IMPROVING SUB-MESSINIAN IMAGES IN THE NILE DELTA USING FWI AND LEAST-SQUARES Q MIGRATION

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Summary

The Messinian interval in the West Nile Delta, offshore Egypt, is a thin evaporite layer characterized by highly irregular velocities with rapid spatial variations. Its complexity poses unique challenges for sub-Messinian reservoir imaging, resulting in erratic gather curvatures, distorted structures, and non-uniform illumination. Conventional ray-based tomography suffers from unreliable curvature picking due to poor gather quality, complex gather move-out, and inaccurate ray tracing through the fast and complex Messinian layer. Previous full-waveform inversion (FWI) had little success in this area because of strong amplitude mismatch between recorded data and modelled data at the Messinian layer and the limitations of the existing multi narrow azimuth (multi-NAZ) streamer data, which lacks good low frequencies and has limited offsets. We present a case study that utilizes a model building flow driven primarily by Time-lag FWI (TLFWI) starting from a tomography model with a reasonable long-wavelength velocity. TLFWI using both refraction and reflection data resolved the velocity errors in and below the Messinian interval and provided good uplifts to sub-Messinian reservoir imaging. In addition, least-squares Q-Kirchhoff (LSQ-Kir) migration with the improved velocity model compensated for irregular illumination and earth attenuation without over-boosting noise, thus further improved the S/N and resolution of the reservoir image.

Introduction

The Nile Delta, and Mediterranean Sea in general, has been an area of great interest to the petroleum industry for its significant hydrocarbon potential. However, regional geological features, such as shallow gas pockets, mud volcanos, and Messinian unconformities (Dolson et al., 2001), pose some unique challenges for seismic imaging. In our study area near the West Nile Delta, offshore Egypt, a fast and spatially varied Messinian layer results in erratic gathers and distorted structure in the sub-Messinian area if not addressed properly with an accurate high-resolution velocity model. Traditionally, ray-based reflection tomography plus manual interpretation have been the primary tools to obtain a "detailed" velocity model (Baptiste and Manning, 2009; van der Burg et al., 2010; ElBadry et al., 2012). Although the tomography-based method is able to improve the sub-Messinian image at places, remaining small-scale velocity errors still present as the main obstacle to reliable interpretation of deeper structures. Over the past decade, full-waveform inversion (FWI) has been an effective method for building high-resolution sedimentary models, but with only limited success in areas with high velocity contrasts, such as the Messinian layer here, because of the amplitude mismatch issue between recorded data and modelled data. With a recent breakthrough in the algorithm, Time-lag FWI (TLFWI) (Zhang et al., 2018; Wang et al., 2019), using a traveltime-based cost function, has demonstrated the ability to update models with strong contrasts by mitigating the amplitude mismatch issue, and brings a step change improvement to images in very complex areas, such as subsalt Gulf of Mexico. Here we present a successful model building workflow driven primarily by TLFWI using existing multi narrow azimuth (multi-NAZ) data to improve the seismic image, especially in the sub-Messinian section. In addition to the kinematic impact, poorly illuminated and low-resolution zones are observed in the sub-Messinian from strong scattering caused by Messinian anomalies. Least-squares Q-Kirchhoff (LSQ-Kir) migration with the improved velocity further improves the S/N and resolution of the reservoir image.

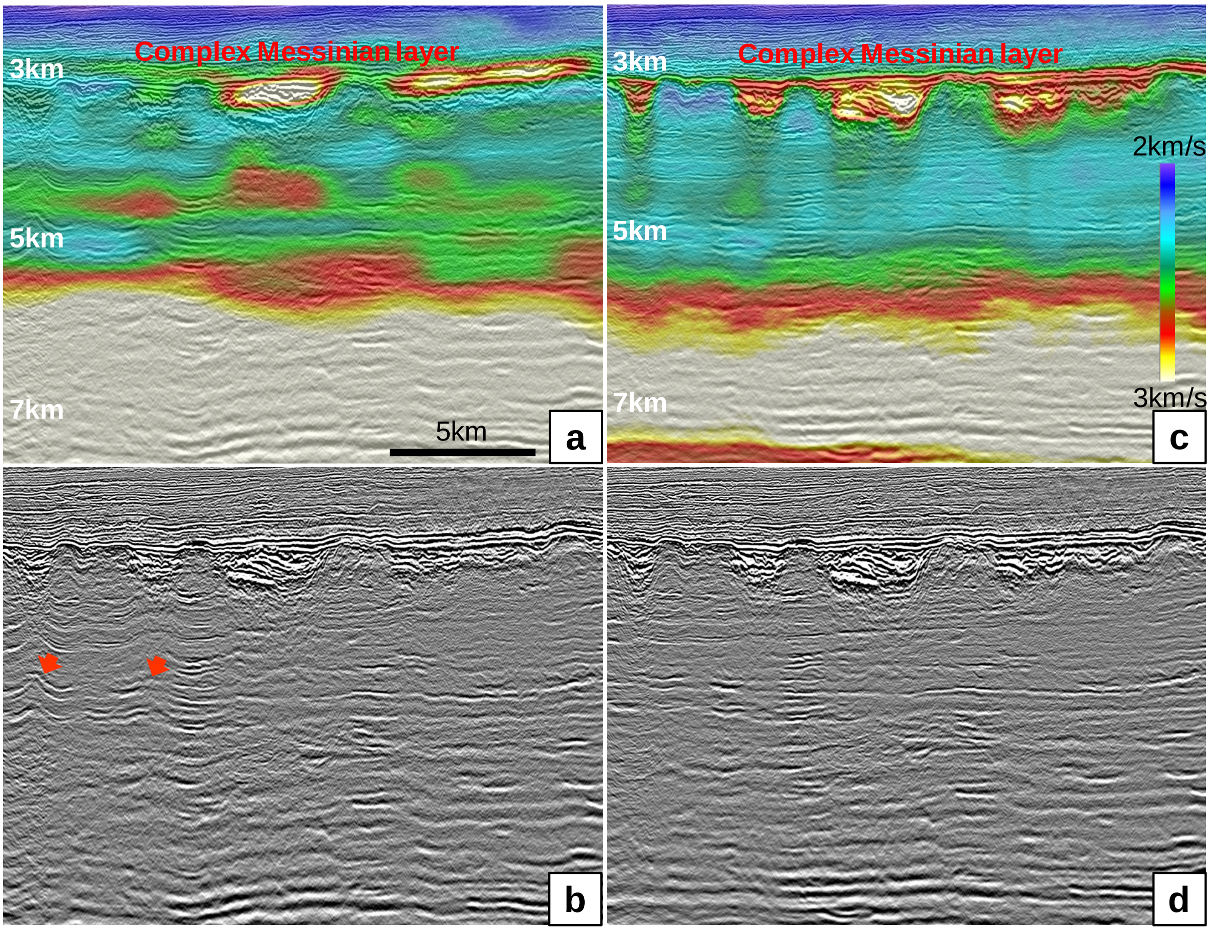

Figure 1 *(a) Legacy model (tomo-driven) overlaid on stack, (b) Kirchhoff stack migrated with legacy model, (c) final model (FWI-driven) overlaid on stack, (d) Kirchhoff stack migrated with final model.*

FWI-driven model building workflow

The study area is covered by multi-NAZ acquisitions with different shooting directions and maximum offset up to 6 km: three surveys with azimuths 0, 40, and 90 degrees in the north, and six surveys with azimuths 0, 30, 60, 90, 120, and 150 degrees in the south. The legacy velocity model from a tomography-driven model building flow only partially resolved the velocity anomalies in the complex Messinian layer at around 3 km depth (Figure 1a, an example in the north), thus resulting in defocused events and undulated reservoir reflectors in the sub-Messinian section (red arrows, Figure 1b). Our proposed TLFWI-driven model building flow successfully addressed these Messinian complexities (Figure 1c) and led to reduced undulations in the sub-Messinian reflectors and improved event continuity and focusing (Figure 1d). This model building flow was carefully tailored to the geological challenges of the area and the limitations of the available multi-NAZ data.

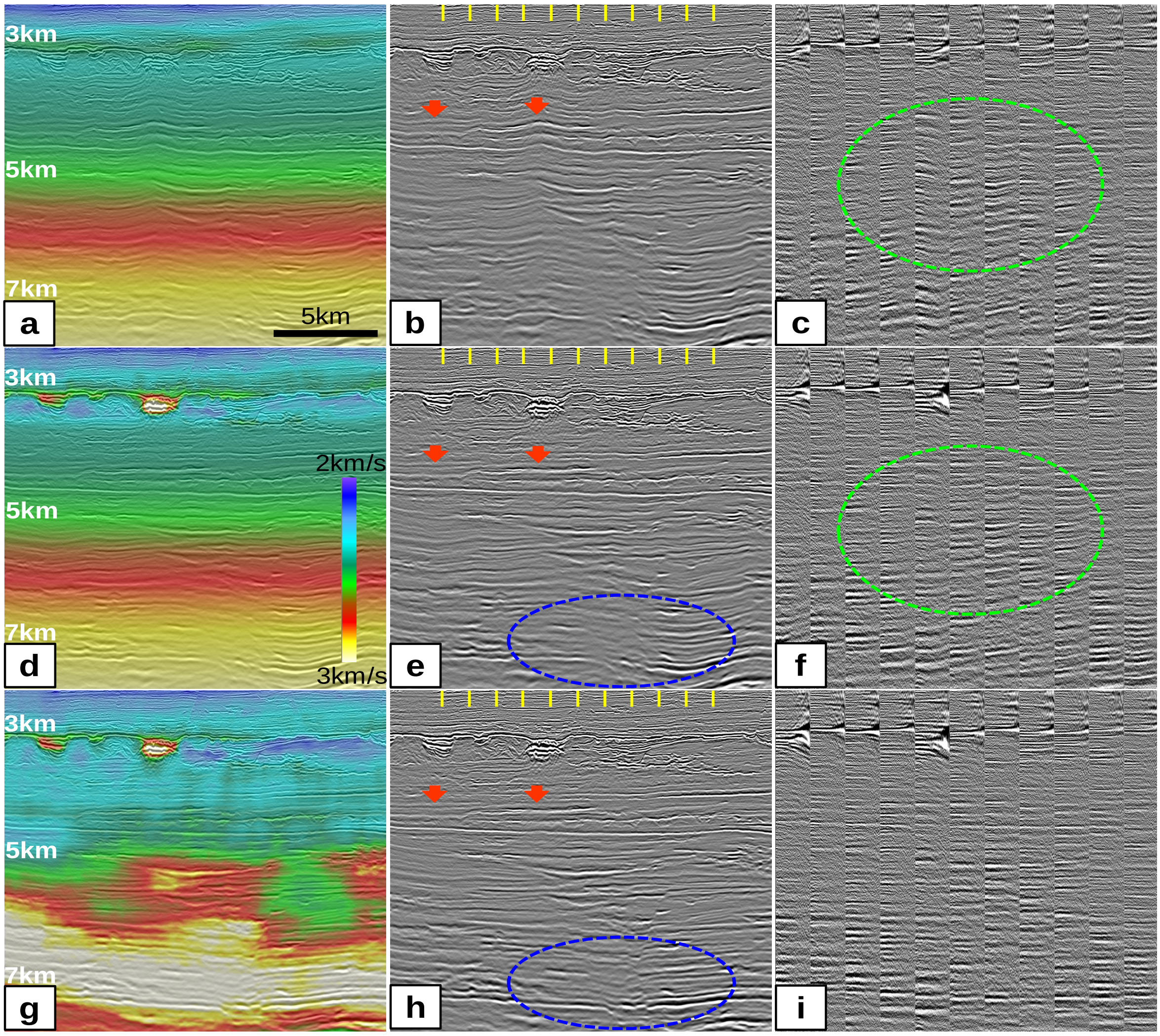

***Figure 2** (a) Initial model overlaid on stack, (b) Kirchhoff stack and (c) gathers migrated with initial model; (d) First-round TLFWI model overlaid on stack, (e) Kirchhoff stack and (f) gathers migrated with first-round TLFWI model; (g) Second-round TLFWI model overlaid on stack, (h) Kirchhoff stack and (i) gathers migrated with second-round TLFWI model.*

The lowest available frequency of the existing multi-NAZ streamer data in this area is around 3.5 Hz, which is not sufficient to resolve large velocity errors. In addition, since the maximum offset of 6 km limits the diving wave penetration down to only the top portion of the Messinian interval, the sub-Messinian TLFWI update had to rely mostly on reflection energy, which is incapable of resolving the background velocity errors. For these reasons, ray-based reflection tomography and well calibration were still required to improve the top-down background velocity prior to TLFWI. However, because of the unresolved velocity errors in the complex Messinian layer, the sub-Messinian reflectors (red arrows, Figure 2b) were distorted and poorly focused, and the corresponding gathers were erratic with conflicting curvatures among neighbours (green circle, Figure 2c), which were difficult for ray-based tomography to resolve. Based on the understandings of the geological challenges and data limitations, our model building flow consisted of two key steps: shallow update down to the base of Messinian and then top-down update. First, one iteration of tomography was performed on the smoothed legacy model (Figure 2a) to improve the background velocity from the water bottom to the base of the Messinian layer, followed by one iteration of TLFWI driven mainly by diving wave energy to address the velocity anomalies in the Messinian layer. After the shallow update, the more plausible geologic structure and simplified gathers in the sub-Messinian section (green circle, Figure 2f) indicated that the shallow and Messinian layer velocity anomalies were properly resolved by the detailed TLFWI velocity model (Figure 2d). With the improved gathers, a deep update using tomography became feasible. A second iteration of tomography below Messinian after well velocity calibration was carried out to produce a model with a better sub-Messinian background velocity for the subsequent TLFWI update. Although the second round of TLFWI was applied from top to bottom, the major update was the short-wavelength details in the sub-Messinian region from reflection energy, and the shallow update was subtle because of the previous shallow TLFWI update. The final velocity model derived from the TLFWI-driven model building workflow captured the small-scale velocity features in the Messinian interval and conformed well to the geology (Figure 2g). As a result, the sub-Messinian stack undulations were significantly reduced (red arrows, Figure 2h), the faults were better defined, and the event focusing and continuity (blue circle, Figure 2h), as well as gather flatness (Figure 2i), were improved.

Least-squares Q-Kirchhoff migration

The stack image was improved by the TLFWI workflow; however, weak illumination and low-resolution zones were still observed in the study area (Figure 3a), which corresponded to strong absorption from shallow gas pockets and strong scattering from Messinian anomalies. LSQ-Kir migration, the combination of least-squares migration (LSM) and Q-Kirchhoff migration, has shown to be effective at compensating for attenuation effects and inhomogeneous illumination without boosting excessive noise (Shao et al., 2017). In this study, the Q model (Figure 3b) was derived by Q-FWI (Wang et al., 2018). Decoupling the residual velocity errors from quality factor Q is known to be difficult. Therefore, a precondition update-mask created from velocity anomalies is used to reduce the crosstalk between velocity and quality factor Q. The final Q model represents strong absorption and scattering bodies above weak and low-frequency zones reasonably well. Compared to the raw migration stack (Figure 3a), although Q-Kirchhoff migration boosted event amplitude and improved image resolution, especially in the weak zones (Figure 3c), it also greatly amplified high-frequency noise and migration swings. In contrast, LSQ-Kir migration improved S/N by significantly reducing noise and migration swings while retaining the benefits of Q migration with improved reflector amplitude consistency and image resolution (Figure 3d).

Conclusions

To tackle the velocity issues arising from the complex Messinian interval, a velocity model building workflow driven by TLFWI coupled with tomography was developed to cope with the deficiencies of the available multi-NAZ streamer data and resolve both long- and short-wavelength velocity variations. The first iteration of TLFWI was an important step in this model building flow to improve the gather quality of the sub-Messinian layers, allowing for the subsequent background velocity update by tomography. This workflow that interleaves tomography and TLFWI effectively addressed the velocity issues using only the available multi-NAZ data and provided a better solution to the imaging challenges in the West Nile Delta. Due to the data limitations in this study, the deep update heavily relied on reflection energy and could have larger velocity uncertainties than the shallow part, which was constrained by diving waves. Better data, such as ocean bottom node data with long offsets up to 20 km or more and good low frequency down to 1.5 Hz, would help further improve the accuracy of the model. On the imaging side, LSQ-Kir can balance the illumination and improve imaging resolution and S/N of the reservoir layer. Although uncertainties remain in the Q model, LSQ-Kir is worthwhile to pursue after obtaining a good velocity model.

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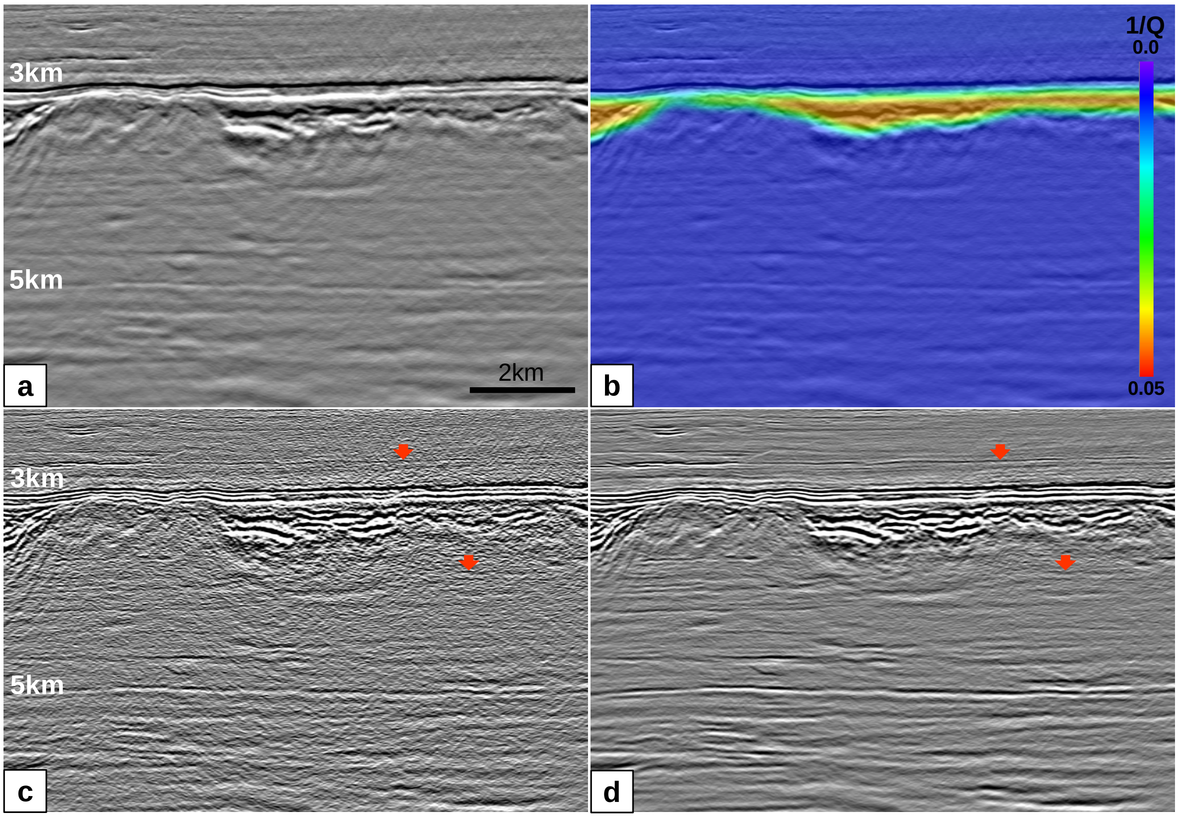

Figure 3 *(a) Raw Kirchhoff stack, (b) 1/Q model overlaid on raw Kirchhoff stack, (c) Q Kirchhoff stack, (d) LSQ-Kir stack.*

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