Anisotropic Seismic Depth Migration to aid Tight Gas Prospectivity in the Mountain Front region of the Anadarko Basin

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Summary

We describe a seismic depth imaging workflow that helps delineate tight gas prospectivity in the Mountain Front area of the Anadarko basin in the mid-continent United States. Our workflow involves extensive pre-processing of the seismic data, pre-stack Kirchhoff time and depth migration incorporating appropriate velocity models, and accounts for local anisotropy. Compared to previously available time migrated seismic data from the Mountain Front region, the resulting depth migrated seismic data from the application of our workflow shows substantial improvement in revealing the complex structural geology of the region. Improved clarity of the subsurface image, particularly in the deeper areas around the Mountain Front, leads to improved interpretability of the data, and hence puts us in an advantageous position to generate prospects which in turn helps make sound business decisions. Our workflow also has the potential to serve as an example for evaluating tight gas prospectivity in a similar tectonic environment.

Introduction

The Mountain Front region of the Anadarko basin is characterized by complex structural geology that results in poor seismic images and thereby causes difficulty in their interpretation. Extensive exploration during the last several decades resulted in discovery and exploitation of prospects that are seemingly obvious on the seismic data from the region. However, subtle structural and stratigraphic traps with strong potential for tight gas particularly in the deeper areas around the Mountain Front still exist and are yet to be discovered. Although technological advancements over the past decade in seismic imaging have significantly improved our capabilities to image the subsurface, the presence of an overthrust section in the Mountain Front continues to pose a challenge to producing high quality seismic images, which in turn inhibit the accuracy of their interpretation. Therefore, efforts continue to improve seismic imaging and hence interpretability (e.g., Peyton et al., 1998; Suarez et al., 2008). In this case study we describe an anisotropic seismic migration workflow and demonstrate its application to seismic data from the Mountain Front.

Pre-processing and Pre-stack Time Migration

Geographically, our area of interest spans ~700 square miles in southwestern Oklahoma (Figure 1) around the Wichita Mountain Front of the Anadarko basin. The objectives of the project include merging and re-processing several different 3-D seismic surveys, providing an improved subsurface image and precise velocity model in the area, evaluating sub-thrust plays, and resolving trap geometries. Several of the 3-D seismic surveys include high definition volumes that contain ~1 million traces per square mile. Figure 2 shows a generalized fold map in the area of interest. Full fold across the area of interest varies from low thirties to over one hundred and forty.

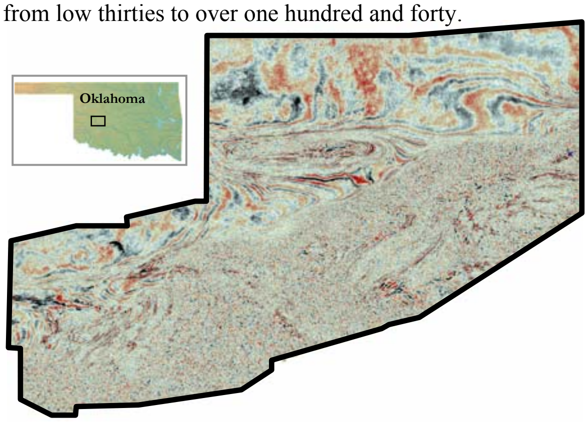


Figure 1: Geographic location map of the area of interest (inset). Area within the smaller box is magnified and includes a depth slice at 10,000 feet of the seismic data.

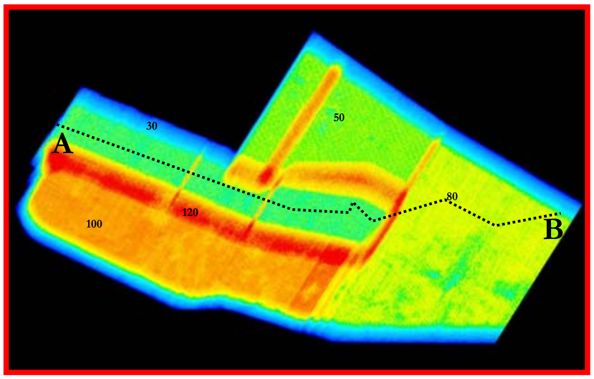
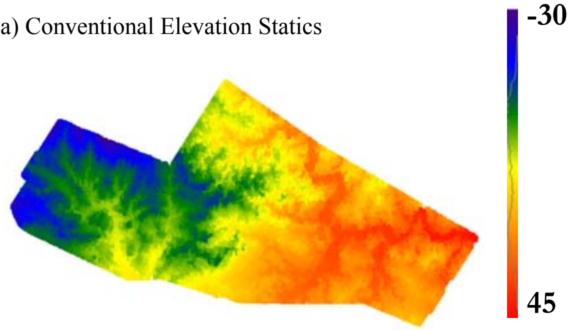


Figure 2: Generalized seismic fold map of the area of interest. The warmer and cooler colors indicate higher and lower fold respectively. The numbers on the colors indicate representative fold for scale. The dotted line A-B shows the location of the seismic image shown in Figure 4.

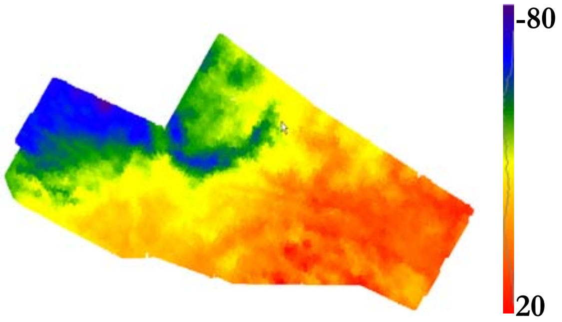
We carry out a host of usual pre-processing steps to prepare the seismic data for effective interpretation, however, we particularly emphasize aspects of processing multiple surveys such as: (a) pre-stack merge of surveys (b) global refraction statics solution (c) AVO-compliant amplitude and phase (d) actual topography versus floating datum and (e) integrity of the underlying velocity model.

Merge of the surveys include a careful and systematic phase matching over the 3-D surveys acquired using various vibroseis and dynamite sources, as well as acquisition geometry. We use strict acceptance criteria for our cross-correlation measured phase rotation (15 degrees) and time lag (2 ms) at multiple intersections before and after phase corrections. For the global refraction statics solution, we use a consistent interpretive tracking of first breaks across multiple surveys to derive a single contiguous near-surface velocity model. We also use the geologic outcrop (independent of seismic) to validate spatial details derived from refraction statics (Figure 3). To derive the AVO-compliant amplitude and phase we apply a controlled wavelet transform filtering technique, surface consistent deconvolution and amplitude correction. We also compare distribution of the seismic amplitudes from individual surveys to the merged population and eliminate any outliers.

(a) Conventional Elevation Statics



(b) Refraction Statics tied to surface geology



(c) Difference between refraction and elevation statics

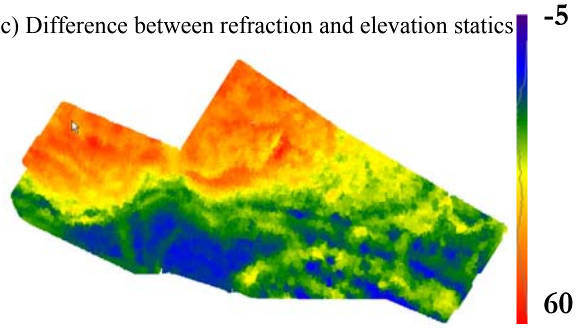


Figure 3: Comparison of (a) conventional elevation statics (b) refraction statics tied to surface geology and (c) difference between refraction and elevation statics.

While we reference the time domain processing to a floating datum (usual practice), we perform the velocity tomography and pre-stack depth migration (PSDM) from the surface (true topography). We also convert the near surface model from time to depth for validation. We also cross-check seismic derived information with independent measurements, compare trends, and average values for quality control.

A project of such scale and complexity (geological and geophysical) requires efficient project management. Constant interaction and sharing of pertinent information related to decisions on parameters is essential. For example, sound knowledge of surface geology helped in increasing our confidence in refraction analysis derived statics, and understanding trade offs between resolution and signal to noise ratio enhancement which reduce the risk of adverse irreversible impact on seismic amplitudes.

In this processing routine, we use tomography derived velocities in an iterative and interpretive manner. Our near-surface refraction-derived velocity layer complements the shallower parts where angle/offset coverage limits the resolution of reflection velocity analyses. We further calibrate the velocity layer against well ties before it is incorporated into the initial PSDM velocity model. We describe the details of these steps in later sections. In subsequent iterations, we perform tomography in successive smaller scales, whereas in the final run we use simultaneous multi-scale tomography joint inversion (MuST).

MuST uses multiple grids of different sizes as a stabilizer for the inversion. We represent the earth as a grid, solving equations at each grid node. In an area of complex geology such as the Mountain Front, high resolution is necessary, requiring smaller cell sizes within the grid. However, the inversion may become unstable and expensive. MuST takes advantage of the fact that we only need high resolution in some places and not everywhere. It also assumes that the subsurface contains structures of many different sizes and shapes. The algorithm uses (picked) depth errors from the migrated gathers at every offset and depth (Cai and Witcombe, 2006) with a set of specular reflection angles and inverts (in a least squares sense) while minimizing velocity errors. Two-point ray tracing from locations of sources and receivers is used to compute travel times and honor the acquisition geometry and azimuthal factors.

In Figure 4 we show an example of a pre-stack time migrated (PSTM) seismic image along an arbitrary line A-B across the area of interest. We also show horizons 1-6 that we map throughout the area with good confidence (Figure 4).

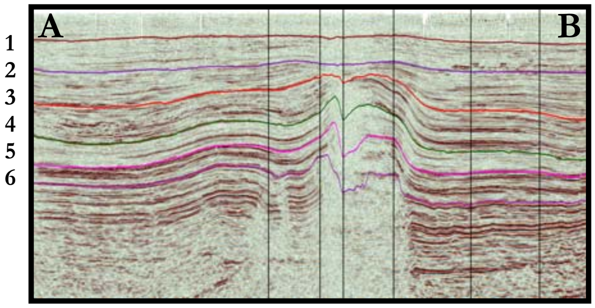


Figure 4: Arbitrary PSTM seismic line A-B across the area of interest showing the mapped horizons 1 - 6 (numbers are in the order of increasing two-way travel time vertically down).

Although the PSTM seismic data shows a promising picture of the subsurface, the processing does not consider a velocity model constrained by available well control in the area. Furthermore, the area of interest has complex structural dip and lateral velocity variations suggesting that PSTM alone is inadequate to provide a true picture of the subsurface, instead pre-stack depth migration (PSDM) and accounting for anisotropy is necessary. Therefore, our next steps involve building a reliable velocity model across the area of interest using well control, and determining the appropriate anisotropy parameters for PSDM.

Building a Velocity Model and Anisotropy corrections

First, on the PSTM seismic data we identify and map key horizons (reflectors) that we are able to confidently follow across most of the area of interest. Figure 4 shows these key reflectors. We also identify several wells spanning the working area that have reliable gamma ray, sonic, density, and resistivity logs. In all, we identify 21 such wells. Wherever available we use the checkshot survey data to compare with the sonic data at the well. If a checkshot survey is not available we use one nearby that lies within similar structural settings, to compare with the integrated sonic. The synthetic is stretched and squeezed within reasonable velocity constraints to correlate with the PSTM seismic and obtain time-depth functions. In most of the wells we are able to obtain reliable ties with the seismic data. We show an example of a well tie in Figure 5. In addition to the 6 mapped reflectors and 21 time-depth functions from the tied wells, we also utilize 80 geologic picks in 27 wells to build our velocity model. Integrating all of these data we build a velocity model that is fairly smooth (without abrupt changes) and ties most picks with associated horizons within ±20 feet. Figure 6 shows a snapshot of the velocity model.

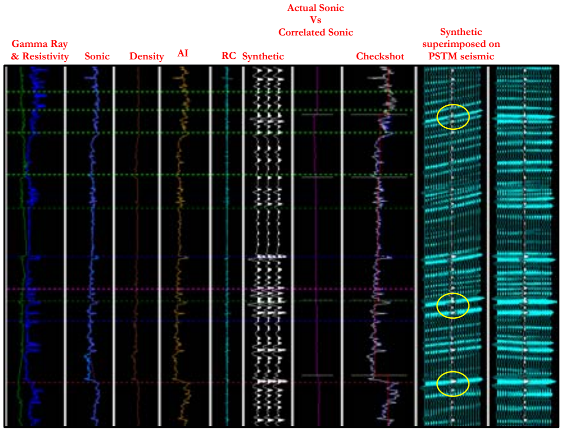


Figure 5: An example of a well tie with PSTM seismic data. Yellow ellipses highlight the quality of the ties.

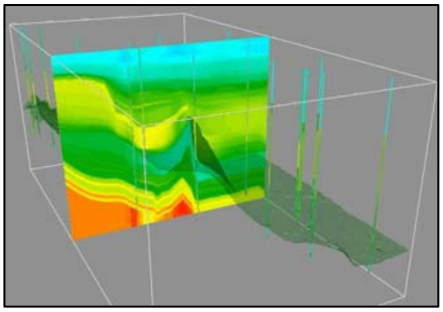


Figure 6: A snapshot of our velocity model (far end being northwest and near end being southeast). The vertical lines indicate the locations of the wells whose time-depth functions we use to build our velocity model. The velocities range between 4,000 feet/s and 24,000 feet/s, cooler and warmer colors representing slower and faster velocities respectively.

To obtain an estimate of the values of anisotropy parameters (δ and ε; Thomsen, 1986) to use in PSDM, we use our velocity model to convert the PSTM seismic data to depth domain. We then compare the depth converted seismic data at the wells with test PSDM lines in the same position. In the process we compile a list of differences in depth at the wells for all six reflectors. These differences along with literature related to rock types in the region, allow us to estimate values of δ to use in the PSDM. We also observe that in our un-muted seismic gathers from the region, the typical “hockey stick” signature that is diagnostic of ε is not abundant. Furthermore, our data do not contain adequate number of offsets for precise estimation of ε. Therefore, for the purposes of this study we assume ε is equal to δ and use a value less than 10% in the shallower parts and between 10% and 15% in the deeper parts. Finally, we run the PSDM throughout the area of interest and compare the resulting seismic images with previously available PSTM volumes.

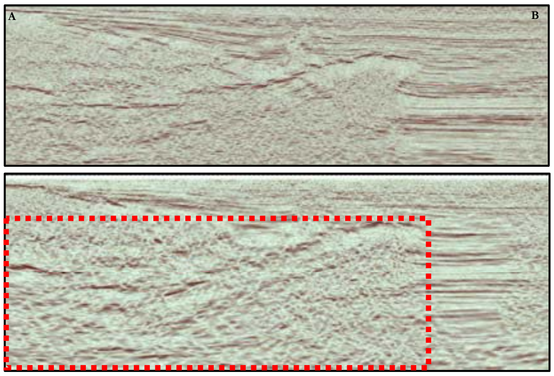
Pre-stack Depth Migration Images and Comparison

In this section we compare seismic images following PSDM that incorporates a velocity model honoring well control and anisotropy, to images of the same lines from previously available PSTM seismic data. Figure 7a - c show examples of the comparison. The PSDM seismic images (Figures 7b – d) particularly in intermediate to deep areas reveal more continuity, character, and show improved resolution of panels of structural dip. In the shallower parts however, the PSTM images generally show better fidelity and resolution. Future methods involving smaller depth sampling in the shallow intervals and better interpolation may address these concerns.

Discussions

Application of the workflow described in this paper to produce PSDM seismic images around the Mountain Front provides encouraging results with significant improvement in imaging in the intermediate to deep areas. This enhances our capability to accurately interpret this complex structural terrain. We recommend however that interpreters use a combination of PSTM and PSDM images to interpret structure in some areas. This case study has the potential to serve as an example for work in other similar geologic regions.

(a)



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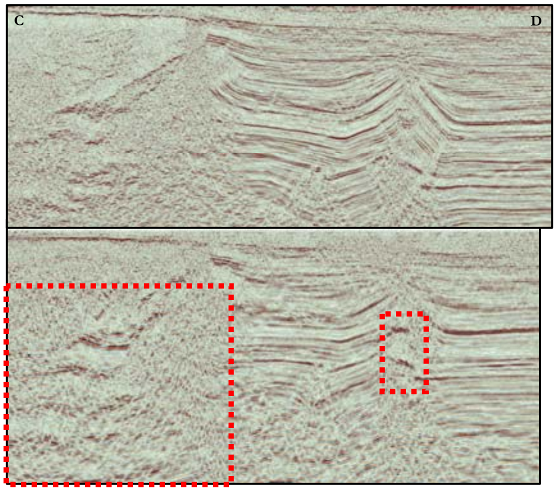

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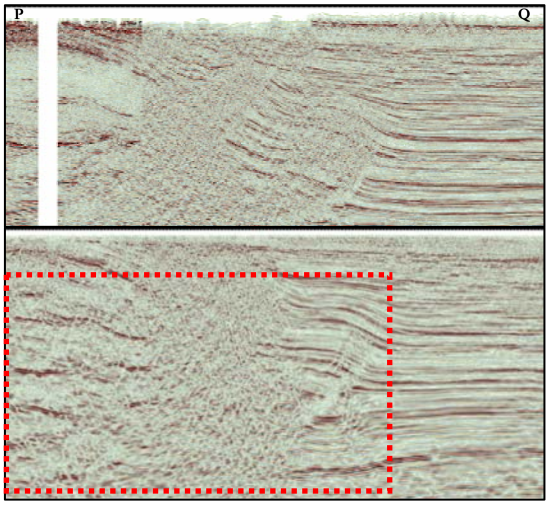

Figure 7: (a – c) Examples of images from vintage PSTM (top panels) and PSDM from this work (bottom panels). Dashed red boxes indicate areas where improvements are more prominent.

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