A case study: Improved subsalt imaging through TTI model building and imaging of a WAZ survey in the Gulf of Mexico

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Summary

Here we present a case study of improved subsalt imaging for a wide azimuth (WAZ) survey in the Mississippi Canyon/Atwater Valley area in the Gulf of Mexico. The key technologies to impact the subsalt images are: 1) WAZ acquisition, 2) True Azimuth Multiple Elimination (TAME), 3) Tilted Transverse Isotropic (TTI) model building and imaging, and 4) Reverse Time Migration (RTM) based Delayed Imaging Time (DIT) scans to update the subsalt velocities.

The area was previously imaged with Narrow Azimuth (NAZ) Vertically Transverse Isotropic (VTI) Kirchhoff migration and WAZ VTI Kirchhoff and RTM algorithms. Application of TTI RTM has resulted in significant improvements of subsalt images.

Introduction

The Mississippi Canyon/Atwater Valley area has produced some of the largest hydrocarbon discoveries in the Gulf of Mexico. In this area, the most current imaging techniques have been applied throughout the years. The Tertiary sub-salt target structures are difficult to image due to the complex ray paths incurred by the geometry and thickness of the salt. The structures can also be obscured by the complex multiples generated by the water bottom and tops of salt bodies.

This project is part of the Freedom WAZ survey located between the Mississippi Canyon and Atwater Valley areas in the Gulf of Mexico. The acquisition and processing challenges of WAZ data were discussed by Baldock et al., 2009.

This area remains active to production and there are structures that prevent acquisition. In order to improve the low fold-coverage caused by these obstructions, older NAZ acquisition data was incorporated in the north of the study area.

The objective was to improve the definition of salt flanks with overhangs and subsalt structures truncating against the steeply dipping base of salt.

A key element in improving the overall image and in particular the subsalt structures, is the use of the latest multiple attenuation techniques. Multiples not only mask the subsalt events, but they also interfere with the base of salt interpretation. 3D True Azimuth Multiple Elimination (TAME) is applied as part of the time pre-processing workflow.

Previous VTI velocity and anisotropic models were the starting point in the modeling workflow. TTI anisotropic models were built by Focusing Analysis (FAN) approach as described by Cai et al. (2009) and Yang et al. (2009). A combination of Kirchhoff and RTM migration was used to define the salt model. The subsalt velocities were updated via RTM DIT scans.

Multiple attenuation

Consider the azimuth variation for a WAZ survey; to attenuate the surface related multiples, a data-driven 3D true azimuth multiple elimination technique, TAME, was applied to this dataset (Cai et al., 2010). The subsalt events imaged after applying TAME are cleaner and the complex multiples below salt were considerably reduced (Figure 1). Radon de-multiple was not applied to avoid removing turning waves.

The 3D true azimuth surface related multiple attenuation scheme used in this project consists of three main steps:

- Data interpolation/regularization: multi-dimensional data interpolation improves the surface condition and spatial sampling while preserving the azimuth information. This process partially overcomes the acquisition imperfections and in turn improves the multiple prediction quality. The cable spacing was reduced from 120 m to 30 m by interpolating three cables between existing cables.
- Multiple prediction: to handle both wide azimuth and narrow azimuth surveys, true azimuth information is used in the construction of the multiple-contribution gather. True azimuth information also defines the aperture for each predicted output multiple trace.
- Adaptive subtraction: A robust frequency variant adaptive subtraction is used to remove multiples.

TTI imaging

The Mississippi Canyon/Atwater Valley area has been extensively imaged using NAZ datasets (Whiteside et al., 2008) and WAZ acquisition (Baldock et al., 2009; Ma et al., 2010). It has been demonstrated that the introduction of anisotropy in the velocity model assuming VTI media, results in more accurate placement of events and general improvement of the image quality.

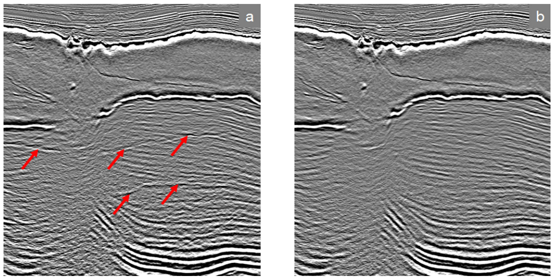

Figure 1: Kirchhoff TTI image without (a) and with (b) TAME The red arrows point to multiples.

The dips of the supra-salt bedding in general are gentle in the area, but at the margins of the mini-basins the beds are steeper along the flanks of the salt. In the subsalt area, especially near deep salt stocks or feeders, steep dips are observed (as shown in Figure 1). To image the steep dips properly, a new anisotropy modeling technique, Titled Transverse Isotropy (TTI), has been used in recent years. Bowling et al. (2009) were encouraged by a test assuming the same Vo, epsilon and delta as the final VTI model, and measuring the symmetry axis from the final VTI model; Huang (2009) had success assuming TTI media in areas with salt withdrawal mini-basins.

In this paper we describe how we built a full TTI model (Figure 2) and combine Kirchhoff and RTM imaging to further improve the image and better place events.

The TTI model building process starts with a previous vertical velocity model (Vz) built for VTI media and calibrated to check-shots. From an isotropic depth migrated volume the dips are first scanned and smoothed to define the predominant dip, and then the axes of symmetry, which are assumed to be perpendicular to the bedding, are derived,. A two-step anisotropic model building approach was carried out. Using focusing analysis (FAN), epsilon and delta are analyzed at check-shot locations. FAN involves constructing the true focusing operator by de-migration of a CIG back to the time domain, then calculating the focusing operator for different values of epsilon and delta from the focal point (zero offset image), and searching for the minimum objective function (the difference between the true focusing operator and the calculated focusing operators).

FAN was applied to a group of image gathers around the check-shot locations. The epsilon and delta models were obtained by averaging the functions from each of the image gathers at the check-shot locations and tying the delta or epsilon function to the water bottom. Vertical velocity, Vz, was converted to velocity along the symmetrical axis, Vo, according to experimental relation. The maximum values of delta and epsilon are 4 and 8 percent respectively. Delta and epsilon were verified and refined for each iteration. The final anisotropy models are shown in Figure 3.

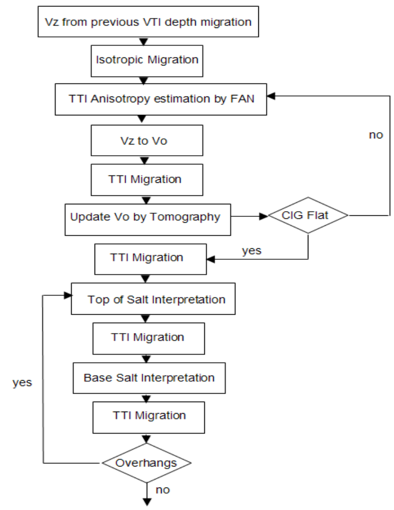

Figure 2: TTI model building workflow

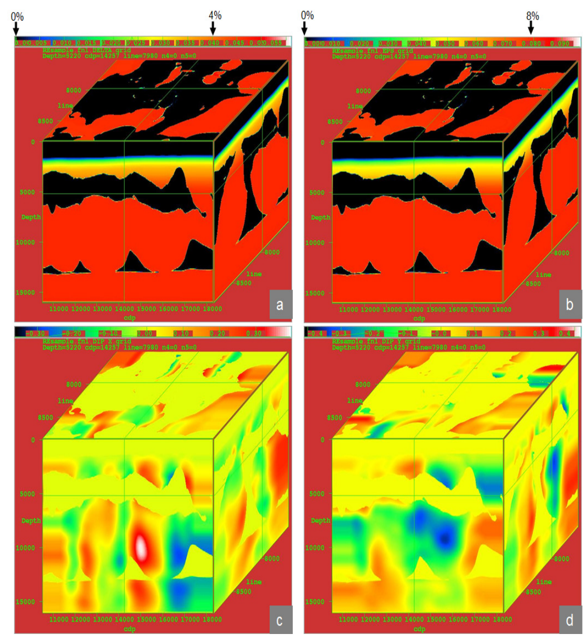

Figure 3: a) Delta b) Epsilon c) Dip in the inline direction d) Dip in the cross-line direction

Vo was refined above salt through two subsequent passes of multi-azimuth grid tomography and one pass of high-resolution grid tomography. Taking advantage of the wide-azimuth acquisition, the data was sectored into three azimuthal ranges and each sector was migrated separately. The azimuth sectors were selected so each sector provides good fold coverage and is as narrow as possible to ensure accuracy in the ray tracing step. For each dataset, the dips were automatically measured from the stacks, residual depth curvatures were calculated on imaged gathers and both attributes were used for ray tracing. No rays passing through the salt were allowed. Travel time errors from the three sectors were inverted simultaneously and used to update Vo.

The TTI anisotropic sediment model was validated by analyzing the flatness of the image gathers, comparing the velocity trend at check-shot locations to the trend of the velocity model, and checking the well salt depths against the top of salt horizon.

After the sediment model was updated, TTI Kirchhoff with turning waves and TTI RTM were used to define the top of salt. The salt model was built in a top down approach, alternating sediment flood and salt flood migrations. Kirchhoff migration is efficient and provides high-resolution images that are very good for top of salt interpretation. However, overhangs and multiple salt bodies in close proximity can make ray-tracing difficult so RTM is also used. RTM is a wave-equation based algorithm with no high-frequency approximation; it is capable of handling multi-pathing, meaning it can image areas with sharp velocity contrasts. Also, RTM better images event termination against steeply dipping salt flanks, which helps to define salt boundaries. The combination of TTI Kirchhoff with turning waves and TTI RTM provide a better toolbox for achieving a more accurate top of salt interpretation.

The next step was to flood with constant salt velocity below the top of salt. Successive passes of sediment and salt floods were run, not only to define overhangs, but also to interpret small lenses of sediments within the salt. RTM's accurate two-way-propagator gives it the ability to use prism waves to increase the angle of illumination in shadow areas. Good illumination compensation allows better imaging of subsalt events, particularly below a steeply dipping base. The top and base of salt are accurately positioned as verified from well data.

Subsalt velocity update via DIT scans

The subsalt velocity model was updated using RTM-based Delayed Imaging Time (DIT) scans (Wang et al., 2009). When the incorrect velocity is used for migration, the energy is focused at the zero offset with a non-zero time imaging condition.

Generating positive and negative non-zero-time imaging conditions (DIT) produces data that emulate imaging with variable velocities. The DIT images are sorted to gathers and conditioned; then semblances are generated. The semblances are automatically picked as described by Wang et al., (2011). The DIT picks are converted to residual velocities and the velocity model is updated. For quality control purposes, composite images are formed by selecting the DIT panels that produce the best focused and coherent images.

This technique not only produced uplift in the subsalt image quality (Figure 4), but also helped to detect salt geometry errors allowing us to build a more accurate salt model (Wang et al., 2011).

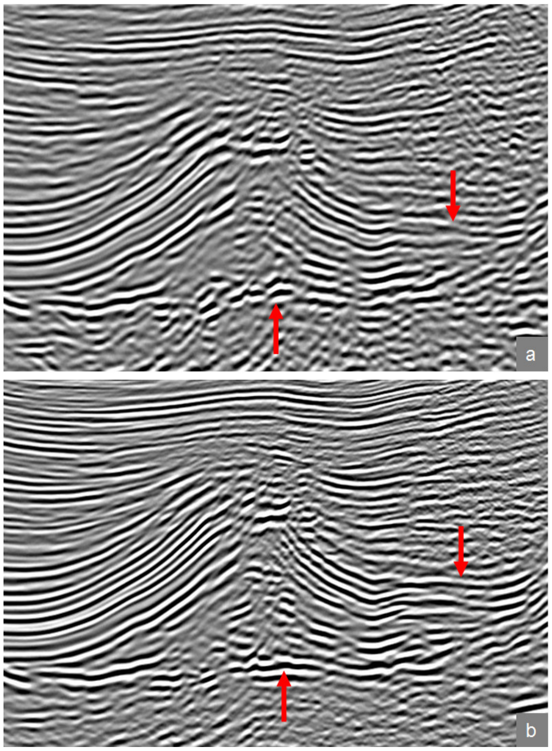

Figure 4: Subsalt image a) before and b) after subsalt velocity update via DIT scans.

Image comparisons

The results were compared to previous processing in the area. When comparing VTI imaging, WAZ acquisition considerably improves the image compared to NAZ acquisition (Figures 5a and 5b). Additional uplift is achieved when the model is built assuming TTI media. Figure 5c shows a Kirchhoff image migrated with a TTI velocity model. The events are more continuous below salt and the small basin on the edge of the salt is more clearly defined. Figure 6 compares RTM using velocity models built assuming TTI and VTI media.

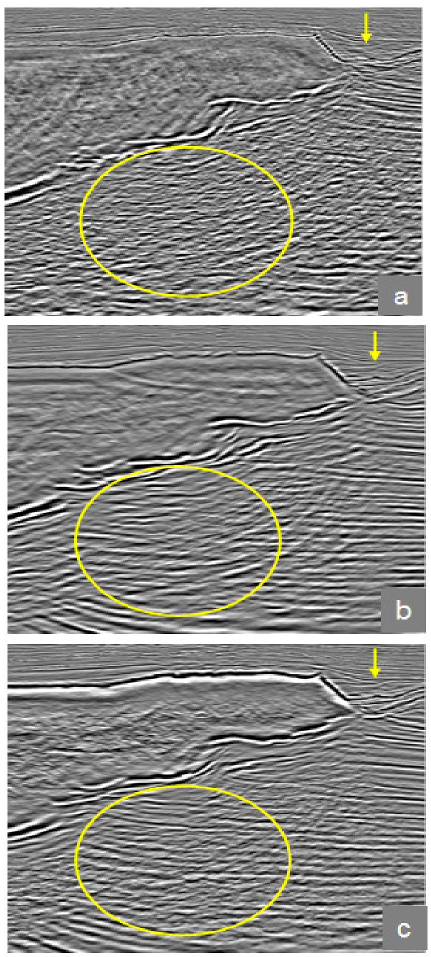

Figure 5: A Kirchhoff image for narrow azimuth (NAZ) data imaged with VTI velocity model (a) and wide-azimuth data imaged with VTI (b) and TTI (c) velocity models

Conclusions

Though considerable progress has been achieved in imaging subsalt structures, the availability of wide azimuth (WAZ) data, 3D true azimuth surface related multiple elimination techniques, TTI Kirchhoff and RTM migrations open new possibilities to further improve the image.

Advances in available technology allow continual improvement to our subsurface images. Imaging existing NAZ data assuming VTI media improved the overall image and placed events at the correct depths, but poorly illuminated areas still could not be improved. The introduction of WAZ acquisition brought a big uplift through the additional illumination that comes with increased azimuth coverage. As the algorithms and implementation of 3D true azimuth multiple attenuation and RTM become more efficient WAZ acquisition, in combination with salt model building assuming TTI media from start to end, provides additional improvement in areas of azimuth-dependent dipping beds, such as in mini-basins and below a steeply-dipping base of salt. TTI imaging and DIT scans produce better definition of sub-salt events. Through several data comparisons we have proved the value of these new techniques and technology.

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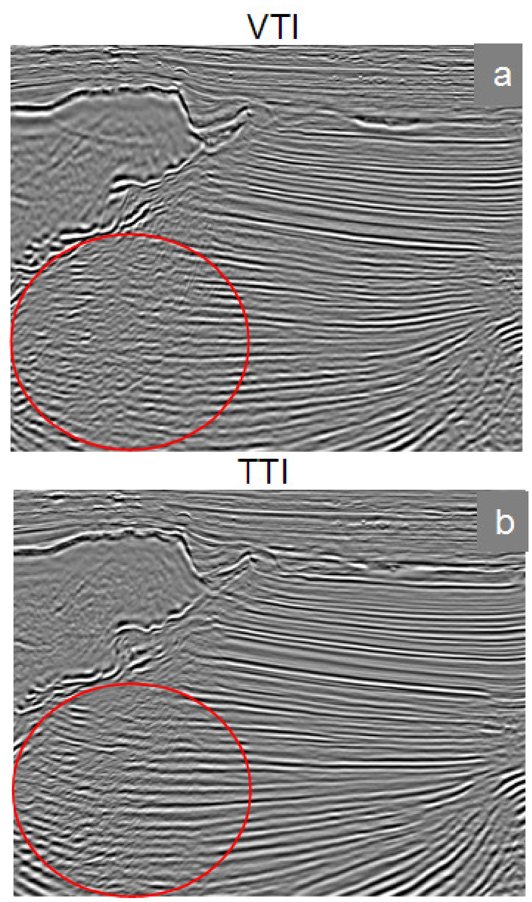

Figure 6: RTM assuming a) VIT media and b) TTI media

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