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Improving Reservoir Imaging with Time-Lag FWI in the Partitioned Zone Between Kuwait and Saudi Arabia

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ABSTRACT

The Partitioned Zone (PZ), located between Kuwait and Saudi Arabia, is one of the most prolific oil-producing regions in the world, featuring multiple layers of carbonate reservoirs. However, the complex karst structures and strong velocity contrasts at alternating slow and fast layers pose great challenges for reservoir imaging in this area. To improve imaging accuracy, a dense 3D seismic survey was acquired in the PZ during 2014-16.

In the present work, Time-Lag FWI (TLFWI) is employed to resolve velocity details with PZ data. TLFWI builds velocity models through waveform fitting and addresses large velocity contrasts by alleviating the amplitude discrepancy and cycle-skipping issues between field and synthetic data using a kinematic cost function [1]. First, we built an initial model for FWI with well data, shallow refraction tomography and reflection tomography. This ensured a reasonable background velocity, which is especially important for regions beyond diving wave penetration. After that, TLFWI was carried out to update the model and capture velocity anomalies from shallow to deep, using both refraction and reflection energy.

The final 24 Hz TLFWI achieved a high-resolution velocity model and improved seismic images. The karsts and collapse features in a shallow limestone formation were well resolved, as well as the sharp velocity contrast of a deeper thin limestone formation sandwiched between sandstones, giving a good match with the well logs. Kirchhoff PSDM with the updated model led to flatter gathers and more coherent events on the stack. Additional least-squares migration further improved image quality by attenuating migration swings and compensated for illumination variations. This study demonstrates that TLFWI can produce a high-fidelity velocity model and improve seismic images at reservoir levels in a challenging land setting.

INTRODUCTION

The Partitioned Zone, located onshore between Kuwait and Saudi Arabia, is characterized by several geologic features, shown in Figure 2 (C). Perhaps the most challenging, in the context of FWI, is a shallow fast-velocity anhydrite layer, underlying a very slow weathering layer (2500 ft/s near the surface). This combination limits the angle of transmitted seismic energy and generates strong surface waves which mask reflection energy in the recorded data. Deeper carbonate layers alternating with slower formations form another barrier. As in most land surveys, the near surface model is heterogenous and spatially variable, including karsts and collapse features that have expressions both in the seismic data and in surface satellite imagery.

The PZ survey was acquired in 2014—2016 to address imaging challenges in this geologically complex area. It features 12.5 m shot and receiver spacing and an 8400 m maximum offset. While 8400 m max offset is not unusual for land data, combined with the shallow fast-velocity layers, it limits the diving wave penetration depth. Furthermore, the Vibroseis source used for acquisition only had signal above 3 Hz. Together, these factors make the low-wavenumber component of the model poorly sampled by the acquired data.

In contrast with limitations to deep recorded energy, there are benefits of the high-density acquisition and high fold in the PZ survey. The small shot and receiver spacing in the survey prevented aliasing of surface waves [2] and helped to ensure their effective attenuation, as discussed below.

Previous imaging of PZ data employed joint inversion of surface waves, well information and first arrivals to build a shallow initial model, followed by deeper reflection tomography [3]. However, this could not fully capture small-scale velocity details and strong velocity contrasts due to its limited resolution. In this study, we applied Time-Lag FWI to the PZ dataset to improve model resolution and reservoir imaging. The final TLFWI model successfully captured velocity details and improved focusing and coherency for both shallow and deep events.

METHODS

Acoustic wave modelling was adopted in the present work. This makes it difficult to accurately model near surface energy, which involves elastic effects, an unconsolidated weathering layer and a land-air free surface. In order to improve the match between modelled and recorded shots, we removed the surface-wave energy from the data prior to FWI, as shown in Figure 1. In so doing, we follow previous successful applications of land FWI [2, 4]. In addition, surface consistent deconvolution was also performed on this data to address shot-side and receiver-side variations and improve data consistency [5].

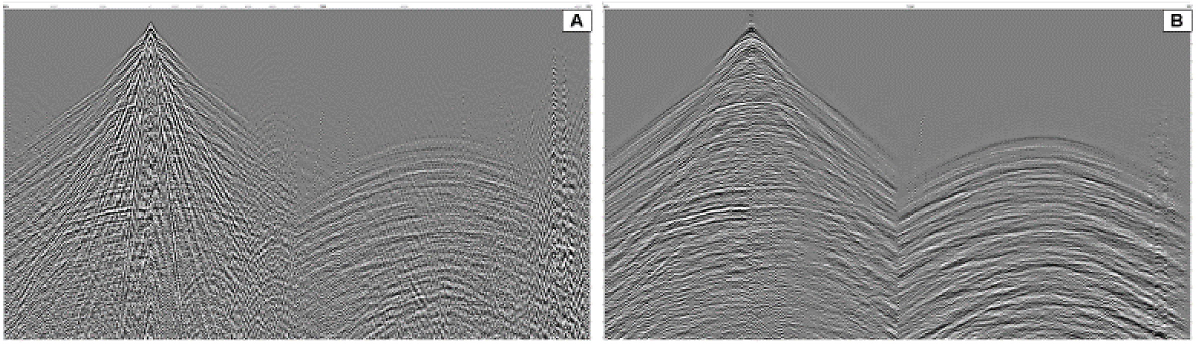

Figure 1. An example of a raw shot gather (A), and a preconditioned shot gather for FWI input (B).

For the initial model building process, we used the few available well logs, which were located in widely separated locations. To avoid unphysical extrapolation of inter-well spatial variation of the velocity to areas without well control, we created a single combined log, consisting of the most representative parts of the available logs concatenated together in depth. The combined log was then laterally extrapolated along geological horizons. The model was then smoothed to keep only the low wavenumber trend, as shown by the orange curve in Figure 2. Above approximately 1000 ft, first-break inversion via ray tracing (refraction tomography) was performed to refine the initial model, being more dependable than well logs and having far greater spatial coverage. As a consequence of the fast near-surface velocity layers and the maximum offset, diving wave penetration in this data set is limited. Also, FWI driven by reflection energy is not able to provide an accurate long wavelength model update [2]. Hence, to improve the deep initial model, reflection tomography was performed to update the deep background velocity trend before FWI.

Along with a good initial model, perhaps the most important factor in the success of land FWI in the current study is the choice of cost-function. A conventional FWI cost-function is based on the least-squares difference between observed and modelled traces. TLFWI instead seeks to minimize the time-lag at which maximum correlation occurs between observed and modelled data and makes better usage of low frequency data [1]. This makes TLFWI less sensitive to cycle skipping and shortcomings in amplitude matching. TLFWI was carried out from 4 Hz to 24 Hz in this study.

RESULTS

The ability of TLFWI to update the velocity model using both refraction and reflection energy is beneficial given the limited diving-wave penetration depth of this land dataset. Small velocity features corresponding to karst structures are resolved as deep as 7000 ft, at the limit of the reach of diving waves (Figure 3). In particular, we examine the Limestone C formation, a thin layer of carbonate sandwiched in between thick sandstones. As shown in

Figure 3, the resolved velocity model features show a good match with the features imaged in the stack.

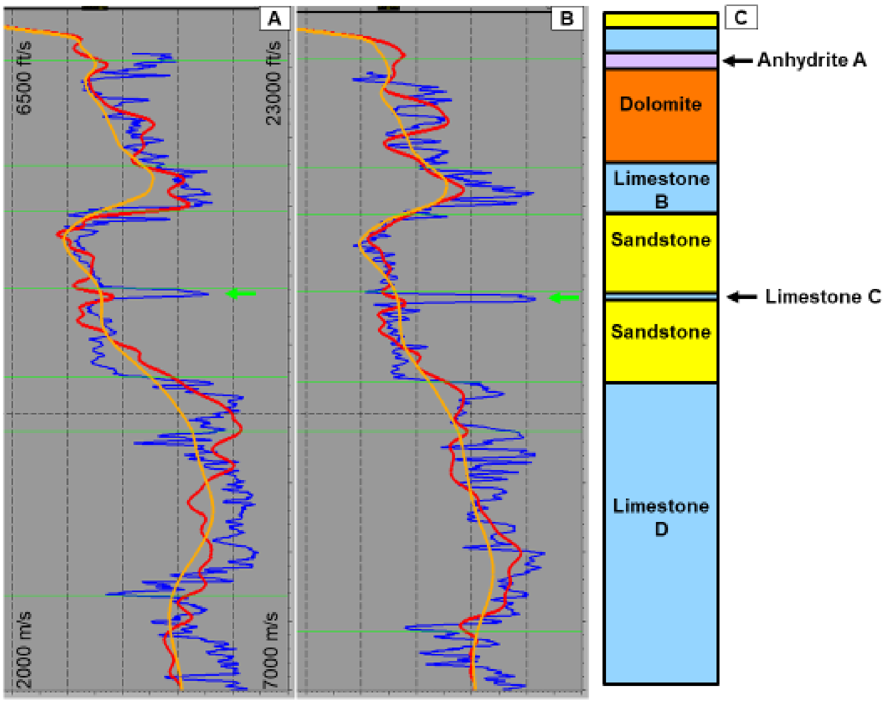

Figure 2. Sonic velocity logs (in blue) from two different wells (A-B). The initial model velocity profile is shown in orange, and the velocity after 24 Hz TLFWI is in red. The green arrow indicates the Limestone C formation, a carbonate layer approximately 200 ft thick. 24 Hz TLFWI was not able to fully capture the amplitude of this thin velocity contrast, but its position is visible as a small bump in the red curve. A simplified stratigraphic column for the study area is shown in (C), adapted from [6].

Compared with the FWI initial model (Figure 4), the migrated gathers and stacks show the detailed 24 Hz TLFWI velocity model significantly simplified gather curvatures and stack structure. Velocity corrections at the bottom of the fast Limestone B formation fixed the stack event undulations that had been present in the PSDM stack of the initial model. Correction of residual move-out is likewise observed on the common offset gathers, leading to a better focusing of seismic events, including in the shallow (1000 ft). The match between the well sonic logs and the velocity model has also been improved after TLFWI, as shown in Figure 2.

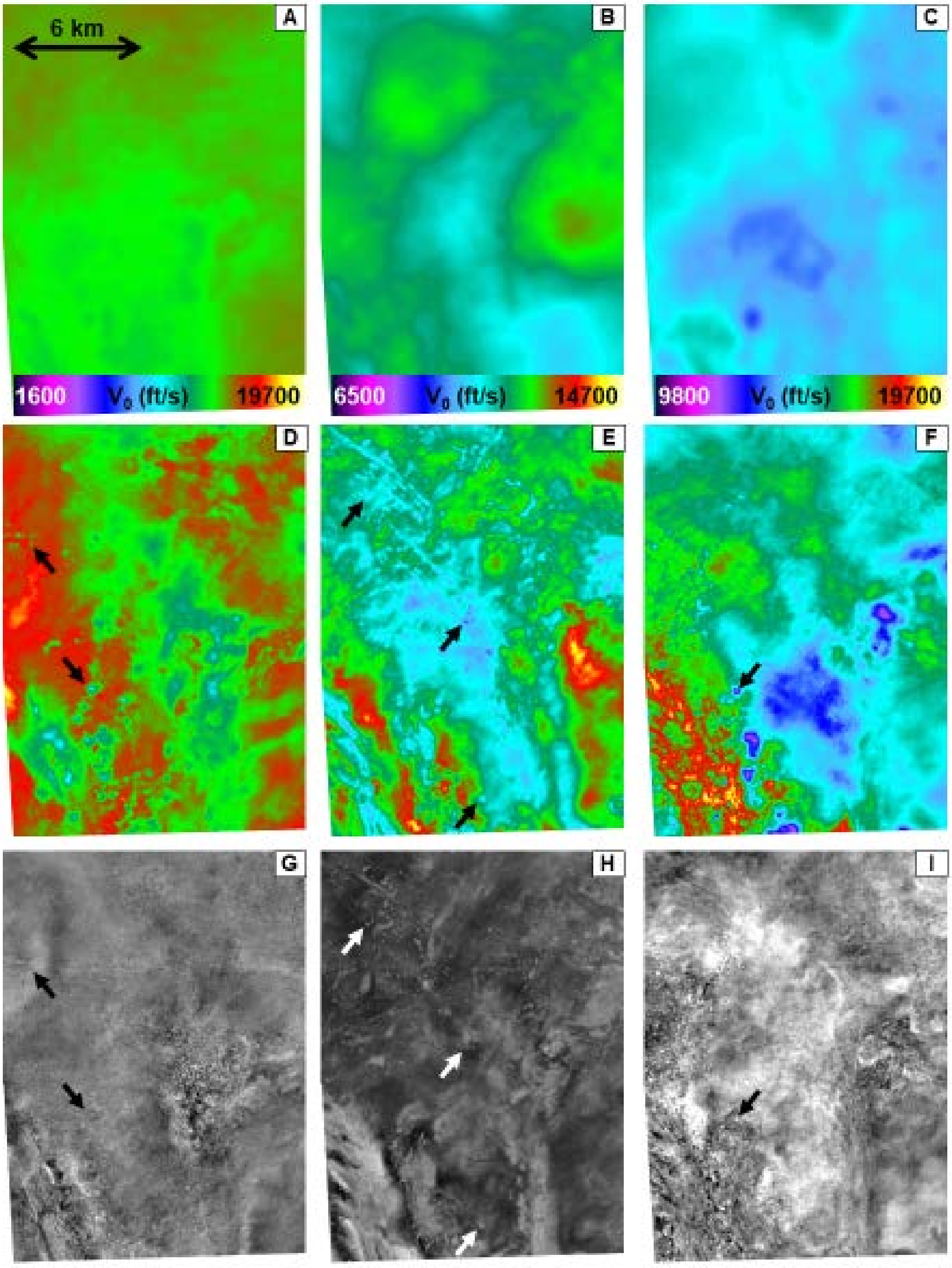

Figure 3. Depth slices of the initial model (A-C), 24 Hz TLFWI model (D-F) and the corresponding PSDM stack (G-I). The slices are geologically conformal through the Limestone B (A, D, G), Limestone C (B, E, H) and the top of Limestone D (C, F, I) formations. The Limestone B formation is near the deeper limit of diving wave penetration, and the other two slices are deeper. Note the karst features, indicated by the black and white arrows, visible as small pale spots, which are also observable in the TLFWI model.

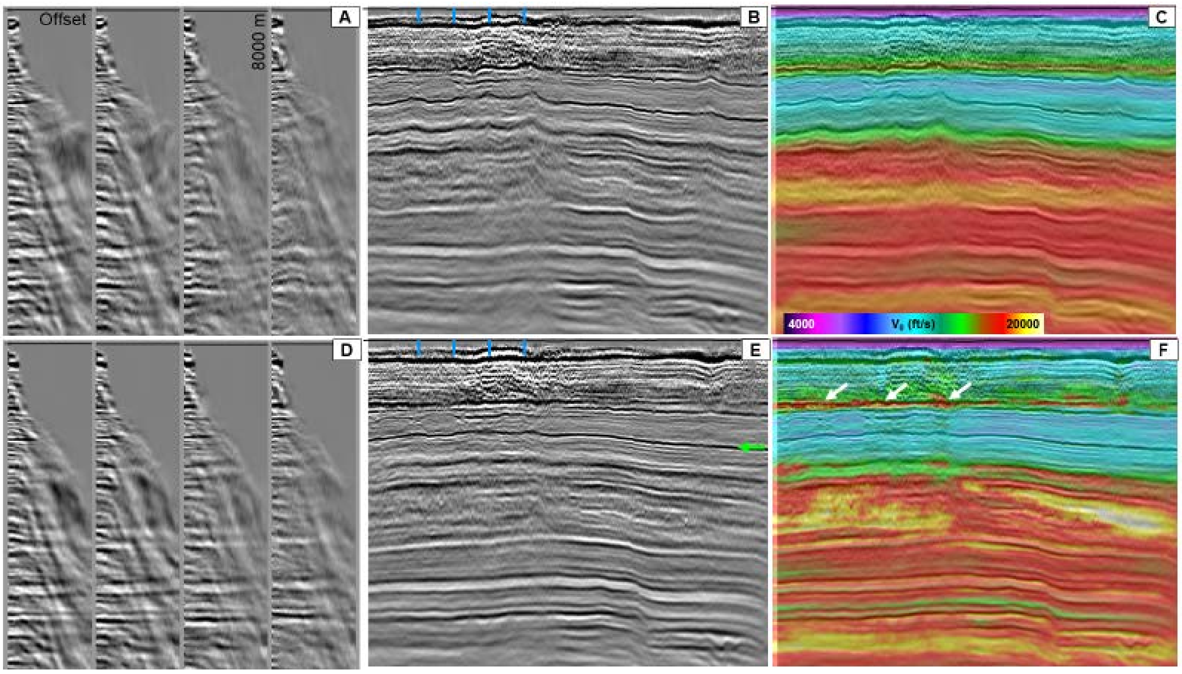

Figure 4. Kirchhoff PSDM gathers (A), stack (B) and the TLFWI initial velocity model (C). (D-F) show the gathers, stack and the velocity model after TLFWI. The green arrow shows the Limestone C formation. The white arrows highlight velocity details revealed by TLFWI which reduced event undulation and simplified structures below.

Kirchhoff migration was used to generate high-resolution gathers and stack with the 24 Hz TLFWI model. Due to the complex overburden velocity structures and acquisition footprint, the conventional Kirchhoff results were affected by migration artefacts such as swings, cross-dipping noise, and footprint (Figure 5). To mitigate these effects, gather-based least-squares Kirchhoff PSDM was carried out in the image domain [7]. As shown in Figure 5, least-squares migration further improved gather and image quality, with fewer migration artefacts present and improved coherency and signal to noise ratio.

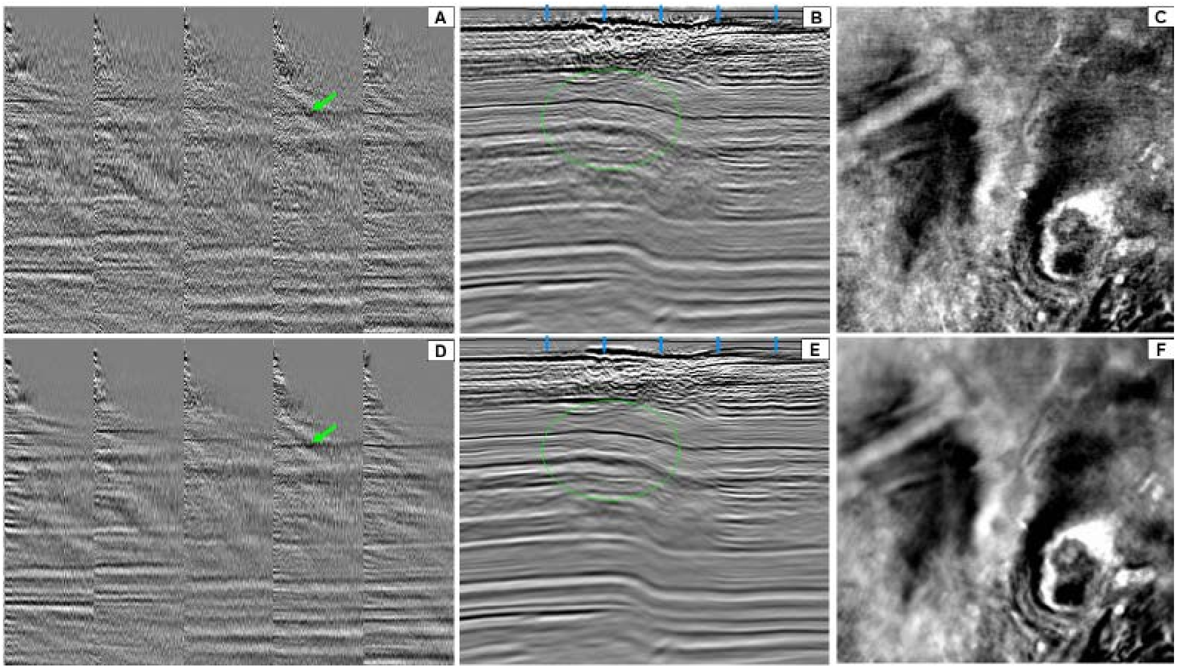

Figure 5. Conventional Kirchhoff PSDM gathers (A), stack (B) and depth-slice through the Limestone B formation (C). Least-squares Kirchhoff PSDM gathers (D), stack (E) and depth slice (F). Least-squares migration shows more coherent events with less migration noise (swings).

DISCUSSION AND CONCLUSIONS

We have shown a successful application of TLFWI on a land dataset in the Partitioned Zone between Kuwait and Saudi Arabia. Despite challenges such as a near surface fast velocity layer limiting diving wave penetration, the final 24Hz TLFWI model was able to capture relevant velocity details. It improved gather curvature and fixed stack event undulations, an effect which would be almost impossible to be achieved through reflection tomography. At the same time, the high-resolution TLFWI model itself could be a useful volume for interpretation.

It is also important to acknowledge the limitations of our current 24 Hz TLFWI update. As seen in Figure 2, velocity contrasts in the TLFWI model are still not as sharp as in the well logs, and the velocities of thin anhydrite and limestone layers are not as fast as they ought to be. Part of the reason for this is that reflection and transmission from these large velocity contrasts in the recorded data are influenced by elastic effects, which could not be modelled by the acoustic wave propagation engine used in this work [8]. Additionally, near-surface energy could not be accurately modelled. Thus, ground roll and other surface waves were not used for the FWI update. An avenue for future work is to incorporate more physics, such as elastic effects, into wave modelling and to make use of the near surface energy to better constrain the velocity model [9].

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