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From Full Waveform Inversion to Kirchhoff Least-Squares Migration – Correcting the Effects of Mass-Transport Complexes for Better Reservoir Imaging

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Summary

Complex overburden geology often creates difficulties for imaging any underlying reservoir. One such example is the thick layers of mass-transport complexes (MTCs) below the seabed in a Gulf of Mexico study area. The presence of MTCs poses two main imaging issues. One is the kinematic error due to the unresolved rapid lateral velocity changes from highly-variable, small-scale internal structures within the MTCs. The other imaging issue is uneven illumination resulting from seismic waves passing through the inhomogeneities within the MTCs. We utilized full waveform inversion (FWI) to derive a high-resolution velocity model within the MTCs and then kinematically restored the structural positions of underlying events through Kirchhoff depth migration. This procedure did not correct the amplitude distortion at the reservoir level due to uneven illumination. Utilizing the velocity model derived from FWI, we were able to model the amplitude distortion in the recorded data and compensated for the energy lost due to uneven illumination through the process of Kirchhoff least-squares migration (LSM). With the combination of FWI and LSM, both structural integrity and amplitude fidelity of the image of the deep reservoir horizon were improved.

Introduction

Full waveform inversion (FWI) and least-squares migration (LSM) are two closely related technologies. They both use forward modelling to create synthetic data and derive their respective solutions by minimizing the differences between synthetic and recorded data using least-squares inversion methods. FWI utilizes mostly kinematic differences between the synthetic and the recorded data to update velocity (Pratt, 1999). In contrast, LSM utilizes amplitude differences between the synthetic and the recorded data to update reflectivity with the assumption that the kinematic differences have already been corrected, i.e., the migration velocity is correct (Nemeth et al., 1999).

FWI is now often used after conventional ray-based tomography to obtain a more accurate and higher-resolution velocity model. A good FWI result relies on many factors, including rich low frequency content and long offset data, a stable and known source wavelet, and a good starting velocity model. A good starting model is needed to avoid cycle skipping when matching synthetic to recorded data. Since it is difficult to know if a starting model is “good enough”, the initial iteration of FWI usually starts from low frequency to reduce the chance of cycle skipping. As the velocity model is updated and becomes closer to the true model, the frequency can gradually be increased to gain higher resolution.

LSM performs the reflectivity inversion using the full seismic bandwidth. A good LSM result is largely dependent on whether the velocity model closely describes velocity anomalies in the overburden. The requirement of an accurate velocity model is our motivation to combine FWI with LSM. Among the many different LSM algorithms, we chose to use a single-iteration LSM approach (Guitton, 2004; Wang et al., 2016) for reasons of both efficiency and robustness. We first run Kirchhoff migration using the velocity model obtained from FWI. Next, we use the migrated stack as the reflectivity model combined with the same velocity model to generate synthetic data, and re-migrate. We then compute filters for each offset separately to approximate the so-called Hessian operator by matching the re-migrated data to the reflectivity model. Finally, we apply these filters to the original common offset migrated data to compensate for illumination effects, hopefully captured in this round-trip of modelling/migration process, which are due to imperfect acquisition and shallow overburden variations. Because these effects are both angle and frequency dependent, the Hessian matching filters are preferably computed in the curvelet domain.

In this study, we used a narrow azimuth field dataset from the East Breaks area of the Gulf of Mexico (GOM) to demonstrate the combined benefits of FWI and the Kirchhoff-based single-iteration LSM.

Field data example

The study area is located at the foot of the East Breaks submarine landslide (ten Brink et al., 2008), where thick layers of mass-transport complexes (MTCs) are prevalent. Complicated internal structures and small-scale features within the MTCs create both rapid lateral velocity changes and uneven illumination. The existing velocity model is a tilted transverse isotropic model derived from ray-based tomography. Ray-based tomography derives the background velocity but is not capable of resolving MTC-related small scale anomalies. Hence, a producing reservoir (at about 3200 m depth on Figure 1a) underneath the MTCs shows small scale distortions in structural positioning on the Kirchhoff stack image (Figure 1a), local non-hyperbolic residual curvatures on the common image gathers (CIGs) (Figure 1b), and strong amplitude variations extracted from the top reservoir horizon (Figure 1c).

To improve the structure and amplitude of the reservoir imaging, we first performed multiple iterations of FWI from 3 to 18 Hz to derive a high-resolution model. FWI was able to identify velocity anomalies within the MTCs and remove distortions in the structures beneath (blue arrows in Figures 1a and 1d). Also, non-hyperbolic gather curvatures became flatter after FWI (Figures 1b and 1e) and reservoir amplitude stripes were partially mitigated (Figures 1c and 1f). However, amplitude distortions due to uneven illumination are still present in the migrated image. Subsequently, we applied LSM using the FWI-derived velocity model to further improve the result. We observed reduced migration swings on the LSM stack compared to conventional Kirchhoff (yellow circles in Figures 1d and 1g). The CIGs from LSM maintained the curvatures and had improved S/N (Figures 1e and 1h). Weak high dip events with lower illumination were also compensated (yellow arrows in Figures 1d and 1g) and reservoir amplitude stripes caused by illumination variation were reduced (Figures 1f and 1i).

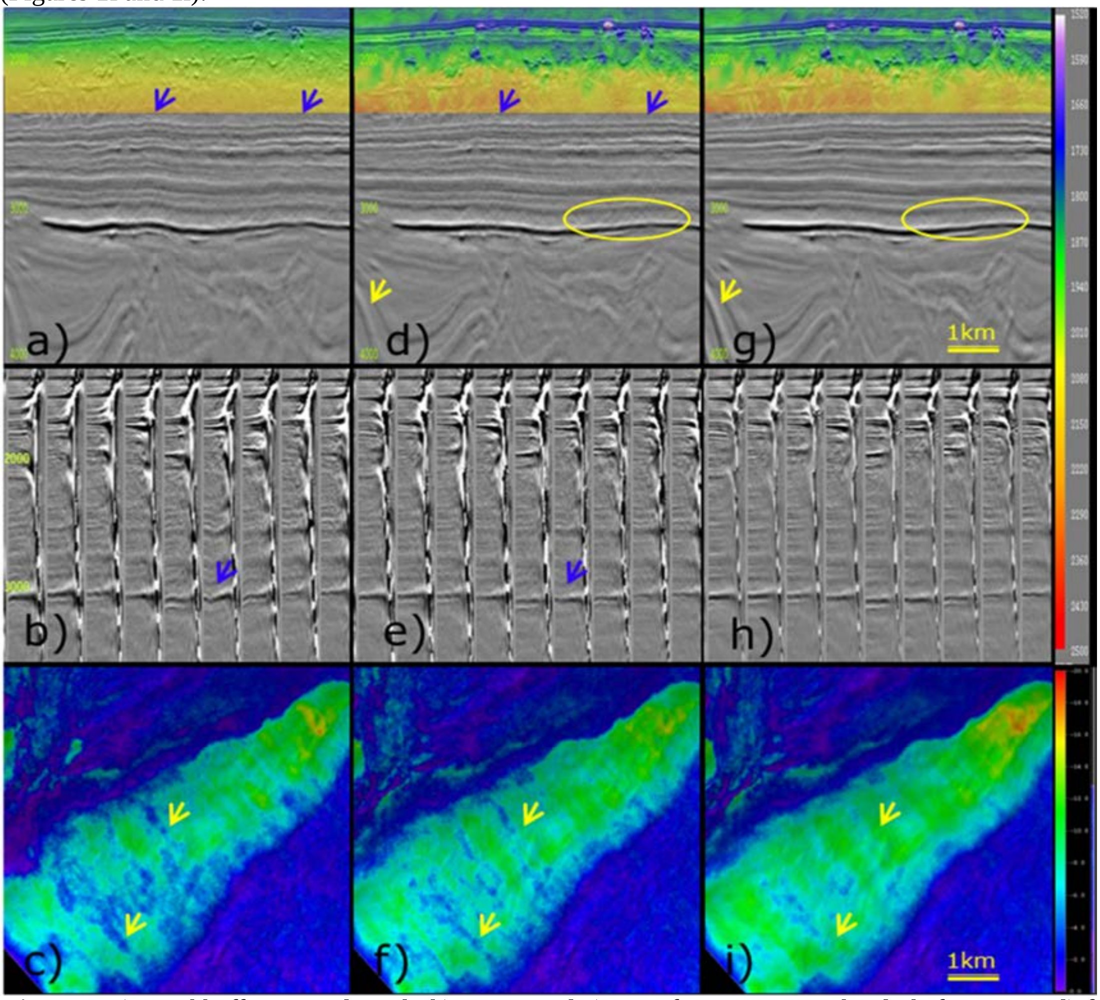

Figure 1 *a) Kirchhoff migrated stack, b) CIGs, and c) top of reservoir amplitude before FWI; d)-f) Kirchhoff migrated stack, CIGs, and top of reservoir amplitude after FWI; and g)-i) Kirchhoff migrated stack, CIGs, and top of reservoir amplitude after FWI and LSM. Velocities within MTCs were overlaid with stack images. The maximum offset of the CIGs is 8km. The FWI velocity is higher resolution and improves the structural position and CIG flatness after migration. LSM further reduces migration swings and enhances high dip events. Amplitude stripes indicated by yellow arrows in c) were progressively healed in f) and i).*

An accurate high-resolution velocity is the key to the success of this case study. The dataset used for this study has a maximum offset of 8 km, which provides enough depth of diving waves penetrations to cover the interval of the shallow MTCs but not enough for the deeper reservoir. We included both reflections and diving waves in FWI in order to improve the velocity resolution for the shallow MTCs and obtain a reasonable update at the reservoir. Figures 2a and 2b show that the velocity update from 3-8 Hz FWI has higher resolution by including reflection data in FWI. We further improved the velocity resolution by increasing the maximum frequency in FWI to 18 Hz. The final velocity model with multiple iterations of 3-18 Hz FWI (Figure 2c) shows sharper geology delineation than the 8 Hz FWI and closely matches well logs (Figure 2d).

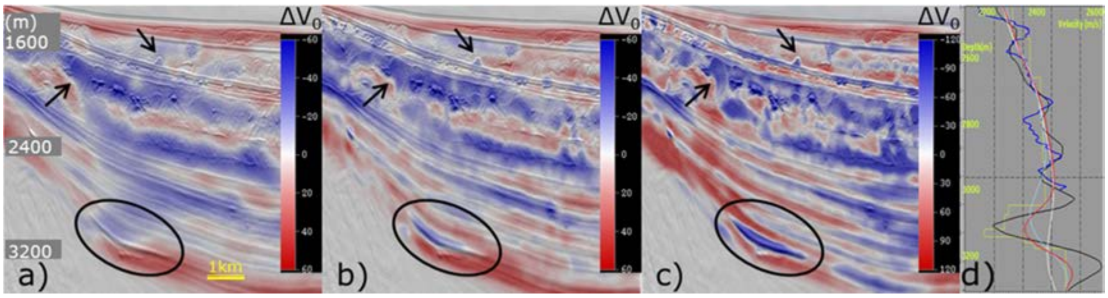

Figure 2 *Velocity update from 3-8 Hz FWI overlaid with stacked image: a) using diving wave only, b) using both diving wave and reflection data, c) velocity update from the final result, which has multiple iterations of 3-18 Hz FWI, and d) the updated velocity profiles at a well location. White is the initial velocity, light blue is 3-8 Hz diving wave only FWI velocity, red is 3-8 Hz diving wave and reflection FWI velocity, black is final velocity, yellow is check shot and blue is smoothed sonic log. We can improve FWI update resolution by adding reflection data and increasing the maximum frequency.*

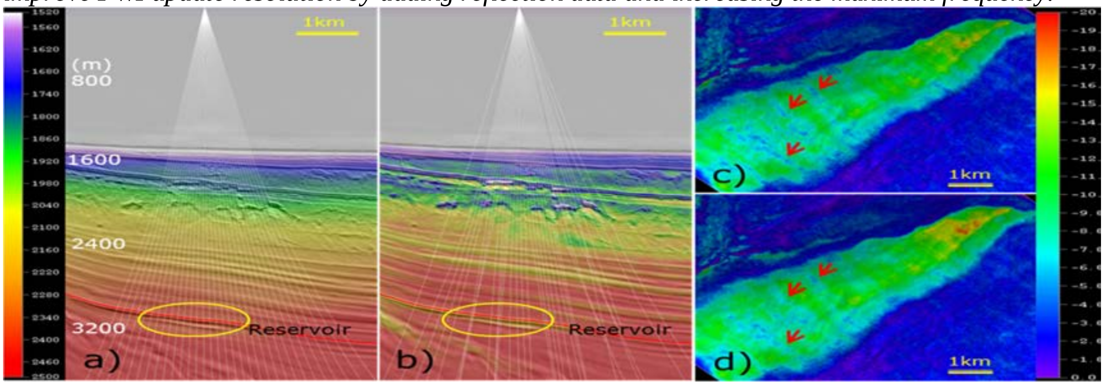

Figure 3 *a) Ray-tracing with the initial velocity model did not show obvious illumination variations at the reservoir level; b) Ray-tracing with the FWI velocity model showed uneven illumination at the reservoir level due to shallow velocity anomalies within MTCs. Reservoir amplitudes extracted from: c) LSM using initial velocity, and d) LSM using FWI velocity, which shows a reduction in amplitude stripes after LSM using the more accurate FWI velocity (denoted by the red arrows).*

LSM holds the promise of providing better images by compensating for imperfect acquisition geometry and variable illumination caused by complex overburdens. However, these promises, especially the illumination compensation, are possible only when we have an accurate high-resolution velocity model. We performed a LSM experiment by replacing the velocity model in forward modelling and re-migration with the velocity model before FWI. Due to the smoothness of the initial model, the corresponding rays are evenly distributed (Figure 3a). Meanwhile, rays using the FWI velocity model properly replicated the focusing or scattering effect from the shallow MTCs (Figure 3b). As a result, amplitude stripes caused by illumination variation were reduced after LSM using the FWI velocity (Figure 3d), while this benefit was compromised by using the initial velocity model (Figure 3c).

To highlight the combined benefits of FWI and LSM in imaging the reservoir, Figure 4 shows the CIGs zoomed at the reservoir level and amplitude extractions before FWI, after FWI, and after LSM. The FWI velocity corrected the complex curvatures and resulted in a well-behaved reservoir event across the CIGs; LSM reduced noise on CIGs to provide more coherent AVO. These improvements are essential for subsequent seismic inversion and a better understanding of the reservoir properties.

Conclusions and discussion

Good reservoir imaging requires well focused stacks and CIGs, correctly positioned structures, and amplitude fidelity on both stacks and CIGs. Complex overburden geology present difficulties in imaging reservoirs underneath them: 1) inaccurate velocity can induce distorted structure and non-geologic amplitude variations; 2) small scale overburden complexity can cause focusing and scattering as seismic waves propagate through the anomalies, causing illumination-related amplitude variation. These challenges can be addressed by FWI and LSM, respectively.

We used a field dataset from the GOM to demonstrate the benefits of combining FWI and LSM. FWI was able to generate a high-resolution velocity model above the reservoir, including the MTCs in the overburden. Migration using the FWI-derived velocity model generated flatter CIGs and removed structural distortion beneath the MTCs. However, amplitude and AVO distortion at the sub-MTC reservoir horizon was only partially improved. Utilizing the velocity model from FWI, LSM was able to further improve the reservoir amplitude fidelity by compensating for the overburden and acquisition illumination effects through a round-trip of modelling/migration process.

Besides requiring an accurate migration velocity model, the effectiveness of LSM also depends on how well the forward modelling mimics the true wavefield propagation through the subsurface. In this study, we used a Kirchhoff acoustic engine for the modelling. Wave-equation-based modelling may improve the results by more accurately modelling the illumination effects. Additional propagation factors such as absorption should also be considered, particularly for unconsolidated sediments.

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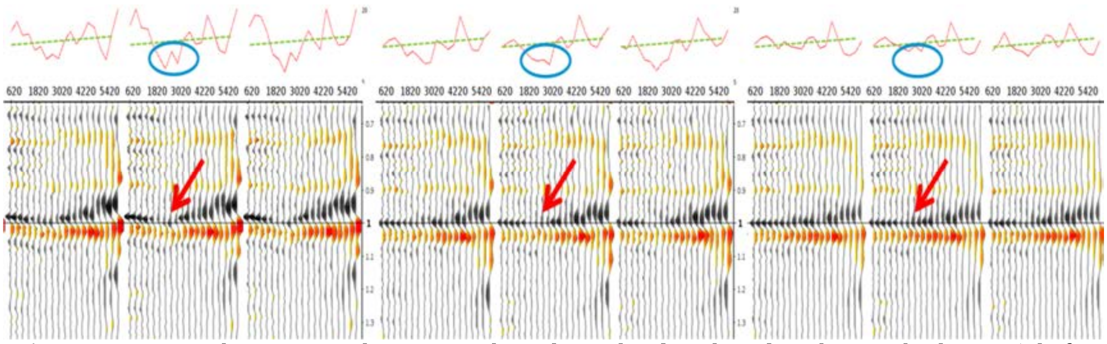

Figure 4 *CIGs at the reservoir location with peak amplitudes plotted in the graph above: a) before FWI, b) after FWI, and c) after FWI and LSM. Amplitude anomalies due to velocity error and illumination issue are reduced by FWI and LSM, respectively.*

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