AVO waveform inversion for estimating the fluid contact with fluid transition zone

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The fluid distribution in the hydrocarbon reservoir affects waveforms acquired in seismic reflection method. A reflected wave changes its waveform at the transition zone of the interface of two different fluids as a function of volume fraction of the two. AVO is in general used to estimate the difference in the P and S wave velocities for the interfacing two media at the interface without any assumptions on the existence of the transition zone. The consideration of the effect of the volume fraction of a fluid to the other in the waveform could be a key for evaluating the fluid mixture around the fluid contact in the reservoir. Therefore, we try to use the waveform directly to estimate fluid distribution in the transition zone that has not been done in the practice of AVO. In our research, we consider the effects of the transition zone at a gas-water contact (GWC) in a horizontally stratified medium on seismic waveforms. The numerical simulation reveals that the fluid distribution of transition zone distorts the seismic waveform both in amplitude and in phase. We developed a full-waveform AVO inversion method to apply to the fluid substitution problems to see if the method is applicable to estimate the fluid contact with the transition zone, while the conventional AVO only utilizes the amplitude derived from observed data. The simulation results imply the advantages in the estimation of the parameters including the thickness of the transition zone under that assumption of linear trend in the volume fraction in a contrast porosity condition. We suggest that the phase information should be used simultaneously for the inversion process to get the closer contact image.

1. INTRODUCTION

Time-lapse survey is one of the fluid monitoring methods using seismic reflection survey. The fluid distribution change in the hydrocarbon reservoir affects the observed waveform at the surface receivers. To estimate the fluid distribution, the attribute analysis is used with the observed data¹⁾. This analysis applies a statistical process to the receiver data to evaluate the fluid property. We can use the relationship for estimating how the fluid moves with the oil and gas production. However, physical relationships between the fluid distribution and the observed waveform are not considered in this method.

The AVO inversion estimates the reflection contact in the subsurface reservoir. The conventional AVO inversion estimates the elastic parameters, P-wave velocity, S-wave velocity and density, with the maximum amplitude of the PP-reflected wave derived from the observed waveform data under the assumption of the horizontally stratified fluid contact. The fluid contact in the reservoir has a complicated fluid distribution and the fluid transition zone distorts the reflected waveform. Since this causes the

misinterpretation for the evaluation of the hydrocarbon potential, the distortion of the reflected wave due to the fluid transition zone should be considered in the AVO inversion.

In this paper, we first confirm the effect of the fluid transition zone on the reflected waveform. Then we try to use the waveform difference for fluid contact estimation with a full-waveform AVO inversion based on the GLI method. We consider the effective magnitude of noise for reliable estimation using our AVO inversion method.

2. THEORY

(1) Elastic and fluid parameter

We simulate the wave propagation using an elastic finite-difference method. In order to derive the seismic waveform changed with the fluid alteration, we use the Gassmann's relation. The inclusion-based model can consider the fluid and solid phase as the elastic parameter. In this paper, we assume the fluid contact with a transition zone. The bulk modulus K_f and density ρ_f of fluid mixture is calculated by the Reuss and Voigt average of two fluid saturation ratios f_i .

$$\frac{1}{K_f} = \sum_{i=1}^N \frac{f_i}{K_i} \quad (1)$$

$$\rho_f = \sum_{i=1}^N f_i d_i \quad (2)$$

(2) AVO inversion based on GLI method

The GLI (Generalized Linear Inversion) method is an iterative inversion procedure which updates the calculation model parameter minimizing the misfit derived from the calculation and true model⁽²⁾. We assume that the transition zone affects the seismic waveform. The AVO inversion uses the maximum amplitude, A_θ with the incident angle θ , of PP-reflected wave. When the amplitude is changed by the elastic velocities and thickness of the transition zone, the misfit function E is calculated using the partial differential term,

$$E = \sum_{\theta} \left(\Delta A_{\theta} - \frac{\partial A_{\theta}}{\partial V_{P2}} \Delta V_{P2} - \frac{\partial A_{\theta}}{\partial V_{S2}} \Delta V_{S2} - \frac{\partial A_{\theta}}{\partial D} \Delta D \right)^2 \quad (3)$$

where V_{P2} and V_{S2} are the elastic velocities of the layer under the transition zone and D is the thickness of the transition zone. ΔA_{θ} means the subtraction of the amplitude of the true model and calculation model and ΔV is the value of the model updating. The updating value is calculated for minimizing the misfit function by the least-square technique. In this paper, we assume that the transition zone condition is known such as fluid mixture law (determined by Reuss and Voigt average) and the linearity of fluid alteration.

(3) Full-waveform AVO inversion

The fluid transition zone mainly influences the change in the phase of the reflected wave. To use the time series data, we propose an advanced AVO inversion method. The misfit function using the amplitude of a certain time t is written as below;

$$E = \sum_t \sum_{\theta} \left(\Delta A_{\theta,t} - \frac{\partial A_{\theta,t}}{\partial V_{P2}} \Delta V_{P2} - \frac{\partial A_{\theta,t}}{\partial V_{S2}} \Delta V_{S2} - \frac{\partial A_{\theta,t}}{\partial D} \Delta D \right)^2 \quad (4)$$

With the same procedure in the case of the maximum amplitude, we calculate the update parameter by minimizing the misfit function. In this method, we can use PP-reflected wave and PS-converted wave simultaneously.

3. SIMULATION RESULT

Figure 1 shows the calculation model used in this paper. The model is 4000m x 2000m composed of shale in the upper layer and sandstone in the lower with a contact at the depth of 1500m. The shale is saturated with water. The sandstone is saturated with gas in 1500m-1510m, and from the depth of 1510m, the transition zone begins at the gas-water contact (GWC). The gas is lineally alternated by water in this zone. The source and 60

Table 1 Rock property

	Shale	Sandstone
Bulk modulus (GPa)	10	35
Sheer modulus (GPa)	5.1	5.9
Density (g/cm ³)	2.6	2.6
Porosity	0.1	0.2

Table 2 Fluid property

	Water	Gas
Bulk modulus (GPa)	2.25	0.022
Density (g/cm ³)	1.0	0.1

Figure 1 Calculation model: At the depth of 500m, X represents the source and a thick line is a receiver array. The contact of shale and sandstone is at the depth of 1500 m.

receivers per 50m are set at the depth of 500m. To ignore the effect of the reflected wave from the model boundaries, we assume the absorbing boundary at all the four edges. We used the rock and fluid properties shown in **Table 1** and **2**.

(1) Wave form change with transition zone

We obtained the waveform data from different transition zone model; model 1 has no transition zone, model 2 and 3 have the transition zone of 10m and 40m thickness, respectively. **Figure 2** shows the maximum amplitude of PP-reflected wave observed at each receiver (the value is normalized by the amplitude of each incident wave). The amplitude changes at most 7% in model 2 and 35% in model 3, compared with no transition zone model. **Figure 3** shows the traveltime lag of the PP-reflected wave. We compared the lag of model 2 and 3 data subtracted from model 1 data. The traveltime delay is 3-5ms in model 2 and 12-25ms in model 3. **Figure 4** shows the phase delay of waveforms observed by the model 1 and 3 in the frequency domain. The gradient of the figure represents the time delay.

The forward simulation shows that the transition at the GWC changes the reflected waveform. We can use this change for estimating the GWC property, elastic parameters and a thickness of transition zone by AVO inversion.

(2) Estimation of elastic parameters and thickness of the transition zone

Figure 2 Amplitude changes by the offset (+: no transition zone, circle: 10m thickness, square: 40m thickness)

Figure 3 Time delay from the waveform of no transition zone model (circle: 10m thickness, square: 40m thickness)

Figure 4 Phase delay between 0m and 40m thickness transition zone model in the frequency domain.

In chapter 2(3), we explained the AVO inversion with full-waveform. The reflected waveform has the effect from the GWC as the changes in the amplitude and phase, so we can apply the full-waveform AVO inversion to estimate the GWC. We applied our inversion method to the observed data derived from the 40m-thick transition zone model. The result (Table 3) shows the 3 estimated parameters are close to the true ones. Figure 5 shows the decrease of the misfit function. Figure 6 shows the waveform residuals between the data of the initial and true model (upper) and of the estimated and true model (lower). The residuals became almost zero by 8 iterations.

(3) Estimation with the data including noise

Table 3 AVO inversion result

	True model	Initial model	Inversion result
P-wave velocity (m/s)	3126	3500	3127
S-wave velocity (m/s)	1245	1267	1245
transition zone thickness (m)	40	60	40

Figure 5 Misfit function

Figure 6 Waveform residuals subtracted by the observed (true) waveform: the initial (upper) and the inversion result (lower)

The AVO inversion using all waveform data has an advantage for applying it to the noise-included data. We apply the two AVO inversion methods, using the conventional PP-wave amplitude and all waveform to the data including 10 % noise for the maximum amplitude at each receiver. Table 4 shows the inversion result. Although the conventional amplitude inversion estimated different value from the true parameters, the full-waveform AVO inversion estimated almost the same value. The increased amplitude with noise led to the wrong parameters shown in Figure 7. The full-waveform AVO inversion minimizes the misfit

Table 4 AVO inversion result (data with 10% noise)

	True model	Amplitude inversion	full-waveform inversion
P-wave velocity (m/s)	3126	3135	3126
S-wave velocity (m/s)	1245	1240	1245
transition zone thickness (m)	40	39	39

Figure 7 Amplitude per incident angle; +: observed data without noise, X: observed data with 10% noise, triangle: inversion result **Figure 8** Waveform residuals of estimated subtracted by the observed waveform with 10% noise **Figure 9** Misfit function in 3(3); solid line: noise free, long dashed line: 10% noise, dotted line: 20% noise, short dashed line: 24% noise (finished in 2 iterations)

function calculated by all receiver data, causing the better result (**Figure 8**). We also apply the full-waveform AVO inversion method to the data with different value of noise. We confirmed that the inversion is effective for 20% noise data, but in the case of 24% noise, the misfit function increased and the inversion didn't converge. We show the waveform residuals of the true with noise and

Figure 9 Waveform residuals of estimated subtracted by the true waveform with 20% (upper) and 24% (lower) noise.

estimated model in **Figure 9**.

4. CONCLUSION

We proposed an estimation method for the thickness of transition zone around a GWC and demonstrated the effectiveness of the method. The fluid distribution changing linearly with depth affects the amplitude and phase of the reflected waveform. Our AVO inversion for the full-waveform data can make best use of the whole change of the waveform. We applied the conventional amplitude method and full-waveform method to the synthetic data distorted by noise. The result showed that the full-waveform AVO inversion estimates closer value to the true model than the conventional one.

In this paper, we assumed an ideal model with stratified layers to focus on the confirmation of our AVO inversion method. It is necessary to apply this method to more complicated model such a case as the nonlinear fluid distribution in the transition zone or the fluid mixture law. The rock physics would assist this inversion method to estimate more complex reservoir.

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