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# High Resolution Anisotropic Earth Model Building on Conventional Seismic Data Using Full Waveform Inversion: A Case Study Offshore Australia

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## SUMMARY

We present a case study from the North West Shelf of Australia where the complexity of the overburden consists of several thin multi-level channel systems filled with a combination of anomalously high or low velocity sediments. Not accounting for these strong velocity variations accurately, can lead to subtle image distortions affecting the underlying section down to and including the reservoir level. This can have significant impact on the volumetric estimates of reserves in place. To resolve these complexities in the overburden, full waveform inversion (FWI) was utilized to generate an updated earth model exploiting both early arrivals and reflection events. One caveat to using full waveform inversion is the need for low frequencies to be present in the seismic data, or, the initial starting velocity model must contain the correct low wavenumber components. However, conventional seismic data acquired at shallow tow depths are usually band limited particularly at the very low frequencies. Our case study will discuss these issues along with other limitations that this "conventional data" presented along with the workflows and quality control methods adapted to this data in order to converge to a plausible, high resolution earth model.

**Key words:** full waveform inversion; FWI; high resolution model; north west shelf Australia; model building

## INTRODUCTION

An accurate earth model is fundamental to any depth imaging project. Full waveform inversion is an advanced model building technique incorporating the full two way wave equation. Full waveform inversion produces an accurate high resolution earth model by simultaneously using the information of travel time, amplitude and phase contained in the full recorded seismic wavefield. One pre-requisite to full waveform inversion is an initial starting model. In this case study, the initial starting model was derived from a smooth version of a reflection travel time tomography velocity field derived from a depth migration workflow. The full waveform inversion process utilizes this model and a two-way wave equation finite difference acoustic wavefield propagator to generate modelled seismic data. These modelled shots are then compared to the acquired (observed) recorded seismic shots. The residual differences are backward propagated from time to depth domain, into velocity gradients and velocity changes required to obtain an updated model (see Figure 1). As with solving any non-linear inversion problem, it is an iterative process and is repeated as required until the residuals between the modelled shots and the actual observed seismic data are minimized. Iterations start at low frequencies and progress to higher frequencies.

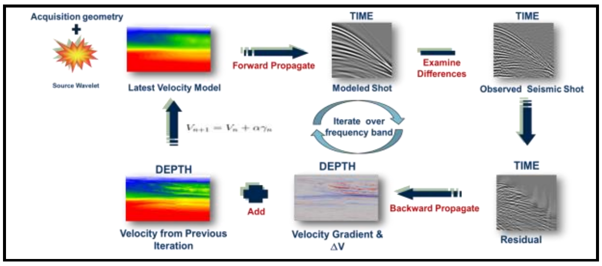


**Figure 1: Full waveform inversion general workflow for the time-space domain approach.**

## FULL WAVEFORM INVERSION

Full waveform inversion based on the finite difference approach was originally introduced in the time-space domain (Tarantola 1984; Pica et al. 1990; Sun and McMechan 1992). Inversion can also be implemented in the frequency domain (Pratt et al. 1998, 1999; Ben-Hadjali et al. 2008). In the frequency domain implementation, only specific single frequencies are inverted per iteration. However the frequency required to resolve velocity anomalies is dependent on the depth of the event; which is typically variable. For the time-space domain approach, t-x zones can be defined to target specific waveforms and a range of frequencies or frequency bands are used for the inversion (see Figure 2). Iterations start from a low frequency range to a higher frequency range in this multi-scale approach to minimize the risk of local convergence.

Depending on the depth of the target and the earth velocity gradient, first breaks or reflection data or a combination of both can be used to construct an accurate earth model. In this case study, we will apply full waveform inversion in a time-space domain approach utilizing both early arrivals and reflection events.

## THE NORTH WEST SHELF CASE STUDY AREA

The area of the FWI case study lies on the North West Shelf (NWS) of Australia with the reservoir being overlain by some of the most complex overburden in the region. This overburden consists of several phases of thin palaeo-chanelling with varied infill from relatively lower velocity shale material through to high velocity carbonates. By not resolving these strong lateral velocity variations within these complex channels can lead to image distortions at the deeper reservoir level.

The field is covered for the most part by a high resolution, 3D narrow azimuth towed streamer survey. It was acquired with eight streamers of maximum offset of 5550m, 75m apart and towed at 6m depth. In 2004 and 2005, the dataset was processed through an anisotropic pre-stack time migration workflow and in 2006; a subset of the data was further processed using anisotropic pre-stack depth migration using reflection travel time tomography. An interpreter driven solution was introduced in the final steps of the model building in order to remove the overburden imprint on the deeper target structure. However the final delivered product at this date still retained the problematic imprint of the overburden which had to be dealt with in a depth calibration workflow.

In 2013, the survey was reprocessed from field tapes through a more detailed depth imaging workflow incorporating high resolution travel time reflection tomography. The higher quality reflection tomography model in conjunction with the minimally processed shot domain dataset provided a stepping stone to perform this case study of full waveform inversion to resolve the complexities of the overburden in the North West Shelf of Australia.

## DATA ANALYSIS AND INPUT DATA PREPARATION

The existence of very low frequency signal in the input data and good signal to noise is necessary for the success of full waveform inversion. In addition, the initial velocity model must contain accurate low wavenumber components and the acquisition geometry should contain sufficiently long offsets to record refracted and turning waves. In order to validate the current acquisition geometry with limited maximum offset and limited low frequencies from shallow source and detector tows, various quality control checks were performed to quantify the success that could be obtained with full waveform inversion.

*Signal to Noise Ratio*

Since the data was reprocessed from field tapes, careful noise attenuation was applied to improve the signal-to-noise ratio while preserving the original amplitude and phase of the primary events needed for full waveform inversion.

*Low Frequency Input Data*

To identify the minimum useable frequency for FWI, simple high cut filters were applied to selected time domain shots as well as reverse time migrations (RTM) were performed at different frequencies (see Figure 3) to understand the coherency of events in the image domain. Both tests showed that useful coherent energy was apparent down to 4Hz.

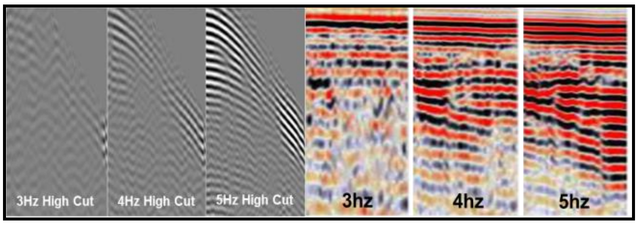


**Figure 3: High cut filters applied to selected shots (left). Frequency limited reverse time migration (stacked) applied to a sail line at 3, 4 and 5Hz respectively (right).**

*Acquisition Geometry*

In order to understand the applicability of full waveform inversion to resolve velocity perturbations, a 2D synthetic prestack dataset was created by forward modeling using a velocity model with checkerboard patterns. This involved taking the initial velocity model and introducing +/-10% velocity errors in a 2km square checkerboard fashion (See Figure 4b). The forward modeling geometry mimicked the real acquisition geometry of 5550 cable length, 37.5m shot point interval, 12.5m receiver group interval with streamer and source depths of 6m and 5m respectively. Full waveform inversion was then used to try to recover these checkerboard features using a smooth initial starting model (see Figure 4a) to determine both the spatial and vertical resolution that could be achieved based on the current geometry design, velocity gradient and depth of target. The result of the test is demonstrated in Figure 4c.

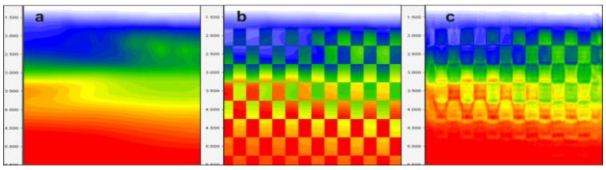


**Figure 4: (a) Initial starting model; (b) checkerboard model (c) Full waveform inversion model result validating spatial and vertical resolution achievable with current acquisition geometry at different depths.**

*Initial Velocity Model*

The choice of a starting model is an important component of full waveform inversion. The model needs to be accurate enough to the true solution so that the modeled shots and observed shots are within the half wavelength criteria to avoid cycle skipping. More importance should be placed upon building a good initial starting model if there is a lack of low frequencies and maximum offset in the seismic data, both of which exist with the narrow azimuth towed streamer dataset in this case study. Since a mature reflection tomography was already derived when the FWI project initiated, this provided an ideal starting point for building an initial FWI model. Several smoothing tests were undertaken on the model. A smoothing operator was chosen so that the long wavelength components of the sonic trend were still honored while localized velocity anomalies were removed. Removing any incorrect velocity anomalies can prevent FWI iterations from converging into local minima.

## CHALLENGES AND RESULTS

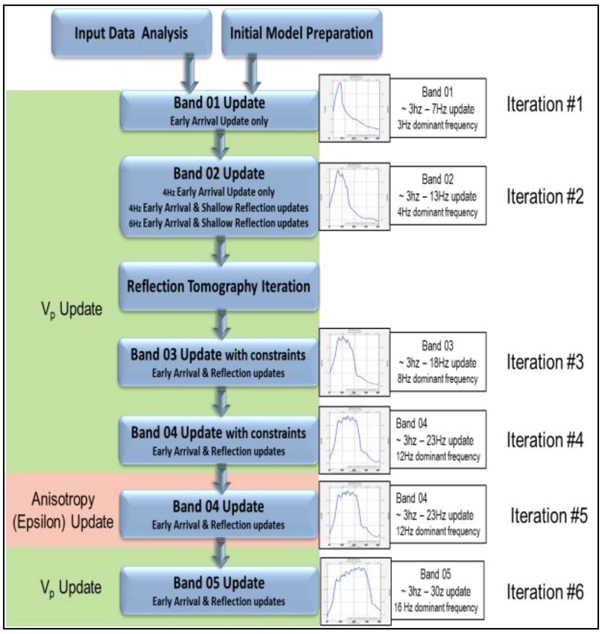


**Figure 5: Full waveform inversion workflow applied to the North West Shelf dataset.**

Six overall iterations of full waveform inversion were performed on this project, each of which contained several “inner loop” iterations (see Figure 5). After performing band one and band two updates of full waveform inversion, convergence of the East side of the model with a complex faster velocity gradient appeared to be resolved well. Conversely, the West side suffered divergence of the model indicated by poorer resolution and increasing residual flatness of the gathers. This was believed to be due to the lack of early arrival information required by FWI. The absence of early arrival information with the current cable length of 5.5km limitation would be more pronounced in the slower velocity gradient part of the model (West side) compared to the faster gradient trend of the velocity model (East side). This was confirmed with observations of the data and ray tracing validation (see Figure 6).

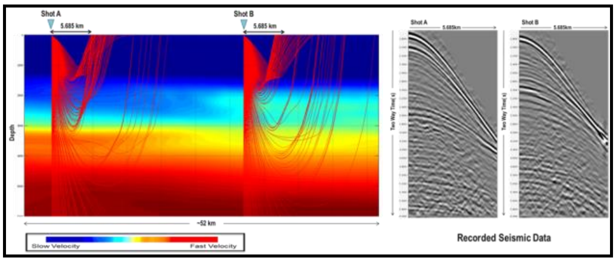


**Figure 6: Ray Tracing QC validated the lack of turning wave energy present in Shot A (West side of model) compared to Shot B (East side of the model).**

Lack of convergence towards a global minimum was also attributed to the lack of low frequency signal present in the shallow towed streamer data. In order to reinstate the low frequency trend, reflection travel time tomography was used in the model building workflow to flatten the events in this region and assist in getting the kinematics correct.

The remaining FWI band updates incorporated the use of both early arrivals and reflection information to update the deeper portions of the model. In order to prevent divergence due to the limited maximum offset and low frequencies inherent in this dataset an additional constraint was applied to the FWI process in the third and fourth iterations. This assisted in ensuring that the updates from FWI preserved the background trend of the reflection tomography model while simultaneously providing a higher resolution update.

Whilst the residual moveout decreased globally after four iterations of FWI, hockey stick features at longer offsets on the gathers were also apparent in some areas of the model; a common symptom for inaccuracies in the anisotropic model. For the fifth iteration of FWI, the compressional velocity Vp remained fixed while epsilon was updated to further decrease the residual moveout on the gathers; the results of which are shown below (see Figure 7).

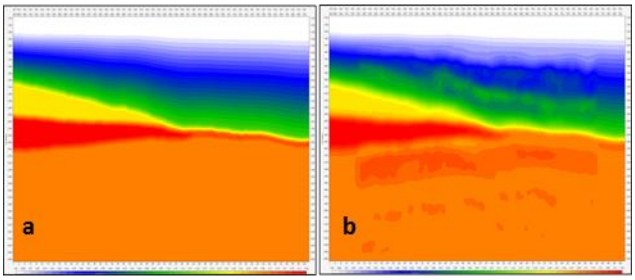


**Figure 7: (a) Initial Epsilon model (b) Epsilon model after FWI band four epsilon update**

The last iteration of FWI utilized both early arrivals and reflection data and the update incorporated maximum frequencies of 30Hz with no priors or constraints applied to the FWI process. Figure 8 compares the FWI model to the intial starting model of FWI. The impressive details in the FWI model have very good geological conformance as displayed in Figure 8. Good conformance to available well sonics and check shots was also observed.

## CONCLUSIONS

Acoustic 3D full waveform inversion was applied to a subset of a North West Shelf narrow azimuth towed streamer dataset. Due to the relatively short cable length and limited low frequency content of the acquired data, careful data analysis and input data preparation was required to understand and maximize the information contained within the dataset for a successful FWI result. Convergence of the model occurred where sufficient turning ray information was available. In areas of the model, where turning rays information was not available, reflection tomography was required to assist in the convergence of the model and getting the kinematics right. Hockey stick features on the gathers indicative of inaccuracies of anisotropy model were reduced by employing one iteration of FWI to update the epsilon model and further reduce the residual moveout on the gathers.

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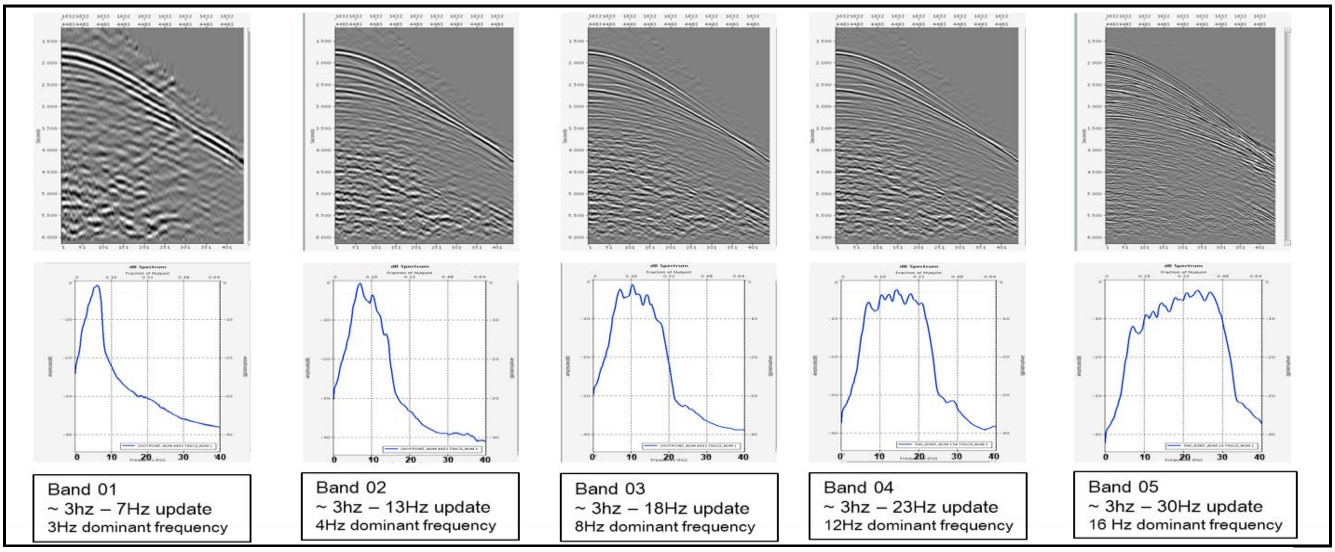


**Figure 2: Observed shots and corresponding normalized frequency spectra for each frequency band update.**

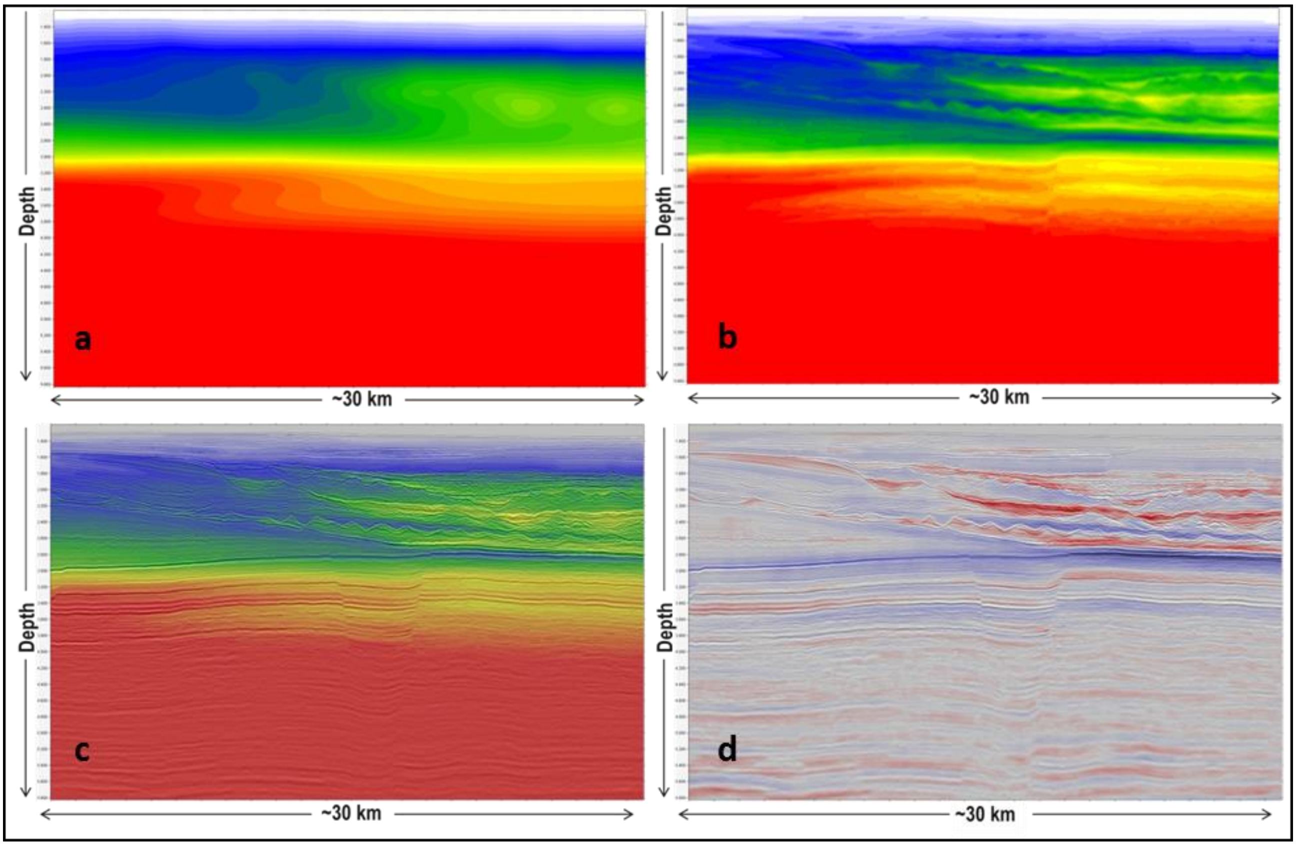


**Figure 8: (a) Initial starting model input to FWI (b) Final FWI model (c) Final FWI model overlaid on final image (d) Total FWI velocity update (final FWI model minus initial); red is speed up /blue is slow down.**