From Isotropic to Anisotropic: Puma/Mad Dog Wide Azimuth Data Case Study
Jerry Bowling¹, Shuo Ji*², Dechun Lin², Micah Reasnor¹, Mike Staines¹, Nick Burke¹
¹BP America Inc.
²CGGVeritas

Summary
Recent seismic acquisition and anisotropic velocity modeling has resulted in improved salt definition and sub-salt imaging at Puma and Mad Dog Fields in the Gulf of Mexico. For these fields, wide-azimuth towed-streamer (WATS) surveys, isotropic imaging, vertical transverse isotropy (VTI) imaging, and tilted transverse isotropy (TTI) imaging were carried out sequentially. This series offers a great opportunity to understand the impact of different levels of anisotropy approximation and why TTI reverse time migration (RTM) should be used for future WATS imaging.

Introduction
Mad Dog was discovered by BP in November 1998, and roughly eight miles away, Puma was discovered by BP in January 2004. Both fields are about 140 miles south of the Louisiana coastline in the southern Green Canyon area within the Atwater (Mississippi Fan) fold belt. As of 2004, due to the complexity of subsurface structures, the seismic images were of only moderate quality. Improved seismic images were needed to further develop both fields.

Figure 1. Puma WATS acquisition configuration.

To improve the sub-salt image, BP started the industry’s first Wide Azimuth Towed Streamer (WATS) acquisition at Mad Dog in 2004, followed by a Puma WATS acquisition in 2006. The acquisition details for Mad Dog WATS can be found in Michell et al. (2007). Figure 1 shows the acquisition geometry for Puma, which is similar to Mad Dog, except that the maximum crossline offset is 5000 meters instead of 4000 meters, and the sail line spacing is 500 meters instead of 250 meters. Since the initial WATS acquisition at Mad Dog, both BP and CGGVeritas (CGGV) have worked to progress WATS acquisition and processing.

Compared to conventional Narrow-Azimuth Towed-Streamer (NATS) acquisitions, WATS acquisitions have much stronger stacking power over multiple energy and better sub-surface illumination (Ver West & Lin, 2007). Even a brute WATS migration yielded a cleaner sub-salt image than fully processed NATS data (Michell et al. 2007). From 2005 to 2006, isotropic WATS processing was carried out for the Mad Dog area. The results were significantly better than old NATS images and changed the structural interpretation a great deal and served to reduce the uncertainty of well outcomes based on it. In 2007, BP began isotropic processing of the newly acquired Puma WATS data. This effort would be the first to combine the Mad Dog and Puma WATS surveys into one image.

In order to reduce project risk and to validate emerging WATS processing technology, BP commissioned CGGV to also rebuild the entire salt model using their new VTI Pre-stack Depth Migration (PSDM) model building workflow. With both projects being worked in parallel, CGGV started reprocessing a combined Puma/Mad Dog WATS dataset using their VTI PSDM flow in late 2007. CGGV and BP worked closely together throughout the VTI imaging project to utilize the best of both groups.

The combined Puma/Mad Dog WATS dataset covers an area of approximately 70 OCS blocks and 2.6 billion traces. Figure 2 shows the location of the study area with an inset of the top of salt (TOS) horizon and project input/output area. The data was put through a full time-processing flow, which includes shot/channel domain de-noise, WATS 3D SRME, and data regularization.

Figure 2. Puma Mad Dog survey location. Enlarged picture shows the input/output area with the TOS horizon overlaid.

Around the same time, TTI imaging, specifically TTI RTM, was gaining momentum in imaging deep water Gulf of Mexico (GOM) (Huang, et al, 2008). The added dip information of TTI can help remove some of the velocity artifacts that are observed in the bottom of deep basins after isotropic/VTI velocity tomographic (tomo) updates. Also, it can more accurately position the steep salt boundaries, and thus produce superior sub-salt images. To investigate the advantages of TTI imaging, a simplified TTI test was carried out after VTI processing.
In this paper we will use this reprocessing case to demonstrate how anisotropic velocity models (VTI / TTI) can improve sub-salt images.

**Anisotropic Velocity Model Building**

In the Gulf of Mexico, due to sediment layering and bedding, it is generally believed that an anisotropic velocity model is a better approximation than an isotropic one. Well mis-ties in previous isotropic migration volumes, steep salt diapirs, and high-dip sediment basins overlying target intervals further supported the usage of anisotropic velocity model building in the Puma / Mad Dog area.

VTI is the simplest anisotropic velocity model and has three components: the vertical velocity $V_0$ and the anisotropic parameters $\delta$ and $\varepsilon$ (Thomsen, 1986). In this VTI processing, the $\delta$ and $\varepsilon$ fields were assumed to be a smooth background. Initial $\delta$ and $\varepsilon$ profiles were built using a 1D joint inversion estimation (Huang et al., 2007) at individual well locations. Separate 1D profiles were then generated for both $\delta$ and $\varepsilon$ by averaging over different wells and extrapolated to the whole survey by hanging from the water bottom horizon.

The previous final isotropic sedimentary velocity derived by BP was then scaled by $\delta$ followed by a smoothing to remove possible artifacts to generate the initial vertical velocity ($V_0$) model. CGGV then applied several iterations of WATS tomography to the vertical velocity $V_0$ model to flatten the gathers. To take advantage of WATS geometry, WATS tomography utilizes vector-offset binning, common vector-offset migration, and velocity inversion. In a vector-offset CIG, an event is a 3D surface in offsetx-offsety-depth space. New tools were developed by CGGV to identify and pick residual curvature along those 3D surfaces and the CGGV inversion software was updated to work with this new geometry.

Salt geometry was built into the velocity model in a top down manner. The complete salt body was built iteratively, alternating sediment flood and salt flood migrations and interpretation. RTM was used extensively in these processes.

**Improved Images from WATS data, RTM, VTI & TTI**

Not only does the choice of migration algorithm affect the overall image quality, but so does the choice of velocity model. In this section, we show comparisons between wave-equation migration (WEM), controlled beam migration (CBM) and RTM as well as differences between isotropic, VTI, and TTI velocity fields to better understand their impact on sub-salt imaging.

RTM is generally believed to be the most accurate algorithm among different propagation operators (Zhang et al., 2008). It images turning waves and prismatic waves, has no dip limitations, and handles complex structures better. The benefits of using RTM includes better definition of the steeply dipping salt flank, details of a small overhang and less imaging artifacts as compared to the wave equation migration (WEM) and controlled beam migration (CBM) as illustrated in Figure 3.
From Isotropic to TTI: Puma/Mad Dog WATS Case Study

Anisotropic effects are most obvious when comparing images migrated using the final isotropic velocity field from BP versus the final VTI velocity field derived by CGGV (Figure 5). The traverse line we show here passes through a well. The yellow marker indicates the position of the base of salt event from drilling (ca. 14,000 feet in depth). For this particular well, the water bottom depth is around 4300 feet, and the top of salt is about 6500 feet. In this case, RTM images using both velocity fields show that in going from isotropic to VTI the well mis-tie at the base of salt has been reduced from 450 feet to 100 feet. These errors are approximately 4.6% and 1%, respectively, when measured below the mud line. For the subsalt velocity field, \( V_0 \) derived from sonic data collected in this well is much slower than the final isotropic velocity field. Accounting for this in the VTI model, appears to have helped remove discontinuities between sub-salt events imaged through salt and those imaged through sediment. Overall, using VTI RTM resulted in better focusing which in turn produced a more coherent base of salt reflection and, more importantly, a cleaner sub-salt image with improved continuity and more structural details than the isotropic result.

However, further investigation showed that even a VTI velocity field may be inadequate for parts of this structure. The WATS data was split into different azimuths and migrated separately, both using the final VTI sedimentary velocity field. Figure 6 shows some “butterfly” image gathers, where the left half of the gather is from 90° degree azimuth data and the right half from 75°. Azimuthal differences in velocity are highlighted by inconsistent residual curvatures in the gathers at the two oblique orientations. Huang et al. (2008) points out that such discrepancy can be resolved through a TTI velocity field. More importantly, a TTI velocity field is much simpler and smoother due to the symmetry axis being perpendicular to the sedimentary bedding. To test this assumption, we carried out a simple TTI migration test, assuming that the TTI velocity had the same \( V_0, \delta \text{ and } \varepsilon \) as the final VTI model and with the symmetry axis measured from our final VTI RTM volume.

Figure 5: WATS RTM images with isotropic (left) and VTI (right) velocity model. The yellow maker indicates the BOS depth from drilling.

Figure 6. VTI CBM CIGs with final sediment velocity. Each CIG is the combination of azimuth 10° (left half) and 75° (right half). The strong events at bottom are TOS.

Figure 7 shows a comparison between VTI RTM and TTI RTM. As mentioned earlier, \( V_0, \delta \text{ and } \varepsilon \) are taken from the final VTI model and the salt model was not updated. The dip angle \( \theta \) and the dip azimuth \( \varphi \) were estimated using the final VTI RTM stack. Even with this simplified test, TTI helped to reduce the over-migrated swings in the high-dip sub-salt area. Focusing and continuity of events within the circle is better defined in the TTI migration. Given that all other variables were kept constant, the improvement in reflections would be a direct result of tilting the symmetry axis of the velocity field normal to the sedimentary bedding. Although simple, this
TTI test is encouraging and suggests that a full TTI model building flow including TTI tomographic updates for the sediment velocity and a re-interpretation of the salt body would likely produce a better image than the final VTI image.

Conclusions

Subsalt fields such as Puma and Mad Dog will undoubtedly continue to yield surprises despite advancements in seismic acquisition and processing. However, the algorithms and model building workflow discussed here have yielded superior images to what was available just a few years ago. Justifiably, the style of data acquisition, type of velocity model, and migration algorithm contribute to the overall subsurface image quality. From the processing projects at Puma and Mad Dog, a WATS style of acquisition offered better azimuth coverage and stronger stacking power to reduce multiple forms of noise. VTI velocity model building also demonstrated superior imaging ability over isotropic imaging in terms of better spatial positioning and well ties. Additionally, early tests indicate that TTI velocity modeling can improve results over both isotropic and VTI velocity modeling, but a full-field test (complete salt model rebuild) is still necessary. Lastly, RTM should be used for its ability to better image complex structures. In all, these results indicate that the combination of a WATS style of seismic data acquisition, TTI velocity model building and RTM have the most potential for future imaging of complex subsalt fields such as Puma and Mad Dog.

Acknowledgements

We would like to thank BP and Puma/Mad Dog co-owner companies BHP Billiton, Chevron, and StatoilHydro for giving us the permission to present this work. We would like to thank CGGVeritas for giving us the permission to present this paper. We would also like to thank all members of the Puma and Mad Dog subsurface teams from BP, BHP Billiton, Chevron, and StatoilHydro for their invaluable feedback and contribution to this project. We would also like to thank the CGGVeritas Puma team for help in processing the data.