic change in slow S-wave AVO intercept and gradient with changing crack density(c).

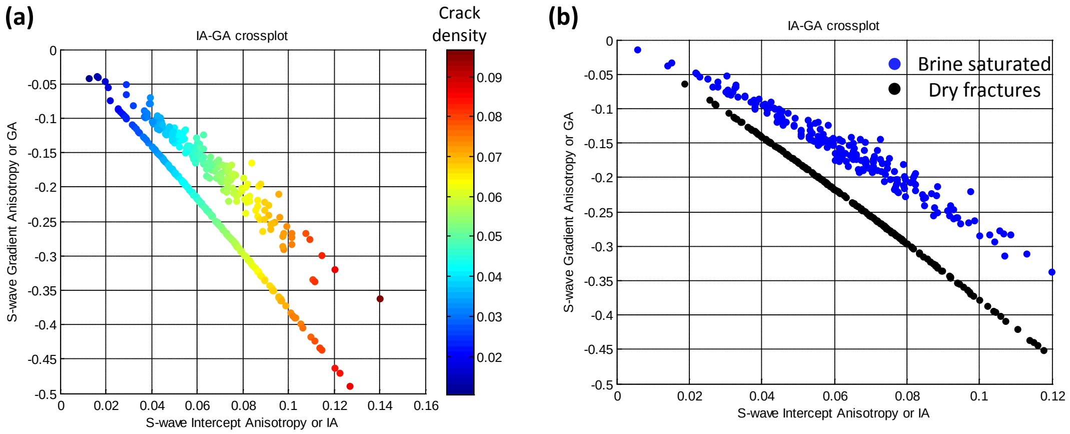

Figure-7: Direct S-wave Gradient Anisotropy (GA) vs Intercept Anisotropy (IA) for dry and brine saturated fractures. (a) IA-GA cross plot demonstrating relationship of Intercept anisotropy with Crack density. (b) IA-GA cross plot showing separation between brine saturated and dry fractures.

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