Azimuthal anisotropy analysis of wide azimuth data after prestack migration
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Summary
The wide azimuth (WAZ) data provide higher signal to noise ratio (S/N) and better illumination than conventional narrow azimuth data. However, Direct stack WAZ seismic data after NMO or migration often results in reduced S/N and low-resolution sections. It is because horizontal anisotropy exists in most field cases. In cases of fracture-induced azimuthal anisotropy, seismic waves propagate faster along the fracture orientation. The analysis of azimuthal variation of seismic wave attributes, such as travel time, stacking velocity, reflected wave amplitudes, etc. not only offers ways to yield high quality stacked images but also provides important geological information. This paper describes two approaches for azimuthal anisotropy analysis and correction, one in the time domain and the other one in the depth domain, both after prestack migration.

Introduction
With the increasing demand for hydrocarbons, and declining oil and gas reserves, fractured reservoirs have attracted much attention from the petroleum industry. The presence of natural and induced fractures in reservoir rock can significantly enhance oil and gas production. On the other hand, it brings new challenges to the oil industry in terms of anisotropic velocity model building and imaging.

Azimuthal anisotropy in rocks can be induced by the presence of one or more sets of aligned vertical fractures. Many efforts have been made for extracting reliable fracture properties by analyzing the azimuthal variation of seismic travel times, amplitudes and attenuation. Tsvankin (1997) introduced the reflection moveout analysis to HTI (Horizontal Transverse Isotropy) parameter estimation while Perez (1999) studied the azimuthal variation of P-wave AVO responses. Li (1999, 2003) first analyzed the azimuthal variation of P-wave moveout for fracture detection. The azimuthal variation of P-wave seismic attributes, such as travel time, stacking velocity, reflected wave amplitudes, impedance, etc. can be approximately described by an ellipse. The long axis of the ellipse indicates the fracture orientation, and the relative ratio of the long to short axes of this ellipse is proportional to the fracture density or intensity of the rock concerned (Li, 1999 & 2003).

The wide azimuth (WAZ) data provide higher S/N and better illumination than conventional narrow azimuth data. Therefore, more and more data are collected with WAZ coverage. As an important additional advantage, WAZ data also offer an extra dimension for investigating the azimuthal anisotropy.

In this paper, we describe two approaches for azimuthal anisotropy analysis of WAZ data, one in the time domain and the other one in the depth domain, both after prestack migration. These methods not only provide high quality stacked seismic images but also important geological information of reservoirs such as parameters of fracture properties.

Azimuthal anisotropy analysis in the time domain
In the time domain, WAZ data are first reorganized into offset vector tile (OVT). A proper 5D regularization process is applied to provide a sequence of common-offset-common-azimuthal seismic data set. Each data set is a single fold 3D data volume \( d(x, y, t \mid \alpha, h) \) for a pair of given azimuth \( \alpha \) and half-offset \( h \), where \( x, y \) is the coordinates of CMP and \( t \) is travel time of reflections. We apply an common-offset-common-azimuth phase-shift migration method (Dai and Marcoux, 1999) to the 3D data volume \( d(x, y, t \mid \alpha, h) \).

The phase shift operator consists of phase shift over space as well as phase shift over time:

\[
p = \exp\left[-ik \alpha b + i \frac{2\omega}{v}(A - R) + ik_z z\right], \quad (1)
\]

Where \( k_\alpha = k_m \cdot h/h \) is the projection of the horizontal wave number on the azimuth direction, and

\[
k_z = \sqrt{\left(\frac{2\omega}{v}\right)^2 - k_m^2} \quad (2)
\]

The first term in the phase of the operator (1) shifts the energy along the shot-receiver line over a DMO distance \( b \) (Forel and Gardner, 1989). The second term of the phase represents a DMO moveout correction, where \( A \) is the semi-major axis of the ellipsoid of revolution of the prestack migration operator response and \( R \) is the length of the normal ray at a distance \( b \) from a CMP point. The third term is the phase for zero-offset phase shift migration. For a given set of parameters \( (\alpha, v, \omega, k_m, k_0) \) we have

\[
A = \frac{z^2 + k_0^2}{2k_z} \left( 1 + \frac{4k_z^2k_0^2k^2}{z^2 + k^2}\right) + h^2 \quad (3)
\]
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\[ b = z \frac{k^2 - k_z^2}{A^2 - k_z^2} \]  
\[ R = z \frac{k}{k_z} \]  
(4)

with \( k = 2\omega/v \).

The equations are derived for constant velocity model. Therefore, it can be used for prestack time migration by defining \( z = v t_m/2 \), where \( t_m \) is the migration time. For spatially varying time migration velocity \( v(x, z) \), proper designed interpolation procedure provides accurate prestack time migration images. Because the migration operates on the common-offset-common-azimuth data set, it is named as CoCa migration. Comparing with prestack Kirchhoff time migration, CoCa migration is a very efficient migration module in BGP’s GeoEast system. The efficiency depends on the size of input data set. For most cases, we see CoCa migration is 10 times to 20 times faster for a same data set and on a same computer cluster.

After CoCa migration are performed on all offset-azimuth data volumes, the resulted images are reorganized into 3D offset-azimuth image gathers, which are ready for azimuthal anisotropy analysis. A typical such image gather is shown in Figure 1, where (a) is the raw output of CoCa migration and (b) is the same gather after azimuthal anisotropy correction. Figure 1a displays visible wavy time difference of the reflection events across the range of azimuth for a given offset in places where strong azimuthal anisotropy presents. Figure 2 shows a stacked image section of the same data set, where (a) is the direct stack of CoCa migration output and (b) is the stack of the same migration output but after azimuthal anisotropy correction. It is obvious that after eliminating, the time difference caused by azimuthal anisotropy the quality of stacked migration image is greatly improved with uplifted resolution, stronger and more continuous reflection horizons.

Azimuth-dip image gathers (ADIG) in depth domain

In the depth domain, we conduct azimuthal anisotropy analysis based on 3D azimuth-dip image gathers (ADIG) generated by performing shot-profile depth migration, such as an RTM for instance (Dai and Zhang, 2014).

During an RTM imaging procedure, all partial images from each shot are stored as disk files. The stack image can be used to compute the structural dip. In three dimensions it is equivalent to evaluating the apparent dips in both the in-line and cross-line directions.

For a given shot, the simulated source wave field in RTM can be used to estimate the incident wave propagation directions. We extract frequency components from the forward modeling source wave field and use the wave fronts to estimate the incident wave propagation directions. Once we have the normal direction of structure and the incident wave direction, the incident angle of reflection is simply the open angle between the two directions at each subsurface point. The azimuth angle is given by the intersection of the reflection plane and horizontal plane. The energy of the partial image is then mapped into the azimuth-dip image gathers accordingly.

Our approach for generating 3D ADIGs is computationally efficient, facilitating production of dense ADIGs for an entire 3D project. Because it is performed after the migration is completed, the angle gather generation may be executed repeatedly with different parameters as needed. This efficient approach makes it is possible to use RTM ADIG for azimuthal anisotropy analysis in production processes.

Azimuthal anisotropy analysis based on ADIG

In areas where horizontal transverse isotropy (HTI) presents, the image of TTI RTM is still not able to focus, although a TTI RTM provides better image than isotropic migration. One of the reasons is we can find depth moveout at different azimuth for one image point. The geological reason may be vertical fractures in rocks. When azimuthal
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Anisotropy is ignored (or the parameters are unknown) the prestack depth migrated ADIG at location \((x, y)\) can be written as (Hou et al, 2014)

\[ g(\theta, \varphi, x, y, z - s(\theta, \varphi, z)) \]  

where \(\theta\) denotes the incident angle, \(\varphi\) the azimuth, \(z\) the imaged depth. \(s(\theta, \varphi, z)\) is a shift function that represents the depth variation caused by the azimuthal anisotropy.

\[ s(\theta, \varphi, z) = \sum_{i=1}^{n_i} \Delta z_i \delta_i \cos^2(\varphi - \varphi^o_i) \sin^2 \theta \]  

In equation (7) where \(z = \sum_{i=1}^{n_i} \Delta z_i\), the shift function is the total outcome of the interval azimuthal anisotropy effects of the overlying strata, while \(\delta_i\) is the Thomson parameter \(\delta\) of HTI in the \(i\)-th layer, which controls the maximum shift and is proportional to fracture density; \(\varphi^o_i\) is an azimuthal angle perpendicular to the fracture orientation of the \(i\)-th layer. To obtain \(\delta_i\) and \(\varphi^o_i\), a 2D scanning method is proposed. We start by dividing the image volume into depth windows. We then scan parameter \(\delta_i\) and \(\varphi^o_i\) to choose the optimum values of each layer for the maximum stacking power of each ADIG. The end products of this 2D scan workflow are a 3D volume of \(\delta\) and a 3D volume of \(\varphi^o\). These parameters provide geological information about the fractures and can be used in orthorhombic velocity model building. They can also be used to correct azimuthal depth errors in the ADIGs for enhanced quality of the stacked images. Figure 3 illustrates the curved surface of depth correction to the ADCGs in the domain of \((\theta, \varphi)\) for a single azimuthal anisotropy layer:

\[ \Delta z^* = -\Delta z \delta \cos^2(\varphi - \varphi^o) \sin^2 \theta \]  

Figure 4 shows the improvement of the stacked images by applying the azimuthal anisotropy corrections to a TTI RTM result.

Conclusions

We presented two different approaches for azimuthal analysis of wide azimuth seismic data. Both methods are based on 3D image gathers obtained by prestack migration. One of them works in the time domain. We first sort the data into common-offset-common-azimuth (CoCa) volumes, to which we apply a highly efficient CoCa prestack time migration in the frequency domain. In the other method in the depth domain, we perform TTI RTM migration directly to the shot gather data. The partial images of each shot are mapped into 3D azimuth-dip image gathers (ADIGs). These 3D image gathers display azimuthal variation of migration time or depth when horizontal transverse isotropy exists. Extracting this variation not only offers ways to make correction for higher quality stacked images, but also provides geological information about fracture distribution in the survey areas.

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