Resolution of the complex overburden with FWI: A case study from Nile Delta, offshore Egypt

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Introduction

In this study we focus on the benefit of using full-waveform inversion (FWI) to build a high- resolution earth model. This earth model is capable of resolving shallow velocity details with high-resolution which is expected to give better understanding of the overburden hazards along with better input to pore pressure prediction. This is expected to benefit the assessment of drilling risk and improve drilling efficiency.

We present a case study from the West Nile Delta, offshore Egypt. The Nile Delta has a complex geological history that imposes challenges on the building of a geologically meaningful earth model. The geological setting of the Nile Delta has been described in numerous publications, for example by Huguen (2000), Dolson et al. (2001).

Examples of those challenging geological features in the West Nile Delta are the Rosetta Canyon, mud flows, mud volcanoes, shallow channel systems with varied lithological infill, gas clouds and the complex Messinian evaporites.

In this case study, we describe how the starting model for FWI was created and how it was refined. We continue the discussion describing the design of the workflow using FWI and reflection tomography, then describe the quality control procedures used to assess the results and ensure the convergence of the inversion process. Finally, we show examples of geologic features in the post-Messinian, which are better defined using the FWI updated velocity model.

Method and workflow

FWI is a data-fitting technique based on finite-difference forward modeling, and requires a number of iterations to obtain an optimal velocity field. FWI concepts have been well documented in the time domain (Tarantola 1984; Pica et al. 1990; Sun and McMechan 1992), and in the frequency domain (Pratt et al. 1998; Pratt and Shipp 1999), with each domain showing advantages and disadvantages. In this case study we used the acoustic implementation of FWI in the time domain, which is robust and highly parallelized to invert 3D surveys with a large numbers of shot points. The inversion utilizes anisotropic propagators using tilted transverse isotropy (TTI); In this case we only used the inversion to update the velocity.

In general FWI consists of three main steps:

A. Compute the differences between the acquired data and forward-modeled data to check the accuracy of the current model.

B. Crosscorrelate the back-propagated residual wavefield with the corresponding forward propagated source wavefield at each time step and sum over all time steps to produce gradient volume.

C. Calculate the amplitude of the gradient at each spatial point proportional to the velocity change (i.e. the step length).

The FWI method used for this study is implemented in the time domain using the acoustic wave equation. A conjugate gradient method was adopted for updating the velocity field by iteratively reducing the global misfit:

$$E = \frac{1}{2}\sum_{S}\sum_{R}\left\| d_{obs} - d_{\mathrm{mod}} \right\|^2 \quad (1)$$

where E is the global misfit, d_{obs} and d_{mod} are the observed and modeled shots.

The success of FWI is sensitive to both the acquisition design and the accuracy of the starting velocity model.

FWI benefits from long offsets, low frequencies and wide or multiazimuth coverage, as well as a starting model that contains accurate low-wavenumber components to bridge the gap to the available frequency and offset information in the seismic data.

The dataset used for this study is a multiazimuth (MAZ) streamer dataset 640 km^2 in size.

For the purpose of building and updating the velocity model we used three evenly distributed suites of azimuths acquired at 0 ^{o}, 60 ^{o} and 120^o.

It is very important to start with a good match between the calculated data and the observed data, which should be within a half wavelength to avoid the risk of the velocity model converging to a local minimum. This mainly depends upon the low frequencies available in the data and/or the accuracy of the starting model. The starting model is a TTI model that was built from

available well information from the area and extrapolated along defined layers. It was then updated by two iterations of long scale-length reflection tomography to adjust the velocities in places where we lack well control.
FWI was performed in a multiscale manner using the lowest bandwidth first. Once satisfactory results were achieved within that bandwidth the next broader bandwidth is introduced. Three frequency bands were used with frequency high cuts of 4 Hz, 6 Hz and 9 Hz, allowing the details of the model to progress from a fairly smooth model to a high resolution model.

Results

The FWI velocity model shows significant details below the water bottom, especially within the Rosetta Canyon, which is very important for the understanding of shallow geohazards in the area. Also, other geological features in the area, such as slump features, mud volcano flows and smaller channels are imaged more clearly. The example in Figure 1 shows velocity fields extracted along a post-Messinian horizon showing the progress of the velocity model from a smooth starting model to a higher-frequency band model showing details of the channel.
This dataset has relatively short offsets that impose a limitation on the resolution of the FWI update at depth. To mitigate this issue the completed model building workflow was designed to include reflection tomography to attempt to resolve the deeper targets in the pre-Messinian section.
The process of updating the model using FWI requires detailed quality control (QC) procedures to assure model convergence at each stage. Two QCs were performed, a standard for the kinematics and the classical FWI QC: (1) The standard QC used for MAZ velocity model building – generation of target line migrations at different azimuths, inspection of butterfly gathers, stacks, velocities extracted along horizons, stacks overlain with velocities, and residual moveout QCs (RMO QC) to help illustrate error distributions and allow for the association of moveout errors to seismic events and geologic features. (2) The classical FWI QC's – compare the observed and modeled shots, display the data residuals in the shot domain, perform a gradient analysis, and inspect the spatial variation of crosscorrelation between acquired and simulated shots.

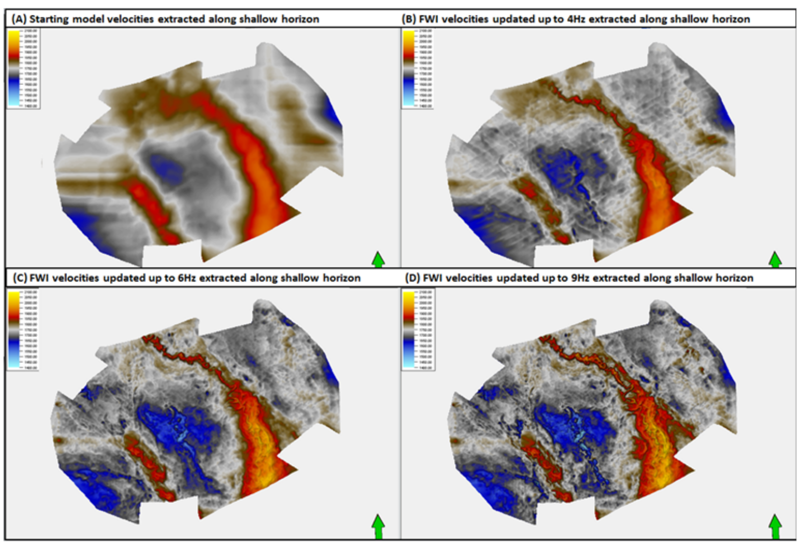

Figure 1: Velocity fields extracted along a post-Messinian horizon showing the progress of the velocity model from (A) the smoothed starting model to each higher frequency band model showing details of the channel at (B) 4Hz, (C) 6Hz, and (D) 9Hz.

Conclusions

We demonstrate a successful approach to building a high- resolution earth model using an acoustic 3D FWI workflow together with reflection tomography. These highly accurate shallow velocity details may be used to better interpret hazards associated with the shallow overburden. The use of FWI in the modern depth imaging workflow shows its place, and the high-resolution velocity field might serve as a proxy to the image we all use for interpretation. This high- resolution velocity field is also anticipated to provide a more accurate pore pressure prediction, which is expected to reduce drilling risks and improve efficiency.

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