Broadband seismic and FWI to resolve an incised shallow carbonate platform, Indonesia

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Summary

Full Waveform Inversion (FWI) has become an important tool to resolve velocity anomalies, especially in shallow water environments, where the limitation in offset and/or angle range creates uncertainty for velocity model updating using travel-time reflection tomography.

In a newly acquired 3D broadband seismic survey, offshore North Madura, Indonesia, shallow gas channels and eroded carbonate platforms lead to uncertainty in accurately interpreting structures and lithologies. Starting from a simple velocity model, the combined use of FWI and ray-traced reflection tomography can address the localized velocity challenges and allow the imaging algorithm to correctly position deeper plays.

A significant advantage of broadband seismic data for velocity model building is its ability to generate useable low frequency input for FWI. This can relax the constraint on the starting model's accuracy by mitigating cycle-skipping. A detailed shallow velocity model conforming to the geology can be derived from this process while conventional reflection tomography remains well suited for model updating in the deeper section. Corrections of small-scale velocity anomalies in the shallow part of the velocity model bring structural uplift in the reservoir plays which include Miocene carbonates and syn-rift Eocene clastic systems.

Introduction

A dual-sensor 3D seismic multi-client survey was acquired over the Central-deep depression and the Madura platform in water depths of 60 to 80 m. Proven plays lie within the Miocene carbonate and Oligocene-Eocene clastic systems with important oil and gas discoveries including the KE38, Ujung and Payang fields. This survey is the first 3D acquisition over this specific area.

The lack of recent broadband 3D seismic data has limited the identification of new prospects and leads. The high resolution and deeper penetration brought by broadband data (Carlson et al., 2007) can reveal additional potential in the proven plays with the integration of Full Waveform Inversion (FWI) (Lailly, 1983; Tarantola, 1984) to address shallow velocity anomalies combined with appropriate imaging algorithms.

Geological settings and survey objectives

North Madura is located in East Java and is part of the back-arc region. The main geological targets in this area are the Miocene Kujung Limestones followed by Miocene sandstones (Fainstein, 1997; Posamentier et al., 2005). The Ngimbang formation in the Eocene-Oligocene sequence is a potential prospect currently classified as an under-explored play (Figure 1).

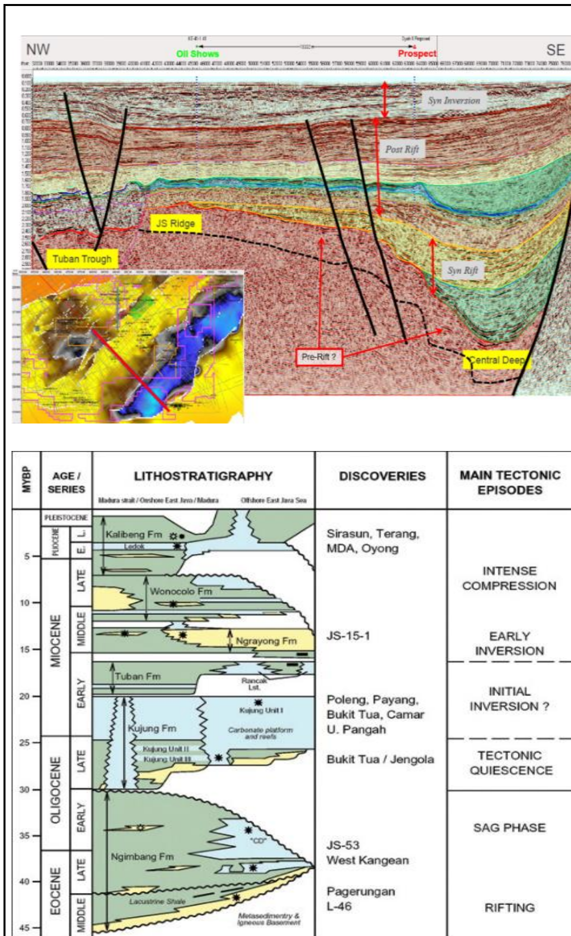

Figure 1: North Madura seismic cross-section and lithostratigraphy chart (Basement structural map, modified after Australian Worldwide Exploration, 2016).

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A major imaging challenge in the survey is the presence of shallow river channels with widths of around 400 m that introduce a distinct velocity variation of around 150 m/s. Moreover, an extensive shallow carbonate platform dating from the early Pliocene (Ledock formation) covers a large part of the survey and was incised by valley rivers in the late Pliocene (Kalibeng formation). For the incised carbonate platform the narrowest width is around 1000 m and has a corresponding-velocity variation of around 325 m/s. If unaddressed, such velocity anomalies will introduce errors in the structural imaging at deeper target levels.

Data and method

The triple-source acquisition with eight dual-sensor streamers of 7050 m offset and nominal separation of 150 m covers an area of approximately 2600 km^2. The source and receiver depths were set respectively at 7 m and 20 m. Minimal pre-processing was applied to the shot gathers input to FWI. This included swell noise and mechanical noise attenuation and statics corrections. Free-surface energy was left in the input shot gathers as the forward modeling used a ghost-free source wavelet and free-surface boundary at the top of the model generating all orders of free-surface multiples as well as source and receiver ghosts.

The modeling was performed using the acoustic, two-way wave equation with pseudo-analytical extrapolation (Etgen and Brandsberg-Dahl, 2009; Ramos-Martinez et al., 2011). Using a simple initial velocity model, the lowest possible frequency input exhibiting coherent signal was used to minimize the risk of cycle-skipping between the recorded and modeled shots. Input gathers with a maximum frequency of 5 Hz were used for the initial iterations of FWI. For such a shallow marine environment and associated velocity anomalies, we concentrated on transmission energy to drive the inversion process. Throughout the velocity model building exercise, the frequencies were gradually increased to a maximum of 10 Hz. The velocity model alone was updated while anisotropy models delta and epsilon (Thomsen, 1986; Alkhalifah and Tsvankin, 1995) were kept unchanged.

In FWI, high resolution velocity models are derived by minimizing the data misfit calculated between the observed and modeled shots (objective function). Theoretically, computing the Hessian matrix, the 2nd order derivative of the objective function with respect to the model parameters, can solve directly the problem. As the computation and storage cost of the Hessian matrix can become prohibitive over large surveys, conventional FWI uses a cross-correlation kernel to compute a gradient (1st order derivative of the same objective function) and applies an iterative approach to solve the FWI problem (Mora, 1987; Tarantola, 1984). This approach can produce a velocity update with reflectivity imprint as the high wave numbers of the migration isochron generally dominate the inversion. To rely more on the diving wave and back-scattered energy, time and spatial derivative kernels are specifically combined to generate an improved velocity kernel (Ramos-Martinez et al., 2016). The newly formed velocity kernel eliminates the migration isochron while preserving the low wavenumber energy (Figure 2).

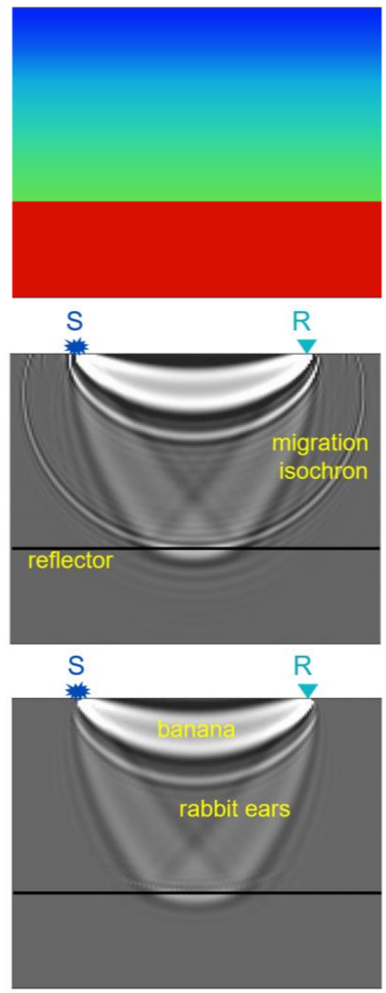

Figure 2: Simple velocity model (top), conventional kernel (center) and improved velocity kernel (bottom).

Convergence and quality control (QC)

To validate the FWI updates, QCs in both data domain and image domain are produced. Data domain QC includes cross-correlation coefficient and corresponding time-shift calculations at various offset ranges between recorded and modeled shots before and after each update (Figure 3).

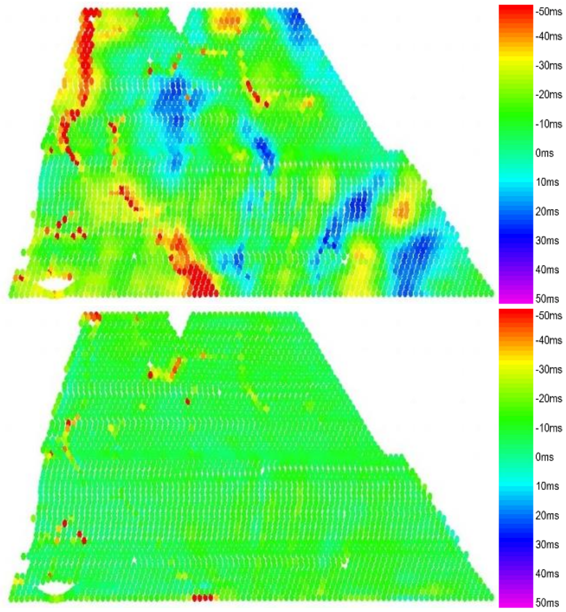

Figure 3: Data domain QC example showing residual errors before (top) and after (bottom) FWI update.

The cross-correlation maps shown above are generated for the first iteration of FWI at 5 Hz. At this frequency, the critical cycle skipping shift value is around 100 ms (1/2 period). The shift values calculated prior to the inversion are well within this range and allow us to validate the input velocity model used in FWI. The process is repeated after the 5 Hz FWI update. The cross-correlation map after this update shows that the residual errors have been greatly minimized. The calculated residual errors being marginal, FWI iterations using a larger frequency band can then be conducted.

In addition to data domain QC, imaging domain QCs are undertaken. The pre-processed input gathers were used to run an efficient implementation of Beam Pre-Stack Depth Migration (BPSDM) (Sherwood et al., 2009). The high speed of BPSDM allows us to migrate the full survey at each iteration and output full volume QC including stacks (full and partial angle stacks) to understand structural correlation between the velocity model and seismic image, Common Depth Point gathers (CDP) for gather flatness estimation and gamma map generation (ratio between geological velocity and imaging velocity).

Results and discussion

Figure 4 shows a vertical section comparing the final Kirchhoff Pre-Stack Time Migration (KPSTM) stack output converted to depth using its migration velocity and the final TTI Kirchhoff Pre-Stack Depth Migration (KPSDM) stack output using the final FWI velocity model. The KPSTM volume clearly shows its limitation with large distortions visible below the main shallow channel and below the incised carbonate platform. Beside the distortions, the amplitude and frequency of the seismic events below those geological structures are also affected in the KPSTM results. While not perfectly solved in the KPSDM because no Q-tomography and Q-migration were run at this stage, the sharpness, continuity and amplitude of those seismic events are greatly improved on the output of the KPSDM.

This is due to the quality of the velocity model derived from FWI. The integration of low frequencies from the dual-sensor broadband seismic data and the FWI engine results in a high resolution velocity model which in turn translates to improved imaging of the full seismic section. The sags related to the shallow channels are minimized, the carbonate platform image is improved as are the seismic events in the deeper section.

Finally, examples comparing the starting and final velocity models at shallow depths of 200 m and 570 m are shown in Figure 5. Details in the final velocity model correlate well with the shallow channels and incised carbonate platform in the seismic image. The final FWI velocity model shows good lateral resolution needed to solve shallow velocity challenges and reduce structural uncertainties by accurately compensating for those near surface anomalies. The shallow river channel system is apparent on the depth slices presented as is the complex shape of the incised carbonate platform.

Conclusions

We applied FWI to a dual-sensor broadband data set acquired in a very shallow marine environment to generate a high resolution velocity model to correct structural distortion and improve the amplitude/frequency content of the seismic events below shallow velocity anomalies. FWI generated a detailed velocity model conforming to the structures observed in the migrated image. The improvement in the migrated image allows the key source and reservoir horizons to be mapped with confidence.

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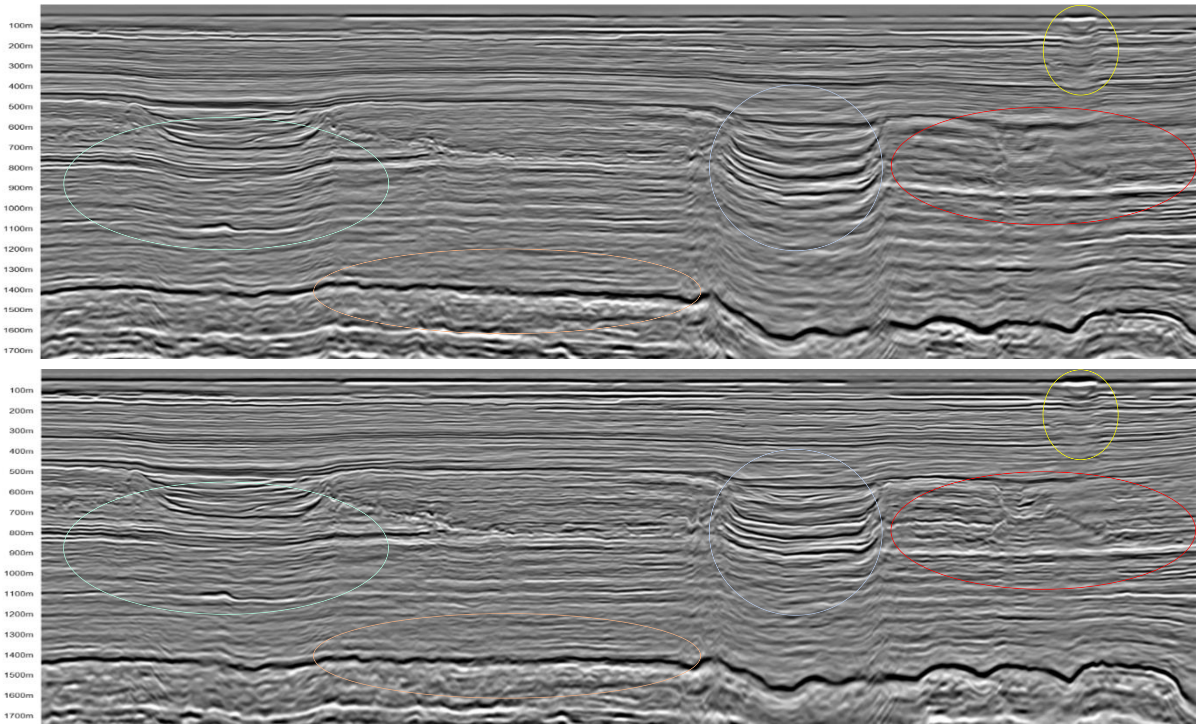

Figure 4: Data domain QC example showing residual errors before (top) and after (bottom) FWI update.

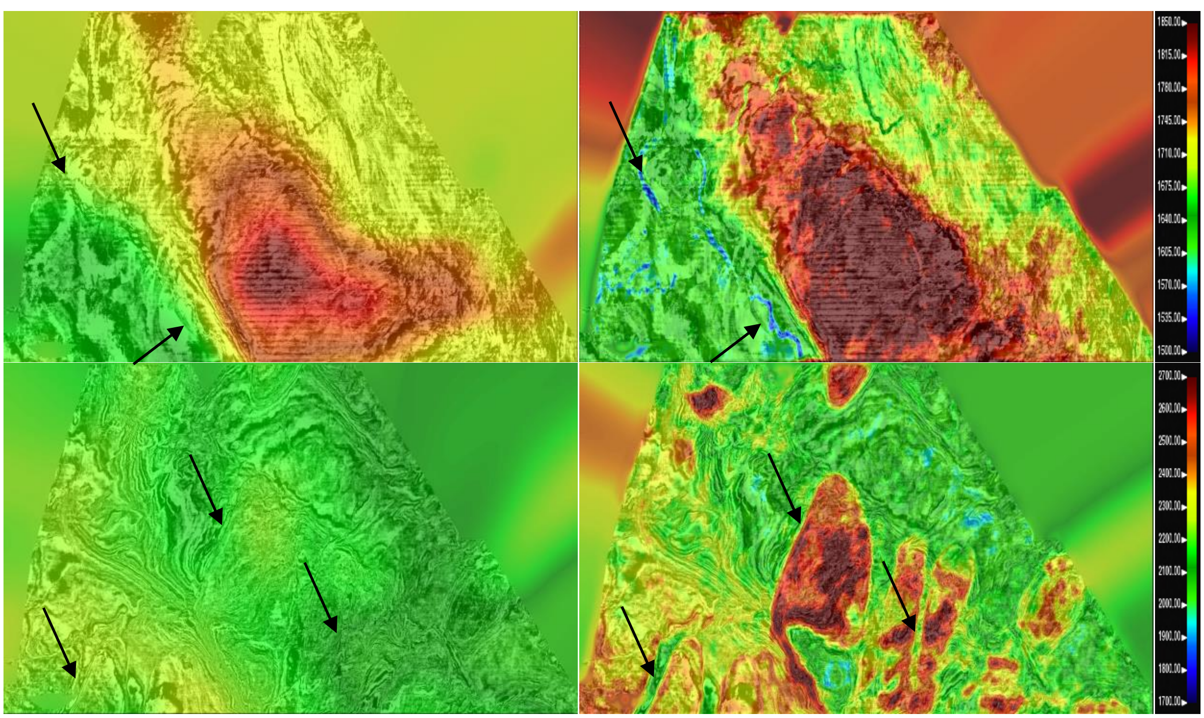

Figure 5: Initial velocity model (left) at 200 m (top) and 570 m (bottom) and corresponding final velocity model (right).

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