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2D Acoustic Time Domain Full Waveform Inversion - A Broadband Application in the Carnarvon Basin, Australia

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SUMMARY

We present an application of Acoustic Full Waveform Inversion to a 2D Line that crosses the North-Western Australian Continental Shelf Margin. The line was acquired by CGG using a Broadseis acquisition system. The line intersects two previously discovered gas fields. A "kinematically crude" initial model was constructed using Migration Velocity analysis. Results from Kirchhoff PreSDM using this initial model showed that significant residual moveout existed in the overburden and at the target level on our common image gathers (CIGs).

2D Acoustic Full Waveform inversion was used to update this initial model using a time domain forward modelling and inversion workflow. A number of strategies have been implemented to successfully perform FWI on this real dataset, including: source estimation strategies, multi-scale inversion, event windowing and a dynamic amplitude correction to account for the invalid acoustic assumption used in the modelling. The kinematically improved velocity model showed dramatically improved alignment of PreSDM common image gathers both in the overburden and at the target level of the two gas fields.

Introduction

Full waveform inversion (FWI) is a wavefield data fitting procedure that is increasingly finding acceptance in academia and industry as a means to extract quantitative information from seismograms (see Virieux and Operto, 2009, for a review). FWI considers the entire time series to be interpreted based on two-way wave propagation. The FWI problem, as a non-linear inverse problem, is an ill-posed problem taking into account that the acquisition geometry is generally limited to near the free surface. For efficiency when considering least-squares minimization, a local linearized optimization is considered from an initial model (Tarantola, 1987). In order to avoid cycle-skipping problems which may prevent converging to the global minimum, the initial model should predict travel times of phases in the observed data within half the period (Beydoun and Tarantola, 1988) which could be expressed as a relative time error depending on the number of wavelengths to be propagated.

In order to avoid "cycle-skipping" phenomena prohibiting a successful inversion, a combination of three strategies has been implemented:

1) Use of ray based methods (Migration Velocity Analysis or Reflection Tomography) (Woodward et al., 2008) to improve the accuracy of the low wavenumber content of the initial model. 2) Broadband seismic acquisition to allow the recording of very low frequencies ($\approx 2\,Hz$), reducing the number of wavelengths to be propagated for a given distance between the source and the receiver. 3) Multi-step hierarchical inversion from lower to higher frequencies in order to mitigate the cycle-skipping problem and to avoid local minima (Bunks et al., 1995; Sirgue and Pratt, 2004).

In this work, we present an application of acoustic FWI to a 2D real dataset transecting the North-Western Australian Continental shelf where these three strategies have been applied. In this region, the water depth changes from values lower than 100 m to high values above 1000 m over just few kilometers. This dataset was acquired with a Broadseis (CGG) seismic acquisition strategy. We have constructed an initial model built from kinematically imperfect pre-stack time migration (PreSTM) velocity analysis. We show via Kirchhoff pre-stack depth migration (PreSDM) that, after application of FWI, the velocity model is kinematically more accurate through an analysis of common image gathers (CIG). These improvements in the kinematics occur both in the overburden and at the target level where two previously discovered gas fields are located.

We first consider the construction of the initial model. Then we will apply the FWI workflow, before concluding with inversion quality control based on CIG analysis.

Initial Model construction

Initial models are built for both P-wave velocity V_p and density ρ. We shall invert for a single parameter, (P-wave velocity) but we require a realistic ρ initial model that honors the sharp contrast between the water column and the subsurface. A Gardner law is applied during the inversion procedure. A multi-parameter inversion following the strategy proposed by Zhou et al. (2014) will be considered at a later stage.

V_p Initial Model Building

The V_p initial model is constructed by merging information from two data sources and is displayed in Figure 1. These datasources are: 1) An expendable bathythermographic (XBT) derived velocity function within the water column. 2) Stacking velocities that are the result of a pre-stack time migration (PreSTM) processing workflow.

Public-domain bathythermographic information is available from the Commonwealth Scientific and Industrial Research Organisation (CSIRO). This bathymetric information connected with the knowl-

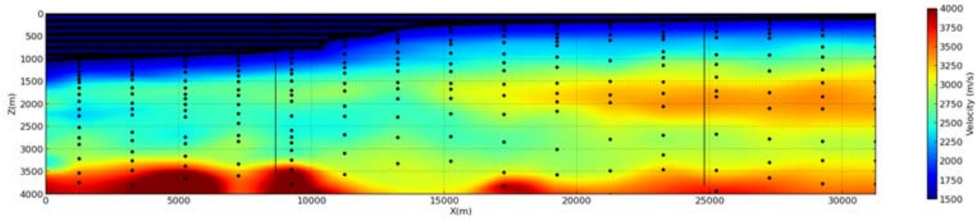

Figure 1 *The initial velocity model. Above the waterbottom interface, the velocity is calculated from XBT information while, below, the seafloor V_{rms} is interpreted every 2 km. The black dots represent position of data points before gridding. The two well paths are marked with vertical black lines.*

edge of the sea water salinity ($\approx 35ppk$) allows an estimation of the velocity in the water column with respect to the depth via an empirical velocity/temperature transform (Medwin, 1975). Stacking velocities obtained from migration velocity analysis performed as part of the PreSTM workflow are converted to interval velocities using the Dix equation. A water-sediment interface is interpretted in time from the PreSTM data after CDP stacking. The velocity that would be predicted by the XBT ($V_{INT}(t) = -48.492t^3 + 155.27t^2 - 165.54t + 1546$ where t is in seconds) velocity column function at the interpreted waterbottom TWT is included to provide a transition between these two zones. Above this interface, the XBT interval velocitiy is used while, below it, the Dix converted MVA RMS velocities are used. All this information is provided on an irregular velocity grid in two-way time. One-dimensional integration of the interval V_{int} pairs converts this irregular two-way-time grid to an irregular depth grid. A regridding step will produce a regular 25 m square gridded velocity model through a cubic polynomial interpolation. A 300 m isotropic gaussian filter in slowness will remove unwanted high frequency variations.

ρ Initial Model Building

Once the initial velocity model is constructed, Kirchhoff PreSDM is performed. The waterbottom depth event is detected and interpreted on this stacked, migrated section. Two wells were intersected by the 2D seismic line (one shallow on the continental shelf above 100 m and another one at a depth greater than 800 m). The depth migration predicted the waterbottom depth of these two wells to within 10m of the true value. Above the waterbottom interface, we consider a constant density of $1000 kg/m^3$ while the Gardner law of the expression $\rho = 310V_p^{0.25}$ is used below this interface. The density contrast at this interface is approximately 50% and, as such, it controlled the amplitude of the waterbottom reflections.

Full waveform inversion

Full waveform inversion is applied, focusing on primarily diving wave energy. We consider isotropic wave propagation using a finite difference approach and perform both forward modelling and inversion of the data in the time domain(TDTD FWI). This allows an approach similar to the one proposed by (Bunks et al., 1995), called 'TDTD Bunks FWI'. Initially, an approximate 3D correction is applied to the data (T^2 gain) in addition to F-K filtering and spectral whitening. We consider different second-order butterworth frequency bands starting with a low frequency ($\approx 3\,Hz$) up to higher frequencies ($\approx 15\,Hz$). We proceed through 6 frequency bands by extending the high frequency limit while keeping always the low one fixed. The output of the velocity from the previous frequency band serves as the input to the next band.

Source functions are estimated in the deepwater portion of the line using the direct wave information at near offsets (500-1700m). Once the source information is obtained, synthetic records are computed in the initial model($\mathbf{d_{mod}}_{initial}$). The near-offset phase and amplitude match is quite good suggesting that the position and the impedance contrast of the water bottom is well represented. We notice significant amplitude discrepancies between between $\mathbf{d_{obs}}$ and $\mathbf{d_{mod}}_{initial}$. Therefore, at the start of the FWI for each frequency band, the ratio of the average amplitude between $\mathbf{d_{obs}}$ and $\mathbf{d_{mod}}_{initial}$ is used to normalize this amplitude discrepancy so that the FWI focused on matching phases of data events rather than amplitude differences. This pragmatic approach is justified as the amplitude difference is influenced by visco-elastic and anisotropic effects that are not yet considered in the forward modeling in our time-domain acoustic finite difference modelling engine. The FWI gradient is computed using the adjoint state method (Plessix, 2006) and the inversion is iterated using a preconditioned steepest descent algorithm. A weak regularization is applied through a gaussian wavenumber filter over the gradient. After each frequency band attained convergence, the inverted velocity model is used as the starting model for the next iteration, while the density model is recomputed using the following expression $\rho = 310V_p^{0.25}$ (Gardner equation) to ensure that features added to the initial model are present in the updated density model as shown in the following algorithm.

Algorithm 1 Algorithm for FDTD Bunks FWI for $\mathbf{V_p}_{(i)}$ from frequency band $i \rightarrow N_{band}$

```
for i to N_band do
    Bandpass filter preprocessed Data using current band to calculate d_obs.
    if i=1 (First Band) then
        Use initial models V_p = V_p_initial and ρ = ρ_initial
    end if
    if i ≠ 1 then
        Set V_p = V_p_{i-1}
        Set ρ(AboveWB) = 1000kg/m^3 & ρ(BelowWB) = 310 V_p^0.25
    end if
    Estimate source from watercolumn direct wavefield
    Forward model using V_p and ρ → d_mod_initial
    Calculate average amplitude ratio (α) for each trace d_obs vs d_mod_initial
    while FWI above convergence criteria do
        Perform FWI minimizing on current band C = ||α d_obs − d_mod||_2
    end while
    V_p_final from FWI → V_p_i
end for
```

Results

The full waveform inversion appears to behave in a quite stable manner. The primary changes to the velocity model are a sharpening of the waterbottom and also a sharpening of the top of a high velocity zone that becomes visible below 1km depth (Figure 2). Gather horizontal alignment on CIGs obtained from Kirchhoff PreSDM is significantly improved across almost the entire line (Figure 3). This is true in the overburden as well as at the depth of previously known gas reservoir sands.

Conclusions

A successful 2D real data application of isotropic acoustic TDTD full waveform inversion has been presented. From a crude initial model built from standard time processing, we have been able to converge to a stable velocity model that improves CIG flatness in the overburden and reservoir target level.

Acknowledgements

We would like to Thank CGG for providing access to the dataset presented in this abstract. This study was partially funded by the SEISCOPE consortium (*http://seiscope2.osug.fr*), sponsored by BP, CGG, CHEVRON, EXXON-MOBIL, JGI, PETROBRAS, SAUDI ARAMCO, SCHLUMBERGER, SHELL, SINOPEC, STATOIL, TOTAL and WOODSIDE. This study was granted access to the HPC resources of CIMENT infrastructure (https://ciment.ujf-grenoble.fr) and CINES/IDRIS under the allocation 046091 made by GENCI.

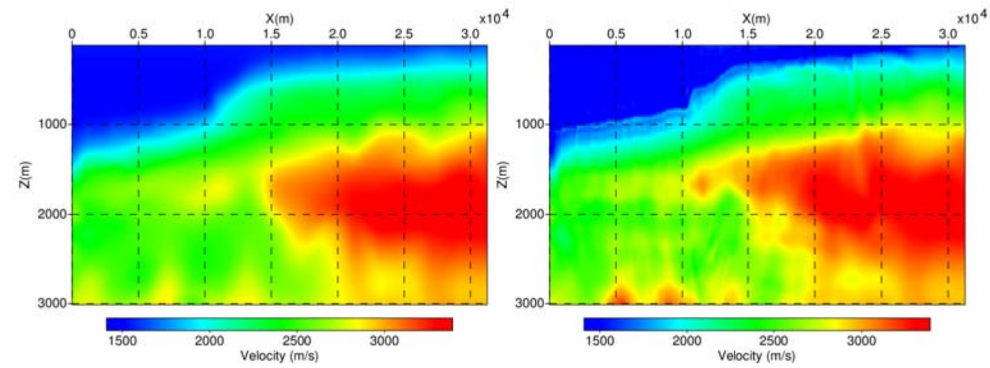

Figure 2 *The initial velocity model is shown in the left panel wil the final velocity model is shown on the right panel. Same color scale is used in both figures*

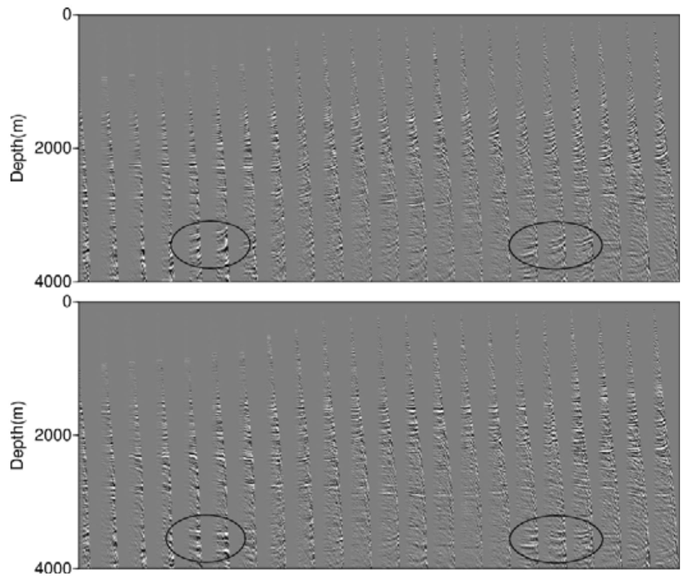

Figure 3 *Common image gathers formed from Kirchhoff PreSDM using the velocity model before (top panel) and after FWI (bottom panel). Note the full waveform inversion improves horizontal alignment of the events in the overburden and at the top reservoir level of the two gas fields (shown in black circles).*

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