Characterization of azimuthal anisotropy in the presence of thin layers using P-Waves

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Summary

In this paper, we study the effect of thin layers on the AVAZ analysis using synthetic modelling. A range of models are constructed by sandwiching a thin-layered reservoir with different thickness between two isotropic layers. Azimuthal gathers are calculated for each of these thin-layered models. After we apply azimuthal AVO analysis to the synthetics, we find that fracture orientation and intensity can be estimated accurately if the thickness of the thin layer is larger than a quarter of the wavelength. However, there are large discrepancies in the orientation and intensity estimates. We finally present a new procedure to improve the detectability of azimuthal anisotropy in the presence of thin layers.

Introduction

Rocks with aligned vertical fractures give rise to azimuthal anisotropy in seismic data, and the recorded P-wave amplitudes show an elliptical variation with azimuth. The direction of the axis indicates the fracture orientation, and the ratio of the long to short axis is related to the fracture density. The attribute (amplitude and travel time) variation with azimuth (AVAZ) may therefore potentially be used to estimate fracture parameters (orientation and intensity) (e.g. Mallick and Frazer, 1991; Lefeuvre, 1994; Lynn et al., 1997; Ramos and Davis, 1997; Pérez et al., 1999) and many methods have been developed(e.g. Li, 1997; Liu et al., 1999).

However, these methods assume that distinct reflections from the top and bottom of reservoirs can be clearly identified. If a reservoir is thin, reflections from the top and bottom will interfere and may not be separated. Slack(1993), Grechka(1998), Dong(1999) and Schoengbeg(1994, 1999) demonstrated that thin reservoirs may still be dectable using AVO analysis. In this paper, we investigate the effect of reservoir thickness on the AVA analysis using synthetic seismograms. We demonstrate that thin layers can have a serious effect on P-wave AVAZ, and we propose a new procedure to improve the detectability of azimuthal anisotropy in the presence of thin layers.

P-wave AVAZ and the effect of thin layers

A noise-free seismic trace recorded on the surface can be written as

$$S(t) = R_{pp}(t) * W(t), \tag{1}$$

where $R_{pp}(t)$ is the reflection coefficient series, $W(t)$ is the wavelet. In the conventional AVO (or AVAZ) analysis, $S(t)$ is normally used to replace $R_{pp}(t)$, and picked from seismic data. However, there are interferences between reflections at successive intervals. This interference makes it very difficult to pick up the reflections from the top and bottom of reservoirs when the reservoirs are thin.

In a reservoir with fracture-induced azimuthal anisotropy, $R_{pp}(t)$ and $S(t)$ become $R_{pp}(t,\,\varphi)$ and $S(t,\,\varphi)$, respectively (φ denotes the azimuth), and the orientation and intensity of fractures may be estimated from Ω_R or Ω_S defined as

$$\Omega_R = \frac{R_{pp}(t,\varphi_3) - R_{pp}(t,\varphi_1)}{R_{pp}(t,\varphi_4) - R_{pp}(t,\varphi_2)}, \tag{2}$$

$$\Omega_S = \frac{S(t,\varphi_3) - S(t,\varphi_1)}{S(t,\varphi_4) - S(t,\varphi_2)}, \tag{3}$$

where φ_1, φ_2, φ_3 and φ_4 are the azimuths of four orthogonal lines intersecting at a common point. If $\Omega_R = \Omega_S$, we may use the amplitudes picked directly from seismic traces to estimate fracture parameters. P-wave interval traveltime $\Delta T_{pp}(t,\,\varphi) = T_{pp}(t_{bottom},\,\varphi) - T_{pp}(t_{top},\,\varphi)$ can also be used if

$\Delta T_{pp}(t, \varphi)$ can be reliably obtained. However, in practice it is almost impossible to have $\Omega_R = \Omega_S$ or have reliable $\Delta T_{pp}(t, \varphi)$ when the thickness of the reservoir layers is less than a certain value.

Synthetic modelling

To investigate the effect of thin layers, we use a simple model made of three flat layers to generate synthetic seismograms. A fractured gas sand is sandwiched between two isotropic layers (Figure 1a). The fracture strike is along the direction of $\varphi = 90^o$. We fix the thickness of Layer 2, and use a 3250m spread with 50m interval to construct full-wave synthetic seismograms using the reflectivity method (Taylor, 1990). Six CDP gathers are generated along six azimuths at 0^o, 15^o, 60^o, 90^o, 105^o, and 150^o. The thickness of Layer 2 is set to be between 0.02 and 20.5m and between 20.5 and 1100m using equations $thick_k = thick_{k-1} * 2$ and $thick_n = thick_{n-1} * 1.23$, respectively. A total of 30 models is used, and 180 seismograms are generated (Figures 1b and 1c).

Error analysis

The gathers are first sorted by thickness, and then by offset. We use azimuthal variation of P-wave amplitudes to estimate fracture orientation and intensity for every offset group in each model. This is repeated over all the models, and finally two 3D diagrams are produced (Figures 2a and 2b). Figure 2a shows that the estimated fracture orientation from the CDPs with thickness greater than 30m are almost the same as the true value (90^o), whereas for the CDPs with thickness less than 30m, there are large discrepancies between the estimated value of the fracture orientation and the true value. A similar conclusion can be drawn for the fracture intensity estimation, as shown in Figure 2b (the true intensity value is 7%). Error analysis in Figures 2a and 2b confirms that there exists a limit beyond which the estimation of fracture parameters is not reliable. This is consistent with the minimum resolution limit, i.e. $\lambda/4 = 22$m in our synthetic case. Here λ is the wave length with centre frequency of 25 Hz, wave speed of 2180m/s.

It is known that amplitudes of seismic waves are very sensitive to noise. We add 50% of random noise to the synthetic data and then apply the AVAZ technique to estimate fracture parameters. Subtracting the model parameters from the estimated values yields two error diagrams, as shown in Figure 2c and 2d. The histograms in the error diagrams show that the estimated values are still close to the true values. This means that the AVAZ technique used for estimation of fracture parameters is not sensitive to random noise. We find that noise can make it difficult when thin layers are present, but the effect of thickness is a more sensitive issue than noise.

Compensation for the effect of thin layers in AVO/AVAZ analysis

We present here a new procedure to improve the detectability of thin fractured layers. It is noted that the azimuthal variation of P-wave amplitudes or $\Delta T_{pp}(t, \varphi)$ is an ellipse for fracture-induced azimuthal anisotropy, and if we add a constant to this ellipse, its basic shape will be similar and the directions of the long and short axis of the ellipse will not change, but the ratio of the long to the short axis will be smaller. This forms the basis of our new procedure. In a four-layer model as shown in Figure 3a, we assume that the target layer, Layer 2, is a thin layer (i.e. $\leq \lambda/4$), and below a reasonable depth the variation in P-wave raypaths to the top and bottom of the target with azimuth for a fixed offset is very small. In other words, the traveltime for the raypath to the bottom of the new target layer (Layers 2+3) equals the traveltime in the thin layer (true target) plus a constant travel time which is the travel time in the isotropic layer. We can then apply the AVAZ technique to the new target layer (Layers 2+3), and this will give the same information about the fracture orientation as the true target (Layer 2). If Layer 3 is properly selected, there should be no difficulty to pick $\Delta T_{pp}(t, \varphi)$.

To test this idea, 180 synthetic CDPs are generated (Figure 3b), with 25% random noise added to the synthetic seismograms. we can see that the top and bottom reflections are still evident for Layer 2+3 even when the thickness of the Layer 2 is smaller than $\lambda/4$ and the reflections from the top and bottom cannot be identified. We use the traveltime from the top and bottom of Layer 2+3 to estimate fracture orientation and density, and find that the error (estimated value - true value) in orientation is less than $\pm 10^o$ (average error of 0^o) (Figure 3c). This shows that our method is reliable and can be used to estimate fracture orientation even if the thickness of the target layer is as thin as 10 m ($\lambda/8$ in our case). The error (estimated value - true value) in intensity is between -7% and -4% (average error of -5.5%) (Figure 3d). The reason for the large discrepancy between the estimated average intensity (1.5%) and the true value (7%) is that the isotropic Layer 3 essentially dilutes the effect of the fractures. Interestingly, this discrepancy and the calculated strike values are stable for all the models in which the thickness of Layer 2 ranges from 10 to 600m. This means that the estimation errors are invariant and independent of the thickness of thin layers, but are related to the underlying layers.

Conclusions

Our study shows that if there is an isotropic layer below a target reservoir (i.e. a fractured thin reservoir), our proposed procedure can give a good estimate of fracture orientation of the target and also a stable fracture density. Error analysis shows that our procedure is not sensitive to random noise and it can provide reliable information about fracture orientations and density even if the thickness of reservoirs is as low as $\lambda/8$.

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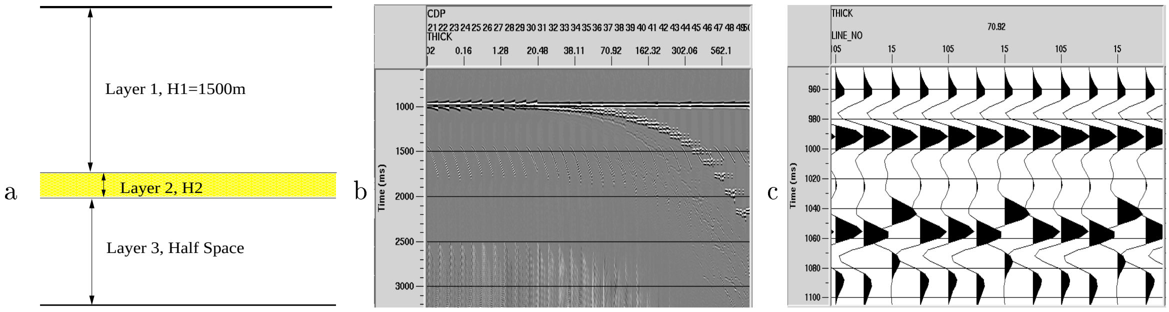
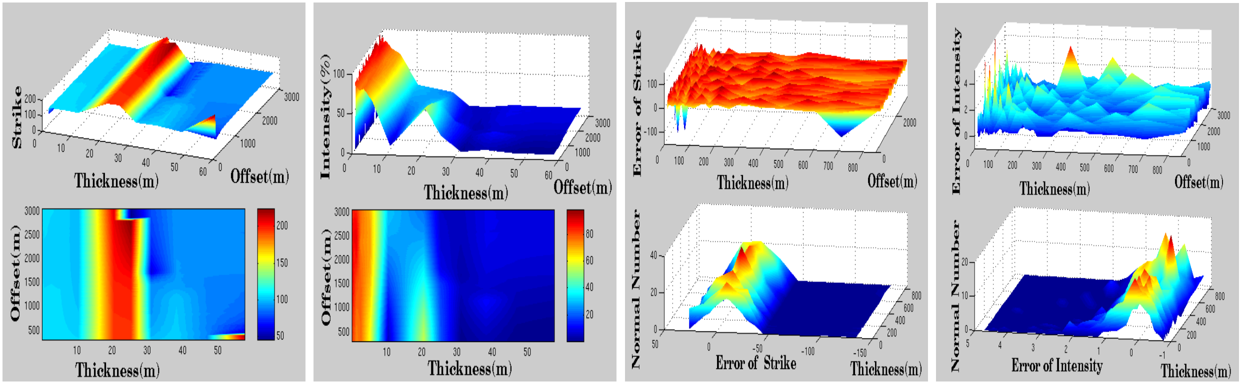
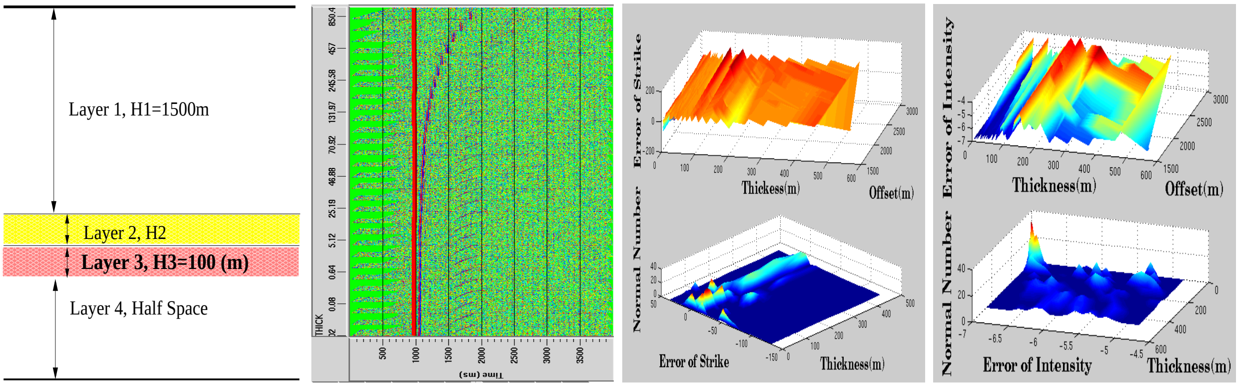


Figure 1: (a) Geological model used in the study. Layer 2 is a fractured gas reservoir. (b) NMO gathers of the 180 synthetic records corresponding to 30 models of Layer 2. (c) Zoom-in of (b).



a **b** **c** **d**

Figure 2: The calculated fracture strike (a) and intensity (b) values from the synthetic data for a layer thickness from 0 to 60m. Both of the values from models with thickness greater than 60m are a constant. The detected fracture strike (c) and intensity (d) results from the synthetic data with 50% random noise.



a **b** **c** **d**

Figure 3: (a) a four-layer geological model. Layer 2 is the fractured reservoir and Layer 3 is a thick fixed isotropic layer. (b) 180 CDPs with 25% random noise at six azimuths for 30 different thicknesses of Layer 2. Error diagrams of strike (c) and intensity (d) are calculated from synthetic data displayed in (b).