Time-lapse velocity changes revealed with joint 4D full waveform inversion.

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Abstract

Time-lapse or 4D seismic has proven to be an effective technology for periodically monitoring mature reservoirs to assess subsurface changes due to ongoing production, maximize hydrocarbon recovery by optimizing drilling operations and manage fluid injections. In recent years, full waveform inversion (FWI) has demonstrated its effectiveness in building high resolution velocity models in complex geological environments and has significantly reduced project turnover times. However, the application of FWI to interpret time-lapse changes directly has been quite limited due to the weak 4D signals being overwhelmed by artefacts caused by non-repeatability of the baseline and monitor surveys and non-repeatable 4D noise. To mitigate these issues and to further reduce the turnaround times of 4D processing, we propose a joint 4D full waveform inversion method using the enhanced template matching (ETM) cost function. Numerical tests on synthetic and field data show that joint 4D FWI using the ETM cost function can successfully help in delineating time-lapse velocity changes in the reservoir with minimal 4D data processing and 4D RTM images obtained from joint 4D FWI have significantly reduced 4D noise than conventional processing.

Introduction

In recent years, advances in data acquisition, optimization algorithms and high-performance computing have made FWI one of the most prominent tools in velocity model building. High-frequency FWI and elastic FWI are now commonly used to generate high-resolution models of the subsurface and FWI-derived products like pseudo-reflectivity volumes have shown their ability to produce images with better illumination compensation, balanced amplitudes, and delineation of steep-dip events than conventional migration images (Shen et al., 2018; Vigh et al., 2022).

It is natural to leverage the capabilities of FWI in the context of time-lapse (4D) seismic imaging and reservoir monitoring. Seismic data are routinely acquired at different intervals of time over producing fields to understand the changes in reservoir properties due to production-induced pressure and saturation changes (MacBeth et al., 2018). Conventional 4D processing techniques do not account for these changes in terms of the velocity field directly and often, the same velocity model is used to migrate the baseline and monitor surveys. Time-shifts or depth-shifts calculated from alignment techniques like dynamic warping are then used to account for the velocity changes. Images from different vintages are aligned first using the estimated shifts and then subtracted to assess the 4D differences. Prior to such alignment, rigorous data processing techniques like 4D binning, regularization, 4D global matching, etc., are carried out to minimize any acquisition-related differences between the different vintages. A combination of all these processing steps makes the 4D imaging and interpretation workflow very complex and prone to inaccuracies.

To mitigate these issues for time-lapse imaging, different variations of 4D FWI, such as parallel FWI, sequential FWI, double-difference FWI, etc., have been proposed (Denli and Huang, 2009; Maharramov et al., 2017; Kamei and Lumley, 2017). For 4D FWI, it is important to invert the baseline and the monitor models simultaneously so that they do not converge to different local minima or suffer from acquisition-related artefacts due to non-repeatable surveys. Since FWI uses the full data (diving waves, primary reflections, ghosts, surface- and interbed multiples) to build the velocity model, it is also desirable to have a robust 4D FWI approach that requires minimal data processing. Hence, we propose a joint 4D FWI method using the enhanced template-matching objective function (Cheng et al., 2023) to invert for the baseline and monitor velocity models simultaneously. The proposed method uses the full data from the different vintages at every iteration of FWI simultaneously and can correct for any production-induced velocity changes naturally. Our approach also does not require most of the data processing steps used in conventional 4D imaging. Since the same starting model is used for both the surveys, joint 4D FWI is not prone to the problem of the baseline and monitor models becoming stuck in different local minima.

Method

Enhanced template-matching (ETM) objective function updates the velocity model, $\boldsymbol{m}$, by minimizing both the kinematic and dynamic errors between the observed and the predicted data as

$$\mathcal{L}_{etm}[F(\boldsymbol{m}), \boldsymbol{d}] = \frac{1}{2}(\|\Delta\boldsymbol{\tau}\|_2^2 + \lambda\|F(\boldsymbol{m}) - \boldsymbol{d}\|_2^2). \quad (1)$$

Here $\Delta\boldsymbol{\tau}$ is a measure of the time-shift between the observed and the predicted data, $\boldsymbol{d}$ and $F(\boldsymbol{m})$, respectively. λ is a hyper-tuning parameter used to adaptively balance the contributions from the kinematic and dynamic terms in the misfit function. The ETM misfit function has proven to be very robust in complex geological environments for both acoustic and elastic FWI. For joint

4D FWI, we propose modifying the ETM objective function in equation 1 as

$$\mathcal{L}_{etm_c}\left[F(\boldsymbol{m}_m), \boldsymbol{d}_m, F(\boldsymbol{m}_b), \boldsymbol{d}_b\right] = \mathcal{L}_{etm}[F(\boldsymbol{m}_m), \boldsymbol{d}_m] + \mathcal{L}_{etm}[F(\boldsymbol{m}_b), \boldsymbol{d}_b] + \alpha\|\boldsymbol{W}(\boldsymbol{m}_m - \boldsymbol{m}_b)\|_p, \quad (2)$$

where $\boldsymbol{m}_m$ and $\boldsymbol{m}_b$ represent the monitor and baseline models, respectively, α denotes the regularization weight, $\boldsymbol{W}$ is the confidence field (Vigh et al., 2015) built around the reservoir and p can be any norm of choice. If $p = 2$, the regularization term penalizes the differences between the monitor and baseline models outside the reservoir area. These differences can be due to inconsistent baseline and monitor acquisitions or non-repeatable 4D noise that often show up as artefacts in the time-lapse difference models. The confidence field, $\boldsymbol{W}$, and p can also be suitably adjusted to perform total-variation regularization to emphasize blocky time-lapse changes to delineate saturation-related hardening or softening in the reservoir. In practice, multiple regularization terms are usually preferred for $\mathcal{L}_{etm_c}$ to simultaneously mitigate 4D noise-related artefacts and emphasize the reservoir changes.

Examples

We first tested joint 4D FWI using the ETM objective function on a synthetic acoustic dataset where there are gas compartments placed in the baseline model. To mimic a production-like scenario, the velocity is only changed in the reservoir compartments in a limited vertical extent up to 20 m. The true baseline model perturbation is shown in Figure 1a while the production-related velocity changes, i.e., 4D DV, are shown in Figure 1b. The joint 4D FWI iterations used a smooth version of the true baseline model as the starting model and were run in a multiscale manner from 3-30 Hz. Figure 1c shows the inverted baseline model perturbation from joint 4D FWI while the 4D DV is shown in Figure 1d. The 4D DV model is obtained by a direct subtraction between the inverted monitor and baseline models. As expected, the 4D differences are concentrated only in and around the reservoir area with very limited leakages elsewhere.

The field-data example is from deep-water Nigeria. The reservoir consists of Miocene turbidite channels with a NE-SW trending dual-culmination anticline (Amoyedo et al., 2020). Due to shallow gas channels and mud volcanoes, ocean-bottom nodes were deployed for both the baseline and monitor surveys to mitigate the impact of seismic attenuation and improve reservoir characterization. The starting model for 4D FWI was obtained from the legacy baseline model and is shown in Figure 2a.

Joint ETM 4D FWI was run upto a maximum frequency of 30 Hz. Figures 2b and 2c show the inverted baseline and monitor models, respectively. The 4D model differences (4D DV), shown in Figure 2d, are obtained by directly subtracting the baseline velocity model from the monitor model. Similar to the synthetic example, the 4D differences are mainly concentrated within the reservoir area.

The conventional 4D RTM image is shown in Figure 3a and is obtained by subtracting the baseline RTM image from the monitor RTM image. The velocity model, shown in Figure 2a, is used for migrating both the surveys. As shown by the black arrows in this figure, the 4D response is contaminated by various spurious events below the reservoir because the velocity changes in the reservoir were not considered for calculating the 4D difference. In conventional 4D processing, this issue is mitigated by measuring depth- or time- shifts between the individual images. The depth shifts are shown in Figure 3b and are used to align the monitor image to the baseline image before subtraction.

Using a similar approach, we obtained the 4D RTM image in Figure 3c where the artefacts below the reservoir have been somewhat mitigated. There are still some residual leakages in this 4D image because alignment cannot accurately account for the velocity changes in the reservoir. The 4D RTM image, shown in Figure 3d, is obtained by migrating the monitor and the baseline data with their respective models from 4D FWI followed by a direct subtraction. It shows very clear 4D signal at the reservoir without any artefacts below it. This is because joint ETM 4D FWI can accurately capture the velocity changes in the reservoir related to saturation- and pressure-related changes due to ongoing production. Since there was no time or depth-alignment required, the 4D image in Figure 3d did not suffer from any wavelet distortion and has better preserved amplitudes than the 4D image in Figure 3c.

Conclusions

We presented a joint 4D FWI approach using the enhanced template-matching objective function to delineate velocity changes in the reservoir due to ongoing production. Numerical tests on synthetic and field data show the benefits of the proposed approach over conventional 4D processing techniques. Migrating both the monitor and baseline data using their own velocities from joint ETM 4D FWI also showed significantly reduced 4D noise below the reservoirs when compared to migrating both the vintages using a common model. The 4D FWI results from this study were limited to only differences in the P-wave velocities between the baseline and monitor models. Besides the P-wave velocity, other subsurface properties like shear-wave velocity, density, attenuation, etc., should also be considered for a complete understanding of the time-lapse changes.

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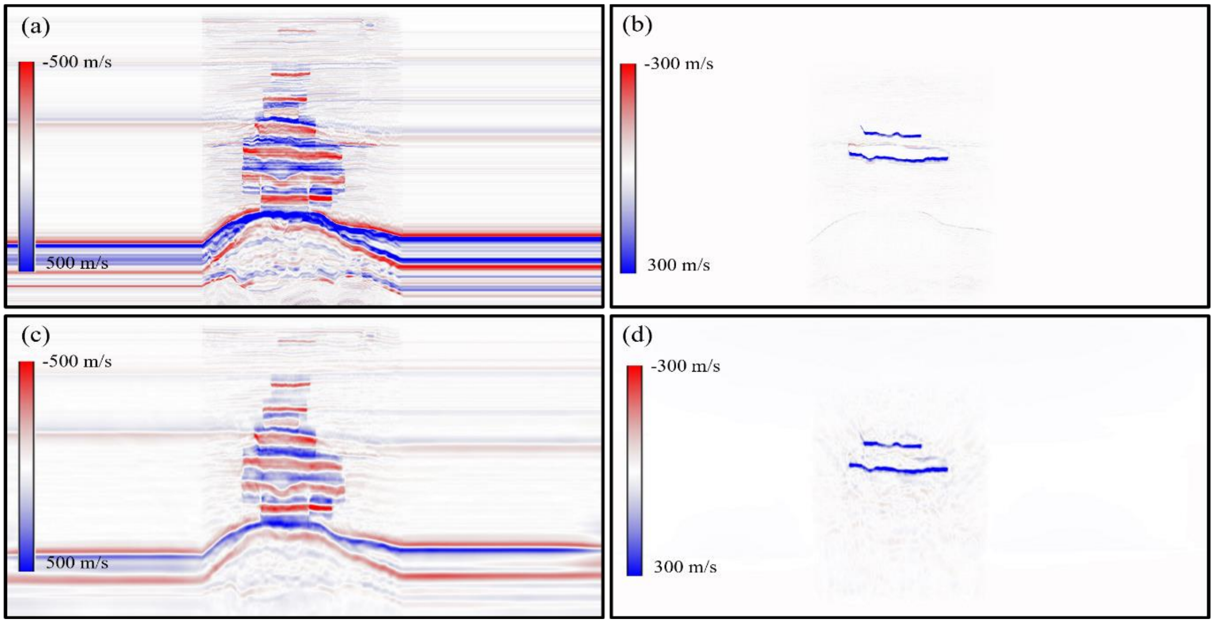

Figure 1 *True (a) baseline model perturbation, and (b) 4D DV. Inverted (c) baseline model perturbation, and (d) 4D DV from joint ETM 4D FWI.*

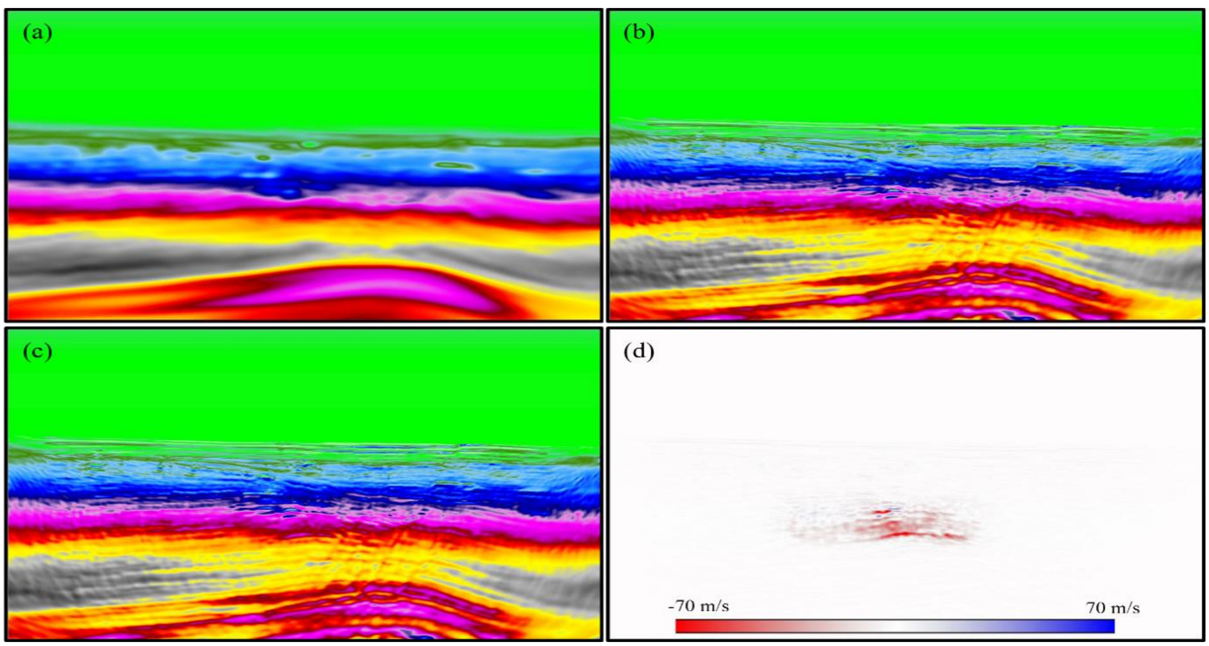

Figure 2 *(a) Starting velocity model used for 4D FWI. Inverted (b) baseline, and (c) monitor velocity models from joint ETM 4D FWI, and (d) their 4D difference.*

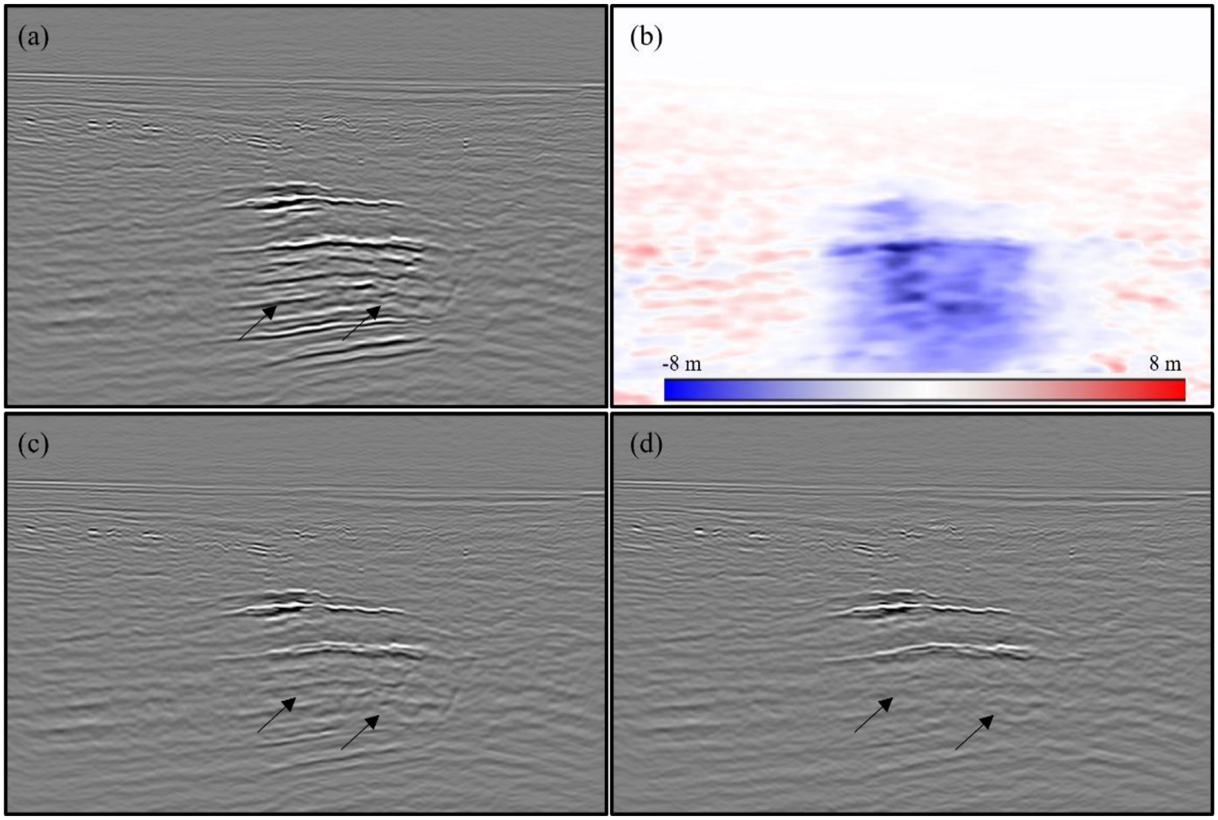

Figure 3 *(a) 4D RTM image using a common velocity model and without any alignment. (b) Calculated depth-shifts to align the monitor RTM image to the baseline RTM image prior to subtraction. (c) 4D RTM image after alignment. (d) 4D RTM image from separate models obtained by joint ETM 4D FWI*.