Depth-velocity modelling and imaging with azimuthal anisotropy in an onshore Middle Eastern field.


Introduction

Reservoirs in complex geological settings require special seismic data acquisition and processing efforts to obtain datasets suitable for geological interpretation and reservoir characterisation. The Middle Eastern onshore field of the current study is a fractured reservoir producing from rotated basement fault blocks with considerable structure. Moreover, the overburden contains several salt domes. A full azimuth 3D seismic survey was acquired in order to guarantee optimum illumination in order to achieve detailed imaging and accurate positioning for the structure below the salt and to estimate stress and fracture related azimuthal anisotropy throughout the field. In order to meet these objectives a prestack depth migration that incorporates azimuthal anisotropy is required. Here, we will discuss issues associated with azimuthal anisotropic depth-velocity modelling and depth imaging.

Wide-azimuth imaging issues

Several approaches can be used if wide or multi azimuth dataset reveals fluctuations in moveout between different acquisition directions. The simple approach uses a separate velocity model for each azimuth (we can call it the multi-model approach). Sometimes, if a VTI format is used for each model, all models have the same common vertical velocity and all the differences are put into the delta and epsilon parameters (Dewey et al. 2006). These approaches can be used to estimate horizontal azimuthal anisotropy for the overburden, but from the imaging point of view, the multi-model technique has serious limitations. More accurate results can be achieved by using a single velocity model that includes horizontal anisotropy. Azimuthal variations in seismic data moveout can be caused by several factors:

A. Short-wavelength velocity heterogeneities in the overburden: seismic rays that arrive at the same common reflection point from different directions cross different localized shallow objects. The interval velocity model stays isotropic but seismic moveout and effective velocities appear to be azimuthally anisotropic. Wide-azimuth data provide better illumination of the overburden by seismic rays coming from different directions and it allows the building of a single isotropic velocity model with higher resolution and reliability to solve this part of the problem.

B. Real azimuthal interval velocity anisotropy. In this case, each seismic ray should be processed (migrated) with a variable velocity depending on the ray’s spatial orientation. Applying different velocity models for different acquisition azimuths can achieve this goal only for a horizontal reflector (from imaging point of view, this is the least interesting case). For a dipping reflector or scattered seismic energy (major objects of seismic imaging), it is not enough to vary the velocity depending only on source-receiver direction. Seismic ray geometry (and its velocity) depends on source-received geometry and reflector geometry. Reflector geometry becomes more important for high dip events (major objective of seismic imaging). Multi-model PSDM ignores reflector geometry and only takes into account acquisition azimuth. For accurate imaging one needs to take care of dipping reflectors and these are correctly imaged only by a single-model PSDM that includes horizontal azimuthal anisotropy. For example, near offset traces of a dipping horizon belonging to different acquisition directions will have theoretically correct similar velocities in the single-model anisotropic PSDM. That is not the case with a multi-model PSDM.

C. Apparent azimuthal moveout anisotropy can be observed on dipping reflectors that are overlaid by overburden with non-elliptical VTI or more complex classes of anisotropy. Such anisotropy creates 4th order moveout for horizontal reflectors and additional azimuthally variant 2nd order moveout for
dipping reflectors. A sufficiently accurate non-elliptical VTI model for the overburden solves this problem.

D. When estimating moveout on real multi azimuth seismic data there are always some random distortions caused by a variety of factors (noise, multiples, irregularities in the acquisition geometry, etc) that can lead to an additional random component in the measured variations of seismic moveout and effective velocities.

Building of a single velocity model with azimuthal anisotropy requires distinguishing and separating all above listed effects during iterative velocity modelling.

**Application**

Our data exhibit strong, spatially variant azimuthal moveout. In order to measure these variations our full azimuth seismic dataset was split into four sub-volumes corresponding to 45° azimuthal sectors. Figure 1 shows an example of PSDM gathers for the same CMP processed in four azimuthal sectors. After an initial isotropic iteration of tomographic model update the variations in moveout between the sectors were stronger than the average moveout. Azimuthal anisotropy became the major issue that had to be dealt with at that stage. We applied a standard 3D autopicking technique separately to each sector and fitted the results into elliptical model that is typical for azimuthal anisotropy.

![Figure 1. Example of isotropic MAZ PSDM gathers for the same CMP with corresponding residual moveout semblances. The black line indicates zero residual moveout. Note the variation of the residuals with the azimuth.](image)

Figure 2 illustrates the anisotropic model update and its effect on the residual moveout on a horizontal slice. Figure 2a shows an amplitude depth slice overlaid with the isotropic velocities at a depth of 1200m. The calculated azimuthal anisotropy for residual moveout is depicted in Figure 2b. The colour display corresponds to the magnitude of azimuthal variations, the arrows indicate the direction of fastest effective velocity (maximum negative residual moveout). This corresponds to the effective velocity azimuthal anisotropy and can be caused by all the factors discussed above. Here we express azimuthal anisotropy using elliptical model. Three independent values (along three azimuths) are required to determine all three parameters of an ellipse. Since there are four sectors it is possible to determine the error of the elliptical approximation. The calculated additional non-ellipticity volume is shown in Figure 2c. It is a useful additional tool for interpreting measured residual moveout azimuthal anisotropy: we assume that real interval velocity anisotropy is elliptical and causes elliptical anisotropy of the effective velocity and residual moveout (note the red pointers on Figures 2b and 2c); heterogeneity in the overburden and random variations are assumed to be the cause of the non-elliptical azimuthal variations indicated by the yellow pointers.

The following sequence was used to update PSDM velocity model and include azimuthal anisotropy: (a) the residual moveout from each sector was used to separately update the initial isotropic interval velocity volume; (b) the four resulting interval velocity models were fitted into a single interval velocity model with spatially variant elliptical azimuthal anisotropy.
Figure 2d shows an example of the horizontal depth slice at 600m through the ellipticity volume of the interval velocities. Arrows indicate directions of the fast axes of the interval velocity ellipses and the colours correspond to the magnitudes. We observe significant azimuthal variations in interval velocity up to 200 m/s (Figure 2d) equivalent to 7% of the average interval velocity at this depth and 30% of its maximum lateral variations. This interval velocity azimuthal anisotropy comes from the long-wavelength component of the moveout anisotropy (marked by red pointers on Figure 2b) with short-wavelength random and non-elliptical anomalies excluded. Azimuthal velocity anisotropy of such magnitude cannot be ignored. The resulting dominant NE-SW orientation is in agreement with the present day maximum stress direction determined from borehole breakout data and drilling induced tensile fractures. The updated interval velocity model with azimuthal anisotropy was used for the next iteration of anisotropic (A)PSDM and residual moveout was picked on the updated APSDM gathers. Figures 2e and 2f show the residual azimuthal moveout and the non-elliptical measured on APSDM gathers, respectively. As it was expected, the introduction of azimuthal anisotropy into the APSDM velocity model removed the long-wavelength azimuthal variations in residual depth moveout. We believe these were caused by the real azimuthal interval velocity anisotropy.

Figure 3 shows the APSDM gathers for the same CMP after the anisotropic model update. A clear reduction of residual moveout can be observed. The flatness of the higher offsets indicates that there is no significant 4th order moveout related to VTI/TTI anisotropy that needs to be taken into account in this case. We assumed that the observed azimuthal anisotropy in interval velocities is caused by vertical fractures reducing the horizontal velocity across the fracture planes. So, the vertical imaging velocity was set equal to the fast horizontal velocity in accordance with an HTI model. A depth calibration to the wells is performed post-migration due to the sparse distribution of wells.
Figure 4 illustrates the structural differences that azimuthal anisotropy can make to the seismic images. Figure 4a shows the PSDM image migrated in depth using the fast horizontal velocity. Figure 4b shows the same section stretched to the new depth scale corresponding to the slow horizontal velocity. As we can see, azimuthal anisotropy creates significant changes. If someone had single azimuth seismic data shot along the fast direction, an accurate processing/images would produce the structure shown in Figure 4a; an acquisition along the slow direction would result in a structure like in Figure 4b. Only full or multi azimuth acquisition and processing can solve this uncertainty.

**Figure 3.** Example of anisotropic MAZ APSDM gathers for the same CMP with corresponding residual moveout semblances. See figure 1 for comparison with isotropic MAZ PSDM.

**Figure 4.** Seismic images migrated in depth with a) the fast horizontal velocity; b) the slow horizontal velocity. Structural differences are highlighted in red.

**Summary**

The current full azimuth survey reveals the presence of strong spatially variant azimuthal velocity anisotropy. It has been taken into account by the presented depth processing sequence including residual moveout estimation in azimuth sectors, velocity model update with azimuthal anisotropy and subsequent APSDM. The resulting data set will be the basis for accurate positioning and analysis of
steeply dipping faults and fracture zones which are the most critical factors controlling production in this field.

References