The effect of interpolation on imaging and azimuthal AVO: A Nordegg case study
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Summary
To address the issue of inadequate sampling, typical of land seismic data, an azimuthal AVO (AVAZ) processing flow should include interpolation and prestack migration prior to the AVAZ inversion. It is well established that seismic data should be prestack migrated before AVO, but the irregular sampling inherent in land data can introduce migration artifacts which distort the estimates of the AVO inversion. With the introduction of the extra dimension of azimuth this is even more a concern for AVAZ analysis.

By performing 5D minimum weighted norm interpolation before PSTM, the wavefield is better sampled leading to better migration and AVAZ results. This has been demonstrated on synthetic examples. This paper demonstrates the benefits of this on a real dataset by comparing AVAZ processing sequences with and without interpolation and correlating the predictions quantitatively to well control. The interpolation/PSTM flow proceeding AVAZ inversion produces better correlations to the well control than only PSTM.

Introduction
AVAZ analysis has proved to be an important tool in characterizing fractures (e.g. Al-Marzoug et al., 2004; Gray & Todorovic-Marinic, 2004; Hunt et al., 2010), however, the results are sensitive to both the seismic data acquisition and the preconditioning. The seismic data should be acquired with sufficient azimuthal and angle information so that the AVAZ inverse problem is well posed. The seismic wavefield also needs to be adequately sampled in order to perform prestack migration. Mosher et al. (1996) showed that AVO should be performed on data that have been prestack migrated. Migration assumes uniform and dense enough sampling to prevent operator aliasing. Inadequate, non-uniform sampling can result in the migration operator not being able to constructively and destructively interfere, resulting in migration artifacts. Due to economic constraints, seismic data are often not sampled sufficiently for the purposes of common offset migration.

Hunt et al. (2008) demonstrated that 5D Minimum Weighted Norm Interpolation (MWN) (Trad, 2009) can be used to improve the sampling within each offset volume, resulting in better prestack time migrated (PSTM) gathers and consequently better AVO results. They quantitatively compared the AVO estimates of various processing flows, with and without interpolation and various imaging techniques, to measurements from 29 wells. Their conclusion was that a PSTM flow with 5D interpolation gave better results than any of the other flows.

Based on this work, we hypothesized that 5D interpolation followed by migration should in a similar fashion improve AVAZ estimates. The problem of adequate sampling becomes worse with the extra dimensions of AVAZ, which requires that azimuthal information be retained. Synthetic and physical modeling studies (Gray and Wang, 2009) demonstrated that interpolation improves AVAZ estimates. Based on that work Hunt et al. (2010) subsequently performed an AVAZ and azimuthal velocity (VVAZ) study at the deeper Nordegg level on the same interpolated dataset as analyzed in the 2008 paper. In this case the same interpolated gathers were used as input to an azimuthally sectored common offset migration. They found the azimuthal attributes had a good correlation with the well control and location and intensity of microseismic events.

In performing the AVAZ work, Hunt et al. (2010) hypothesized the addition of interpolation should help precondition the seismic data better, leading to more accurate AVAZ estimates in a similar manner as it did for the AVO attributes. It is the purpose of this paper to verify this hypothesis on real data. In this paper, the data are preconditioned with and without interpolation. The data are subsequently azimuthally sectored, then migrated followed by AVAZ analysis. The AVAZ estimates are compared qualitatively and quantitatively with the Fullbore Micro Imager (FMI) Log data from two horizontal wells.

We start by discussing the geologic observations of the Nordegg Formation and the importance of detecting fractures. The FMI data from the horizontal wells are used to calibrate the fracture density. We next discuss the processing needed to account for scale differences between the well and seismic data. This is followed by a discussion of the technical details and processing of the interpolation, migration and AVAZ analysis. The principal AVAZ parameter examined is the anisotropy gradient which can be shown through the crack theory of Hudson (1981) to be related to fracture density, providing a physical link between the well and seismic datasets. This allows the different flows to be compared qualitatively to the well control in profile and plan view and subsequently quantitatively. Both the qualitative displays and quantitative measures demonstrate the inclusion of 5D interpolation improves the AVAZ estimates.

The Nordegg Formation
The Nordegg Formation in West Central Alberta is challenging because this gas charged reservoir is deep, structured, and has low permeability. The Nordegg Formation is composed of a lower chert/carbonate rock

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type overlain by an upper porous quartz-arenite sandstone reservoir which is unconformably overlain by the Poker Chip shale (Figure 1). The sandstone reservoir unit is charged with gas. The Nordegg interval within the study area averages about 12m of net pay (> 6% sandstone matrix porosity) with an average log porosity of 7% and 14% water saturation. The core permeability ranges from .01- .1 md. The preponderance of the deliverability and enhanced permeability within the Nordegg is interpreted to come from the area’s complex system of faults and fractures associated with regional strike-slip style faulting. The fracture density and the production capability of wells drilled into the Nordegg vary materially. Thus it is expected this fracturing will affect the behavior of the Nordegg in many ways, from drilling, to the way that the reservoir behaves under fracture stimulation.

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Well Control

Three horizontal wells (A, B, and C) were drilled into several of the interpreted structural archetypes present in the area. Figure 2 illustrates these structural archetypes and the relative positions of the wells.

Well A was drilled along the strike of an anticlinal feature, Well B was drilled into a major strike slip feature, while Well C was drilled in a relatively unstructured setting. FMI logging was performed for wells A and B. The FMI tool provides its electrical image from micro-resistivity measurements. From this log fracture orientation, aperture, porosity, and density can be interpreted and were used in this study. Hunt et al. (2010) analyzed 1800m of FMI log data from the horizontal wells A and B to show that the fractures are vertical and aligned in a preferred orientation. Some 85 percent of the fracture angles are at or greater than 80 degrees to horizontal. The azimuthal data show a dominant strike azimuth of about 50 degrees east of north. This suggests that assumptions behind the azimuthal AVO analysis are met. Further, Figures 3 through 10 of Hunt et al. (2010) show that the AVAZ estimates share similar statistics to the well control.

In order to compare the AVAZ estimates quantitatively with the fracture estimates from the well control we need to be able to plot and analyze the two datasets at the same locations along the two horizontal wells A & B. This presents challenges regarding scale and support. The FMI data are recorded with a resolution on the millimetre scale, and are sampled with average values at a fraction of a meter along a thin well bore. The seismic attributes are processed with a 30m by 60m bin size. In order to compare these, the FMI fracture density data was created at a 10m bin interval along the horizontal well bore. By calculating the FMI bins much smaller than the 3D seismic bins, we gained some flexibility in further averaging the FMI data.

Seismic processing and interpolation

The 3D seismic coverage in the area has a 660m source line interval, 600m receiver line interval and is 27 fold at the target. The acquisition geometry is typical for the area and target. This limited fold gives rise to gross irregularities in the offset and azimuthal distribution. To address this a
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five-dimensional implementation of MJNI (Liu and Sacchi, 2004; Trad, 2007; Trad, 2009), was used to interpolate the data before migration. The 5D interpolation is performed by solving a large inverse problem. In this problem the desired model is a super-sampled seismic dataset, the data are the original seismic dataset, and the linear model is the sampling operator. The resultant super-sampled seismic data contains data for every possible in-line, cross-line, offset, and azimuth combination. In practice this creates too much data to deal with, so the algorithm only outputs a representative subset of this. Hunt et al. (2008; 2010) output twice as many shot and receiver lines as the original and for the sake of consistency we do the same. Since the original data are retained, it is easy to observe whether the interpolation has faithfully reproduced the amplitude trends. It is also possible to compare the original data with the interpolated data. Figure 3 shows the result of a synthetic modeling study before and after 5D interpolation for one offset plane displayed as a function of azimuth for a particular CMP. The synthetic was created with a real 3D geometry and a simple AVAZ relationship. 5D interpolated, 3X3 supergathers were formed. Note the interpolated version is able to recover the AVAZ behavior (shown in red) accurately. The original data are not changed.

In order to retain azimuthal information, the seismic data were migrated with an azimuthally sector common offset migration. The migration employed bin borrowing and area weighting (Zheng et al., 2001) in order to deal with near offset sampling issues. The migration consisted of 8 azimuth sectors, each 45 degrees wide with 22.5 degrees of overlap. Even with these procedures, performing the azimuthally sector migration on the non-interpolated data was difficult. One sector in particular was poorly sampled and negatively impacted the result. Figure 4 shows common azimuth, common offset gathers at well A before and after interpolation. Note the improvement in frequency content and signal-to-noise.

The AVAZ analysis is based on the near offset Rüger (1996) equation

\[ R = \frac{S}{N} \]

The equation models the seismic amplitude \( R \) as a function of azimuth \( \phi \) for narrow angles of incidence \( \theta \) for an isotropic half-space over an HTI anisotropic half-space. The equation is parameterized in terms of the P-wave impedance reflectivity, \( A \), the isotropic gradient, \( B_{\text{iso}} \), the anisotropic gradient, \( B_{\text{aniso}} \), and the symmetry axis of the HTI anisotropic media, \( \phi_{\text{sym}} \). As discussed, the anisotropy gradient is related to the fracture density and is the parameter this analysis focuses on.

Figure 5: Seismic profile showing Anisotropic Gradient for the non-interpolated a) and interpolated b) anisotropic gradient based on 5X3 supergathers. The FMI fracture density superimposed in yellow.

Results

The AVAZ inversion was performed on both the interpolated and non-interpolated flows. In both cases the seismic data were processed in an amplitude preserving fashion for AVAZ analysis (Gray et al., 2009). The S/N ratio of the results was not as high as desired, so the AVAZ analysis was also performed on 5X3 supergathers to increase the fold. However, the resultant improvement in S/N comes at the price of potentially smearing anomalies and so must be used with care. The 3D attributes were extracted along the horizontal trajectories of well A and B and compared to the FMI data. Figure 5 shows anisotropy gradient with the horizontal well bore superimposed in yellow. Figure 6 shows scatter plots comparing the extracted value of \( B_{\text{aniso}} \) versus the binned FMI data. In this particular case the FMI bins were averaged with a 7 point running smoother, so the FMI bin size would be the same as the seismic. The data were also analyzed at the finer 10 m FMI bin size. To account for vertical resolution
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The objective of producing a good stacked image. AVO analysis requires extra acquisition effort. Offsets need to be sufficiently well sampled that enough angles and fold are present for the problem to be well posed. Azimuthal AVO places extra demands on the acquisition by also requiring good azimuthal sampling. Ideally, high density acquisition should be considered when azimuthal attributes are of interest.

The fact that using supergathers improved the correlation coefficient suggests that outputting the interpolated data in a denser fashion might be advantageous. For example, two additional source and receiver lines could be output instead of one. This test is currently being performed.

Rather than performing azimuthally sectored migration, the seismic data can be processed and migrated using Common Offset Vector (COV) tiles (Cary, 1999; Vermeer, 2002). This scheme addresses some of the sampling issues but introduces other problems. In this particular case the COV tile size without interpolation is 1320m by 1200m. These large bins introduce offset bin smearing into the AVAZ inversion, which causes large systematic error (Downton, 2010). This again may be mitigated by interpolation and is the subject of ongoing testing.

Conclusions

Including 5D MWNI in the processing sequence improved the AVAZ parameter estimates for this Nordegg case history. The acquisition parameters are typical for this area and for other targets this deep, suggesting that other surveys might benefit by interpolation. The results are consistent with previous modeling studies and expectations generated by Hunt et al. (2008). As in the 2008 AVO study, this improvement is probably due to the increased fold due to the interpolation and better sampling leading to a better migration.

The use of 5D MWNI should not be viewed as a justification to acquire sparser seismic data. The interpolation inverse problem is undetermined. If insufficient data are acquired then the interpolation will be unable to properly reconstruct the data. For example, interpolation cannot make narrow azimuth data wide azimuth.

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differences between the well and seismic data, the anisotropy gradient attribute was extracted using various window sizes ranging from 8 ms to 42 ms. The overall trends remained the same in all cases but we found the 32 ms window gave the best results and so display the scatter plot with this window.

Table 1 shows the correlation coefficients for this window. Correlation coefficients are shown for both the interpolated and non-interpolated flows. Performing 5X3 supergathers improve the correlation for the interpolated data. Averaging the 10m FMI bins also improves the correlation for the interpolated data. In all cases the interpolation flow gives a significantly better correlation.

The difference in correlations between the interpolated and non-interpolated flows is dramatic and perhaps disturbing. The AVAZ attribute produced in this study is not statistically meaningful unless interpolation is used. The acquisition parameters used in this area are typical for land data with this target depth, suggesting a disconnection between these techniques and acquisition effort. Part of the problem is that seismic data are often acquired solely with

![Figure 6: Scatter plots showing regression between the FMI data and seismic attributes calculated using 5X3 supergather as input. The interpolated version b) is more highly correlated than the non-interpolated version a).](image)

<table>
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<tr>
<th></th>
<th>1X1 raw</th>
<th>5X3 raw</th>
<th>1X1 avr.</th>
<th>5X3 avr.</th>
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<td>0.030</td>
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</tbody>
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Table 1: Correlation coefficients for interpolated and non-interpolated flows. The supergather size is indicated on the column label (e.g. 5X3) as well as whether the 10 m FMI bins were averaged.

Discussion

The difference in correlations between the interpolated and non-interpolated flows is dramatic and perhaps disturbing. The AVAZ attribute produced in this study is not statistically meaningful unless interpolation is used. The acquisition parameters used in this area are typical for land data with this target depth, suggesting a disconnection between these techniques and acquisition effort. Part of the problem is that seismic data are often acquired solely with
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