Extreme Near-surface Velocity Heterogeneities from High-fidelity Outcrop Analog Models and Their Effect on Land Seismic Data

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Summary

This study constructs a 3D high-fidelity outcrop-based analog velocity and density model capable of capturing and replicating geologically realistic meter-scale intrinsic depositional heterogeneities of carbonate rocks for near-surface seismic applications. The models are constructed based on documented Late Jurassic outcrop analog studies of three different stratigraphic locations in Arabia and lab-measured rock properties. The simulated shot gather from the model results in very noisy incoherent synthetic data despite the model not containing topography and karst field, typically attributed as the primary factors of the low-quality land data in the arid area. This model is an essential first step toward building more complex near-surface scenarios. Finally, the model can already be utilized as a medium to test acquisition design or processing workflow to improve the data quality in the arid area.

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Introduction

Depositional lithofacies of carbonate strata are inherently heterogeneous. Traditionally, this fundamental geologic heterogeneity is considered critical only from the perspective of reservoir characterization. One of the most challenging conundrums in carbonate reservoir studies is to spatially decipher meter-scale interwell depositional heterogeneity and incorporate it into the reservoir models. Perhaps unbeknown to most carbonate geologists, the geophysicists that work on land seismic data in the Middle East encounter a similar problem. This region's near-surface geology (top ~200 m) consists of carbonate rock formations (Powers et al. 1968). Strong scattering caused by sub-wavelength near-surface heterogeneities of these formations strongly deteriorates the quality of seismic data acquired in the arid area (Bakulin et al. 2022).

The SEAM Arid Model (Oristaglio 2012; Regone et al. 2017) is the latest and most commonly used model to replicate the near-surface complexity of the arid area. However, the model does not include meter-scale intrinsic depositional heterogeneity prominent in the carbonate rock formations. This geologic factor can very well be the "culprit" that causes even more disorganization of all coherent events, including reflections and organized noise (Bakulin and Silvestrov 2021). This study aims to construct a 3D outcrop-based analog velocity and density model capable of capturing and replicating geologically realistic meter-scale intrinsic depositional heterogeneities of carbonate rocks for near-surface seismic applications. We aim to capture and replicate meter-scale intrinsic near-surface complexities as the essential first step toward building an optimum acquisition design and processing workflow to address the low-quality seismic data in the arid area.

Method

We constructed the model based on the documented Late Jurassic outcrop analog studies (Jacquemyn et al. 2018; Ramdani et al. 2022) from three different stratigraphic locations (Figure 1A – Sites A, B, and C). The three locations highlight different meter-scale depositional facies heterogeneity that typified Middle Eastern carbonate strata.

Outcrop site A exposes ~75 m interval of the Late Oxfordian to Early Kimmeridgian strata. The most evident depositional heterogeneity in site A is the stromatoporoid/coral biostromes/bioherms facies (Figure 1D) and their associated flank strata (Al-Mojel et al. 2020; Ramdani et al. 2022). Outcrop site B exposes ~35 m thick of the Late Kimmeridgian strata. The most noticeable depositional facies heterogeneity (Figure 1C) of this outcropped interval is the chaotically bedded conglomeratic rudstones that form channel-like geometry (Jacquemyn et al. 2018). Outcrop site C exposes ~50 m interval of the Late Kimmeridgian to Portlandian(?) strata with stromatoporoid/coral and rudist biostrome facies (Figure 1B) as the most notable depositional heterogeneity (Schneider and Al-Mojel 2022).

This study separates the model into two main frameworks (Figure 2): the near-surface and the subsurface zones. The near-surface zone is the first ~155 m of the model (Figure 2), where we incorporate the reported 3D meter-scale depositional facies heterogeneity from the three outcrop sites. The subsurface zone (Figure 2) is the rest of the model, from a depth of ~155 m (base of the near-surface zone) to the base of the model at 2200 m. The model size is 4 km x 4 km by 2200 m thickness at 3 m x 3 m by 0.3 m grid resolution.

We built a geologically realistic 3D depositional facies model in the near-surface zone using a combination of Sequential Indicator Simulation, geological process-based modeling, and object-based modeling (Figure 2). We intentionally did not include variation in surface topography, and karst field since the model is intended to investigate the effect of near-surface meter-scale depositional heterogeneity on seismic data. Ramdani et al. (2022) and Chandra et al. (2021) drilled near-surface cores from the three outcrop sites. They performed cm-scale high-resolution facies description and laboratory-scale P-wave velocity, S-wave velocity, and density measurements from the cores. We utilized their measured properties to populate the resulting 3D outcrop analog near-surface depositional model with P-wave velocity, S-wave velocity, and density (Figures 3A and 3B). We then populate the subsurface zone using 1D homogenous parallel-bedded P-wave velocity, S-wave velocity, and density (Figures 2, 3A, and 3B) reported in Bakulin and Silvestrov (2021).

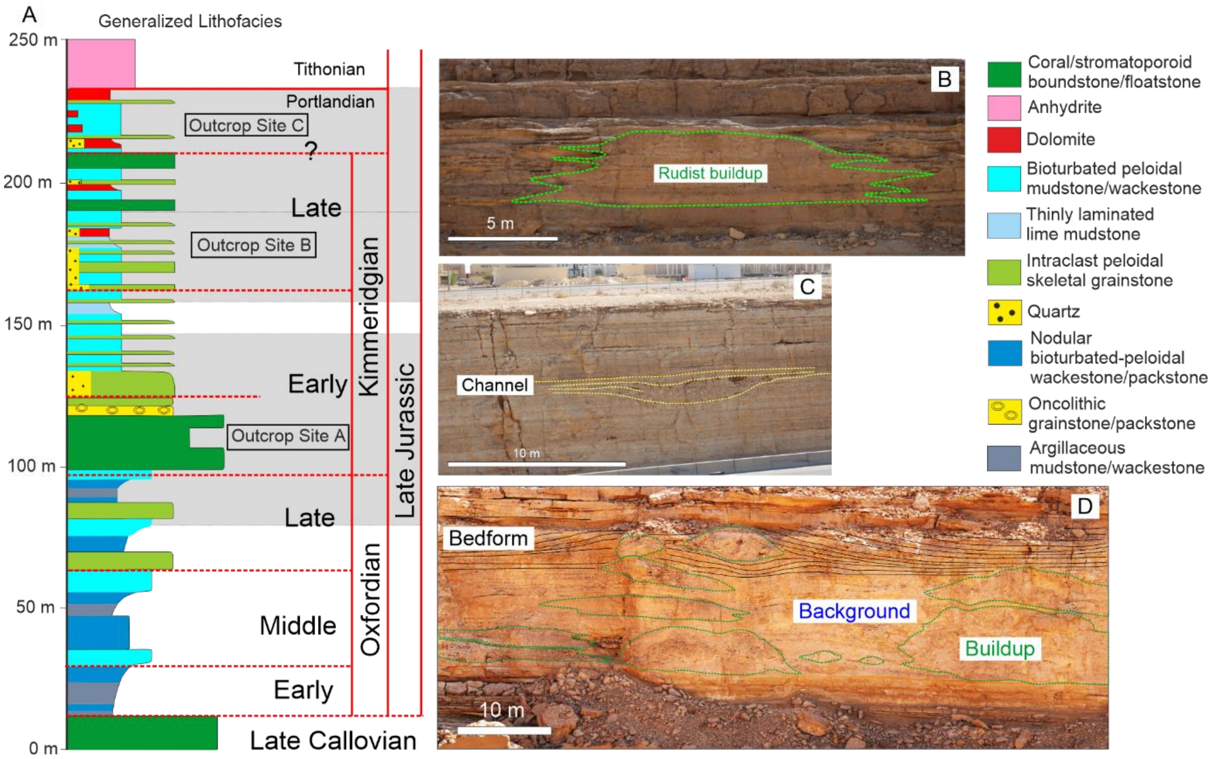

Figure 1. *(A) Generalized Late Jurassic vertical stratigraphic column and lithofacies of central Arabia from Al-Mojel et al. (2020). The shaded part of the column highlights the stratigraphic interval covered by each outcrop site. (B) An example of rudist biostrome in Site C. (C) An example of rudstone channel in Site B. (C) An example of stromatoporoid/coral bioherm in Site A.*

Examples

We simulate an elastic 2D shot gather from the center part of the 3D model to exemplify the effect of the meter-scale depositional heterogeneity on the quality of seismic data (Figures 3A and 3B). The simulated acquisition geometry is split-spread with a 25 m receiver interval and Klauder wavelet with a maximum frequency of 60 Hz (Figure 3D). The simulated gather results in very noisy incoherent near-surface and broken-up reflections from the subsurface (Figure 3C) despite the model not containing topography and karst field, typically attributed as the primary factors of the low-quality land data in the arid area.

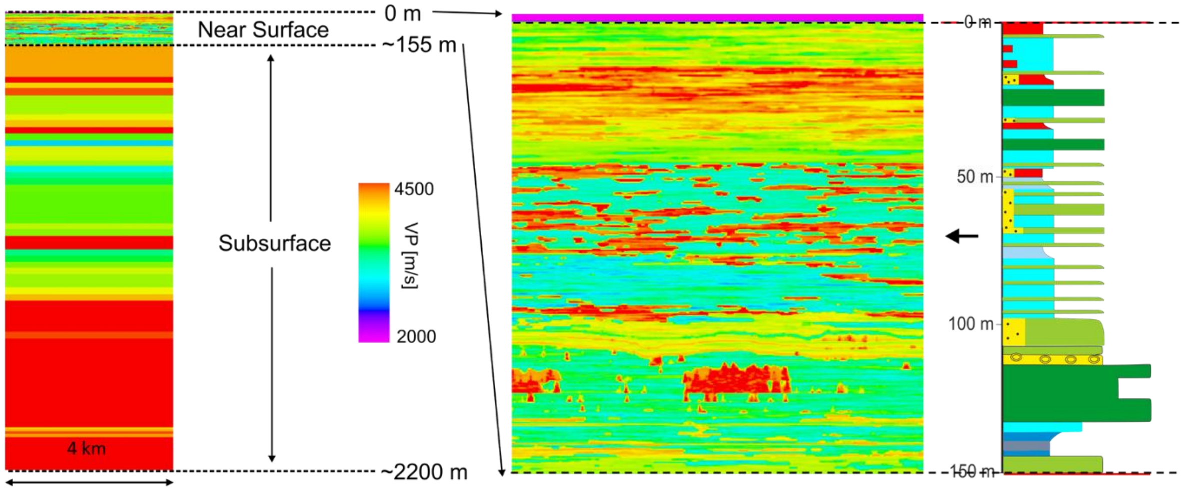

Figure 2. *2D illustration of the model framework from the resulting 3D model. The model is divided into two main frameworks: The near-surface (top 150 m) and the subsurface (from 150 m to 2000 m). The near-surface includes meter-scale depositional facies models from the three outcrop sites, while the subsurface is from Bakulin and Silvestrov (2021). Refer to figure 1 for the color legend.*

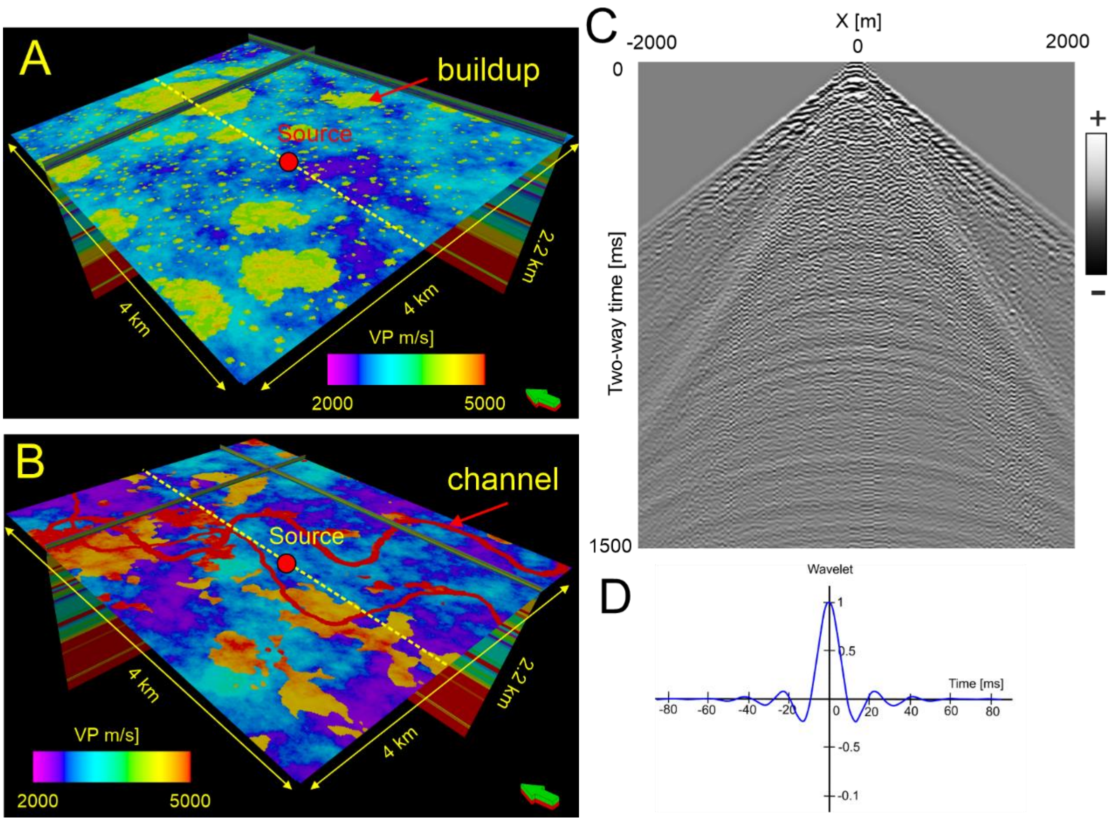

Figure 3. *(A) Perspective display of the 3D P-wave velocity model highlighting stratigraphic levels where the stromatoporoid/coral buildups (A) and rudstone channels (B) are modeled. The dashed yellow line represents the simulated receiver locations, while the red dot represents the shot location. (C) Resulting modeled shot gather. (D) Source wavelet.*

Conclusions

This study has constructed 3D outcrop-analog near-surface velocity and density models incorporating realistic meter-scale depositional heterogeneities of carbonate strata characteristic of Middle Eastern near-surface geology. 2D shot gather simulated from the model resulted in relatively uncoherent near-surface and subsurface events. This model is an essential first step toward building more complex near-surface scenarios. Finally, the model can already be utilized as a medium to test acquisition design or processing workflow to improve the data quality in the arid area

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