High-resolution near-surface land FWI across the Delaware basin Fill zone

Terence Krishnasamy*, James Sheng, Ronaldo Florendo, James Beck, TGS; Antonio Sierra, Sam Murphy, Jay Siebens, Yvonne Iwo-Brown, EOG Resources.

Summary

The near-surface in the Delaware basin in the Permian is characterized by interbedded thick deposits of late Permian halite and anhydrite introducing a high velocity layered system, in addition to the strong lateral velocity variation due to evaporite dissolution which is known as Fill zone. This represents a challenge for velocity model building and imaging. We present here a case study of strategically applying different FWI cost functions to generate a stable high-resolution near-surface velocity model that allows for robust imaging of the complex near-surface. Additionally, we also show the potential of the high-resolution velocity model for generating a high-resolution FWI image that can address some of the deficiencies in traditional seismic migration where only the reflection data is used.

Introduction

Near-surface characterization is important for imaging deeper targets in any onshore exploration seismic data. Due to the limited offset coverage at shallow depths, conventional model building techniques like reflection tomography are inadequate for near-surface velocity updates. Typically, a diving-wave or first arrival tomographic approach is used to update these shallow depths. Though useful, this method can only provide low resolution shallow velocity model updates. This can have a significant impact on imaging of deeper targets.

Full waveform inversion (FWI), introduced in the 1980s (Tarantola, 1984), has mainly been limited to marine datasets. Successful examples on land datasets are much fewer (Plessix et al., 2010; Mei et al., 2015; Sedova et al., 2017; Vigh et al., 2019; Brown et al., 2019; Tang et al., 2021) due to challenges associated with elastic effects, low signal to noise ratio (especially at lower frequencies), and irregularities in acquisition geometries. Specially designed acquisition efforts have afforded excellent FWI results by addressing some of the deficiencies in land datasets; however, the cost of these high effort acquisitions is prohibitive.

In this case study we show how a multistage acoustic FWI approach utilizing different cost functions for diving waves and reflection data can be used to generate a high-resolution velocity model on a conventional onshore seismic data acquired in the Delaware basin (nominal source and receiver spacing of 165 ft x 990 ft, maximum offset of about 20,000 ft, vibrator sweep 4-76 Hz). Additionally, we show how this high-resolution (40 Hz) velocity model can be utilized to generate an estimate of reflectivity, the FWI image (Zhang, et al., 2020; He, et al., 2021). This FWI image shows enhanced features and provides an alternative image for areas with poor signal to noise ratio and sampling.

Geological context and challenges

The Delaware basin is characterized by complex near-surface geology with shallow thick interbedded halite and anhydrite in the Salado and Castille formations introducing a high velocity layered system. This can extend from the surface to depths of about 6000 ft. These sharp velocity contrasts limits diving wave penetration, and therefore applicability of diving wave FWI. The very shallow Rustler formation appears to collapse in some areas due to irregular evaporite dissolution below and is subsequently filled by much slower Cenozoic deposits creating a complex zone of high attenuation and scattering. This zone is commonly referred to as the Delaware basin Fill zone and has been historically difficult to image with seismic data. The boundary between the Fill zone and the surrounding rocks juxtaposes the relatively slow velocity shallow fill with the extremely fast formations around it, Figure 1.

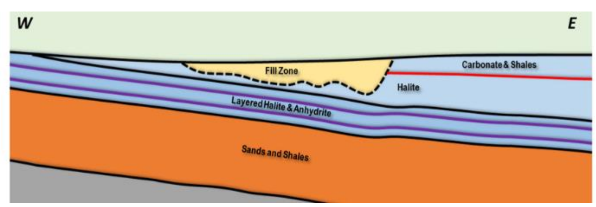

Figure 1: Typical East to West geological cross-section of the study area. Showing the Cenozoic Fill zone with relatively slow velocities, surrounded by very fast halite and anhydrite rocks.

FWI Workflow

The initial near-surface model was built using diving wave tomography where possible, supplemented by limited shallow sonic log information. Figure 2a shows the initial velocity model from diving wave tomography overlaid on the corresponding Kirchhoff migrated stack. Despite the data preconditioning effort to remove unwanted signal that acoustic forward modelling is unable to model, the usable starting frequency for the FWI is limited to 6 Hz. Given the uncertainty in our initial velocity model, this was inadequate to start the diving wave FWI without cycle skipping. To overcome this, we implemented an optimal transport cost function using the quadratic Wasserstein distance (Engquist et al., 2016; Yang et al., 2018) that uses the trace envelope to compute the travel time information for the misfit. Using only diving waves and iteratively increasing the maximum offset, we were able to update the long wavelength background velocity model where low frequencies were deficient.

With this refined shallow velocity model, we switched to a multi-channel dynamic matching (DM) cost function. Multi-channel DM FWI uses normalized local cross correlations to measure the time-dependent difference between the recorded and synthetic data, thus focusing on resolving the kinematic difference between these two datasets during the inversion. Multi-channel windowing is used to mitigate the influence of noise in the input data (Mao et al., 2020; Sheng et al., 2020).

DM FWI using diving waves was iterated up to a frequency of 15Hz. Figure 2b shows the resulting velocity model and the Kirchhoff migrated stack. This was followed by a pass of reflection tomography and well calibration to update the velocity and anisotropy. The tomography step was necessary as diving wave penetration into the halite and anhydrite layer is limited. With this updated model, we continued the velocity model refinement using reflection FWI (RFWI) with the DM cost function.

RFWI requires sharp boundaries in the model to generate reflection events, not present in the relatively smooth model obtained from diving wave FWI. We obtained these sharp boundaries by migrating the input data at each RFWI iteration which is used to generate a pseudo-density model (Mao et al. 2019). The frequency bands used in RFWI were progressively increased up to 30Hz. Figure 2c shows the resulting velocity model and Kirchhoff migrated stack. With the introduction of reflection events the velocity breaks that we expect to see in the halite and anhydrite layer are clearly visible.

Finally, for a smaller subset of the data, the frequency bands used in RFWI were increased up to 40 Hz to obtain a high-resolution velocity model (Figure 3b and 3d). By calculating the normal derivative of this high-resolution model, we can generate an FWI image. Figure 3a and 3c compare the Kirchhoff migrated image using the pre-processed data and the generated FWI image from the 40 Hz FWI velocity model.

The resulting FWI image shows improved coherency, less migration artifacts, and benefits from the contribution of diverse propagation modes (diving waves and reflections) that are used in RFWI to invert for velocity (Wang et al., 2021). The Delaware basin Fill zone is successfully imaged showing the complex collapse and dissolution features limited to the Rustler and Salado formations while maintaining the laterally consistent boundaries in the Castille formation below.

Conclusion

We have presented the successful application of onshore FWI to build a high-resolution near-surface model, capturing the strong lateral velocity variations and interbedded halite and anhydrite layering in the Delaware basin. The application of FWI in this study area posed several challenges. By strategically taking advantage of different FWI cost functions, we addressed these challenges. We also show the potential of a high-resolution velocity model from RFWI by generating a high-resolution FWI image that can address some of the deficiencies in traditional imaging where only the reflection data is used. This has allowed us to substantially improve imaging in the complex Delaware basin Fill zone.

Acknowledgments

We would like to thank TGS and EOG Resources for permission to present this work, and Andrew Peterson, Hassan Odhwani and Xinxiang Li for their efforts in preparing the data used here. We acknowledge Fairfield Geotechnologies for permission to use the field data examples.

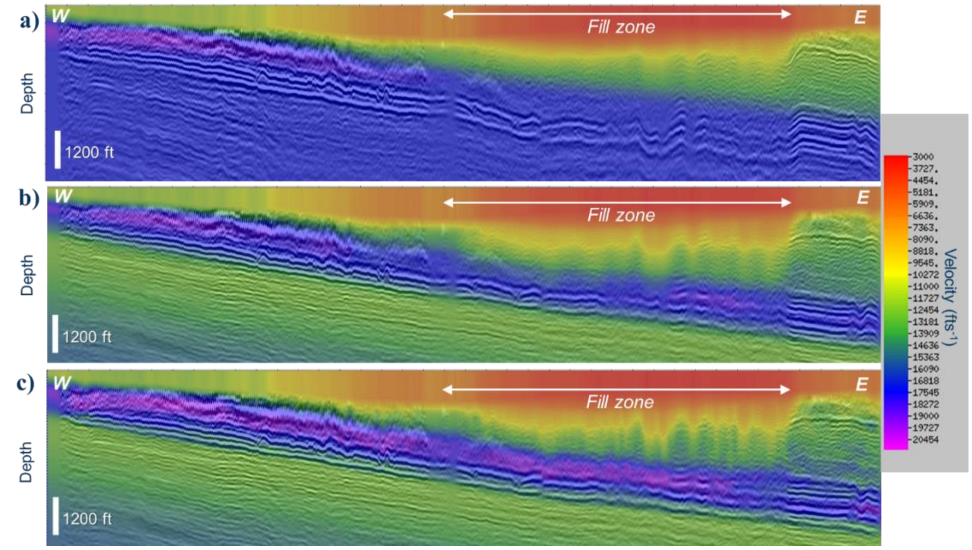

Figure 2: Velocity model with Kirchhoff migrated stack overlay; a) initial model used in the FWI; b) velocity model after diving wave DMFWI, showing improvement of the structure at the base of the interbedded halite and anhydrite layer below the Fill zone; c) velocity model after RFWI at 30 Hz, showing further refinement of the base of the interbedded halite and anhydrite layer below the Fill zone. The faster velocities expected in this layer are now clearer.

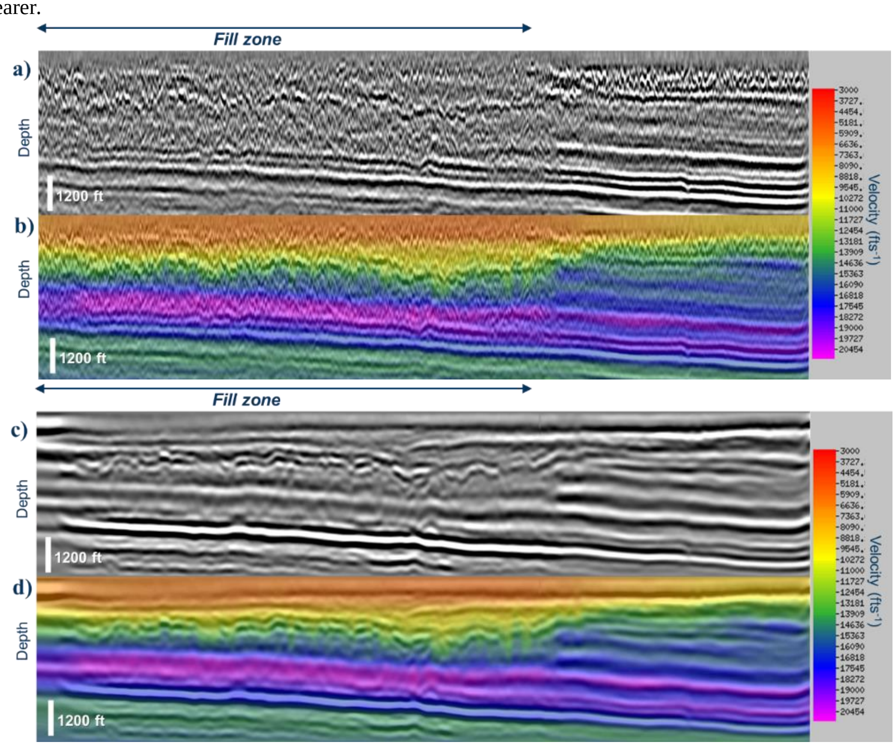

Figure 3: High-resolution (40 Hz) RFWI velocity model; a) & b) Kirchhoff migrated stack using seismic data and the high-resolution (40 Hz) RFWI velocity model; c) & d) FWI image, generated from the normal derivative of the velocity model and the same velocity model