Amplitude versus angle (AVA) using controlled-order multiples

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Summary

Similar to primary reflections, multiples also carry the amplitude versus angle (AVA) information. An alternative approach is proposed to estimate the amplitude changes of multiples with respect to incident/reflection angles. The method is referred as multiple amplitude versus angle (mAVA), with which, the multiples are first decomposed into different orders using the surface-related multiple elimination (SRME). Then, the amplitude change with incident angle for a specific-order multiple is measured based on a wavefield angle decomposition method. The dip angle of the reflector is obtained from the image generated by multiples. From these, the multiple reflection angle can be estimated, and the related angle domain common image gathers are obtained. After illumination correction, we can obtain the mAVA for analysis in the cross-plot domain. Numerical examples are provided to demonstrate the AVA analysis using surface multiple data.

Introduction

The amplitude versus angle (AVA) analysis attempts to use information carried by angle-dependent reflectivity to detect anomalous velocity and density contrasts across an interface (Foster et al., 2010; Castagna et al., 1998). It was originally introduced (Ostrander, 1982) as a technique for evaluating seismic amplitude anomalies associated with attributes of media. Rutherford and Williams (1989) analyzed the gas-related bright spots by stacking traces within certain offset ranges (thus related to certain incidence angles). A traditional procedure for AVA analysis examines the alignment of images with multi-offset data. This method worked well for flat structures. However, if seismic signals reflected from the reservoir passing through complex overburden structures, they are likely be distorted. On the contrast, if the surface seismic data are migrated into the target area, the propagation effects including the geometric spreading and attenuation can be properly removed (Mosher, 1996). In particular, if the target dipping angle and the local incident angle can be determined, the local AVA analysis can be applied to the migrated wavefield right at the target. This can replace the surface AVA analysis with greater accuracy and flexibility (Yan and Xie, 2012).

Conventional AVA analyses are dominantly applied to the primary reflections (Wang, 1999). Multiple reflections overlapped with the primaries corrupt seismic amplitudes, resulting in difficulties in AVA analysis and the following stratigraphic interpretation. As a result, multiple removal is often a necessary step for subsequent AVA analysis. However, multiples used to travel longer paths, illuminate a wide area where primaries cannot reach, and carry more subsurface information. Recently, multiples have been used in the depth imaging (Liu et al., 2011). If multiples can be included in the AVA analysis, they would improve the AVA results dramatically.

In this paper we regard multiples as signals rather than noise and propose a novel method to extract true-amplitude angle-domain common image gather of multiples (mADCIG) for multiple amplitude versus angle (mAVA) analysis. The multiples are first decomposed into different orders using SRME (Verschuur et al., 1992). The specific-order receiver-side multiple wavefields are migrated from the virtual source into the target area using full-wave reverse-time propagator, followed by being decomposed into angle components along all directions to construct the local image matrix (LIM) (Xie and Wu, 2002; Sava and Fomel, 2003; Xu et al., 2011). The LIM relates to local medium parameters across the interface, but also affected by the propagation effects and acquisition footprint. The mADCIG and reflection-angle-dependent illumination are extracted from the LIM and target illumination matrix. Corrected by the corresponding illumination, the mADCIG becomes true-amplitude and gives the correct mAVA information.

Decomposing multiples into different orders

If multiples can be separated into different orders and properly paired, the artifacts from crosstalk can be avoided. The following workflow presents a step-by-step approach to predict a specific-order multiple (Liu et al., 2016):

1) Predict the primaries and multiples of all orders by the surface-related multiples elimination.
2) Convolve predicted primaries with multiples in time domain to generate higher-order multiples
3) Adaptively subtract jth-order multiple from j+1th to estimate an isolated order multiples.
4) To predict other higher-order multiples, repeat steps 1 to 3.

Multiple amplitude common imaging gather

To conduct the mAVA analysis, we must estimate dipping angle of the target reflector. Reverse time image from multiples is extracted to determine the local dipping angle of
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The reflector. Similar to primaries, multiples can be used for characterizing the rock properties using mAVA analysis. When multiples are isolated into several orders, a great number of receivers are converted to virtual sources. We target to investigate the mAVA feature of multiple reflection and extrapolate the multiple data with controlled order RTM (Figure 1). First, the time-domain multiple wavefields are transformed to frequency domain, followed by being decomposed into local plane waves using slant stacking:

\[ u(x, \omega, \theta) = \int W(x - x') u(x', \omega) e^{i \omega p (x - x')} dx', \]

where \( u(x', \omega) \) stands for either source or receiver side multiple wavefield and \( u(x, \omega, \theta) \) is the decomposed local angle domain wavefield propagating along the slowness vector \( p \) towards \( \theta \). The local angle domain imaging condition using controlled order multiples is defined by

\[ I(x, \theta, \theta_g) = \int d\omega u(x, \theta, \omega) u_\omega(x, \theta_g, \omega), \]

where \( \theta_g \) (Figure 1) is the local incident angle, \( \theta_g \) is the local scattering angle, \( \omega \) is frequency, \( u_\omega \) is virtual source forward propagated wavefield, and \( u_\omega \) is virtual source back propagated wavefield. This common multiple reflection angle gather should be corrected with the local illumination function \( I_F(x, \theta, \theta_g) \) in the form of \( I(x, \theta, \theta_g) = I(x, \theta, \theta_g) / I_F(x, \theta, \theta_g) \) (Figure 1). Since the illumination function is rather complex, the multiple imaging condition can be approximated by the source side illumination \( S(x, \theta_g) = \int d\omega u_s(x, \theta_g, \omega) u_\omega(x, \theta_g, \omega) \), in the form of

\[ I(x, \theta, \theta_g) = I(x, \theta, \theta_g) / S(x, \theta_g). \]

As a result, we acquire the true amplitude common multiple reflection angle gather by

\[ R(x, \theta) = \int_{\theta_g \theta_g} d\theta_g d\theta_g \delta (\theta - \theta_g) I(x, \theta, \theta_g). \]

To illustrate the relationship between the partial image \( I(x, \theta, \theta_g) \) as a function of incident and scattering angles, the structure of a 2D local imaging matrix (LIM) is shown in Figure 2, where the horizontal and vertical axes are the incident and scattering angles, while the two diagonals are the multiple reflection and dipping angles. For a locally planar reflector, the energy is distributed along a strip in the LIM. If the reflector is horizontal, the strip is located along the main diagonal of the LIM. If it is dipping, the intersection of the energy strip and the dipping axis gives the dipping angle of the planar reflector (Xie et al., 2006). For diffractors, or scatterers other than a locally planar, the energy will be more scattered over the LIM and leads to complex patterns.

Amplitude versus multiple angle (mAVA) estimation

With known incident angle from the virtual source and dipping angle of the structure, we can obtain the first-order multiple scattering angles. To create angle domain common imaging gather for multiples (mADCIG), we project the multi-frequency source and receiver waves along incident and scattering directions using local slant stacking equation 2. After obtaining the directional source and receiver waves, we can form the angle-domain partial images for multiples and map it from \( \theta_\omega / \theta_g \) domain to reflection angle \( \theta_\omega \) domain based on the Figure 2. Finally, the mAVA response is obtained by correcting mADCIG with the illumination. For small incidence angles, usually less than 30 degrees, the reflectivity of the compressive wave can be expressed by the Shuey approximation (Shuey, 1985):

\[ R(\theta) = A + B \sin^2(\theta), \]

where \( A \) is the normal incident P-wave reflectivity and \( B \) is the gradient, and \( \theta \) is the reflection angle. For an interface crossing which the velocity and density contrasts are small, the intercept and slope can be approximated by (Foster and Keys, 1999; Foster et al., 2010)

\[ B = (1 - \theta_\omega^2)A + 4\theta \Delta \rho + (4\theta^2 - 1)(\Delta \rho / 2\rho), \]

where \( \gamma = V_s / V_p \). For \( V_s \) and \( \rho \) are average P- and S-wave velocities and density. \( \Delta \rho \) and \( \Delta \rho \) are perturbations across the interface, respectively. In a crossplot of \( A \) versus \( B \), if there is little change in \( \gamma \), the reflection tends to fall on the fluid line

\[ B = (1 - \theta_\omega^2)A. \]

From equation 6, the key elastic properties controlling the angle dependent reflectivity are the acoustic-impedance contrast and the contrast in \( \gamma \). Compared with the original reflectivity curves, using intercept A and slope B is a concise and intuitive way to represent mAVA behavior. Shown in Table 1 are elastic parameters of shale and nine types of reservoirs. The corresponding nine pairs of intercepts and slopes are calculated by equations 4 and 5 and are shown in crossplot in Figure 3, where the dashed line indicates the fluid line, the lines on the left side of the dashed line represent the top of the reservoirs while the lines on the right side of the dashed line represent the bottom of the reservoirs.

![Figure 1. Diagram showing the coordinate system used in the angle-domain decomposition.](image)

Numerical examples

We first use nine sets of reservoir models to test the theory and calibrate the amplitude measurement. The model parameters are shown in Table 1. The synthetic data are simulated with a 16th-order 2D stagger-grid elastic FD
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operator with free-surface boundary on the top and PML absorbing boundary on other three sides. Primary reflections and first-order multiples from a shot are separated and shown in Figure 4. Prior to extracting the true-amplitude angle gathers, the LIMs are corrected by illumination using equation 3. Figure 5 shows the corrected LIMs of the top and bottom of the reservoir. The mADCIGs before and after illumination correction are compared in Figure 6, which demonstrates the importance of the illumination correction on the results. Internal multiples that generate artifacts near depths 500 m and 2000 m are not removed. The AVA curves are extracted from the illumination corrected mADCIGs and compared with the corresponding theoretical curves in Figure 7. We see that most of the extracted mAVA curves fit the theoretical curves well. Next, we test our method using a model shown in Figure 8a, in which the Vp is from the Pluto 1.5 (Irons, 2000) and the Vs in the sediments is scaled from Vp by a factor of Vp/Vs=1.9, while in the reservoir is scaled by Vp/Vs=1.63. A 20-Hz Ricker source is used for data simulation. The mAVA curves are calculated from the mADCIGs after illumination correction. The parameters A and B are extracted from AVA curves and illustrated in the crossplot in Figure 9. Since the Vs/Vp perturbations are small in the background medium, the reflections (green crosses) from there are close to the fluid line (the dashed line). The reflections from the top of reservoir appear at the lower-left side of the fluid line and the bottom reflections appear at the upper-right side of the fluid line. Both can be clearly identified from the background reflections. Some randomly scattered data points are from the RTM artifacts resulted from imaging noises generated by internal multiples due to high velocity of the reservoir, which is out of the scope of this paper.

<table>
<thead>
<tr>
<th>Percentage Porosity θ</th>
<th>Vp (m/s)</th>
<th>Vs (m/s)</th>
<th>Density ρ g/cm³</th>
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<tbody>
<tr>
<td>Shale</td>
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<td>3170</td>
<td>1668</td>
</tr>
<tr>
<td></td>
<td>23%</td>
<td>3170</td>
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<td></td>
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<td>1668</td>
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<tr>
<td>Gas</td>
<td>20%</td>
<td>3500</td>
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</tr>
<tr>
<td></td>
<td>23%</td>
<td>3500</td>
<td>2231</td>
</tr>
</tbody>
</table>

Figure 3 A-B relations for reservoir models in Table 1. The red, green and blue lines indicate the shale-gas, shale-oil and shale-brine reservoirs, respectively. The dashed line indicates the fluid line. On its left and right are for top and bottom of the reservoir, respectively.

Figure 4 Shot gathers of primary (a) and first-order multiple (b) obtained by SRME.

Figure 5 LIMs using multiples of top (a) and bottom (b) of the reservoir.
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Figure 6: mADCIGs before (a) and after (b) the angle domain illumination correction. The events near depths 500 m and 2000 m are artifacts generated by internal multiples.

Figure 7: Extracted mAVA curves from mADCIGs (solid lines) compared with theoretically calculated curves (dotted lines). The 9 panels are for 9 sets of reservoir parameters. Blue and red colors are associated with the top and bottom reservoir, respectively.

Figure 8: a) The Vp from the Pluto1.5 model; b) The RTM image using multiples.

Figure 9: The crossplot of the AVAs measured from the synthetic multiple data. The green crosses are from the background reflections. The blue and red crosses are from the top and bottom of the reservoir, respectively.

Conclusions

The multiple reflections are composed of useful information regarding the subsurface structures, and can fill up the gap in which the primary reflection cannot reach to. The mAVA is presented to analyze AVA behaviors of free surface multiples. Illumination correction is applied to the result to compensate the effect of propagation and acquisition geometry. The accuracy of predicting multiples is vital in successfully performing the mAVA.

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REFERENCES


