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Enhanced Intra-Carbonate Imaging through High-Resolution Model Building and Least-Squares Kirchhoff, Offshore Sarawak

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Summary

Imaging of intra-carbonates is a recognized challenge for carbonate reservoirs in Central Luconia, Offshore Sarawak, Malaysia. This is primarily due to issues such as migration noise, limited illumination, and the need for highly accurate subsurface models in this complex environment. In this paper, we present the application of an advanced depth velocity model building workflow together with a single-iteration least-squares Kirchhoff depth migration (LS-KDM) to resolve both the kinematic and dynamic complexities surrounding carbonate sequences. The work presented uses numerous velocity model building techniques, including full-waveform inversion (FWI), to derive a high-resolution, geologically conformal velocity model that resolves the sediments surrounding, and within the carbonates. Illumination uncertainties and migration noise that plague a conventional migration technique such as Kirchhoff depth migration (KDM) are addressed through the use of a single-iteration image domain LS-KDM. We compare the LS-KDM derived reflectivity to that of the KDM to demonstrate the former's ability to improve image illumination, reduce migration artifacts and increase amplitude fidelity.

Introduction

Miocene carbonate reservoirs are historically associated with gas discoveries in Central Luconia, offshore Sarawak, Malaysia. However, the presence of carbonate and shallow gas often cause model building and imaging challenges such as migration noise and limited illumination. A 3D narrow-azimuth (NAZ) shallow-marine seismic dataset located within the Luconia / offshore Sarawak Basin was acquired in 2011 over an area characterized by the presence of a vast structural body of carbonates together with several smaller pockets of carbonate reefs located in the deeper portion of the subsurface. The acquisition was performed using a dual source and 6 streamers configuration with a maximum offset of 8.1 km spanning a total area of roughly 500 km^2. In this paper we address the model building and imaging challenges surrounding the carbonates through an advanced depth model building workflow and the application of an image-domain least-squares Kirchhoff pre-stack depth migration (LS-KDM).

Method

The key preprocessing steps applied to the seismic dataset included deghosting, internal and free surface demultiple and 4D (inline, crossline, time and offset) regularization. This was followed by a comprehensive depth velocity model building sequence consisting of refraction and reflection tomography, estimation of the anisotropic models using two wells in the survey area and a multi-scale TTI diving-wave full-waveform inversion (FWI) approach from 4 Hz to 24 Hz. With FWI having well resolved the shallow velocities, a final set of TTI reflection tomography iterations were performed to refine the deeper parts of the model. Velocity scanning was also performed during one of the anisotropic tomography iterations to refine the update of the fast carbonate anomalies as their positioning sits well below the FWI diving-wave penetration limit.

With the velocity and anisotropy models well resolved through the model building workflow, it was then prudent to address the illumination imaging challenges caused by the carbonate bodies. Least-squares migration offers a solution to this challenge as it can compensate for variations in illumination, improve amplitude fidelity and reduce migration noise and acquisition-related footprints. This is traditionally achieved by iteratively determining a reflectivity model that minimizes the “misfit” between the recorded seismic traces and those synthesized with a modelling operator. The “misfit” is often quantified by the square of the l2-norm, referred to as the objective function (Nemeth, 1999). With each iteration the point spread functions (PSFs) of the migration operator (which are characterized by the Hessian matrix) are partially deconvolved from the data, thus providing a better estimate of the true subsurface reflectivity.

In the example presented, a single-iteration image domain LS-KDM was applied to overcome the illumination uncertainty issue and improve the clarity of the KDM-led structural imaging within the carbonates. This approach estimates the inverse of the Hessian matrix using non-stationary matching filters (Guitton, 2004). The LS-KDM was performed with TTI symmetry using the same 4D-regularized gathers and earth models used for the KDM.

Results

The derived anisotropic parameters facilitated mis-tie reductions between the supplied well markers and key horizons in the TTI 3D Kirchhoff preSDM throughout the model building, particularly at horizon-C as shown in figures 1a-b.

The velocity model computed through FWI effectively captured the strong, lateral velocity variations in the near surface as demonstrated by the shallow depth slice (figure 2a-b). This provided an excellent starting point for the subsequent reflection tomography iterations to update the deeper section. This model building workflow generated a geologically conformal velocity model which resolved the carbonate base (figures 3a-b).

The final depth velocity model showed a good agreement with the well checkshot trend (figure 4a). The derived models and input gathers were then used to perform a final TTI 3D KDM. Figure 4b shows the resulting KDM section which demonstrates the successful imaging of the carbonate top and base platform. However, it still suffers from illumination challenges along with the presence of migration-related noise that obscures the structural imaging within and beneath the large carbonates (indicated by the yellow arrows). Typical approaches to attenuate the migration noise rely on post-imaging targeted denoising algorithms. Such approaches can risk attenuation of the underlying primaries and do not resolve the illumination uncertainties.

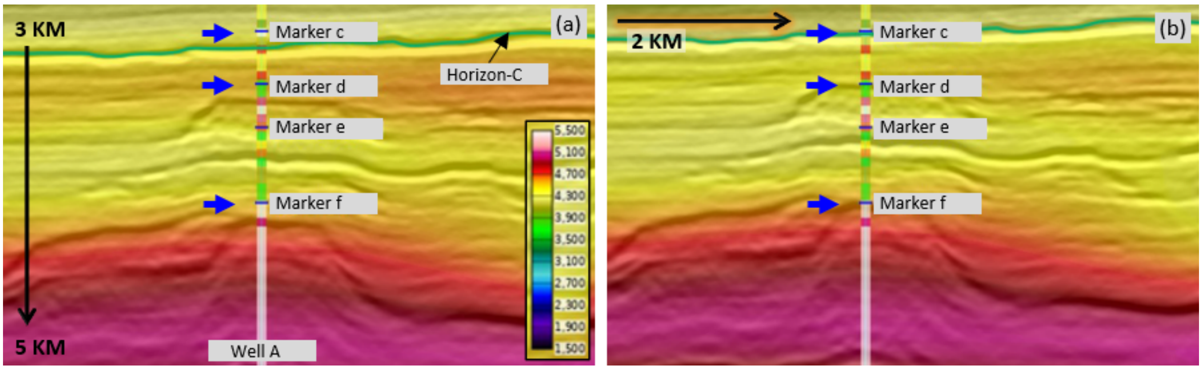

Figure 1. *(a) KDM section overlain with its Vp model prior to refinement of anisotropy models, and (b) KDM section overlain with its Vp model after deriving refined anisotropic models. Well markers and key horizons are also shown.*

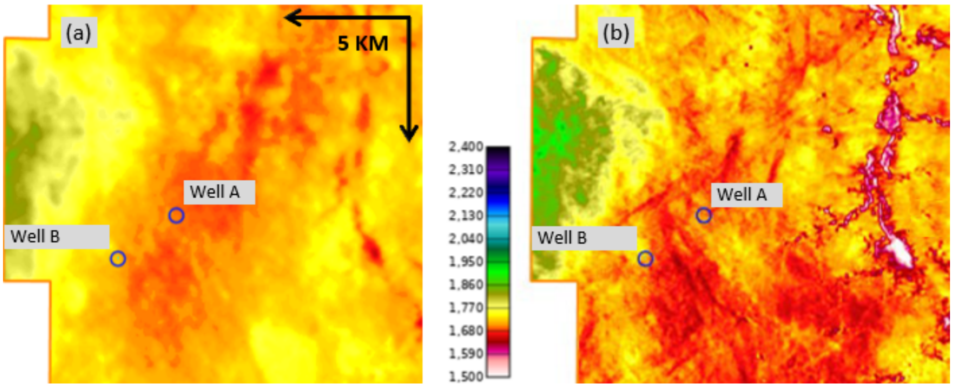

Figure 2. *A shallow depth slice through (a) the initial velocity model, and (b) the 24 Hz FWI velocity model. Wells A and B used as part of the anisotropic modelling, are also plotted.*

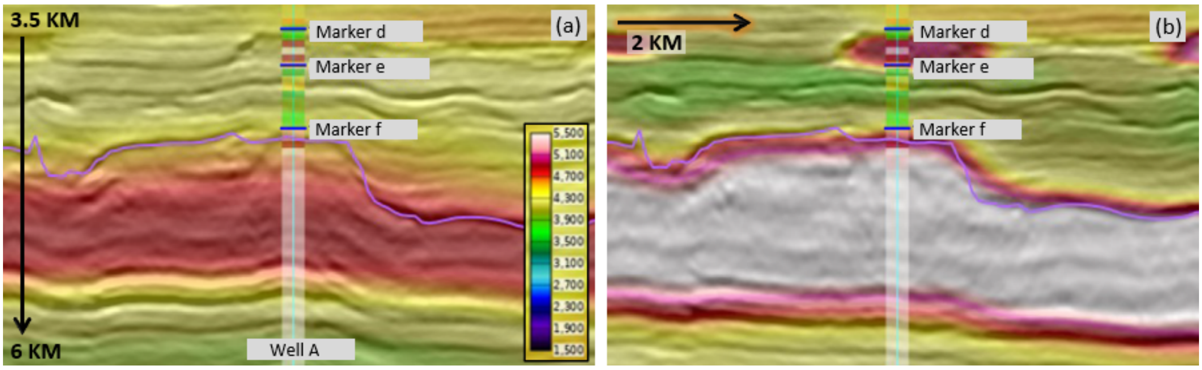

Figure 3. *(a) initial KDM section overlain with its velocity model, and (b) the resulting KDM section overlain with its velocity model at a later stage in the model building workflow.*

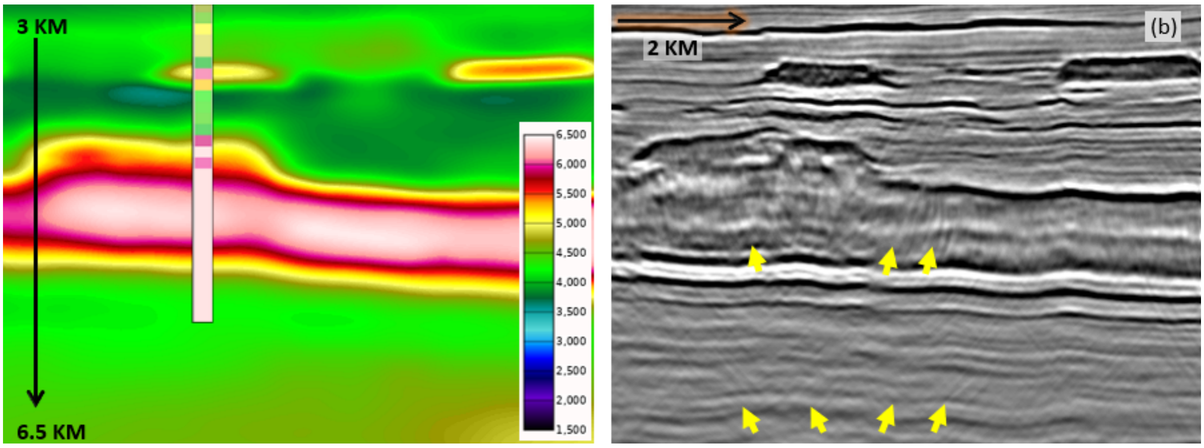

Figure 4. *(a) Final depth-imaging velocity model and (b) KDM section demonstrating the area surrounding the carbonates.*

Figure 5 shows a significant improvement in resolution evident in the LS-KDM result when compared to the KDM, particularly within the large carbonate structure. Migration noises are abundant in KDM seismic section (figure 5a), penetrating the carbonates and obscuring the reflectors within. Such noise, however, is effectively suppressed in the LS-KDM result (figure 5b). The illumination and amplitude fidelity of reflectors within the intra-carbonate are shown to have also improved as indicated by the blue arrow.

Figure 6a-b further highlights the KDM and LS-KDM comparison at a depth slice positioned around the top of the large carbonate body (black arrow in figure 5). Here, migration noises are observed to manifest as an interference pattern which would be difficult to eliminate without affecting primary reflections when considering conventional denoise techniques. The suppression of such artifacts by LS-KDM demonstrates better amplitude continuity, improved resolution and clearer interpretation of several structural trends as highlighted by the yellow arrows. Figures 6c-d show a similar observation for a KDM and LS-KDM depth slice positioned at the depth of the internal reflector layer (blue arrow in figure 5) within the large carbonate section. Suppression of the migration artifacts resulted in clearer imaging of this package across the depth slice.

Conclusions

We have demonstrated the benefits of an advanced depth velocity model building workflow to resolve the carbonate kinematics, followed by a single-iteration LS-KDM to resolve imaging issues caused by strong reflecting, carbonate-induced layers as evident in a dataset from the offshore Sarawak region. Least-squares Kirchhoff imaging delivered a clear reduction of migration artifacts and improvements in terms of image illumination compensation and amplitude fidelity.

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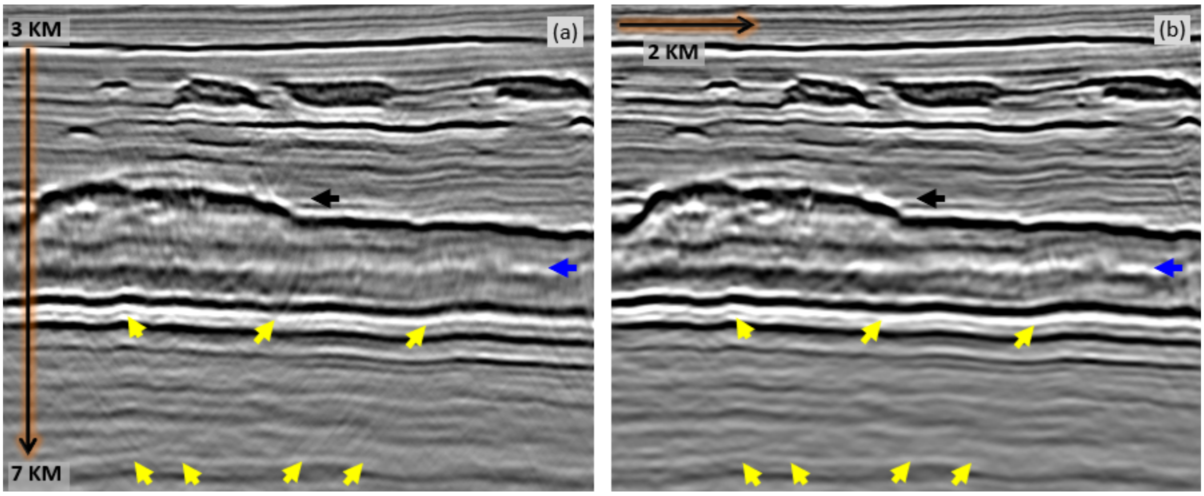

Figure 5. *A migrated image comparison between (a) the final KDM and (b) the LS-KDM. Yellow arrows point to migration artifacts and illumination ambiguities in the KDM and their improvements in LS-KDM. Black and blue arrows refer to depth slice positions in figure 6.*

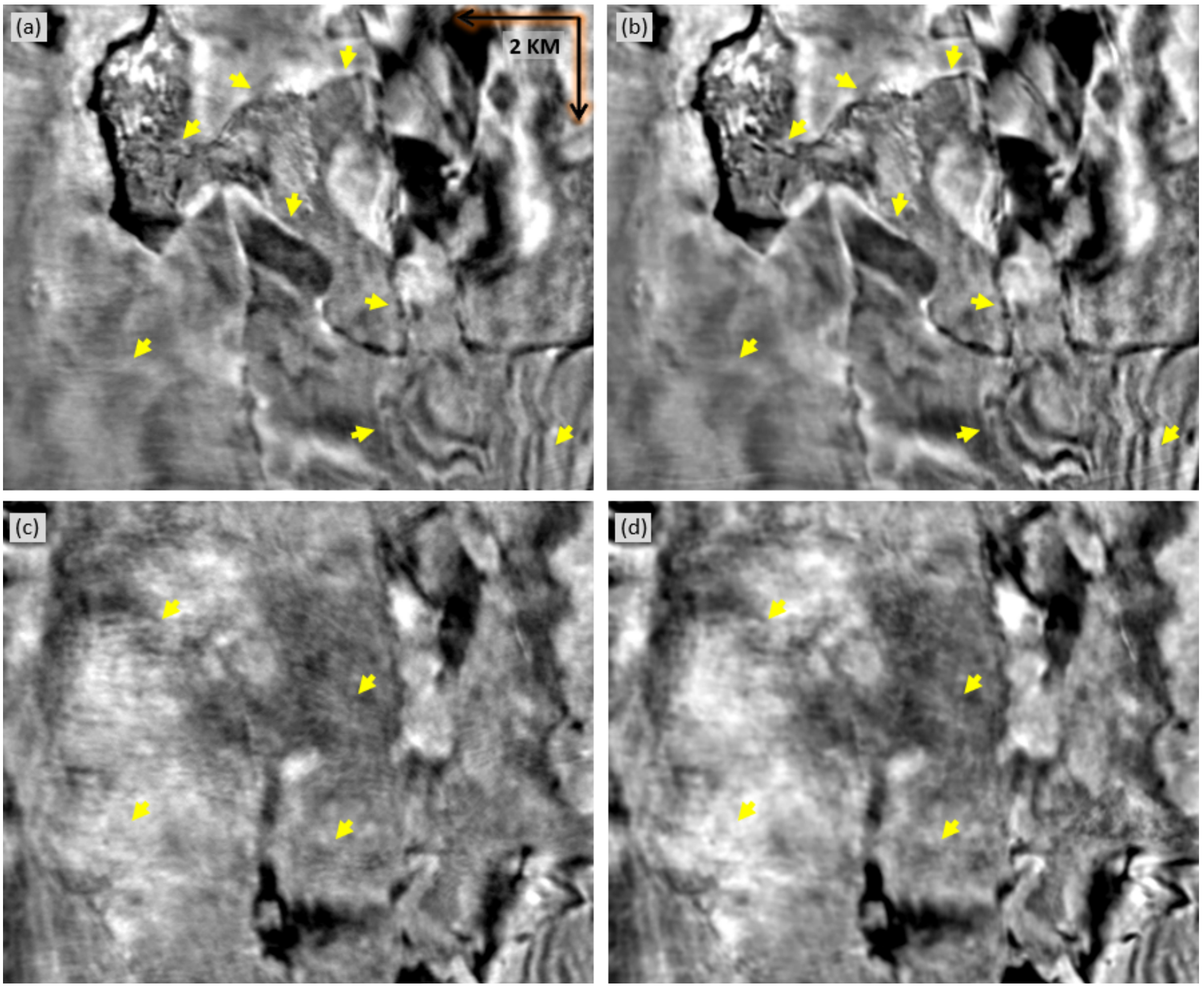

Figure 6. *Depth slice comparing the (a) KDM and (b) LS-KDM, positioned around the large carbonate top. Additional slice positioned at the intra-carbonate reflector, for (c) KDM, and (d) LS-KDM. Yellow arrows indicate migration artifacts and illumination ambiguities which are subsequently resolved by the LS-KDM.*