Crack density discrimination for thin layers using offset-dependent spectrum characteristics

Z.Q. Guo (British Geological Survey; Jilin University, China), X.Y. Li (British Geological Survey)

SUMMARY

Current AVO analysis is generally based on the model of single interface separating two half spaces. This assumption ignores the presence of widespread thin-layer formations in the subsurface whose AVO response is very different from the case of a single interface. In this paper, we exploit the spectrum characteristics of the AVO response of a thin-layer reservoir in order to get more valuable information within the reservoir. Study shows that peak frequencies of both P-P and P-S waves reflected from the thin reservoir deviate from each other and vary with offset, which are not observed for the reflection from a single interface. And the offset-dependent peak frequency of P-P wave is also a good indicator of the variation of crack density for thin reservoirs. The correlation of offset-dependent peak frequencies of P-P and P-S waves can also be a diagnostic feature for different crack density.

Introduction

Targets of current seismic exploration become thinner than ever before as quality thick reservoirs in the real world are gradually exhausted. The reflection characteristics of thin bed are very different from the case of a single interface. Therefore, traditional AVO technology is often inefficient for analyzing reflections from thin beds. In order to fill this gap, AVO technologies aiming at thin-layer reservoirs have been researched for many years. Carcione (2001) studied the AVO response of pressure-seal and thin hydrocarbon source-rock layer with the presence of anisotropy and attenuation. Ursin and Stovas (2002) calculated the reflection and transmission coefficients for thin-layered stacks with layers exhibiting visco-elasticity. Liu and Schmitt (2003) investigated the AVO response from a single thin bed and analyzed the influence of Possion's ratio and thickness of the thin bed. Moreover, the frequency-dependent AVO response of thin-layered reservoirs was also researched by Marmalyevskyy and Roganov (2006), and Li et al (2009). These studies showed that the reflection response of a thin layer is complex functions of the thickness of the thin layer, wavelet frequency, as well as offset and may differ significantly from the AVO response of a single interface. The main difficulty in thin bed reflection analysis lies in the complex expressions describing thin bed reflection, which limits the application of thin bed AVO analysis, especially in terms of AVO inversion.

This study focuses on the use of the frequency characteristics of thin bed AVO response for both P-wave and mode-converted S-wave to distinguish the variation of crack density of thin reservoirs. The equivalent medium theory of Liu et al. (2000) is used to represent the model of the fractured medium, and wave field modelling of the thin bed reflection is carried out by pseudo-spectral method.

Method

Our objective is to discriminate crack density of thin bed using spectrum characteristics of reflection amplitudes. This idea was introduced by James et al. (1988), whose research confirmed that the offset dependent variation of peak frequencies for both P-wave and mode-converted S-wave reflected from a thin layer will be different from the case of a single interface. In our research, this idea will be extended to discriminate thin-layer crack density. The thin-layer fractured reservoir is represented by a transversely isotropic medium with a horizontal symmetric axis (HTI) using the equivalent medium theory (Liu et al., 2000).

First, the models of with different crack densities are constructed using the equivalent medium theory and full-wave synthetics is calculated through pseudo-spectral wave fields modelling. This is followed by the application of Fourier transform to the reflected P-wave and mode-converted S-wave separately. Finally, offset-dependent peak frequencies are extracted from the spectrums and analyzed for the purpose of crack density discrimination.

Examples

We consider a thin fractured sandstone reservoir with vertically aligned cracks and background P and S wave velocities α=3300 m/s, β=1800 m/s, and density ρ=2200 kg/m^3. The thin reservoir is embedded in a background isotropic medium with the P and S wave velocities α_0=2800 m/s, β_0=1400 m/s, and density ρ_0=2100 kg/m^3. The cracks have an average aspect ratio of 0.01. The thin layer is located at the depth of 500 m and the geometry has an offset up to 2000 m, which corresponds to the maximum reflection angle of 63^0. An Ricker source wavelet is used with a dominant frequency of 40 Hz.

For comparison, we firstly generate the seismic synthetics for two models with different thickness of reservoirs which have the same crack density of 0.15. One of them has an infinite thickness representing the single interface reflection, and the other has a finite thickness of 40 m corresponding to a thin bed reflection. Synthetic seismograms and the relevant spectrum for both P-P and P-S waves are shown in Figures 1 and 2, respectively. Obviously, the spectrums of thin bed reflection have specific features which are very different from the case of single interface.

We then concentrate on the analysis of offset-dependent frequency characteristics for the purpose of crack density discrimination. Peak frequencies shown in Figure 3 are extracted from the spectrums in Figures 1 and 2. Figure 3a indicates that, for the single interface model, peak frequencies of P-P and P-S reflection wave is almost the same, except the dramatic increase in the peak frequency of P-P wave at offset about 700 m, corresponding to a polarity reversal on the reflected P-P event (Figure 1a). However, for the case of thin layer reflection, peak frequencies for both P-P and P-S waves have their own specific trends and deviate from each other, which are very different from the single interface. This reveals the potential to obtain more information of the thin fractured layer by analyzing the offset-dependent frequency characteristics of the reflections from the thin reservoir.

We design fractured thin layered reservoirs with a series of crack densities ε of 0, 0.05, 0.10, 0.15, and 0.20. Figure 4 shows AVO response from these thin beds, which are calculated from the spectrums of the full-wave synthetics (Skopintseva et al., 2009). Each AVO response is normalized by corresponding maximum value. As shown in Figure 4a, the AVO responses of P-P waves for models with different crack density show a similar trend of variation, and there are no diagnostic features among them. Therefore, it is very difficult to use the traditional PP AVO cross-plotting (Richard et al., 2004) to discriminate crack density. In contrast, as shown in Figure 4b, there is a shift of peak amplitude of the mode-converted P-S reflection waves as the crack density changes. The offset corresponding to the peak amplitude shifts from 690, to 810, 1000, and 1110 m, as crack density increases from 0.05, to 0.10, 0.15, and 0.20. The offset-dependent amplitude corresponding to crack density $\varepsilon =0$ has a different trend from other crack densities.

Figure 5 shows the shift of peak frequencies with offset for both P-P and P-S waves reflected from the fractured thin layers with crack densities ε : 0, 0.05, 0.10, 0.15, and 0.20. Peak frequencies of P-P waves increase dramatically at the offset corresponding to polarity reversal. Moreover, the bandwidth of P-P wave peak frequencies increases with crack density, which may also be used to discriminate crack density. Peak frequencies of P-S waves show a simple increasing trend with crack density and offset until a critical offset where the peak frequency drops sharply. This phenomenon deserves further investigation.

By correlating offset-dependent peak frequencies of P-P and P-S wave shown in Figure 5, we obtain the scattergram illustrated in Figure 6 for the discrimination of crack density. The discriminating feature is the separation of the points for various crack densities into different regions of the scattergram (Figure 6). The points of a certain colour correspond to a fixed crack density and a variation in geophone offset position. Figure 6a shows the correlation for the near offset from 0 to 500 m, and Figure 6b illustrates the correlation for far offset from 1200 to 1700 m. The criteria for offset selection are to avoid the critical offset where the peak frequency drops sharply. As shown in Figure 6, the crack densities can be better discriminated in the far offset scattergram than the near offset.

Conclusions

We have carried out a study of the frequency characteristics of thin bed AVO response of both P-wave and mode-converted S-wave in order to distinguish the variation of crack density of thin fractured reservoirs. Our study shows that it is possible to discriminate the variation of crack density of fractured thin layer using the offset-dependent shift of peak frequency of the reflected P-P wave, and the correlation of the frequencies of P-P and P-S waves. Further research should include the explanation of the meanings of dramatic change in peak frequencies at a certain offset for both P-P and P-S waves, which may offer us further opportunity for the estimation of properties within thin layer.

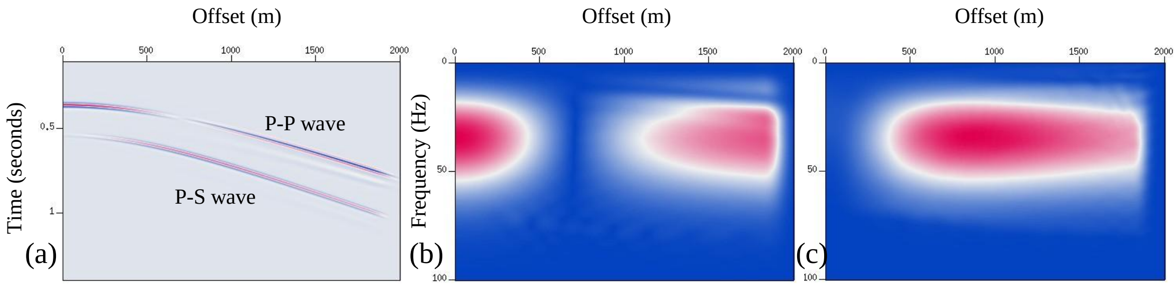

Figure 1: *(a) Seismogram for single interface model. (b) Spectrum of P-P wave in seismogram (a). (c) Spectrum of P-S wave in seismogram (a).*

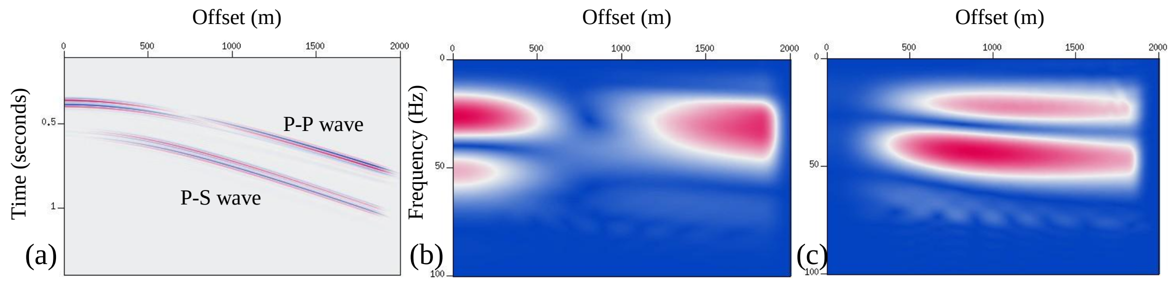

Figure 2: *(a) Seismogram for cracked thin reservoir model with a thickness of 40m. (b) Spectrum of P-P wave in seismogram (a). (c) Spectrum of P-S wave in seismogram (a).*

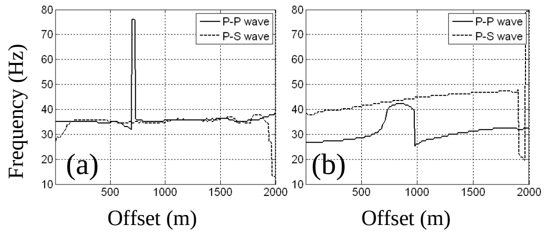

Figure 3: *(a) The peak frequencies of waves reflected from a single interface. (b)The peak frequencies of waves reflected from a cracked thin layer with a thickness of 40 m. Solid lines correspond to P-P waves and dashed lines represent P-S waves.*

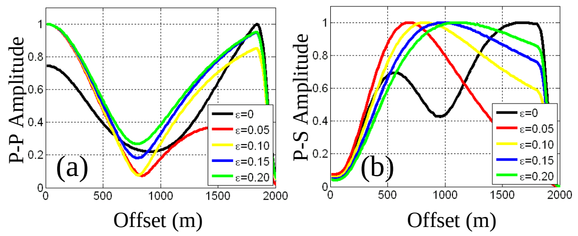

Figure 4: *AVO responses of P-P and P-S waves reflected from a cracked thin bed with a thickness of 40 m. Crack density varies from 0 to 0.20. (a) AVO response of P-P waves. (b) AVO response of P-S waves.*

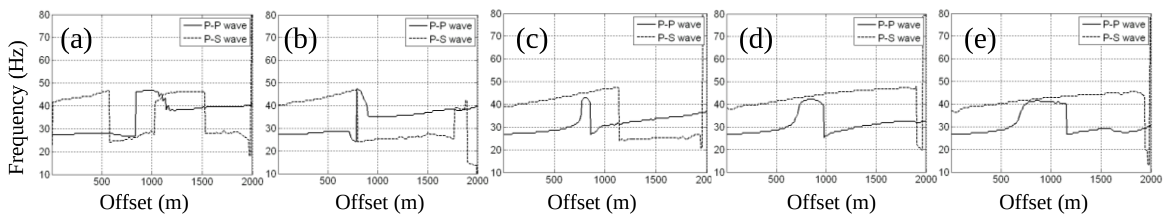

Figure 5: *The peak frequencies of waves reflected from a cracked thin layer with a thickness of 40 m. (a),(b),(c),(d) and (e) corresponds to the crack density of 0, 0.05, 0.10, 0.15, 0.20, respectively. Solid lines correspond to P-P waves and dashed lines represent P-S waves.*

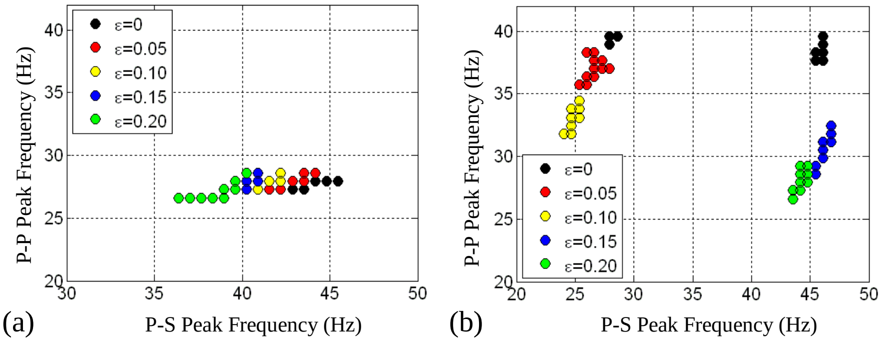

Figure 6: *Scattergrams of the offset-dependent peak frequencies of P-P waves versus the peak frequencies of P-S waves corresponding to Figure 4. The fractured thin layers have the crack density of 0(black), 0.05(red), 0.10(yellow), 0.15(blue), and 0.20(green).The points of a certain colour correspond to a fixed crack density and a variation in geophone offset position. (a) corresponds the case of the near offset from 0 to 500 m, and (b) the far offset from 1200 to 1700 m.*

Acknowledgements

This work is sponsored by the sponsors of the Edinburgh Anisotropy Project, and is presented with the permission of the Executive Director of British Geological Survey (NERC).

References

Carcione, J.M. [2001] AVO effects of a hydrocarbon source-rock layer. *Geophysics* **66**(2), 419-427.

James N. Lange, and H. A. Almoghrabi. [1988] Lithology discrimination for thin layers using wavelet signal parameters. *Geophysics* **53**(12), 1512-1519.

Jingye Li, Xiaohong Chen and Rao Huang. [2009] Seismic AVO modelling and analysis for thin inter-layer reservoir. *79th Annual International Meeting, SEG*, Expanded Abstracts, 316-320.

Liu, E., J. A. Hudson, and T. Pointer. [2000] Equivalent medium representation of fractured rock. *Journal of Geophysical Research* **105**, 2981-3000.

Liu, Y. and Schmitt, D.R. [2003] Amplitude and AVO responses of a single thin bed. *Geophysics* **68**(4), 1161-1168.

Marmalyevskyy, N., and Y. Roganov. [2006] Frequency depending AVO for a gas-saturated periodical thin-layered stack. *76th Annual International Meeting, SEG*, Expanded Abstracts, 274-278.

Richard L., and Gibson, Jr. [2004] Composite reflection coefficients for stratified reservoir models. *74th Annual International Meeting, SEG*, Expanded Abstracts, 267-270.

Skopintseva, L.V., Ayzenberg, M.A., LandrØ, M., Nefedkina, T.V., and Aizenberg A.M. [2009] Testing the performance of AVO inversion based on effective reflection coefficients on long-offset synthetic PP data. *71 th EAGE Conference & Exhibition*, Extended Abstracts, S022.

Ursin, B. and Stovas, A. [2002] Reflection and transmission responses of a layered isotropic visco-elastic medium. *Geophysics* **67**(1), 307-323.