Interpretation driven salt halo calibration for AFWI model and its impact on imaging: a case history.

Dhananjay Tiwari, Brahma Mekala, Simon Dean, Gan Yu, and Ika Novianti, TGS

Summary

Building velocity models using full waveform inversion (FWI) has now become the standard practice in complex geological environments, such as those with salt formations in the Gulf of Mexico (GOM) area. Advancements in FWI algorithms have enabled the optimization of salt geometry through data-driven methods rather than solely relying on full interpretation. FWI can potentially address gross errors in long wavelength within the velocity model, depending on the quality of available input data, such as low-frequency content and long offset. When input data is limited, such as lacking ultra-low frequency content or having restricted offset and azimuth coverage, it is a standard practice to mitigate gross errors in the velocity model before starting FWI. This is typically achieved by initially calibrating the velocity model using available checkshots and well markers followed by a few iterations of tomography. A commonly employed approach involves using a salt model that features smoothed salt and sediment boundaries as the initial model for FWI. Acoustic FWI (AFWI) remains a widely employed method for updating the overall velocity model. However, one drawback associated with AFWI is the elastic effect stemming from significant impedance contrasts (Liu, et al., 2024). This elastic effect manifests as a smoothing effect around the salt, commonly referred to as "salt halo imprint". To address this issue, we propose a calibration approach driven by interpretation around the salt geobodies. This aims to minimize the salt halo imprint in the AFWI model, thereby enhancing both the AFWI velocity model and the imaging quality around complex salt overhangs.

Introduction

Delineating hydrocarbon prospects through seismic imaging in complex salt formations presents a considerable challenge in the Gulf of Mexico. To improve imaging quality, several steps are crucial. Firstly, the input seismic data must exhibit a favorable signal-to-noise ratio across both low and high frequencies. Next, it's essential to derive an accurate model using available data such as seismic, checkshot, and well markers. Finally, employing appropriate imaging tools that seamlessly integrate the earth model with the input seismic data is necessary to generate the final seismic image. Sophie's Refocus 3D NAZ survey, depicted in Figure 1, covers the southern extent of the Ship Shoal, South Timbalier and Grand Isle areas of the Gulf of Mexico shelf and borders areas of Ewing Bank and Mississippi Canyon protraction areas. It combines 3D NAZ streamer and OBC data, with several motivating factors for its reprocessing. Firstly, input seismic data processed carefully aiming to reduce the overall noise and multiple with preserving primary and enhance the bandwidth of the data. Secondly, efforts were made to enhance the velocity model by leveraging in-house dynamic matching acoustic full waveform inversion (DM-AFWI) to update the model from shallow to deep followed by additional sub-salt tomography using common offset reverse time migration (COR) gather. Finally, the use of directional imaging stacking (DIS) TTI reverse time migration (RTM) was pursued to achieve improved imaging compared to Legacy tilted transverse isotropy (TTI) RTM. The initial velocity model was built using the legacy TTI final model. Thomsen anisotropic parameters (epsilon and delta values) (Thomsen, 1986) were estimated utilizing all available checkouts. The initial salt geometry was adopted from the existing legacy model to initiate the DM-AFWI process.

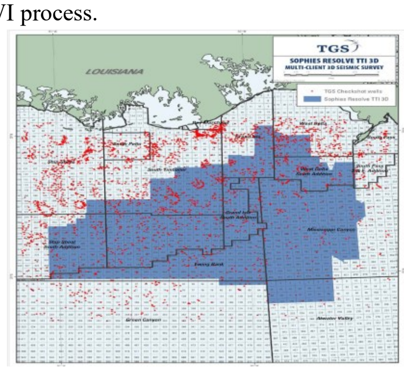

Figure 1: Survey Location marked on blue shaded area.

Input data processing: broadband processing

In Ocean Bottom Cable (OBC) seismic data processing, integrating both the hydrophone (P) and vertical geophone (Z) components is a widely adopted approach crucial for distinguishing between upgoing and downgoing wavefields, thereby minimizing interference from ghosts and multiples. However, the vertical components often suffer from contamination due to converted shear waves caused by scattering in the shallow subsurface. Therefore, meticulous elimination of Vz noise is essential to optimize P/Z calibration and enhance wavefield separation.

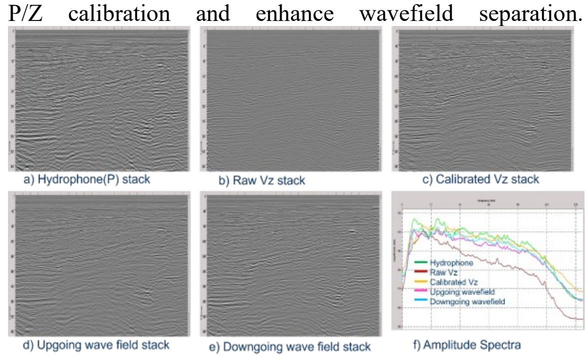

Figure 2 (a) Hydrophone (P) stack (b) Raw Vz Stack (c) calibrated Vz stack(d) Upgoing wavefield stack(e) Downgoing wavefield stack (f) amplitude spectra.

To achieve this, an initial denoising pass is conducted on both P and Z components to eliminate spikes and constant source noises, performed cross-ghosting analysis to match the phase of P and Z after amplitude matching at each receiver location proves to be effective. By carefully analyzing the P and Z components utilizing advanced techniques in the curvelet domain, achieved precise removal of unwanted shear wave noise while accurately aligning coherent events between the P and Z datasets. P/Z summation executed to generate the upgoing and downgoing wavefields. Additionally, employed source-side deghosting and shallow water demultiple approaches further suppress the multiples on upgoing and downgoing fields separately while broadening amplitude spectra. These techniques refine the seismic data by mitigating noise and enhancing the signal quality, resulting in clearer imaging of subsurface structures and more accurate interpretation of geological features.

Velocity model building

The 3D NAZ and OBC seismic data were acquired between 2003 and 2005, but they have limitations, notably the absence of ultra-low frequency, long offset, and limited azimuthal coverage. These aspects are crucial for FWI, particularly in cases where significant gross errors exist in the starting model. Based on the status of the current seismic datasets, following steps were performed to fully build the velocity model:

- Initial velocity model for FWI
- FWI to improve velocity model resolution.
- Interpretation driven salt halo calibration on FWI velocity model.
- Sub-salt tomography using COR gather.

Initial velocity model for FWI

The initial velocity model was derived from the legacy TTI final model and calibrated with 115 checkshots and top-of-salt markers. An isotropic Kirchhoff pre-stack depth migration (KPSDM) was conducted using the calibrated velocity model, with resulting image gathers used to estimate spatially variant anisotropic parameters - delta and epsilon. 3D dip scanning was employed on these migrated stacks to build the initial TTI velocity model.

To further refine the sediment model, three passes of tomography were conducted, starting with longer scale lengths, and progressively decreasing to shorter scales. The legacy salt horizons were map migrated based on the updated velocity model to reconstruct the salt velocity model. The salt velocity model was subsequently smoothed to create the initial velocity model for Dynamic Matching AFWI(DM-AFWI).

FWI to improve velocity model resolution

DM-AFWI addresses the highly nonlinear inversion problem in the data domain by optimizing model parameter(s) to achieve the best fit between synthetic and field data. DM-AFWI utilizes all available data, including both reflection and refraction information, to refine the depth model. By minimizing amplitude impacts while highlighting kinematic differences, this approach mitigates issues like cycle skipping and remains robust even with data characterized by a low signal-to-noise ratio (Mao, et. al.,2020). Several challenges were encountered during the wavelet estimation process. Moreover, near-offset data was insufficient and noisy, while mid-far offsets were unreliable due to contamination from diving waves, multiples, and diffractions. Given the complexity of these challenges, obtaining a perfect wavelet proved demanding. However, after comparing input and synthetic data, the hydrophone-based (upgoing) wavelet provided the closest match and is utilized for DM-AFWI inversion.

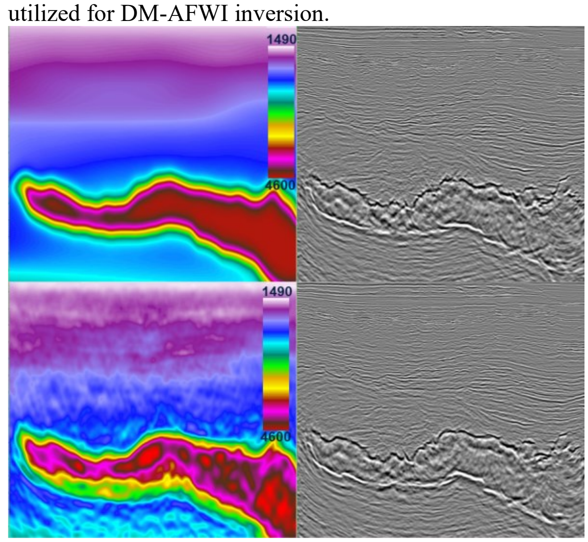

Figure 3: Velocity and KPSDM stack before (top) and after (bottom) DM-AFWI.

Two passes of DM-AFWI were conducted, with each pass involving updates across several frequency bands. Input data quality control measures, such as octave plots and phase plots, were employed to determine the appropriate frequency bands for DM-AFWI updates.

In the first pass, updates were performed across three frequency bands (3-5Hz, 4-6Hz, and 6-8Hz). It's important to note that the 3-5Hz band represents a high-cut filter without any low-cut application. Following the first pass of AFWI, salt scenario testing was conducted to optimize the salt geobody. Subsequently, the second pass of DM-AFWI included updates across four frequency bands (3-5Hz, 4-6Hz, 6-9Hz, and 9-12Hz) to obtain a higher-resolution AFWI velocity model for RTM and KPSDM purposes. It's worth mentioning that if FWI imaging, which is a normal derivative of the FWI velocity, is the focus of the work, it is advisable to use higher frequency bands for FWI. Figure 3 depicts the velocity model alongside the corresponding migrated KPSDM stack. The enhancement in velocity resolution and its effect on the KPSDM stack are evident. Notably, there is an improved definition of the top and base of salt after DM-AFWI. Additionally, subtle geological features with small scale lengths are captured in the DM-AFWI velocity model.

Interpretation driven FWI salt halo calibration

The halo effect surrounding high-impedance contrast geobodies presents a notable challenge in acoustic FWI. The halo effects occur due to the pronounced elastic response around areas of high impedance contrast. This effect, particularly evident around salt and sediment boundaries, often manifests as a smoothing effect known as the halo imprint. To mitigate this issue, in recent years, we have seen the application of elastic FWI on real data. In acoustic FWI, the initial velocity model is typically smoothed to ensure a gradual transition across salt and sediment boundaries. However, these smoothed boundaries may persist after AFWI updates. To minimize this effect, we propose an interpretation-driven calibration approach focused specifically around the salt boundary.

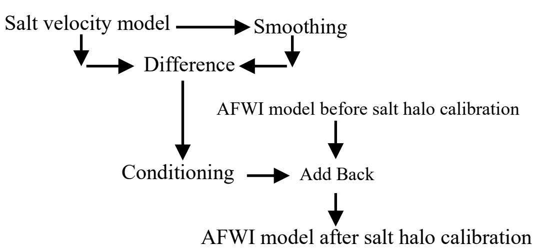

Figure 4: Salt halo calibration workflow

The degree of calibration required depends on uncertainty, which can be assessed using pre-existing salt markers. Availability of both top and base of salt markers simplifies the quantification of necessary calibration adjustments.

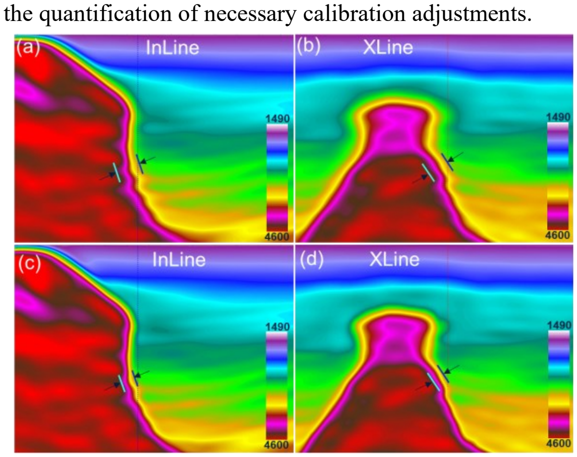

Figure 5: (Top) AFWI velocity before salt halo calibration (Bottom) AFWI velocity after salt halo calibration

The calibration extent is governed by the salt mask, which is typically spatially expanded to encompass the smoothing scale length utilized during the initial velocity model building for FWI. Figure 4 shows the generalized workflow for salt halo calibration.

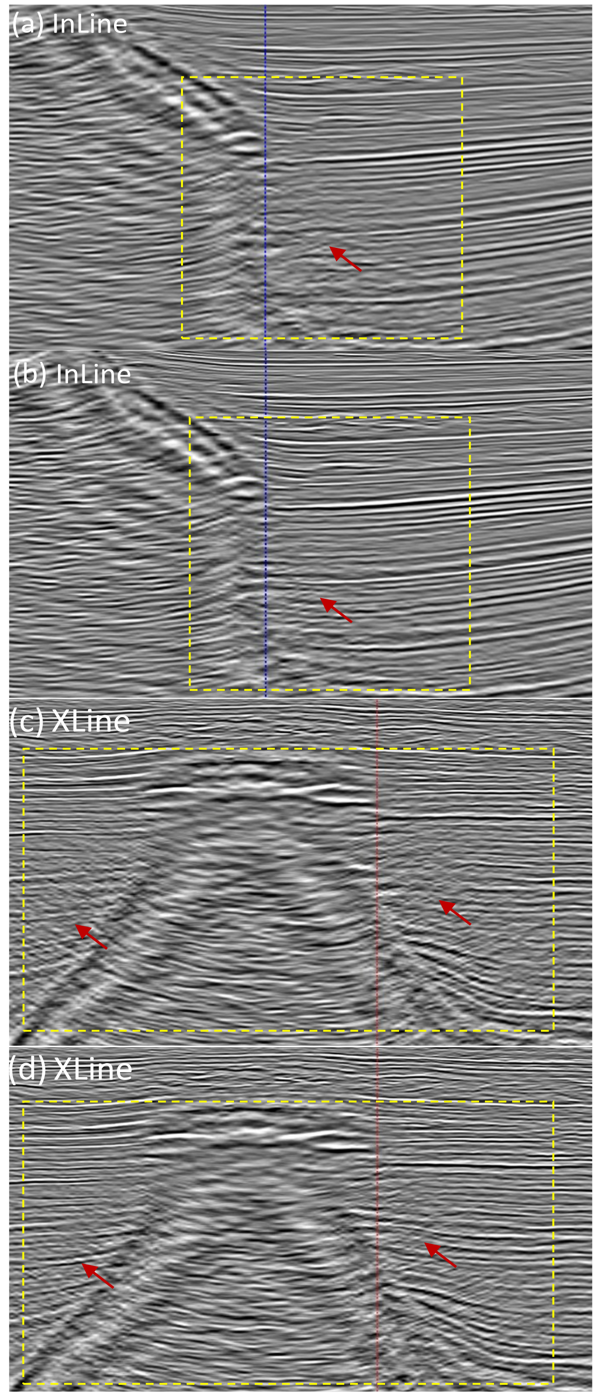

Figure 6: (a) & (b) KPSDM Stack before and after salt halo calibration in inline direction, (c) & (d) KPSDM Stack before and after salt halo calibration in cross line direction

In Figure 5, the top panels (a & b) display the AFWI velocity model before the salt halo calibration. The smoothing effect around the salt bodies remains unresolved after the AFWI which is expected due to elasticity effect dominance around salt body. This smoothing effect is minimized after the salt halo calibration, as depicted in the bottom panels (c & d) of Figure 5.

Figure 6 illustrates the Kirchhoff pre-stack depth migrated stack using the velocity model before and after AFWI salt halo calibration. Within the highlighted yellow box, the stacked image reveals notable enhancements, particularly in terms of improved lateral continuity of the sediment event near the salt-sediment boundary.

Overall, there is an improvement in the resolution of salt and sediment truncation observed in the KPSDM stack utilizing the AFWI salt halo calibrated velocity model. Salt marker tie typically degrades after smoothing the velocity model as prerequisite for AFWI. In this project, it has been observed that after AFWI, the salt marker tie does not fully recover to its original level prior to smoothing the model. However, after the salt halo calibration, significant improvement in salt marker tie has been observed, as illustrated in Figure 7.

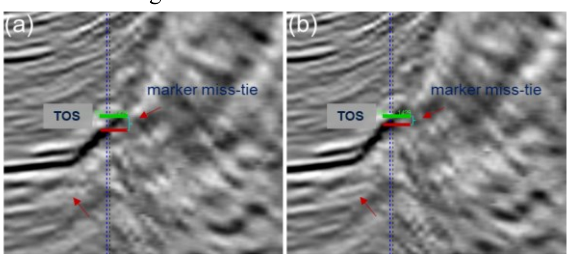

Figure 7: (a) KPSDM Stack before salt halo calibration and (b) KPSDM Stack after salt halo calibration with TOS well marker overlay.

COR Subsalt tomography

Due to the offset and azimuth constraints of the input data, velocity updates of AFWI at deeper subsalt levels were less optimal. To enhance the subsalt velocity updates, two passes of subsalt tomography updates using common offset RTM (Rodriguez et al., 2016) gathers were conducted. Additionally, the incorporation of the salt at deeper depths was implemented to achieve improved modeling and imaging at the basement level.

Velocity model and Image Comparison

Figure 8(a) and (b) depict the comparison between the legacy and most recent velocity models. The current velocity models notably exhibit enhanced resolution both above and below the salt body. However, due to limited offset and azimuth, the updates from AFWI were restricted to depths up to 10km, with deeper updates primarily influenced by COR RTM gather-based tomography. Calibration of the salt halo around its boundary contributed to sharpening the delineation between salt and sediment, thereby reducing the extent of the salt halo. Both model uplift and updated input data have led to significant enhancements in the final enhanced DIS TTI RTM stack compared to the legacy TTI RTM stack, spanning from shallow to deep sections as shown in Figure 8(d). The latest DIS TTI RTM stack demonstrates improved imaging quality for subsalt structures and salt overhangs. The application of broadband processing techniques to the input data contributes to enhancing resolution at the reservoir level in the final TTI DIS RTM stack. Additionally, refinement in the salt modeling at deeper sections has contributed to better imaging of the basement in the final DIS RTM stack.

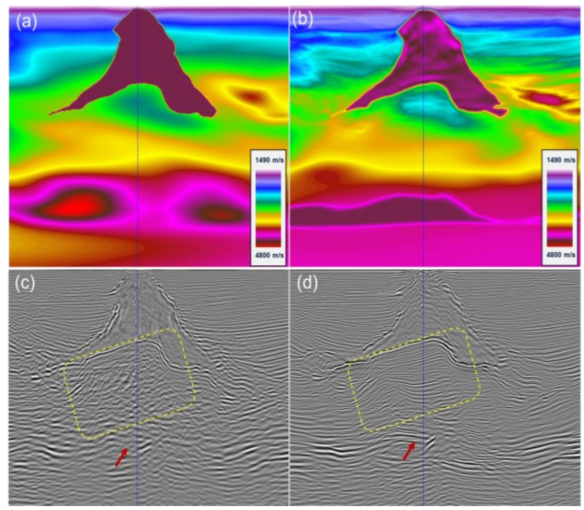

Figure 8: (a) Legacy TTI velocity model (b) Final AFWI velocity model (c) Legacy final enhanced TTI RTM Stack (d) Final enhanced DIS RTM Stack

Conclusion

We have demonstrated that addressing the salt halo, a significant challenge in AFWI-derived velocity models, is feasible by calibrating the model post AFWI. By utilizing salt markers, we can quantify the scaler needed to calibrate the AFWI model around the salt body, thereby sharpening the salt-sediment boundary and reducing the salt halo effect. We have shown improved imaging especially in overhang area as well as sub-salt using salt halo calibrated AFWI model.

We've illustrated that salt markers exhibit improved tie with the seismic image following salt halo calibration, a critical factor for precise well placement.

Furthermore, our study serves as an exploration of alternative methodologies for mitigating the salt halo effect, particularly in scenarios where the implementation of elastic FWI methods may not be feasible due to project constraints or resource limitations.

Acknowledgements

The authors express their gratitude to Josef Heim, Bin Wang, and Faqi Liu for their valuable contributions and insightful discussions. Additionally, we extend our appreciation to the management of TGS for granting permission to publish this paper.