4D OBN processing and imaging of the Agbami field. Part II: FWI high resolution TTI model building

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Introduction

Discovered in late 1998, the Agbami field is located in a water depth of approximately 1500 m (~4800 feet). To date, five seismic acquisitions have been conducted in order to image the structure, characterize the reservoir and monitor fluid activities in this field. Two of the surveys are towed-streamer, narrow-azimuth (NAZ) data, and three are ocean-bottom-node (OBN) data.

The existing velocity model provides satisfactory seismic resolution at the center of the field; however, there is a need to further improve the image quality in the northwest area. Imaging this region is challenging mainly due to the presence of shallow anomalies and the lack of well control.

The key to improving the current seismic image lies in the accurate modeling of shallow velocity anomalies (Jones, 2012). These anomalous bodies are close to the surface, ranging from 10 to 500 meters underneath the water bottom. They are characterized by low velocity and exhibit an irregular distribution, giving rise to high lateral velocity contrasts. These bodies are generally related to unconsolidated sediments and might be related to erosional channels (Fan et al., 2015). Kirchhoff pre-stack depth migrated gathers were produced using the legacy velocity model and indicated that these bodies have lower velocity compared to the surrounding materials. Theoretical considerations (Snell's law) suggest that such low velocity objects are under-sampled and therefore poorly resolved by ray-based inversion schemes. In this paper, we present a two-step top-down model building flow that utilizes both refraction full-waveform inversion (FWI) and ray-based reflection tomography aiming at resolving the shallow anomalies and providing uplifts to the subsurface migrated images.

Methodology

We developed a model building workflow comprised of two main steps: refraction FWI and ray-based reflection tomography. This workflow follows the traditional top-down approach with refraction FWI updating the shallow velocity above diving wave penetration depth (approximately 3.5 km for this area). Only once the shallow low velocity bodies were resolved, would the ray-based tomography be able to accurately invert for velocity of the deeper section. Therefore, our strategy was to utilize FWI to resolve high lateral shallow velocity contrasts created by near-surface anomalies prior to implementing the reflection tomography.

We first performed a velocity inversion with our time-domain FWI focusing on diving wave energy. The FWI implementation we use in this work is acoustic, under assumptions of constant density and a tilted transverse isotropy model (Wang et al., 2014). The starting model for FWI is a simple 1D function extracted from sonic well-logs and propagated through the whole area via a set of conformal horizons capturing the field's regional geology. The smoothed versions of anisotropic fields were used and were not updated in this step.

The seismic input to FWI is the raw hydrophone component of OBN Monitor 1 survey, with minimal pre-processing steps such as de-spike and de-bubble processes. Compared to NAZ data, the OBN data is a far superior candidate for FWI given its inherent richness in low frequency content, full azimuth and long offset coverages. However, due to the high acquisition cost, OBN surveys normally have sparse node spacing. For this data, the node spacing is 390m in both inline and crossline directions, useful low frequency signal existed down to 2Hz, and the maximum offset is 5km in crossline direction and 12km in inline direction. The input data's sparsity, resulting in low S/N, impacts FWI performance mainly from the increased noise level in the output model. To alleviate this problem, we start FWI at the slightly higher frequency of 3Hz. In addition to that, we adopt a staging strategy (Cobo et al., 2018) consisting of executing FWI with four successive frequency bands, from 3Hz to a maximum of 15Hz. By starting from a low frequency and progressively adding higher frequencies to the inversion problem as the model improves, we aim at increasing the convergence rate and reducing the risk of cycle skipping.

Using the FWI-derived velocity field as the starting model we implement two iterations of reflection ray-based tomography using Kirchhoff depth mirror migration gathers. Mirror Kirchhoff migration uses the down-going wave field, which allows a wider illumination compared to normal Kirchhoff migration using up-going wave field, resulting in better image continuity and higher fidelity gathers in the shallow section. Both velocity and anisotropic fields were updated through this tomographic inversion step.

Despite their azimuth limitation and a relatively short offset range (maximum offset of 5km), the NAZ surveys provide with more coverage compared to the OBN Monitor 1 survey. For this reason, we incorporate NAZ data in one of the tomography iterations to improve the stability of the inversion at the edge of the field.

Results

The upper row of Figure 1 shows the forward modelling data QC of a common near offset (approximately 1000m) pre-stack data section, whereas the lower row shows a far-offset (approximately 5000m). The synthetic data are shown in green, overlaying the field data plotted in grey-scale. The synthetic data were modelled using the same propagator as used in the FWI, performed for TTI anisotropic acoustic-wave propagation with constant density and an absorbing boundary condition (Wang et al., 2014). In the QC display depicted in Figure 1, the green modelled and grey field data should coincide, thus a less visible grey wiggle (field data) indicates better matching between synthetic and field data. Hence, it can be concluded that synthetic data modelled by FWI output model is significantly better matched to the field data compared to that of the initial velocity model, for both near and far offsets.

Figure 2 shows the initial velocity model (2a), FWI output model (2b) and reflection tomography output model (2c). The three models were overlaid with their corresponding Kirchhoff migration stack in the same order shown in Figure 2 (d-f). It is observed that refraction FWI gave a reliable detailed velocity model down to the diving wave penetration of approximately 3.5 km depth. Kirchhoff depth gathers migrated using initial velocity model, FWI output model and tomography output model are presented in Figure 3a-c respectively. These results verified that gather flatness was continuously improved after each of the model building steps. Figure 4 and 5 compare the existing legacy velocity with the final velocity model resulting from our two-step top-down workflow, in depth-slice view (Figure 4) and in cross-section view (Figure 5). To get fair comparisons, Kirchhoff migrations shown in both figures were implemented using the same input data and a consistent set of parameters. The upper row of Figure 4a shows shallow depth slices at 1800 m (approximately 300 m below the water bottom) for legacy model; and the lower row shows the same depth slices for our final resultant model. These depth slices highlight the degree of detail incorporated in our final model. FWI enabled the final velocity model to capture these shallow details which closely follow geology.

Contrary to the shallow section, at depths around 5km, we noticed that the legacy velocity model (shown in Figure 6a) apparently has more details compared to our velocity model (depicted in Figure 5b). However, this high frequency velocity model feature has no correlation with geology and gives less coherent migration images compared to our result, as denoted in blue circles in Figure 5c and 5f. One possible reason for such a false high frequency velocity undulation is the inaccuracy of the legacy velocity in the shallow area. Without being accurately modeled, the shallow low velocity bodies would create distortions and lateral imprints in migrated gathers at greater depth. Relying on the residual curvatures of such gathers, reflection tomography would inaccurately distribute the perturbation update to deeper section.

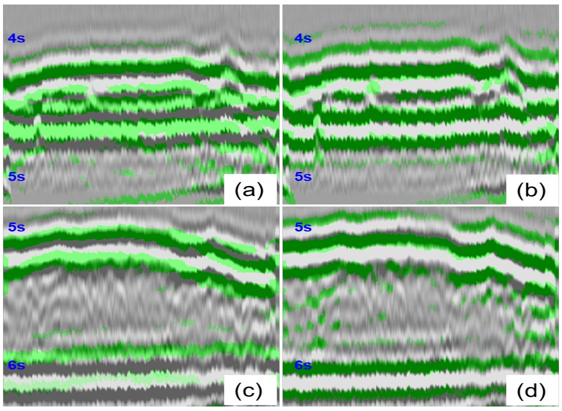

Figure 1 *Common offset modeled data (green) are overlaid on field data (grey-scale). (a-b) Near and (c-d) far offsets, approximately 1000 m and 5000 m offset, respectively, for (a and c) initial model, (b and d) FWI model.*

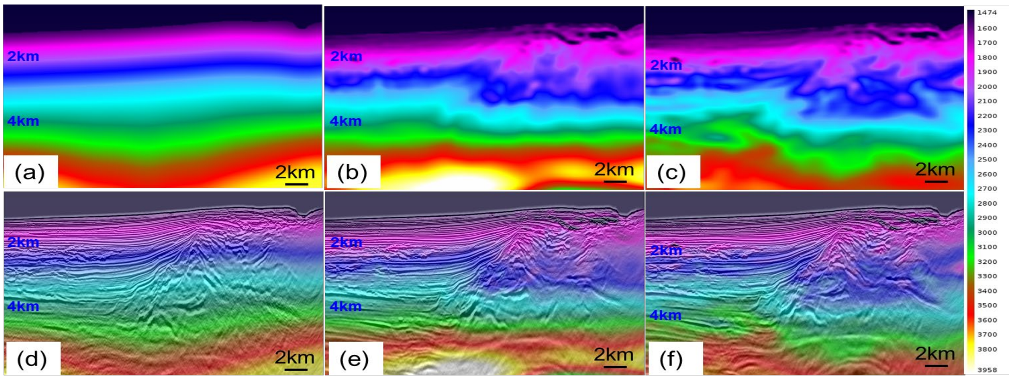

Figure 2 *Velocity model in m/s (a-c) without and (d-f) with corresponding Kirchhoff migration stack overlaid. Initial model (a and d). After FWI update (b and e). After FWI and tomography update (c and f).*

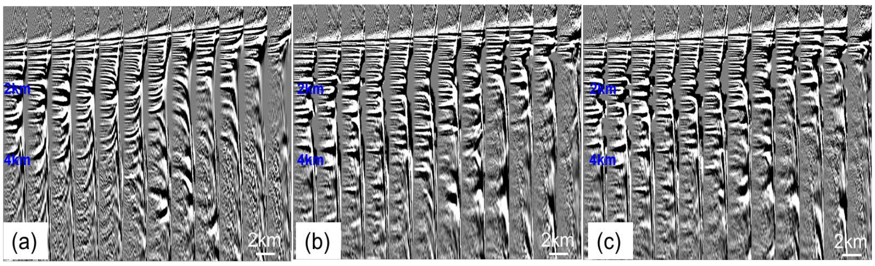

Figure 3 *Kirchhoff PSDM gathers migrated using (a) initial model (b) FWI output model and (c) final model (FWI followed by tomography).*

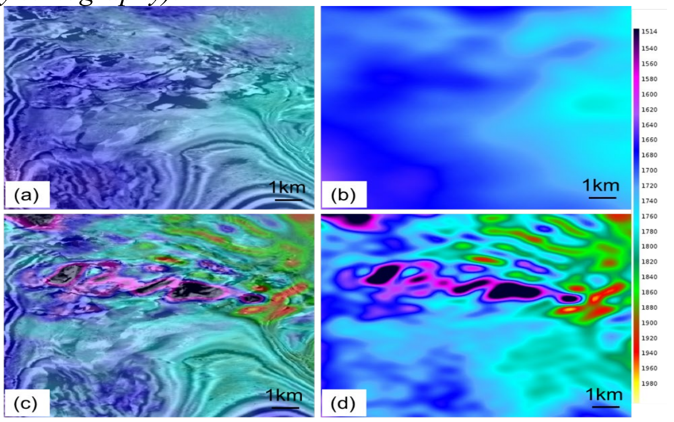

Figure 4 *Depth slice display at approximately 300m below water bottom for legacy model (a-b) and final model (c-d).) with corresponding Kirchhoff migration stack overlaid (a and c).*

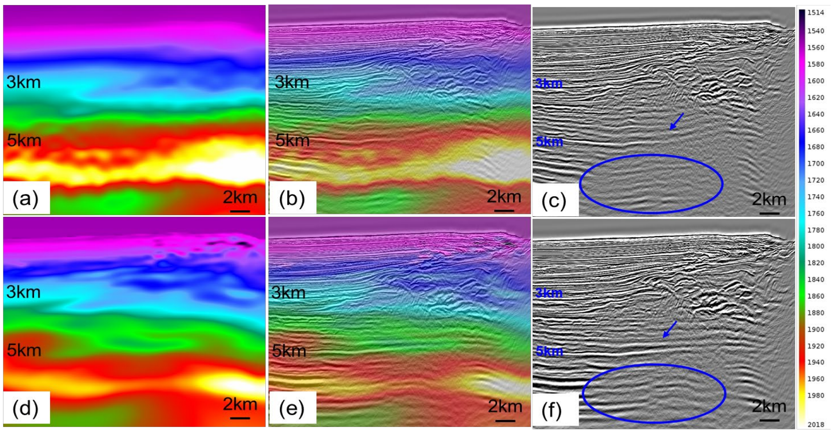

Figure 5 *Velocity models and corresponding Kirchhoff migration stack display for legacy model (a-c) and final model (d-f).*

Discussions

By strategically using refraction FWI to resolve shallow anomalies prior to ray-based reflection tomography, our two-step top-down velocity model building workflow resulted in substantial improvement in model's accuracy and seismic event's continuity. One limitation of this workflow is lack of high resolution at the deep section. Future work can increase the velocity model's resolution by implementing reflection FWI (Cobo et al., 2018). In addition to that, future monitor surveys might also consider utilizing a low frequency or enhanced bandwidth source to acquire data with better low frequency fidelity.

Conclusions

We presented a two-step top-down velocity model building workflow combining FWI and tomography. This workflow successfully resulted in a detailed velocity model and improved seismic image quality at the Northwest area of the Agbami field. The two-step model building approach was strategically staged to resolve near surface low velocity anomalies using diving wave acoustic FWI prior to traditional ray-based reflection tomography. Future work might further utilize reflection FWI or newly acquired seismic input data with better low frequency fidelity to achieve interpretable velocity property volume at larger depth.

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