Extracting azimuthal information from 3D full azimuth gathers using automatic RMO analysis and AVAZ

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Summary

A workflow for analyzing azimuthal anisotropy of target layers (shale, carbonates, etc.) from migrated seismic gathers is presented. This workflow involves a very effective automated algorithm for RMO analysis for the three parameters that characterize azimuthal anisotropy. The antistrophic zones are automatically identified and analyzed. This is a very robust methodology which provides reliable anisotropic attribute maps along target horizons.

Introduction

Azimuthal seismic analysis is becoming increasingly important, due to the growing interest in unconventional shale plays, where stress directions and facture orientation are in some sense the "Holy Grail". An exciting way to process seismic data is through the use of a full-azimuth angle domain migration (Koren and Ravve, 2011).This migration accurately recovers amplitudes and produces 3D gathers which are densely sampled in reflection angle/azimuth space, and contain information on subsurface reflection angles and azimuths. The next challenge is to extract maximum information on the nature of the azimuthal variations from these gathers. In this paper we refer to azimuthal variations which can be characterized by three parameters (α_1,α_2,β) and (G_1,G_2,β). α_1 and α_2 are the primary axes of the residual velocity ellipse, G_1 and G_2 are the primary axes of an AVAZ ellipse, and β is the orientation angle (Grechka and Tsvankinm, 1998; Ruger, 1998). The source of these azimuthal variations can be HTI, TTI or orthorhombic anisotropy. Specific layers of interest, typically carbonates or shales, exhibit such azimuthal variations. Our goal is to obtain a horizon oriented map for these layers displaying attributes of interest, such as orientation angle β or (α_1 - $\alpha_{2)}$, similar to the Eagle Ford example shown in Figure 1. Ideally, zones of low S/N, low azimuthal anisotropy, non-normal moveout or AVAZ should not be included in the final maps.

The 3D gather is normally a result of a full-azimuth migration using a VTI velocity model; therefore, the azimuthal variations are to be detected post-migration. Figure 2 shows a 3D gather which contains azimuthal variations in both residual NMO and AVAZ. In this figure traces are grouped into reflection angle sectors, and organized in increasing order. In each sector all 360 degrees of azimuth are visible. Residual moveout due to azimuthal velocity variation is visible as an oscillating effect and is described in more detail in Koren, Ravve, and Levy (2010). Amplitude variations along this event can also be observed.

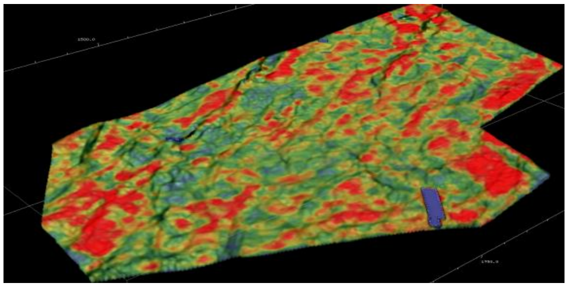


Figure 1: AVAZ azimuthal intensity along the Eagle Ford shale layer displayed in combination with a structural attribute.

Extracting azimuthal information from 3D gathers involves two main steps. First we flatten the gathers to prepare for AVAZ. In this step we can derive (α_1, α_2, β). In the second step we extract (G_1,G_2,β) using AVAZ. A three-parameter residual moveout (RMO) analysis is required in the first step. Manual picking is not a very practical option for this task, so we use an automatic procedure, which is very effective. One could concentrate on a target horizon and find RMO parameters which will flatten this single event, but for AVAZ analysis the full gather needs to be flattened.

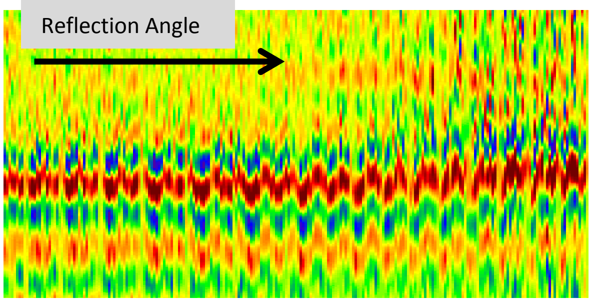
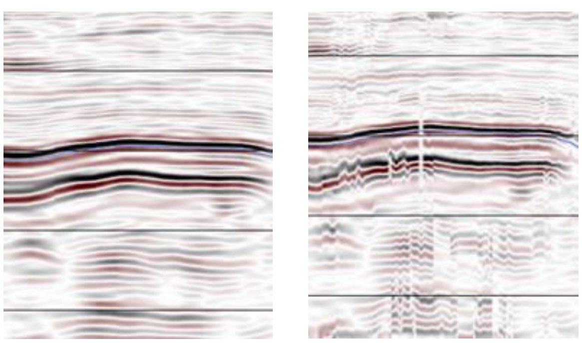


Figure 2: Example of a 3D gather from the Barnett Shale. Oscillating effects are due to azimuthally varying NMO.

In Canning and Malkin (2009) we presented an automatic residual velocity analysis method which was based on Swan's approach (Swan, 2001) and could be used to automatically and effectively perform azimuthal residual RMS velocity correction on 3D gathers. Here we use a more robust extension of that method. This is a critical part of our workflow (Figure 4). Automatic RMO is not a simple task since we try to automatically estimate three parameters for every sample in the data, and data variability can cause instability. We implemented the basic algorithm in 2009, and with experience we noted a number of problems which cause instability. Here are some:

- The analysis is applied on each gather independently, so lateral consistency cannot be included in the algorithm. This results in significant lateral discontinuity in the resulting residual velocity field. This field needs to be smoothed out before RMO is applied to the data. Without such filtering significant artifacts are introduced to AVAZ attributes derived from the corrected gathers (Figure 3).
- Some regions have low S/N, and should be excluded from the analysis. This calls for vertical interpolation between high S/N zones.
- Some layers are isotropic and don't show azimuthal variations. In those layers, estimating orientation angles can be unstable. Since the RMO data goes through interpolations and filtering, this can significantly damage the results.
- Attempting to bypass these problems by performing RMO + AVAZ on the target horizons only is also not ideal. This approach relies on the accuracy of the picked horizon, which is often questionable. Artifacts caused by shifts and stretch between near and far traces in the gather can cause errors in the estimation when it is limited to horizons at this stage of the workflow. Moreover, this target oriented workflow does not accommodate lateral filtering of the residual velocity field prior to its application on the data, which is an important step in the process.



a) Stack b) Stack after RMO.

Figure 3: Demonstration of the artifacts involved in automatic RMO analysis caused by the fact that each gather is processed independently. Note that b) contains artifacts but also exhibits much higher frequency content. This is because the oscillations in the gather are resolved before stacking. The artifacts are removed by filtering the RMO field before applying it to the data.

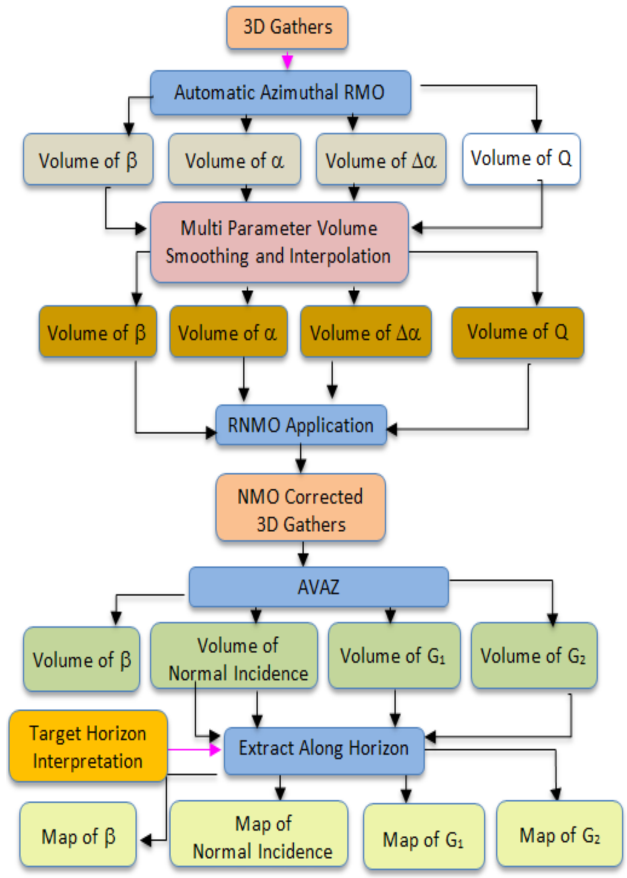


Figure 4: The full workflow

Method

The key elements of our workflow (shown in Figure 4) are:

- Three-component residual velocity analysis is performed automatically.
- A multi-parameter filter is applied to the resulting RMO field which is then used to flatten the gathers. Filtering each parameter independently is not valid here, so we apply a specially designed multi-parameter algorithm. Automatically detected reliably is used to guide the filtering. This is required to solve the problem described in Figure 3.
- AVAZ is applied to full prestack data, and extraction along the target horizon is done only at the end. This enables much flexibility in choosing the optimal algorithm for extraction.

The most challenging step in this workflow is Automatic RMO analysis. Following Swan (2001), we analyze a three-parameter residual velocity for each depth sample in every 3D gather using AVAZ gradients. The basic AVAZ model (Ruger, 1998) is given by:

$$R(\theta,\varphi) = I + [G_1 \sin^2(\varphi-\beta) + G_2 \cos^2(\varphi-\beta)]\sin^2\theta \qquad (1)$$

Where R is Reflection Coefficient, I is Normal Incidence reflectivity, θ is reflection angle, and φ is the azimuth. Residual RMS velocity as a function of azimuth is given by (Canning and Malkin, 2009):

$$\Delta V / V(\varphi) = \frac{\mathrm{Im}(\mathbf{IG}^*(\varphi))}{|\mathbf{I}|^2 f_0 t} =$$

$$\frac{\mathrm{Im}(\mathbf{IG}^*{}_1)}{|\mathbf{I}|^2 f_0 t}\sin^2(\varphi-\beta) + \frac{\mathrm{Im}(\mathbf{IG}^*{}_2)}{|\mathbf{I}|^2 f_0 t}\cos^2(\varphi-\beta) \qquad (2)$$

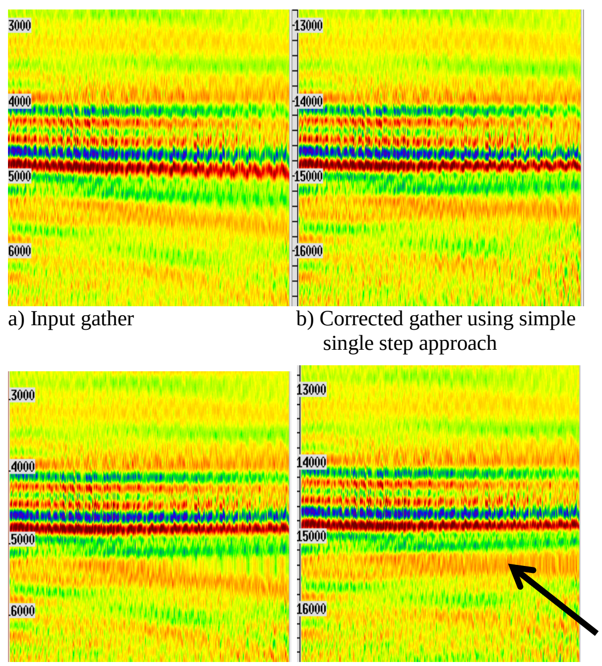
Where $\Delta V/V(\varphi)$ is the azimuth dependent residual velocity $\mathbf{I}$, $\mathbf{G}_1$ and $\mathbf{G}_2$ are the complex traces of I, $G_1$and G_2, and f_0 is the dominant frequency. To estimate the three-parameter residual RMS velocity we first calculate the normal incidence (I) and the AVAZ gradient field (G_1,G_2,β). At this stage, before any anisotropic moveout is applied to the data, the ΔG is very sensitive to azimuthal anisotropy. It is therefore the best stage to estimate anisotropy parameters. Using an L_1 or L_2 norm procedure based on equation (1) we estimate an array of azimuth as a function of depth,$\beta(z)$, and an array of HTI reliability Q(z). Q $=(\breve{G}_1 - \breve{G}_2)/\breve{G}_2$, where $\breve{G}$ is a smoothed envelope of G. Q is set to zero if either $\breve{I}$, $\breve{G}$ or Q are below a predefined threshold. We use the reliability Q to mark the high-quality anisotropic zones in the gather. It is filtered to remove spikes and goes through a clustering algorithm to clearly define the working zones.

The idea is to perform RMO analysis only in the high-quality, highly azimuthal anisotropic zones. Automatic residual velocity analysis is tough enough without mixing isotropic and non-isotropic problems in one step. We therefore perform two steps. First the anisotropic problem is solved, clearing out the oscillations we see in the gather. Now, a conventional RMO analysis can be easily performed, and the gathers are flattened. The anisotropic zone is automatically identified by the algorithm.

For the anisotropic stage we interpolate $\beta(z)$ between zones of Q=0, and filter out spikes. Care must be taken to unwrap angles when interpolating. Now that the orientation angle is known, we begin the residual moveout analysis iterations following equation (2) and the procedure described in Canning & Malkin (2009).

At the end of the iterative procedure we apply post-processing to the data. This prepares the data for lateral interpolation of the three-component residual velocity field. In this post-processing stage we filter out low semblance zones, points in which δ_2 (velocity difference between the slow and the fast directions) is positive (indicating non-normal moveouts), apply tapers, fill in "holes", etc., and then reapply the residual moveout.

A second iteration of conventional automatic RMO is then applied to the data to complete this part of the workflow. Figure 5 shows a comparison between the basic procedure as described in Canning and Malkin (2009), and the enhanced process shown here, which separates the analysis into two steps - target oriented anisotropic and regular isotropic. The entire process is automatic. The improvement is achieved by resolving three azimuthally anisotropic zones independently of the isotropic ones.



a) Input gather
b) Corrected gather using simple single step approach
c) Corrected gather – first Anisotropic step only
d) Corrected gather two steps

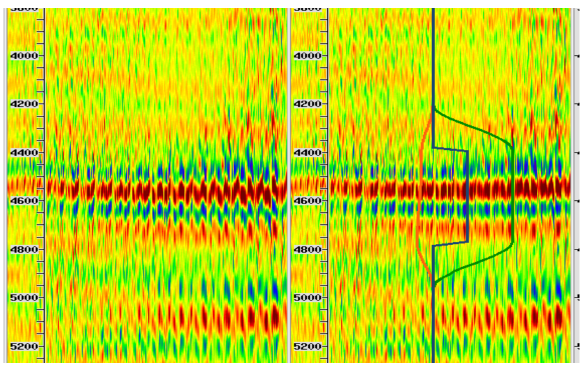
Figure 5: Comparison between the basic method (Canning and Malkin, 2009) and the two step approach presented here. The traces in the gathers are sorted in increasing order of reflection angle. Compare b) and d) and see the improved resolution. Compare c) and d) to see the effect of the second isotropic step.

Examples

Automatic RMO correction of a 3D gather which exhibits azimuthal velocity variations is shown in Figure 6. Figure

6a is the same gather as in Figure 1. Figure 6b is the automatically corrected gather. The curves displayed on these gathers show schematically the estimated orientation angle β (green), reliability Q, (blue) and primary component of the residual moveout α (orange). The Q curve marks the automatically detected zone of interest.

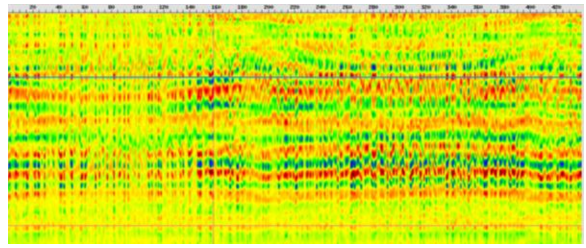
Another way to look at the same data is to reorganize all the traces in the 3D gather in order of increasing azimuth. Figure 7a displays the uncorrected gather ordered this way, and Figure 7b displays the automatically corrected gather. Notice how the reflections become organized with the three- parameter RMO correction. Once the gather is flattened, one can easily detect a clear AVAZ anomaly with high amplitude at around azimuth ~160^0. This illustrates the importance of this process to the AVAZ workflow.



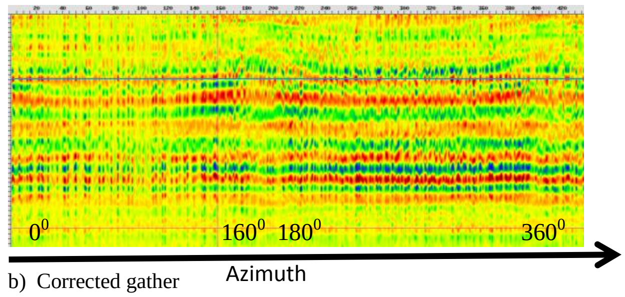
a) Input Gather b) Corrected Gather

Figure 6: Illustration of RMO analysis using a 3D gather with traces sorted in incerasing order of reflection angle. The curves displayed on the corrected gather mark the automatically detected zone on interet and its detected azimuth and RMO.

A Barnett shale example is presented in Figure 8. It shows the stacked data, the three- parameter RMO field that were obtained using the automatic procedure and the target horizon in blue. Note the purple areas, which have been detected automatically and mark the "no analysis" zone., The final attribute maps are extracted from these datasets along the picked (blue) horizon. "Holes" in this data will be "holes" in the extracted map, a process which ensures that bad zones or no-anisotropy zones are not included in the result. The data presented in this figure is the raw data created by the automatic RMO procedure. Three-parameter filtering is applied to it before extracting the horizon oriented attribute maps. "Holes" (low reliability (Q) zones) are used to guide the lateral filtering procedure.

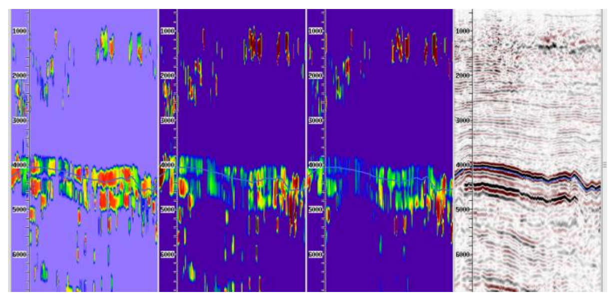


a) Input 3D Gather sorted in increasing order or azimuth



b) Corrected gather

Figure 7: Illustration of RMO analysis using a 3D gather with traces sorted in incerasing order of Azimuth. Notice the amplitude highs which correlats to RMO highs. Note also how easy it is to detect the azimuth at ~160^0.



a) β b) α_1 c) α_2 *d)* Stack

Figure 8: Barnett shale example of RMO analysis. The purple zones are the "no analysis" zones which are detected automatically.

Conclusions

A robust workflow for extracting azimuth dependent attributes from depth migrated 3D gathers was presented. A key element in this workflow is an automatic, three parameter RMO analysis that easily "flattens" the gathers while automatically detecting the reliable zones of interest. Separating isotropic from non-isotropic analysis enhances the process. Reliable horizon oriented attribute (RMO and AVAZ) maps are the final result.

Acknowledgement

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