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A case study in the Delaware Basin: Application of Time-Lag FWI and 3D SRME/IMA multiple attenuation

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Summary

In our pursuit of seismic images with improved structural definition and less multiple interference in the Delaware Basin, we present a case study applying full-waveform inversion (FWI) and a data-driven cascaded multiple attenuation flow to a land reprocessing project. We show that the application of Time-Lag FWI to land data, with proper handling of near-surface topography and attenuation of the direct arrival artifacts, was able to more accurately delineate the complicated near-surface geology, thus improving near-surface structural imaging. A cascaded 3D land surface-related multiple elimination (SRME) and internal multiple attenuation (IMA) workflow was employed to effectively attenuate surface and internal multiples, through a combination of 5D interpolation, proper data preparation, optimized multiple modelling, and adaptive subtraction.

Introduction

The reprocessing area is located in the Delaware Basin and consists of eight surveys with varying acquisition parameters. The Delaware Basin is well known for its complex near-surface geology. The shallow evaporite sequence consists of inter-bedded sandstones, evaporites, and dolomites, which generate sharp impedance contrasts and complex seismic reflectors. Rapid vertical velocity variation, as shown in Figure 1(a), and the spatially variant thickness of inter-bedded salt make conventional depth velocity building very challenging. Figure 1(b) shows the PSDM stack migrated with the velocity derived from conventional traveltime tomography. Due to limited shallow velocity resolution, structural undulations can be observed in the lower sediment reservoir zone. Resolving the evaporite sequence through seismic imaging is essential as it not only poses a potential shallow drilling hazard but also directly impacts the structural imaging of deeper sections, including the conventional Bonespring reservoir, the unconventional Wolfcamp reservoir, and detailed basement structures for salt water disposal.

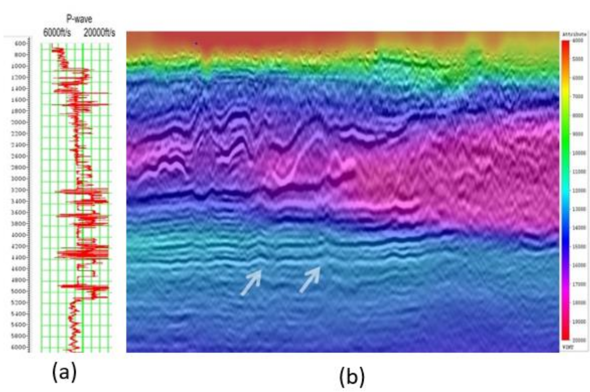

Figure 1(a): Delaware Basin typical shallow well sonic, showing rapid vertical velocity variation; Figure 1(b): Velocity and PSDM stack migrated with conventional approach.

In addition to the complex shallow velocity, another imaging challenge in this area is the presence of strong surface-related and internal multiples, which prevent reliable structural interpretation, especially at the Wolfcamp level where the primary signal is weak. Furthermore, the surface-related multiples generated by a fast evaporite sequence overlap with the primaries, which renders any velocity discriminating demultiple flow, such as Radon transform, ineffective.

In this paper, we present a case study on using land full-waveform inversion (FWI), and land data-driven SRME and IMA to address these two challenges.

Methods

FWI was introduced in the 1980s (Tarantola, 1984; Pratt, 1989; etc.) as an automatic data-driven velocity building tool. The Time-lag FWI (TLFWI) (Zhang et al., 2018) approach uses a more stable cost function to reduce cycle-skipping and amplitude uncertainties, and therefore significantly improves the stability for velocity updates. With this improvement, FWI is now included in velocity model building flows for most marine seismic imaging work, including salt areas with large velocity contrasts.

However, applying TLFWI to land data still faces challenges, including free surface topography treatment in modelling, near-surface-related synthetic artifacts, and poor signal-to-noise ratio (S/N) at low frequencies. To mitigate these issues, Wang et al. (personal communication, 2020) proposed several solutions. The first proposed solution is curvilinear topography modelling. By converting the Cartesian coordinate system to the curvilinear coordinate system, the finite-difference modelling reduces artifacts caused by free surface topography, and therefore a more stable velocity inversion can be achieved. The second proposed solution is near-surface wave attenuation. With near-surface waves attenuated in the synthetic data, diving waves and reflections are clearer and more coherent, thus providing better correlation with the recorded data for a more reliable velocity inversion. The final proposed solution is a frequency-dependent correlation window size for deriving the traveltime-based cost function weighted by the cross-correlation coefficient. For low frequencies with poor S/N, a cost function with longer correlation window and weighted by the cross-correlation coefficient produces more stable velocity updates.

Data-driven multiple attenuation methods like SRME (Berkhout and Verschuur, 1997) and IMA (Jakubowicz, 1998) do not require subsurface velocity information to predict multiple models and have been successfully applied to marine data.

To adapt SRME and IMA to land data, the following challenges must first be addressed: poor and irregular spatial sampling, low S/N, and complex near-surface conditions. Wang and Wang (2013) show that SRME can be effectively applied to land data with special attention to data preconditioning and adaptive subtraction to address the noise and statics issues. Traditional IMA implementation is computationally prohibitive due to its iterative generator identification and model prediction process. Recent development of a two-step modelling approach and optimized modelling algorithm (Dutta et al., 2019) greatly reduces the modelling computation and makes IMA practical for production-size 3D data sets.

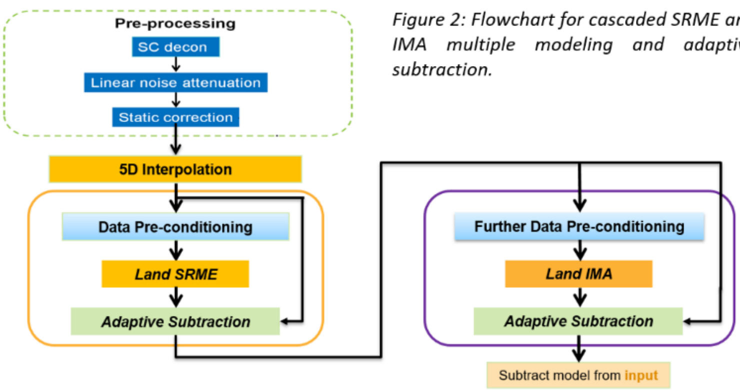

Figure 2: Flowchart for cascaded SRME and IMA multiple modeling and adaptive subtraction.

Figure 2 shows the cascaded land multiple attenuation flow used in this study. It consists of four major steps: pre-processing, 5D interpolation, SRME, and IMA. The 5D interpolation aims to improve spatial sampling for the model prediction and stabilize the solution for adaptive subtraction. Data preparation involves further attenuation of random and linear noise and proper handling of weathering statics to ensure relatively accurate model prediction and subtraction. Two-pass least-squares adaptive subtraction in the offset vector tile (OVT) domain ensures multiple energy is effectively attenuated with minimal damage to primary events.

Examples

Land FWI

The topography elevation of the reprocessing surveys is in the range of 2800 ft to 3900 ft. The average sweep frequency is 4-80 Hz, and the maximum offset varies from 14000 to 23000 ft. TLFWI (5 - 20 Hz) was applied to the data set. Figure 3 shows the velocity models, migrated stacks, and depth slices before and after land FWI. Compared with conventional traveltime tomography, land FWI yielded a higher resolution and more geologically conformal velocity model. The boundary between the shallow slow sediment and the fast anhydrate layer (red arrows) is much sharper, and the slower salt inversions (green arrows) inside the anhydrate body are better delineated. The undulations in the deeper sediment layers (white arrows) due to velocity anomalies above are also effectively reduced.

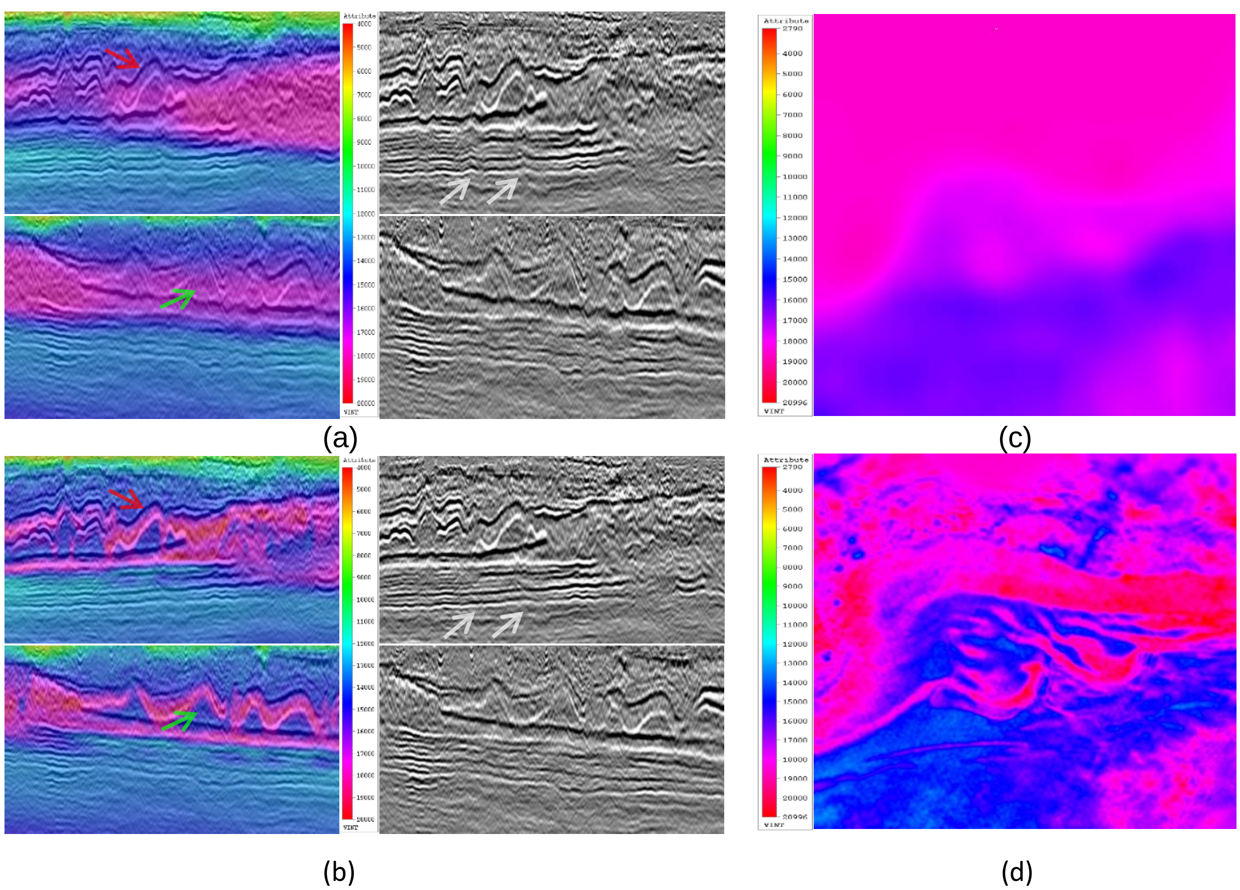

Figure 3: Velocity and PSDM stack comparison before (a) and after (b) FWI update. Velocity depth slice comparison before (c) and after (d) FWI update.

Land SRME/IMA

The proposed cascaded multiple attenuation flow effectively attenuated the multiples in this data set (Figure 4). The Mississippi event (yellow arrows) became more consistent after multiple attenuation. Fault structures can now be identified in the basement (blue arrows), which are also important for salt water disposal. The ringing “multiple train” (green arrows) was attenuated from shallow to deep. On the super-CDP gathers, the multiple attenuation generated more consistent amplitude variation with offset (AVO) response.

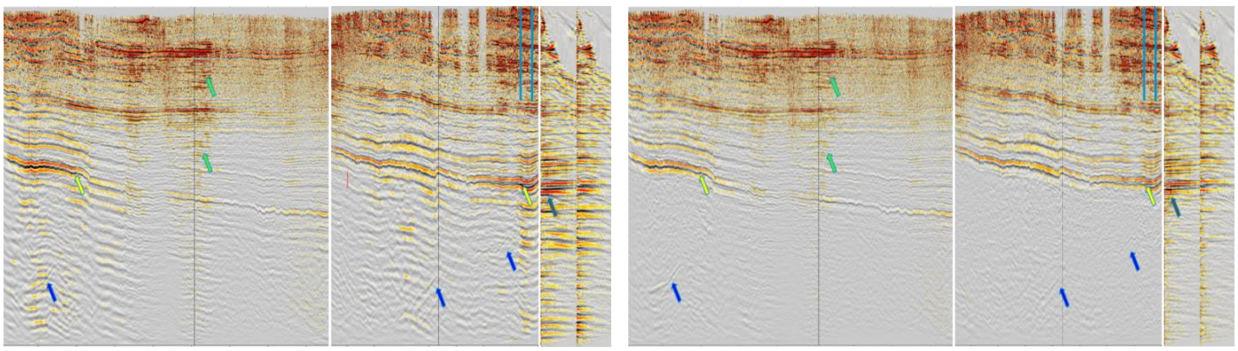

Figure 4: Inline and crossline stack and super-CDP gathers before (left) and after (right) de-multiple

Conclusions and discussions

The Delaware Basin is well known for its complex near-surface geology, which makes it challenging to obtain reliable detailed velocity models with conventional traveltime tomography. By using TLFWI with proper handling of near-surface topography and attenuation of the direct arrival artifacts, we can more accurately delineate the complicated near-surface geology, thus improving near-surface structural imaging and reducing the impact of near-surface uncertainties on the deeper imaging. The details in the FWI-updated velocity model are more conformal to the geology, which provides essential information for drilling decisions.

Seismic data in the Delaware Basin are also heavily contaminated by both surface-related and internal multiples. The proposed cascaded SRME/IMA multiple attenuation flow attempts to mitigate the key challenges with land demultiple through 5D interpolation/regularization, data pre-conditioning, an improved modelling engine, and adaptive subtraction. Seismic images after multiple attenuation feature improved interpretability from shallow to deep sections and more consistent AVO response.

While not demonstrated here, it is important to note that land FWI is still quite limited not only by the FWI algorithm (e.g., acoustic modelling) but also by data insufficiency. It can be more impactful with data consisting of more desirable qualities, such as longer offsets, denser shot and receiver samplings, and higher S/N for low frequencies.

Although 5D interpolation can improve the spatial sampling, multiple modelling is still challenging for shallow and unstable generators, which is typically the case for land data. Land multiple attenuation should benefit from high-density wide-azimuth data with good spatial sampling. In addition, tuning effects (thin bed) and small moveout and structural differences between primaries and internal multiples also make the adaptive subtraction challenging.

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