INTEGRATED HIGH-RESOLUTION MODEL BUILDING: A CASE STUDY FROM THE SULTANATE OF OMAN

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Summary

The geology of northern Oman presents significant challenges for land velocity model building. We show in this paper that these challenges can be overcome by using an integrated high-resolution velocity model workflow, through the combination of different types of waves, that allow resolving different parts of the velocity model. This dedicated workflow consists of Multi-Wave Inversion (MWI) for the near-surface, followed by Optimal Transport Full Waveform Inversion (OT-FWI) and then by ray-based joint reflected and diving wave tomography inversion. It resolves challenges imposed by complex shallow geology and allows for proper imaging of deeper structures. Compared to a conventional ray-based only model building flow, the integrated high-resolution workflow enabled generating a geologically plausible velocity model which minimizes depth positioning errors and greatly enhances structural and stratigraphic trends.

Integrated high-resolution model building: a case study from the Sultanate of Oman

Introduction

The geology of northern Oman presents significant challenges for land velocity model building. For the dataset considered in this paper, the shallow subsurface is characterized by very complex fault networks and fracture corridors. This is compounded by the presence of a low-velocity uplifted crestal carbonate, adjacent to a low angle reverse fault that can be traced up to the surface. Despite the wide-azimuth high-density acquisition, with offsets up to 10 km, the near offset coverage is still poor. The lack of recorded offsets makes it difficult to obtain a reasonable velocity model with conventional reflection-based methods as there is little to no reliable move-out information, and inadequate angle and offset distributions at shallow depths. We show here that the challenge can be overcome by using an integrated high-resolution velocity model workflow, through the combination of different types of waves, that allow us to resolve different parts of the velocity model. This dedicated workflow consists of Multi-Wave Inversion (MWI) for the near-surface, followed by Optimal Transport Full Waveform Inversion (OT-FWI) and then by ray-based joint reflected and diving wave tomography inversion.

Near-surface model update using MWI with de-blended and blended continuous recording data

The near surface exposes an antiformal thrust-fold structure within the Shargi formation. The steeply dipping flanks of the fold are overlain by high-velocity rocks and are underlain by sharply slower-velocity rocks which also comprise the core of the dome (Figure 1d). This velocity inversion is very difficult to capture with either reflection or first-break (diving wave)-based inversion methods due to either insufficient near angles or being impeded by illumination gaps in the presence of strong velocity variations. In this geological context, Masclet et al. (2019) have shown that MWI approach proposed by Bardainne (2018) leads to an accurate estimate of the very near subsurface model.

MWI uses surface and refracted waves travelling through the near surface to retrieve Vp and Vs velocity information. The penetration depth of surface waves is related to their phase velocity and minimum pickable frequency. In our de-blended (active) data this was approximately 150 m with a 2.5 Hz minimum reliable frequency. The high-density acquisition gave a detailed near surface model, capturing the lateral resolution, however, the active-data MWI result lacked deep penetration.

Blended continuous recordings were used to reconstruct ultra-low frequency surface waves (virtual data) through an interferometry process that uses ambient noises present in the data (Le Meur et al., 2020; Al-Droushi et al., 2021). This allowed us to pick dispersion curves with minimum frequency as low as 1.2 Hz giving an increased penetration depth (around 400m below the topography). We observed that the combined use of actual and virtual-data MWI resulted in a near-surface model (shown in Figure 1) whose high resolution and deeper penetration significantly improved the focusing and lateral consistency of the shallow part of the image (deeper events).

Optimal Transport Full Waveform Inversion (OT-FWI)

Full waveform inversion (FWI) is a natural choice to update complex overburdens. Despite the fact that elastic FWI should be the method of choice for tackling the challenges of land data (Perez-Solano and Plessix, 2019; Adwani et al., 2021), the use of acoustic OT-FWI (Messud and Sedova, 2019) has proven to be a cost-effective alternative in several examples from both the North and the South of Sultanate of Oman datasets (Sedova et al., 2019; Hermant et al., 2019; Carotti et al., 2021). OT-FWI mitigates cycle-skipping issues and amplitude effects, thus exploiting the entire potential of the acoustic FWI. Compared to classical least-squares FWI, OT-FWI is less prone to cycle skipping, less sensitive to amplitude differences, and provides a more structurally consistent velocity model. For OT-FWI initial velocity model, we merged the active and virtual MWI near-surface model with a legacy model obtained by anisotropic elastic FWI up to 4.1 Hz (Figure 2a). However, early testing showed that a more detailed input model was needed to attain a stable FWI result. Thus, a pass of ray-based tomography was performed to improve the initial FWI model even further. Input data for OT-FWI were the diving waves which cover the intermediate depth range. The maximum recorded offset was 10km giving a depth penetration of approximately 4 km. This long offset WAZ dataset was processed to enhance the diving and post-critical waves followed by running OT-FWI from a starting cut-off frequency of 2.5 Hz to 9

Hz (Figure 2b). When compared to the initial PSDM image (Figure 2d), many improvements are visible in the entire section (Figure 2e) even below the diving waves penetration depth. The cascaded flow of MWI with OT-FWI resulted in improving the imaging and lateral positioning of the reverse bounding fault and adjacent reservoirs, while reducing the structural uncertainty within the target area.

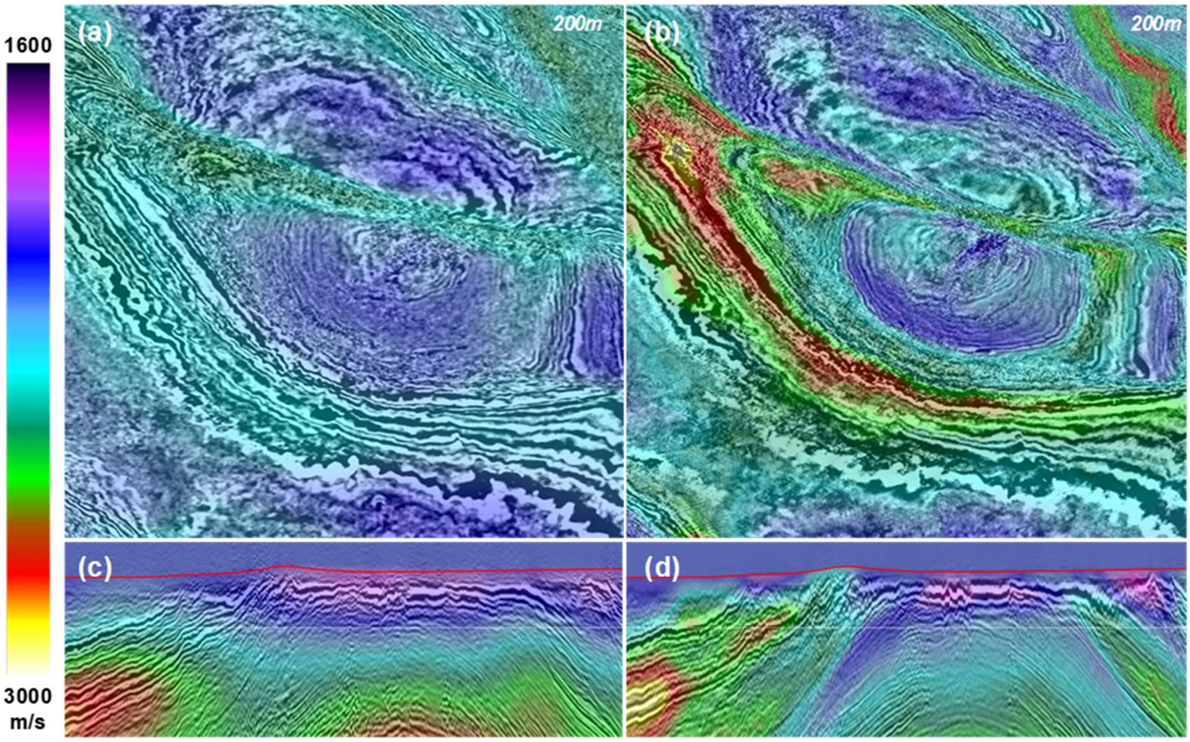

Figure 1: *Depth slice (at 200 m below topography) and inline section of migrated stack image with velocity overlaid for initial model (a and c), and after active & virtual MWI (b and d). Note the improved image of the dipping areas/crestal structure and slow/fast velocity details in the very shallow.*

Non-linear first arrival times and reflection curvatures joint tomography

Reflection data RMO picking is routinely performed for updating the deeper section using ray-based tomography. Thanks to the excellent matching between recorded and modelled diving waves provided by OT-FWI, we used the updated velocity model for computing first-arrival travel times between source and receiver using an eikonal solver, which were then used for a joint reflection-diving wave tomography, as proposed by Allemand et al. (2020). Compared to the reflection-only tomography, the joint-tomography allows updating the epsilon model as well. As a consequence, the focusing and the flattening at the large offsets for the shallow events are improved when using the joint tomography (Figure 3). The multi-layer inversion feature in our tomography (Guillaume et al., 2012) incorporates the reverse fault within the input tomography model with horizon layers split in up and down-thrown sectors truncated to the bounding fault. MWI & FWI brought clear improvements in resolving the shallow structural complexity and significantly uplifting the fault network imaging, allowing for detailed horizon interpretation, which, when integrated into tomography, results in superior velocity model (Figure 2c). Imaging uplifts brought by OT-FWI (Figure 2e) were further enhanced by the last step of joint-tomography (Figure 2f), showing that each step of the integrated model building workflow is important to reach the final result.

Conclusion

The implementation of integrated high-resolution velocity model building offers a robust workflow that resolves challenges imposed by complex shallow geology and allows for proper imaging of deeper structures. Using the MWI and OT-FWI result as a starting model for the multi-layer tomography provided the opportunity to use accurate horizons which honored the complex structure and bounding fault. Compared to a conventional ray-based only model building flow, the described workflow enabled us to generate a geologically plausible velocity model which minimizes depth positioning errors and greatly enhances structural and stratigraphic trends.

Acknowledgments

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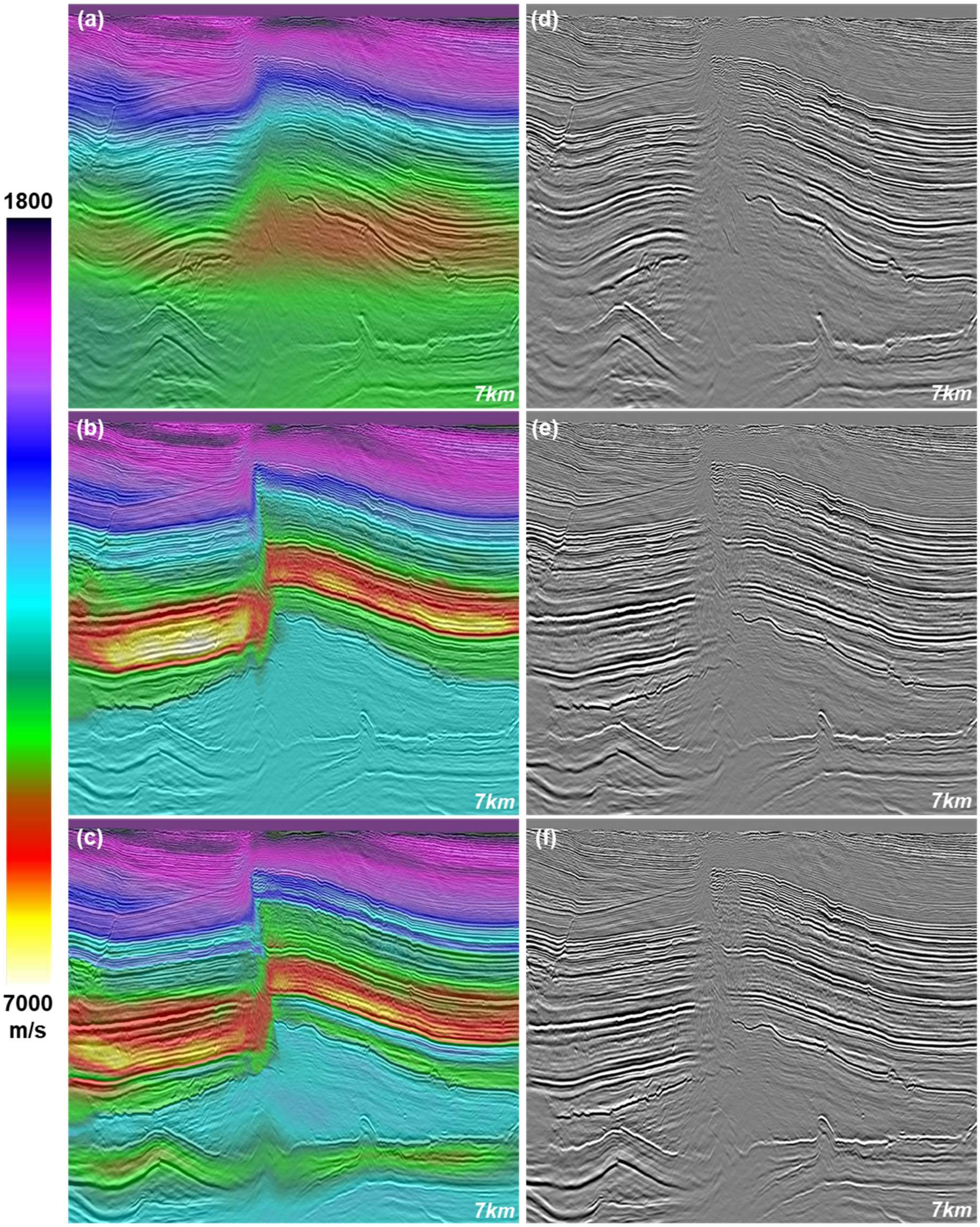

Figure 2: *Comparison of the Kirchhoff PSDM sections with and without the velocity model overlaid: (a & d) legacy model (b & e) MWI + OT-FWI model; (c & f) final integrated high-resolution model. The details in the model lead to visible structural improvements in the fault definition along with each step of the integrated workflow.*

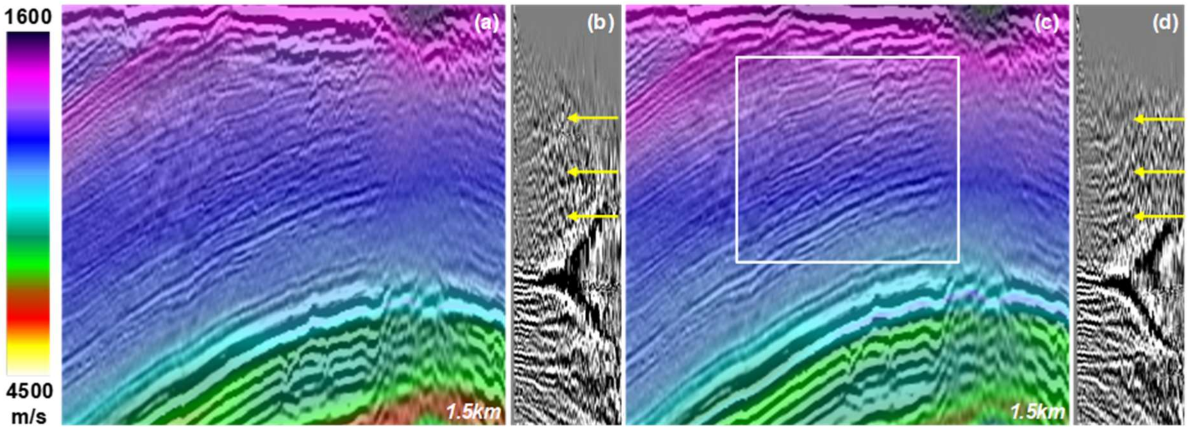

Figure 3: *Comparison of imaging from: (a) Reflection tomography velocity overlaid on stack and (b) Gathers; (c) Joint tomography velocity overlaid on stack and (d) Gathers. Note the improved focusing in the shallow reflectors highlighted by the white box and gather flatness indicated by the yellow arrows after joint inversion.*

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