Time-lapse in shallow water OBN data via multiparameter FWI

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Summary

Time-lapse (4D) seismic data has proven over the years to be an important delivery for reservoir management, with significant influence on understanding the fluid movement and well planning. Advancements in seismic acquisition and processing have direct impact on seismic image resolution and interpretation. OBN data, due to their excellent 4D repeatability, are commonly used for time-lapse projects in both shallow and deep-water settings. Their full azimuth coverage and long offsets make them suitable for accurate velocity updates using full-waveform inversion (FWI) methods. Recently, multiparameter full waveform inversion (MP-FWI) that also estimates reflectivity has emerged as an enhancement to conventional imaging techniques, enabling the delivering high-resolution reflectivity models. In this paper, we apply MP-FWI to time-lapse shallow water OBN data. Results obtained using only a subset of the data set demonstrate enhanced reservoir definition and improved 4D signal fidelity compared with conventional imaging approaches.

Introduction

Due to their full azimuth, large offsets and improved 4D repeatability over the traditional streamer acquisition, the Ocean-Bottom-Node (OBN) data are increasingly being acquired in both shallow and deep water to deliver the best possible images for interpretation. Advances in seismic acquisition were swiftly followed by advances in imaging approaches. For example, least-squares migration (e.g., Nemeth et al., 1999) is a linear inversion process using a preconditioned conjugate gradient scheme. It can be implemented in both data and image domain, with the latter being routinely used due to cost considerations.

More recently FWI has unanimously established its substantial role in subsurface imaging. Single parameter FWI has been widely used for decades now to deliver high frequency velocity models with increased accuracy required to compute FWI derived images. This approach has evolved into multiparameter (MP) inversion of subsurface parameters as an alternative to FWI derived images (Yang et al., 2021). Recent studies using MP-FWI have shown that imaging resolution can be improved, leading to clearer and more reliable structural interpretation for both shallow and deep targets (e.g., Sheng et al. 2026;). A key feature is the scale separation applied to the conventional cross-correlation gradient, which enables the derivation of a tomographic sensitivity kernel for updating the background velocity, and a reflectivity kernel for enhancing image resolution. This separation in the FWI gradient increases the robustness and convergence efficiency of the coupled velocity–reflectivity inversion. Korsmo et al. (2022) successfully applied the MP-FWI approach described by Yang et al (2021), which from the imaging perspective, can be considered as a nonlinear LS-RTM implemented inside the FWI framework, simultaneously updating both velocity and reflectivity.

In this study, we evaluate the impact of MP-FWI on enhancing resolution of the 4D reservoir response in a shallow water setting from OBN data. Considering the excellent repeatability of the base and monitor surveys, we implement a 4D parallel workflow that improves the reservoir definition and strengths the 4D signal.

Acoustic MP-FWI

Multiparameter FWI for velocity and reflectivity estimates is an alternative to FWI derived reflectivity (FDR). In FDR, high-frequency FWI is performed using the cross-correlation gradient and the reflectivity is computed from the velocity field assuming constant density. In MP-FWI, both background velocity and reflectivity are jointly updated within the same FWI framework. This is possible due to the crosstalk mitigation between the two parameters, through an effective scale separation of the FWI gradient based on inverse scattering theory. In addition, the acoustic wave equation is parameterized in terms of velocity and reflectivity to overcome the necessity to build a density model. Scale separation enables the background velocity updates minimizing reflectivity leakage. Likewise, the resolution of the resulting images is enhanced due to both the scale separation and the iterative updating of reflectivity. Furthermore, MP-FWI approach has been applied to derive local changes in density and detect negative correlation between velocity and density, generally observed at targets with Class IIp AVA anomalies (Huang et al., 2026).

Shallow water OBN example

This work builds on single parameter 4D FWI work on shallow water OBN data (Davies et al., 2024), and a 4D joint dynamic matching FWI approach (Fuchun et al. (2024). In these studies, the inverted base and monitor velocity models were used to generate 3D and 4D FWI Images as a QC measure before continuing with the higher frequency 4D FWI run.

Our MP-FWI approach is applied in a 4D parallel fashion using only a small subset, generating separate base and monitor reflectivity images. Figure 1 displays a section through the monitor velocity model, showing high velocities below the reservoir. We implemented our 40 Hz inversion flow by starting with the same velocity model for base and monitor data. The rigorous time-lapse preprocessing applied to both OBN datasets allowed the generation of high-quality results. Figures 2a and 2b display the base RTM and MP-FWI reflectivity images, respectively along the crossline direction. Inverted reflectivity from MP-FWI shows improved resolution throughout the section including at the reservoir level. This is validated by the amplitude spectra comparison in Figure 3, which shows that the inversion flattens the spectrum for frequencies up to 40Hz. Finally, in Figure 4 we show the 4D response computed from RTM (a) and MP-FWI (b), which exhibits better resolution of the several stacked 4D signals corresponding to the different compartments on the inverted volume.

Conclusions

We described a parallel time-lapse data domain workflow based on acoustic multiparameter FWI and successfully applied it to shallow water 4D OBN data. The MP-FWI approach enables the simultaneous updating of velocity and reflectivity by incrementally increasing frequency bands up to 40Hz. The results demonstrate a significant increase in resolution throughout the reflectivity model, including at the reservoir level, after only a few iterations. The inverted 4D response clearly delineates the oil-and-water contact, and a better definition of the expected hardening and softening anomalies within the multi-level reservoir package.

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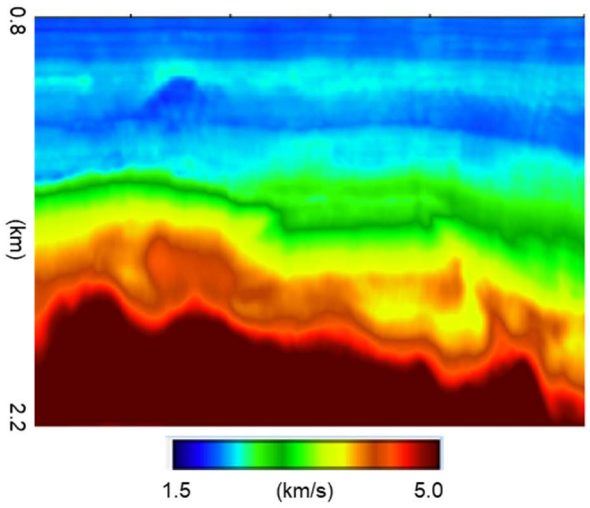


Figure 1: Starting monitor P-wave velocity model

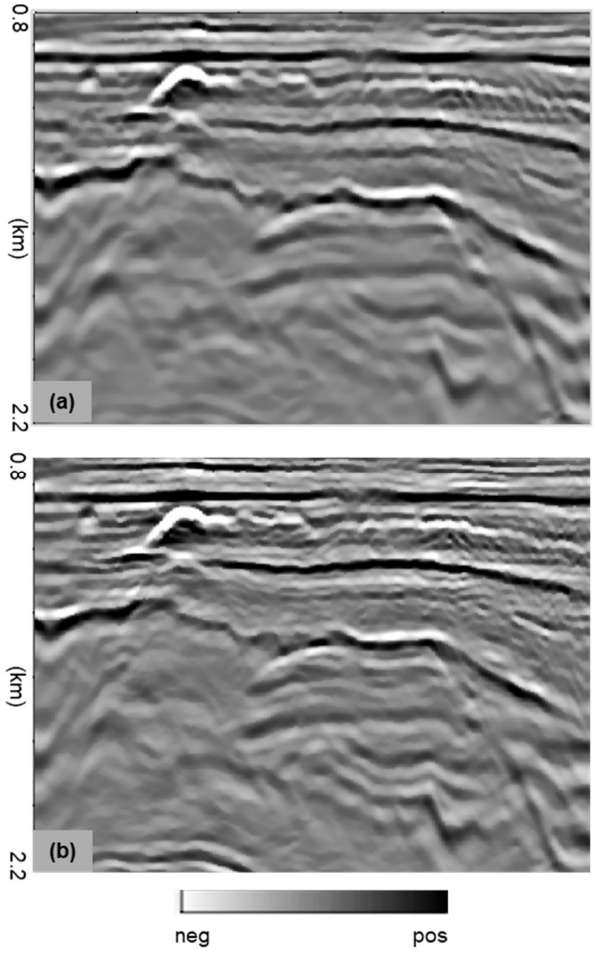


Figure 2: 40 Hz (a) RTM and (b) inverted reflectivity images for the base data along the crossline direction.

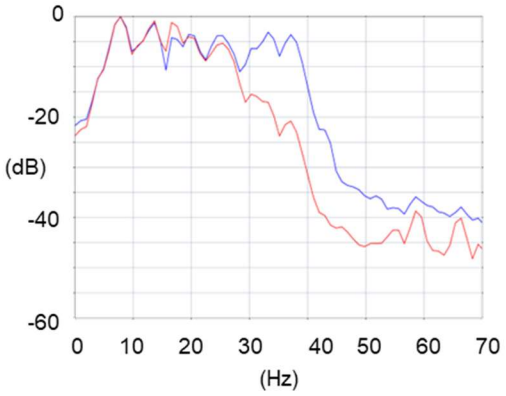


Figure 3: Amplitude spectra for the RTM (red) and inverted reflectivity (blue) images displayed in Figure 2.

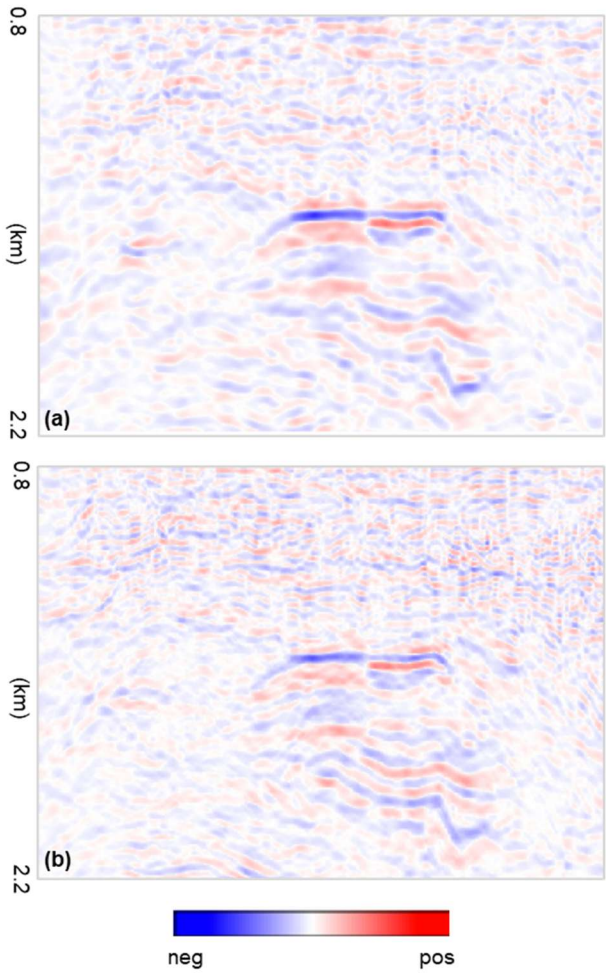


Figure 4: 4D responses at 40Hz computed from the (a) RTM and (b) MP-FWI reflectivity models for both OBN datasets along the xline direction.

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