Azimuthal seismic AVO responses of the fracture zones in the Bakken Formation

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SUMMARY

The presence of vertical aligned fractures in the Bakken Formation results in azimuthal seismic AVO responses. In this paper, we design a realistic geologic model of the fracture zone in the Bakken Formation, and investigate corresponding azimuthal seismic AVO responses. In the model, based on results from formation images, we assume that fractures and cracks cut through all seven major geologic units in the Bakken Formation with a specific ratio of fracture intensity about 3:3:2:1:2:1:1. Corresponding anisotropy parameters are calculated based on Hudson’s theory. We then employ the reflectivity method to generate elastic seismograms. AVO curves picked for four interested geologic units indicate azimuthal variations in amplitudes especially at far offset. The decrease in amplitude at far offset corresponds to the increase in azimuth, and the AVO gradient also presents a linear variation with azimuth. However, because picking of the exact amplitudes is difficult due to interference and the presence of overlying fractures, it may be appropriate to treat the formation as an integrated part and investigate azimuth variations in RMS amplitudes. Comparison results indicate that the stacked RMS amplitudes act as a better indicator of the variations in crack density and fluid saturation than the corresponding AVO gradient.
Introduction

The presence of vertical aligned fractures in the Bakken Formation results in azimuthal anisotropy of elastic properties and therefore azimuthal seismic AVO responses. Ye et al. (2010) analyzed well logs and calculated seismic responses of the Bakken Formation by incorporating effective medium theory to characterize vertical fractures. One objective of our study is to build a realistic geologic model for the fracture zone in the Bakken Formation, in which fractures and cracks cut through the Bakken Formation. We then generate elastic seismograms to investigate the effects of crack density, fluid saturation, and interference on azimuthal AVO responses of the Bakken Formation.

Geologic model of the Bakken Formation

Well logs in Figure 1 (a) illustrate the Bakken Formation consisting of a sequence of geologic units, among which the Upper and Lower Bakken Shale, and the Middle Bakken are three major units, and are surrounded by carbonate rocks as shown by the mineralogy in Figure 1 (b). The Upper and Lower Bakken Shale are similar and recognized as source rocks, while the Middle Bakken is the reservoir. The Upper and Lower Bakken Shales can be assumed to have VTI (Transverse isotropy with vertical symmetric axis) anisotropy related to kerogen content and maturation level (Vernik and Liu, 1997), while the Middle Bakken can be considered as isotropic. In additional, observations from formation images indicate the presence of vertical aligned fractures cutting through all seven geologic units in the Bakken Formation with a specific ratio of fracture intensity about 3:3:2:1:2:1:1, as shown in Figure 1 (c). Therefore, the resulted media are orthorhombic for the Upper and Lower Shales and HTI (Transverse isotropy with horizontal symmetric axis) for other units in the Bakken Formation.

Azimuthal seismic modeling

In this study, we employ the reflectivity method to conduct seismic modeling to calculate azimuthal seismic responses of the Bakken Formation according to the model designed in Figure 2. Five azimuths of 0°, 30°, 45°, 60°, 90° are chosen for the seismic modeling. In the modeling, an explosive source with the Ricker wavelet is used. A number of 40 receivers are placed with a spacing of 100m,
so the maximum offset is up to 4000m, corresponding to a maximum reflection angle around 50° for 3000m burial depth of the Bakken Formation.

Figure 2 (a) Geological settings showing thicknesses and elastic properties of layers for modeling. (b) A close view of the fracture zone model of the Bakken Formation.

Figure 3 illustrates the calculated synthetic seismograms for the model designed in Figure 2. Elastic properties of the background media are given by Figure 2 (a), while the crack azimuth is set as 60°. Crack densities of the vertical aligned fractures are set as 0.1, 0.1, 0.066, 0.033, 0.066, 0.033, and 0.033 for the units from the top to bottom in the Bakken Formation. The dominant frequency of the Ricker wavelet is 40 Hz. Reflections from the fracture zone in Figure 2 are indicated by red arrows on the Z-component panel for the P-P wave and on the X-component panel for the converted P-SV wave.

Figure 4 (a) displays a closeup of Figure 3 (a), showing the P-P reflection from the fracture zone in the Bakken Formation. We implement an anisotropic NMO algorithm for long offset and anisotropy (Li and Yuan, 2003) to flatten reflection events. Two-way travel times of P-P reflections from the top of each individual unit are listed and indicated on the seismogram. Because thin layers in the fracture zone are beyond seismic resolution, reflections from each unit will interfere with each other. Therefore, we can see in Figure 4 (a) that the event is a combination of the reflections from all layers of the target zone. Moreover, such interference will worsen when the dominant frequency of source wavelet decreases from 40Hz to 20 Hz, as illustrated in Figure 4 (b). So, we have to be cautious when picking up amplitudes for AVO analysis.

Figure 3 Synthetic seismograms showing (a) P-P reflection and (b) P-SV reflection from the fracture zone in the Bakken Formation. Figure 4 The closeup of reflection from the fracture zone, showing traveling times for each geologic unit in Figure 2.
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Figure 5 shows the calculated synthetics for the azimuths 0°, 30°, 45°, 60°, and 90°. In the modeling, crack density for the geologic units in the Bakken Formation is set as 0.1, 0.1, 0.066, 0.033, 0.066, 0.033, and 0.033, respectively. The Ricker wavelet with 40 Hz dominant frequency is used as an explosive source. A number of 40 receivers are placed with a space of 100m. In Figure 5, we can observe the azimuthally varying amplitudes especially at far offset. The decrease in amplitude at far offset corresponds to the increase in azimuth.

Figure 6 illustrates the AVO curves picked along calculated two-way travel times for four select geologic units in the fracture zone. We can observe the differences between AVO responses resulting from varied azimuths. The corresponding AVO gradient G is calculated and displayed. Accordingly, the AVO gradients present linear relations with varied azimuths. Reflection features at zero offset for each case can be justified by the contrast in elastic properties for each reflector, but we have to keep in mind that these observed AVO responses are affected by interference and overlying fractures, so that they cannot be predicted accurately by the anisotropic counterpart of the Zoeppritz equations.

Calculations of accurate two-way travel times for each unit in the target zone are impossible if well log data are not available. In this case, it may be appropriate to treat the formation as an integrated part and investigate the azimuth variations in RMS amplitudes. In Figure 7, we compare the calculated RMS amplitudes for three cases with different fluid saturations and crack densities (the crack density of the Lodgepole is indicated as a reference and the crack density for other units can be calculated according to the given ratio). By comparing Figures 7 (a) and (b), we can see that crack density causes obvious variations in AVO responses. However, the comparison between Figures 7 (a) and (c) indicates that different types of fluid saturations result in very subtle variations in AVO responses.
Figure 7 Picked AVO curves of RMS amplitudes for three cases: (a) gas saturated with $\varepsilon=0.1$, (b) gas saturated with $\varepsilon=0.05$, and (c) oil saturated with $\varepsilon=0.1$.

Figure 8 Azimuthal variations in calculated parameters: (a) full stacked amplitude, (b) far-offset stacked amplitude, and (c) AVO gradient $G$. Three cases in Figure 7 are compared on each panel.

In Figure 8, we illustrate the azimuthal variations in full stacked RMS amplitude, far-offset stacked amplitude, and AVO gradient $G$ for the cases shown in Figure 7. We can see that the three cases are more separated on the RMS amplitude panels in Figure 8 (a) and (b) than on the AVO gradient panel in Figure 8 (c), so the stacked RMS amplitudes act as a better indicator for the variations in crack density and fluid saturation. In addition, because crack density and fluid type mainly affect amplitudes at far offset, far-offset stacked RMS amplitudes in Figure 8 (b) present more variations in percentage.

Conclusions

We designed a realistic model of fracture zone in the Bakken Formation for synthetic modeling. Results reveal obvious azimuthal variations in picked amplitudes and AVO gradient $G$. However, due to the interference and the absence of control from well logs, it may be appropriate to treat the fracture zone as an integrated part and investigate corresponding azimuth variations in RMS amplitudes. Results show that compared to AVO gradient of RMS amplitudes, far-offset stacked RMS amplitudes act as a better indicator for crack density. Further study might include investigations on azimuthal variations in converted P-SV waves, and the effect of thickness of the fracture zone.

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