High fidelity full azimuth TTI velocity model building: A Gulf of Mexico case study

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Summary

We demonstrate a novel workflow for high fidelity full azimuth tilted transverse isotropy (TTI) velocity model building in an area of the Gulf of Mexico (GOM) with complex salt geometries. The workflow combines wavelet shift tomography for building a detailed overburden model, angle tomography driven by azimuth sectored reverse time migration (RTM) angle gathers for updating the sediment model in complex mini basins, underneath overhangs, and subsalt, and finally full waveform inversion (FWI) to resolve fine scale features in the overburden model. A full azimuth, long offset dual sensor acquisition provides the illumination needed in this notoriously difficult imaging area, as well the low frequencies and long offsets required for an optimal FWI solution.

Introduction

High fidelity TTI velocity model building for pre-stack depth migration (PSDM) in illumination-challenged environments exhibiting complex salt geometries is a challenge requiring several complementary technologies. Full azimuthal coverage and long offsets are required to provide illumination through complex salt bodies. Ray-based tomographic methods may be used to update sediment velocities, but RTM is required to determine salt geometries and to provide accurate kinematic information for residual moveout analysis near and below salt. This kinematic information, if captured in azimuth sectored angle gathers, may be fed back into ray-based tomographic methods to update local sediment velocities. Wavelet shift tomography, RTM-based angle tomography, and FWI are applied in a complementary fashion to resolve different parts of the model in a manner consistent with each algorithm, and suited to the particular challenges present in different stages of model building.

The data under investigation were acquired in 2013 and 2014 using dual-sensor cables covering approximately 11,800 sq km over 509 OCS blocks in Garden Banks and Keathley Canyon. A novel five-vessel simultaneous shooting scheme (Long et al., 2014) provides high fold, full azimuth coverage with offsets up to 16km. Figure 1 demonstrates the overall offset-azimuth distribution in the data, with complete full azimuth coverage. The figure also shows a diagram depicting the five-vessel geometry, including 2 streamer vessels and 5 source vessels, which enables simultaneous long offset shooting. Several large subsalt discoveries have been made in this area targeting Lower Tertiary objectives (i.e., Tiber, North Platte), however no production has been achieved from these reservoirs. This portion of the deep water GOM is notoriously difficult to illuminate and image due to complex salt geometries

Methodology

The TTI velocity model building workflow is made up of five main elements: wavelet shift tomography (Sherwood et al., 2011), dip estimation, salt interpretation, angle tomography, driven by azimuth sectored RTM angle gathers (Whitmore et al., 2014), and full waveform inversion. The key to producing highly accurate velocity models lies in combining these algorithms in a complimentary fashion in a workflow, such that any weakness that might exist in any one method alone is mitigated.

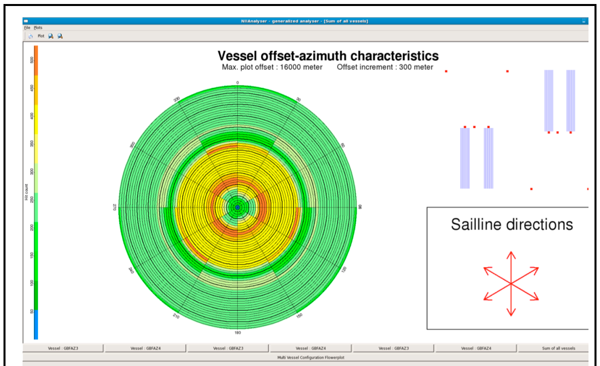

Figure 1: Rose diagram illustration of overall survey offset-azimuth distribution for five vessel acquisition acquired in both sail-line directions for three survey azimuths . The maximum offset shown is 16 km.

The initial sediment model is built using wavelet shift tomography. Rather than relying on picked moveout curves from gathers, this method uses measured wavelet attributes derived during beam migration. The process begins by decomposing pre-processed data into wavelets by scanning for coherent energy over a range of ray parameters. The migration process maps the wavelets into the depth domain, providing several model domain attributes to complement the data domain attributes derived during the data decomposition. All of these attributes may be used to select which wavelets will be used to construct a migrated image. Like other tomographic methods, travel

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time residuals are back-projected to produce slowness updates, but the travel time residuals used in wavelet shift tomography are measured in a 3D sense. Whereas traditional residual moveout analysis methods measure vertical shifts in common image gathers, time residuals for wavelet shift tomography are measured normal to reflectors on a wavelet-by-wavelet basis. Not only does this provide for dense picking, but it enables the accurate measurement of residuals in the proximity of steeply dipping reflectors. The velocity model produced with wavelet shift tomography is very well conditioned, as dense picks, which can be conditioned with all the pre- and post-migration wavelet attributes, are used to drive the tomographic updates. This produces geologically consistent updates of very high resolution.

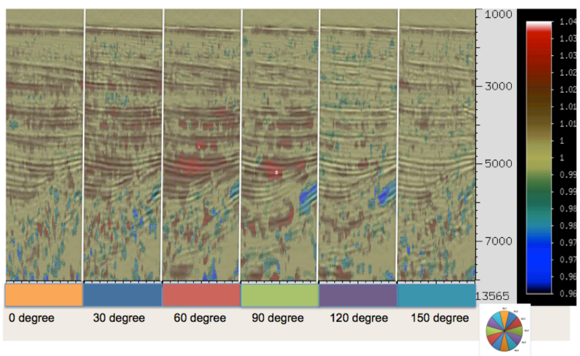

Figure 2: RTM stacks from each binning azimuth overlain with (residual moveout) gamma values derived from the associated angle gathers. Note the variation in gamma as a function of azimuth.

Wavelet shift tomography is applied in a wide azimuth (WAZ) sense simultaneously to all three shooting azimuths, resulting in a full azimuth (FAZ) geometry, which naturally follows the acquisition. Once the anisotropic overburden model is complete, including updates of epsilon and delta, and slope estimation from stacked images, reverse time migration (RTM) is used in an iterative fashion to delineate the geometry of salt bodies using a succession of sediment and salt floods. Once complex salt bodies have been included in the model, slopes for TTI symmetry axes may be re-estimated from RTM images. At this point, ray-based imaging methods will not be able to produce adequate image gathers for measuring fine-scale residual moveout underneath overhangs, in complex mini basins, and subsalt. However, RTM is capable of providing kinematically accurate information for residual moveout analysis in these complex areas from azimuth sectored angle gathers.

RTM is a shot based migration method, where each shot is imaged onto the subsurface independently. During the imaging process, the source and receiver angles can be determined from a combination of the source wavefield direction vectors and subsurface dip (or alternatively, the receiver wavefield direction vectors at the source onset time), giving an opening angle computation given by equation (1), where Ps and Pr are the direction vectors computed directly from the wavefields and subsurface dip.

$$\theta(\mathbf{p}_S,\mathbf{p}_r) \cong \frac{1}{2}\cos^{-1}\left(\frac{\mathbf{p}_S \bullet \mathbf{p}_R}{|\mathbf{p}_S||\mathbf{p}_R|}\right) \quad (1)$$

However, angular decomposition of the RTM image requires removal of the backscattered RTM noise at each time step, which cannot be done by standard correlation based imaging conditions (where the backscattered noise interferes with the decomposition of the data). To mitigate this problem, we employ an advanced imaging condition, which we refer to as an inverse scattering imaging condition (ISIC). The ISIC imaging condition at a fixed time t is shown in equation 2(a) (Whitmore and Crawley, 2012; Op 't Root et al., 2012), where (2b) are the source and receiver wavefields in the frequency domain.

$$\hat{I}(\mathbf{x},t) = W_1(\mathbf{x},t)\nabla\Psi_S(\mathbf{x},t)\bullet\nabla\Psi_R(\mathbf{x},T-t) + W_2(\mathbf{x},t)\frac{1}{v^2(\mathbf{x})}\frac{\partial\Psi_S(\mathbf{x},t)}{\partial t}\frac{\partial\Psi_R(\mathbf{x},T-t)}{\partial t} \quad (2a)$$

$$\hat{\Psi}_S(x,\omega) = \omega^{-(\alpha+1)/2}\hat{P}_S(\mathbf{x},\omega)$$
$$\hat{\Psi}_R(x,\omega) = \omega^{-(\alpha+1)/2}\hat{P}_R(\mathbf{x},\omega) \quad (2b)$$

This imaging condition uses two imaging kernels, which when combined largely attenuate the backscattered RTM noise. This decomposition described in equation 2 generates a backscatter free RTM image that can then be decomposed into subsurface angles. At the same time, the RTM image can also be binned onto output azimuth bins, allowing for a direct mapping to angle-azimuth images during RTM imaging as shown in equation 3.

$$\hat{\hat{I}}(\mathbf{x}_S,\mathbf{x},\theta,\alpha,t) = Bin_{\theta,\alpha}(\hat{I}(\mathbf{x}_S,\mathbf{x},t)) \quad (3)$$

Where θ = angle, α = azimuth, and **x**=(x,y,z).

The final RTM angle-azimuth images are then computed by summing the binned images over all time and then over all of the resultant shot images as shown in equation 4.

$$I(\mathbf{x},\theta,\alpha) = \sum_{x_S}\int A(\mathbf{x},\theta,\alpha)\hat{\hat{I}}(\mathbf{x}_S,\mathbf{x},\theta,\alpha,t)dt \quad (4)$$

This dynamic angle-azimuth decomposition of the RTM image is achieved during the RTM computation and angle-azimuth data is saved at each image point.

Figure 2 demonstrates the complete azimuthal information that can be obtained from azimuth sectored RTM angle gathers for the purpose of updating the velocity model. RTM stacks over angle are shown for each azimuth

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overlain by residual moveout (gamma) values derived from the angle gathers contributing to the stack. Once residual moveout analysis has been performed, ray parameters for each time residual can be inferred from the azimuth and incidence angle bins. This information is back projected in a ray-based angle-domain tomography by shooting from the reflectors using the inferred ray parameters. This enables ray-based tomographic updates of sediment velocities from kinematic information that can only be provided by RTM.

FWI is incorporated to the workflow to resolve fine scale features in the overburden model. Our inversion algorithm uses wave propagation in the time domain and uses a normalized form of the Born scattering kernel to compute the gradient (Tarantola, 1984). The source and residual wavefields are computed by solving the two-way wave equation in anisotropic media using the pseudo-analytic (PA) method. Details and advantages for extrapolation by the PA method are reviewed in Ramos-Martinez et al. (2011). We consider variable density in our extrapolator to obtain a better match of the relative amplitudes. In addition random shot selection per iteration is performed.

Conclusions

We have demonstrated a novel workflow for building highly accurate PSDM velocity models for a complex geological setting. By combining wavelet shift tomography, full waveform inversion (FWI) and angle tomography driven by azimuth sectored RTM angle gathers, we are able to produce high-resolution velocity models that are ideally suited for imaging one of the most challenging areas of the Gulf of Mexico. Each technology is applied at the appropriate stage of the model building flow to compensate for any deficiencies in the other technologies, resulting in a high resolution overburden and accurate velocities in the vicinity of salt.

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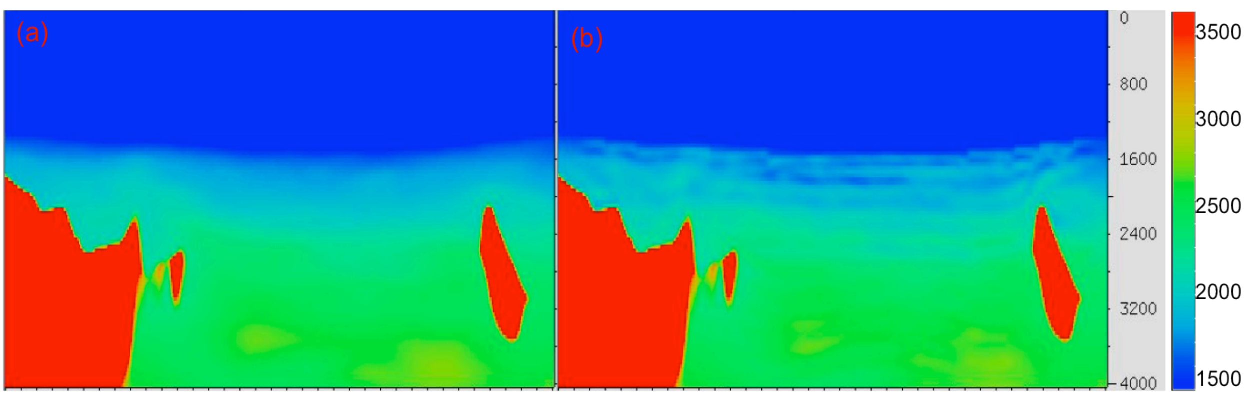

Figure 3: (a) Starting model for FWI, built with wavelet shift tomography, salt interpretation, and angle tomography. (b) Velocity model after FWI updates.

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EDITED REFERENCES

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