Improved time and anisotropic depth imaging in the Appalachian Foothills

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Summary

We present an imaging methodology that resulted in significant enhancements in defining the subsurface geology in a survey in the Appalachian Foothills. The key technologies used were (a) high resolution statics correction, (b) anisotropic model building using Focusing Analysis (FAN), (c) azimuth sector grid tomography, and (e) anisotropic Kirchhoff migration from topography.

Approximately 60 square miles of land, wide-azimuth seismic data located in the Appalachian Foothills were imaged. Significant improvements were achieved by processing the data with the new imaging methodology. Also, the seismic image matches with the lateral well information with less than 1% depth error. Azimuth sector tomography indicates a fast and slow velocity orientation which correlates well with possible fracture orientation.

Introduction

The development of shale oil and gas has led to a renewed investment in land seismic acquisition and processing. The current survey area is in the Appalachian basin to image the Marcellus shale formation. For time pre-processing we followed the work flow outlined below.

- Geometry QC
- Shot domain noise attenuation
- Refraction statics 3D
- Surface-consistent scaling
- CDP noise attenuation
- Surface-consistent deconvolution
- 2nd iteration surface-consistent scaling
- 2nd iteration CDP noise attenuation
- Velocity analysis
- Pre-stack time migration

The field data were heavily contaminated with 60 Hz noise and ground-roll. This noise was suppressed with the application of a notch filter and a 3D linear filter. Further high amplitude noise bursts were removed using band limited spike suppression. Amplitude contamination from local highways was identified and removed during surface consistent scaling. Due to the large variation in surface elevations ranging from 1200-2400ft, the velocity analysis was performed from a floating datum. Data input to the Kirchhoff pre-stack time and depth migrations was referenced from surface, and data output from migration was referenced to a fixed flat datum of 2400ft above sea level; in other words the migration was performed from the topography. Our time processing followed a fairly standard work flow with the exception of a high resolution refraction statics method.

It is well known that anisotropy must be taken into account for successful imaging (Whiteside et al., 2008). Traditional VTI imaging assumes the velocity changes are symmetric along the vertical axis. The VTI model building workflow used for this data set is given in Figure 1. There are four aspects of this project described below that make it unique: (1) high resolution statics correction (2) FAN to define VTI anisotropic parameters, (3) azimuth sector grid tomography, and (4) anisotropic Kirchhoff migration from topography.

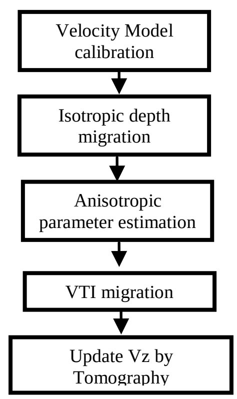

Figure 1: VTI model building work flow.

High resolution statics computation and PSTM

One of the main challenges in land seismic processing is the proper correction of near-surface weathering layer effects—the aim of refraction statics. As the weathering layer is composed of material that is relatively loose and uncompact compared to the bedrock immediately below, it acts as a slow, variable velocity layer distorting source to receiver travel times. These travel time distortions have the effect of generally degraded CDP stack response. If weathering thickness and velocity can be accurately estimated, it is possible to remove the effects of weathering layer distortions and derive a consistent, reliable shot to receiver travel time.

For the refraction statics work, the challenge was to derive a weathering model that could meet two goals. First, the

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model must be consistent with data observations and expected properties of the surface. Second, the model must provide a refraction statics solution that resolves the proper dip of certain reflectors of primary interest to the client. A high-resolution delay-time inversion method together with accurate estimation of the weathering velocity provided a weathering model that satisfied both goals.

The fundamental difference between the high resolution method and conventional methods lies in the handling of refractor velocity. Whereas the conventional method assigns a simplified averaged refractor velocity between a given source and receiver, the high resolution method assigns a space-varying refractor velocity along a gridded path from source to receiver. This allows for greater accuracy in the inversion. In low-lying drainage areas, indicated in the surface elevation map in Figure 2a, we expect the near surface weathering layer to be relatively thick due to deposition while at higher elevations we expect relatively thin weathering layer. Indeed the high resolution model we employed agreed with this expectation, as can be seen in Figure 2b, showing two vertical slices through the weathering model.

Weathering layer velocity was estimated by picking the onset of energy on short offset refracted arrivals and measuring the slope between offset and picked arrival time. This analysis resulted in a weathering layer velocity of 14,000ft/sec. Using this as our weathering velocity, and a refractor velocity and weathering thickness from the high-resolution model, we achieved a refraction statics solution bringing stacked sections in close agreement to information provided by client interpretation. Figure 3a and 3b show PSTM results before and after the high resolution refraction statics correction.

VTI Focusing Analysis (FAN)

To create the initial PSDM velocity model, the pre-stack time migration velocities (t-Vrms) were smoothed and converted to interval velocities in depth. The check shots were not available in this survey area. Two sonic logs from two wells were calibrated to generate the initial isotropic depth velocity model (z-Vz). The resulting vertical velocity model was used to generate isotropic PSDM image gathers (using Kirchhoff migration) and to estimate the VTI anisotropy parameters epsilon (ε) and delta (δ). These fields were derived using an automated FAN methodology. The details of the FAN approach are described in Cai et al. (2009), and He et al. (2009), therefore; only a brief summary is given here. The specific steps for the FAN analysis is as follows:

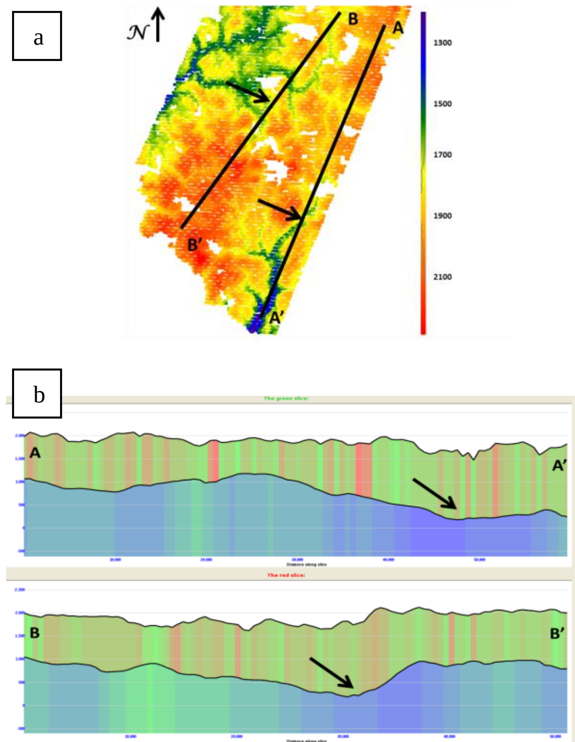

Figure 2: (a) Surface elevation (b) Weathering layer across the two profiles shown in (a).

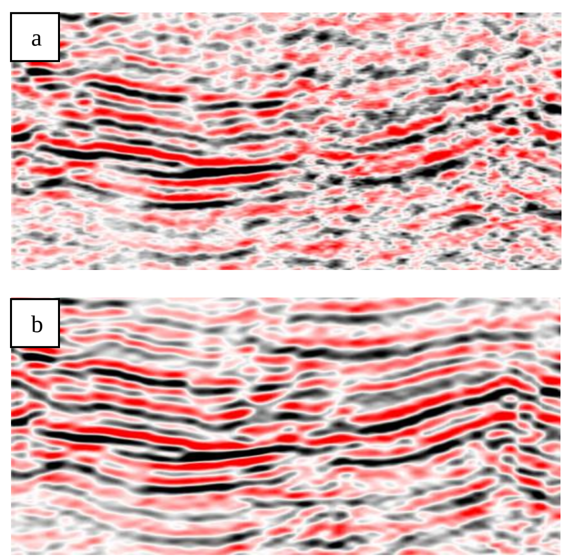

Figure 3: Migrated seismic sections without (a) and with (b) high resolution statics correction.

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(1) Take a zero-offset migration image point in a Common Image Gather (CIG) as a focal point and perform ray based, offset dependent de-migration to get the correct focusing operator in the time domain.

(2) Construct the calculated focusing operators for the current anisotropy model from the focal point for different ε and δ values. The search for the correct ε and δ is done automatically using L1 optimization criteria (to minimize the difference between the calculated and the true focusing operators). The validity of ε and δ is evaluated by the flatness of the image gathers.

(3) Construct a volume of epsilon and delta through geo-statistical interpolation along key horizons.

We built anisotropic model volumes (δ, ε) by interpolating and smoothing along the three key interpreted horizons. The estimated δ and ε models were used for all subsequent iterations of anisotropic migration. The anisotropy had a maximum of 13% for δ and 18% for ε.

Using a velocity, ε and δ, a first pass of VTI Kirchhoff migration was performed to check the gather flatness, focusing and well ties. Figures 4a and 4b show the gathers from isotropic and anisotropic migrations.

Velocity Model Building using Azimuth Sector Tomography

Three iterations of volume based high-resolution azimuth sector grid tomography (Figure 5) were performed to update the shallow sediment velocity model. For each of the tomography iterations, 3D VTI anisotropic pre-stack Kirchhoff depth migration was run. Automatic residual curvature analysis on the resulting image gathers and dip estimation on the PSDM stack volumes were performed (for each azimuth sector) for use in the tomography. Vz was updated from the combined inversion results.

Using a multi-scale iterative approach, long wavelength features of velocity anomalies were derived first. The short wavelength anomalies were gradually added in the subsequent iterations. After each iteration, gather flatness, event focusing and well ties were checked. An intermediate recalibration of Vz, ε and δ was performed.

The final sediment velocity model was validated against horizon marker picks. The marker picks from wells match with the PSDM seismic with less than 1% error indicating the accuracy of the velocity model. After the near surface sediment model definition, a grid based, deep sediment tomography was run to enhance the deeper events, followed by final anisotropic Kirchhoff PSDM.

During the last phase of tomography velocity model update, we estimated the residual delta velocity for three azimuths separately (migration and tomography were performed for each azimuth sector). From the three azimuthal sector velocity models, we constructed an ellipse using least square-fitting criteria.

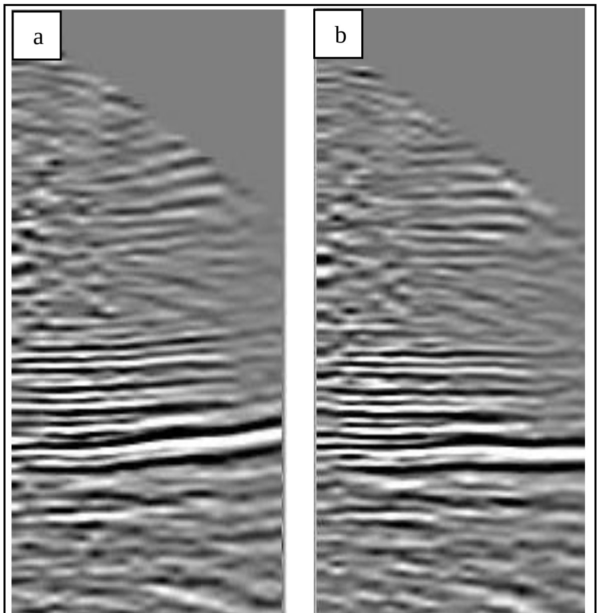

Figure 4: CIGs near a well location imaged with isotropic (a) and anisotropic (b) Kirchhoff migration.

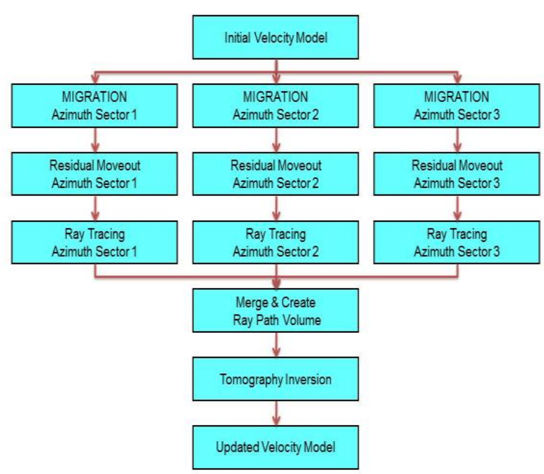

Figure 5: Flow chart for multi-azimuth tomography.

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The two major and minor axes of the ellipse are the faster and slower velocities (Vfast, Vslow). Figures 6a and 6b show a depth slice at 6000ft depth and the corresponding vfast/vslow ratio. We observe a pattern in this figure indicative of a probable fracture orientation.

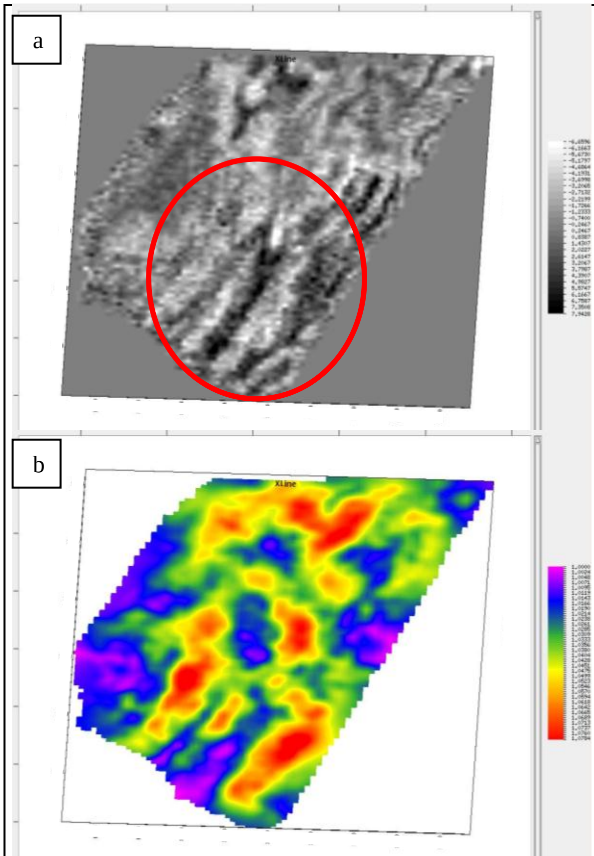

Figure 6: (a) depth slice at 6000ft (b) Vfast/Vslow

Image Improvements

We built geologically constrained anisotropic models using a focusing analysis based VTI parameter estimation methodology and volume based grid tomography that tie the well information. The overall image improved through detailed anisotropic model building. We built sediment models with iterative applications of VTI Kirchhoff depth migration.

Figures 7a and 7b are the inline comparisons of VTI Kirchhoff PSDM before and after high resolution statics correction is applied to the input data. Note that the dip of the event shown in Figure 7a is greatly reduced in Figure 7b. This is consistent with the well information.

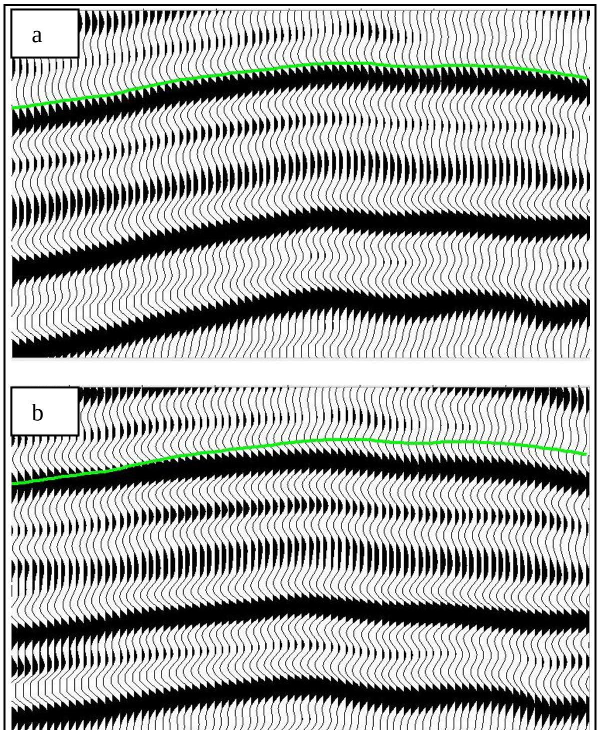

Figure 7: Inline comparisons of VTI Kirchhoff PSDM before (a) and after (b) high resolution statics application to the input data. Note the shift in the horizon.

Conclusions

The improvements to the imaging were accomplished by (a) removing as much noise as possible from the input data without affecting the quality of the signal, (b) applying high resolution statics correction to the input data, (c) utilizing new technologies such as VTI focusing analysis for anisotropic parameter estimation, and (d) VTI Kirchhoff PSDM from the topography. A combination of careful input time data preparation and enhanced model building and migration methodology is the key to the success of this project.

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EDITED REFERENCES

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