Imaging the Delaware Fill Zone with ultra high-density data and high-frequency land FWI

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Summary

An advanced imaging flow including 40 Hz full-waveform inversion (FWI), in conjunction with an industry-supported ultra-high-density survey provides a high-resolution FWI velocity model and FWI Image to resolve complexities related to the Cenozoic sedimentary fill in the Delaware Basin. The more accurate of the near-surface velocity model improved the resolution of the image in the deeper reservoir level.

Introduction

The Delaware Basin has traditionally been challenging to image due to the complexities associated with the Cenozoic sedimentary fill, commonly known as "the Fill". The Fill, resulting from the dissolution of salt from the Salado formation, is widely spread throughout the Delaware Basin. Upon dissolution, the Rustler formation sitting above the Salado collapses and is filled by Cenozoic sedimentary deposits (Anderson, 1981). The sediments comprising the Fill are laterally heterogeneous and generally characterized by slow velocities. As a result, the Fill acts as a zone of high attenuation and scattering for seismic waves passing through. Beneath the Rustler, interbedded halite and anhydrite in the Salado and Castille formations introduce spatially varying fast layers and sharp velocity contrasts. These sharp contrasts trap seismic energy and generate strong surface wave noise. This strong noise makes it difficult to resolve the rapidly changing velocities and complex structure in the near surface, resulting in structural distortions at the reservoir level.

In the past, land FWI has been successfully applied in the Delaware Basin to resolve the interbedded halite and anhydrite layers, simplifying the deep structure and revealing shallow drilling hazard information (Bai et al., 2020). Utilizing land FWI to obtain high-resolution models of the Cenozoic Fill, however, is challenging due to the sparse surface-seismic sampling of legacy surveys. The focus of an industry-supported acquisition design test acquired in Eddy County, New Mexico, in 2024 was to learn what acquisition parameters and processing technologies are required to resolve shallow geological complexities from the Castille through the Fill. The application of 40 Hz Time-lag FWI (TLFWI) (Zhang et al., 2018) to the four-square-mile test area reveals the complexity of the Fill and fine structures of the Rustler, and the corresponding 40 Hz FWI Image further delineates the shallow Fill. In addition, the decimation test demonstrates that dense sampling is important for imaging the Fill.

Ultra-high-density test survey in the Delaware Basin

The four-square-mile ultra-high-density test survey is located in southeast Eddy County, New Mexico (Figure 1a). Within the test area, over 20,000 Stryde nodes were deployed with 247.5 ft line spacing (E-W) and 20.625 ft station interval. Vibroseis trucks, using a broadband sweep from 2 to 84 Hz, were vibrating from south to north with 495 ft line spacing and 41.25 ft station interval (Figure 1b). The trace density is 256 times higher than that of legacy surveys, which usually have 990 ft line spacing and 165 ft station interval for both shot and receiver sides.

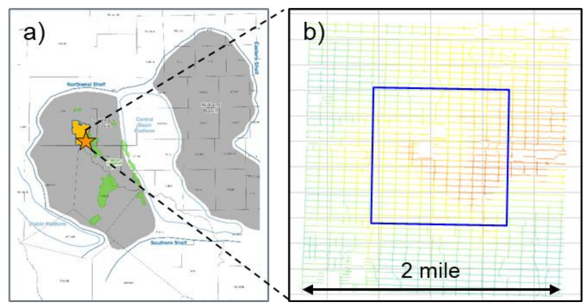

Figure 1: Four-square mile ultra high-density sruvey location a), and shot and receiver map b).

Due to the limited coverage of shots and receivers, only the center one-square-mile area, (blue box in Figure 1b), has offsets beyond one mile, resulting in limited diving wave penetration depth and insufficient migration aperture for the deeper sections. Therefore, this study focused on deriving more accurate velocity down to the LMAR (Figure 4), the base of the thick interbedded fast layer.

Building the starting model for FWI

A good starting velocity model is important for successful FWI application (Huang et al., 2021; Bai et al., 2021), especially when data constraints are insufficient due to lack of low frequency signal and long offsets. In our study, a dedicated model building flow was implemented to build the starting models, which included inverting the shallow velocity model above the fast layer using first-arrival tomography, building the deep background velocity trend based on well sonic logs, and deriving anisotropy parameters through well-tie analysis.

First-arrival tomography relies heavily on the quality of first break (FB) picks. Azimuthally guided functions in combination with an iterative FB picking flow were utilized to address the FB heterogeneity (Figure 2) due to rapid velocity change at the near surface in the Fill. Figure 3 shows the raw stack comparison with and without refraction statics derived from the first-arrival tomography model. The application of refraction statics simplifies the geological structure from shallow to deep and improves the event focusing in the Bone Spring (BSPG) and Wolfcamp reservoir zones. These improvements indicate that the derived shallow refraction tomography model effectively captures near-surface velocity variations.

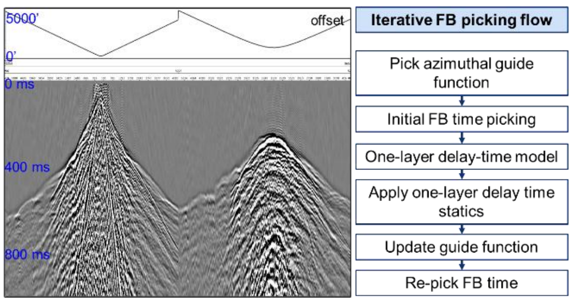

Figure 2: First breaks present strong heterogeneity due to complex near-surface structure and velocity, and iterative FB picking flow was utlized.

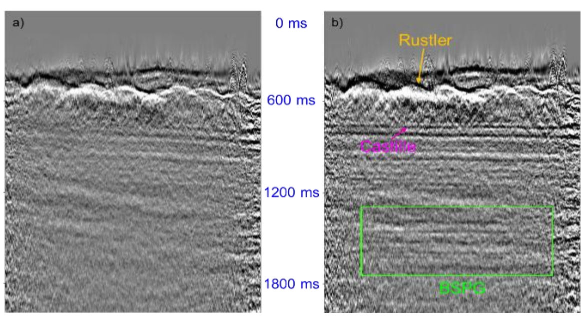

Figure 3: Raw stack without a) and with b) refraction statics derived from first-arrival tomography model.

However, due to the limited maximum offset (~5000 ft) and shallow fast layers, first-arrival tomography was only able to invert the velocity above the fast layer, i.e., above the picked base of weathering (BoW) horizon (Figure 4d). Therefore, the deep velocity model derived from the smoothed sonic trends was merged with the refraction tomography model at the BoW to build the starting velocity model. The anisotropic parameters were derived from preliminary well-tie analysis at the LMAR. Using these starting models and ultra-high-density data, the Kirchhoff pre-stack depth migration (KPSDM) image clearly reveals the Rustler structure (Figure 4b), whereas the legacy final KPSDM (Figure 4a) fails to do so, primarily due to insufficient data density in the near offsets of the legacy data. Despite the discrepancy in the migration input data, the improved image quality suggests that the starting velocity model could serve as a reasonable initial model for FWI.

40 Hz TLFWI

While the starting model captures the near-surface long-wavelength velocity trend, it is unable to resolve the finer geologic detail due to limited resolution of the ray-based method. Thus, 40Hz TLFWI was applied to resolve the fine-scale structures and obtain a high-resolution model.

Due to inadequate signal-to-noise ratio (S/N) at low frequencies and limited offset coverage, acoustic TLFWI was started at 5 Hz to invert a detailed model above the LMAR using both refraction and reflection energies. A dedicated noise attenuation flow was applied to attenuate surface wave noise while preserving the super shallow near-offset refractions and reflections. To define the fine structures and thin layers, TLFWI was then running to 40 Hz.

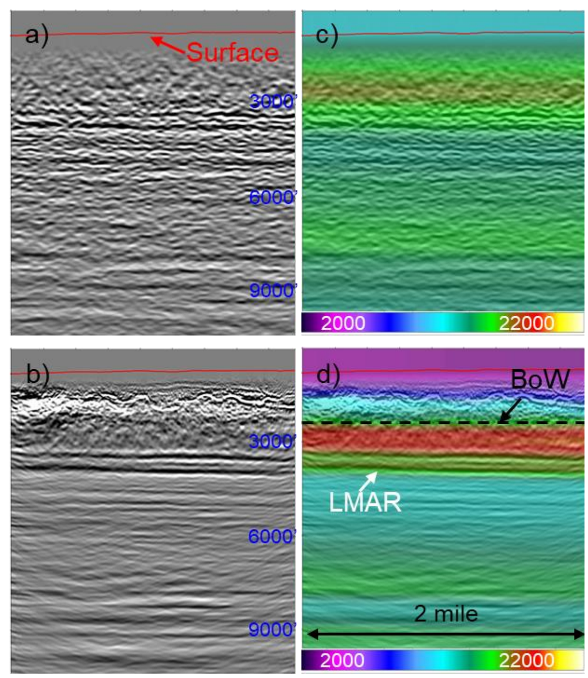

Figure 4: Legacy KPSDM a) and with legacy velocity overlaid c). Test area KPSDM b) and with the starting model overlaid d).

As shown in Figure 5, 40 Hz TLFWI resolved the fine-scale near-surface velocity anomalies in the Fill and clearly delineated the Rustler, along with interbedded fast halite and anhydrite layers. This led to a significantly improved image over the FWI starting model, even down to the deeper BSPG target level. Figure 6 shows 40 Hz TLFWI captured strong velocity variation inside the Fill (Figures 6a and 6c) and the rapid velocity change associated with the complex Rustler structure (Figures 6b and 6d). Although spatial sampling across shot and receiver lines is much denser than legacy surveys, the imprint of acquisition footprints is still observable in the very shallow section (Figure 6c).

Thanks to the iterative least-squares fitting and additional illumination from the full wavefield (Zhang et al., 2020), the FWI Image, the derivative of the velocity model normal to the reflector dips, improves both S/N and near-surface structure compared to the KPSDM. The sediments inside the slow Fill above the Rustler and the top of the fast layer are better defined in the FWI Image (Figure 7).

comparison between the test and legacy KPSDM (Figure 4). To further evaluate the impact of spatial sampling on FWI, a decimation test was carried out. The TLFWI input was decimated to match the legacy acquisition station interval of 165ft and line interval of 990ft, resulting in a 256-times drop in fold. Then, the same 40 Hz TLFWI flow was run using the decimated input. Compared with the TLFWI model using dense input data (Figure 8d), the 40 Hz TLFWI model using decimated input (Figure 8a) shows a much noisier update because of the longer source and receiver intervals and lower stacking power. This noisy model led to a degraded TLFWI Image (Figures 8b and 8e) and reduced coherency in KPSDM (Figures 8c and 8f).

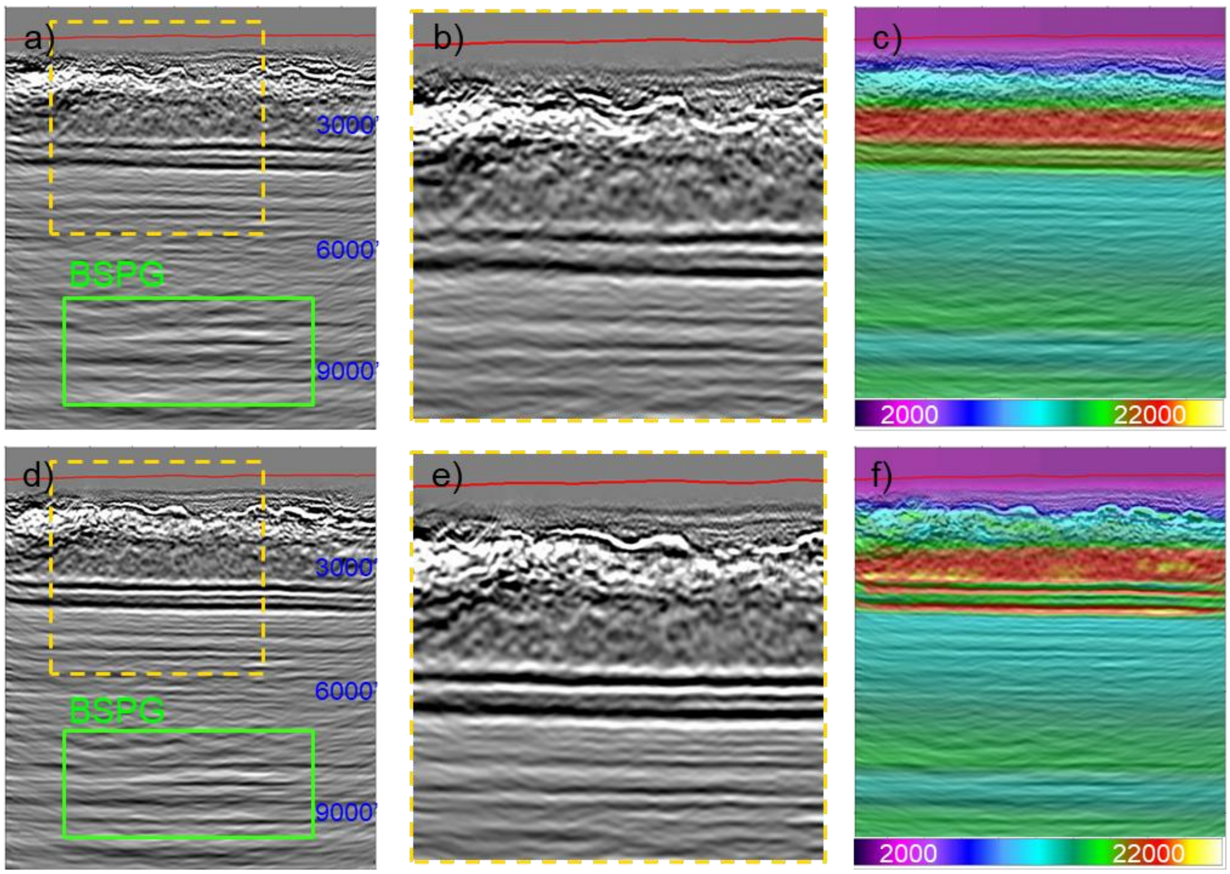

Figure 5: FWI starting model: a) KPSDM stack, b) KPSDM zoom-in, and c) model. 40 Hz FWI: d) KPSDM, e) KPSDM zoom-in, and f) model. 40 HZ FWI resolves fine-scale details and structures above LMAR, and provides imprved KPSDM from Rustler down to BSPG.

Impact of spatial sampling on FWI

Dense acquisition is critical for imaging the geologic complexities associated with the Fill as demonstrated by the

Conclusions

This study demonstrates that the combination of high-frequency TLFWI and densely sampled seismic data is key to achieving a high-resolution velocity model, which leads to a detailed migration image inside the shallow Fill of the Delaware Basin. The accurate near-surface model improves the imaging at the reservoir level as well, and the corresponding FWI Image further delineates the shallow Fill with greater details.

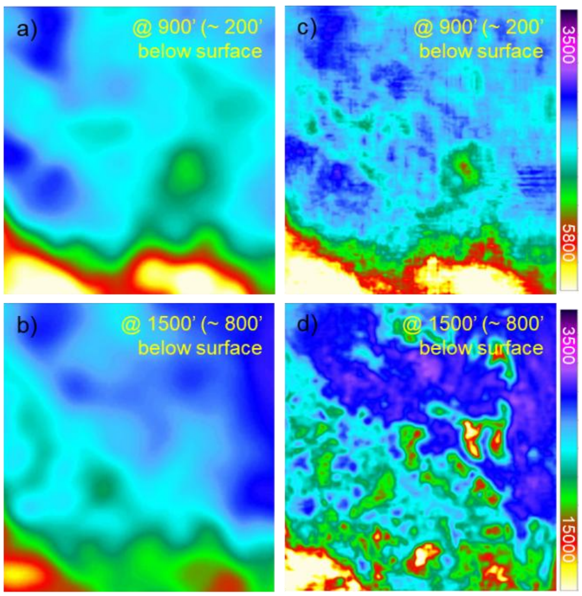

Figure 6: Initial model depth slices a) and c); 40 Hz FWI model depth slices b) and d).

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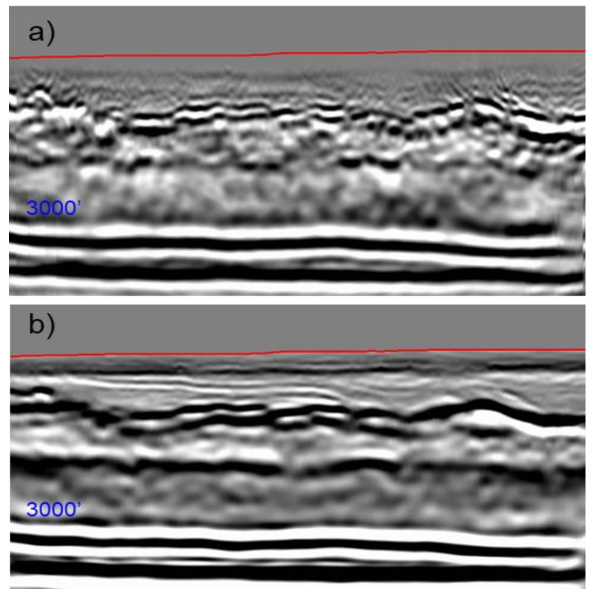

Figure 7: 40 Hz KPSDM a) and 40 Hz FWI Image b).

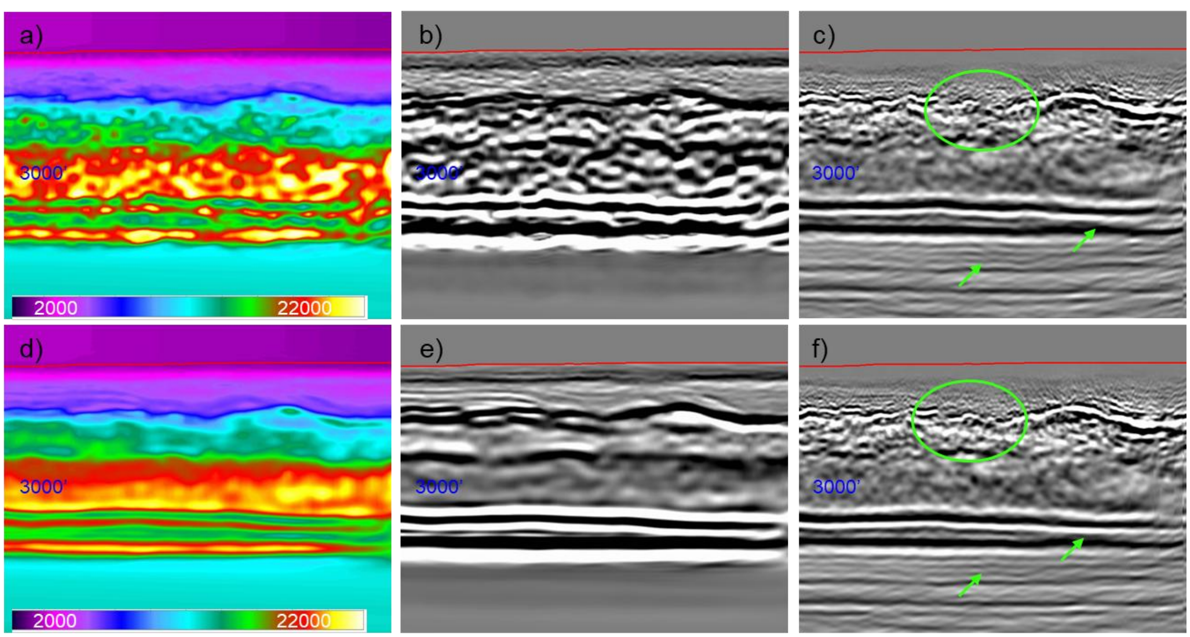

Figure 8: FWI with decimated input: model a), FWI Image b), and KPSDM c). FWI with original dense input: model d), FWI Image e), and f) KPSDM.