Pluto reservoir characterisation: Exploiting advances in Full-waveform Inversion technology

Chris Semeniuk

Chris Elders
Department of Applied Geology
Curtin University

Fabio Mancini
CEED Client: Woodside Energy Ltd.

Abstract

Traditionally, the greatest errors within quantitative reservoir characterisation are a product of the bandlimited nature of seismic data and the accuracy of the local background trend model. The reliance on interpolating low frequency information (<10 Hz) from sparsely spaced wells can heavily bias and smooth results, potentially leading to incorrect reservoir interpretations. A high resolution FWI model was used to provide the missing geological detail between wells, incorporated as part of the low frequency model within the deterministic seismic amplitude inversion workflow. Utilising this information shows promising potential to improve definition of the Pluto gas sands, especially within the upper reservoir units which have limited well control. Currently, the accuracy of the FWI model at reservoir depths is the greatest obstacle in producing an accurate reservoir characterisation over the entire study area. In the case of Pluto, the presence of several areas of anomalous FWI velocity values leads to an incorrect lithology and fluid classification. The effect of these errors can be limited by incorporating the FWI velocity purely as a spatial guide for the interpolation of well information. Despite these nuisances, the overall similarity between the raw FWI constrained and the traditional inversion results (using in-situ logs) suggests that the FWI derived properties may have greatest benefit within preliminary exploration efforts – where there is limited well and interpreted horizon control. Future improvements to the FWI engine and workflow will further enhance the accuracy and usefulness of the data for reservoir characterisation.

1. Introduction

The Pluto gas field is a Western Australian offshore reservoir that has been in production since 2012. To optimise well productivity and enhance the field development strategy, a detailed understanding of the reservoir architecture is extremely important. This includes information about sand quality, distribution/dimensions, connectivity and the presence of any reservoir heterogeneities (Heldreich et al., 2013; Miall, 2006). A common technique used to extract this information is deterministic seismic inversion. This attempts to recover reservoir rock and fluid properties from seismic reflection data. This method has been applied successfully to the Pluto field in the past, however interpretation was limited by seismic data quality & bandwidth, along with inaccuracies within the geological trend model (low frequency model).

Within the deterministic inversion workflow, low frequency information is critical in mapping background geological trends and hence extracting absolute reservoir properties (Ozdemir, 2009; Reiser et. al., 2012). The inability to accurately quantify absolute values of elastic reservoir rock properties inhibits identification of fluid and lithology trends. The lack of low frequencies within conventional seismic data forces geoscientists to rely on a priori models, often created from well or velocity information. The reliance on interpolating low frequency information (<10 Hz) from sparsely spaced wells can heavily bias and smooth results, potentially leading to incorrect reservoir interpretations.

Improving the low frequency content of seismic measurements has been achieved through increased signal bandwidth, along with advances in high resolution seismic velocity model building via the use of Full-waveform Inversion (FWI). Generating detailed, accurate low frequency information facilitates extraction of greater geological detail directly from seismic data. Kneller et. Al (2015) and Reiser & Ribeiro (2012) have shown broadband data alone can improve reservoir characterisation results, however the combined use of broadband seismic and FWI models as input into deterministic inversion has not been properly explored. High resolution FWI models have potential to be a reliable source of missing geological information, for use in low frequency models in the deterministic inversion workflow.

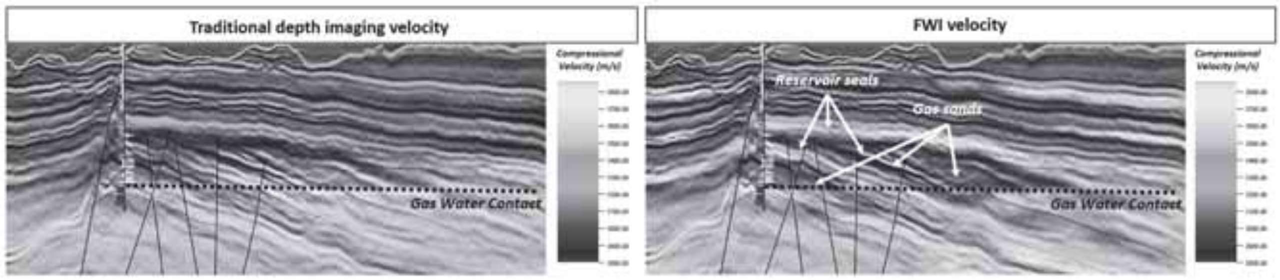

Figure 1 Comparison of additional reservoir detail captured within the FWI velocity (right) versus traditional seismic velocity (left)

This project applies newly available broadband seismic data and the FWI velocity model (see Figure 1) to perform a detailed analysis of the Pluto gas field via a deterministic seismic amplitude inversion and interpretation of the inversion results. This work provides guidance for the adoption of FWI for reservoir characterisation in the near future. Specifically, it provides further understanding on which geophysical parameters (velocity, density or impedance) FWI is most sensitive to at certain depths, and presents an FWI based deterministic inversion workflow that may be fine-tuned in the future (with additional understanding and improved FWI algorithms/implementation). The project has two main objectives:

1. Determine the best method of incorporating current FWI data into the reservoir characterisation workflow.
2. Assess the reservoir characterisation benefits that FWI technology may provide.

2. FWI constrained deterministic seismic inversions

Model-based deterministic seismic inversion is essentially a data modelling and comparison exercise. Using an initial geophysical model (described via acoustic impedance, compressional velocity to shear velocity ratio & density), along with an estimated seismic wavelet, synthetic seismic data is generated. This is then compared to the real data, and the geophysical models are perturbed until the synthetic matches the real data within a specified threshold. Aside from the low frequency models, the workflow was executed in a traditional sense. For this work Schlumberger's Petrel software was used. A total of 8 exploration wells were incorporated into the study, with 3 of them used to extract multi-well seismic wavelets. Three seismic angle stacks were also used in the inversion: 2-14°, 14-27°, 27-40°. Data analysis showed that seismic information above 6 Hz could be confidently used within the seismic inversion. Lower frequency information is supplied via the low frequency model.

Several low frequency models were generated and input into deterministic seismic amplitude inversions. As a baseline, a traditional low frequency model was first generated by interpolating and extrapolating low frequency information from well logs, with guidance from interpreted geological surfaces and a traditional velocity field (in this case the travel-time tomography depth imaging velocity field). A detailed analysis of the FWI velocity field was then performed and multiple low frequency models were constructed.

The accuracy of the FWI velocity was assessed via comparison against the sonic velocity well logs (filtered to match seismic bandwidth). At times less than 2 seconds, the FWI velocity field is expected to match the sonic log very well (there is no well information this shallow). This is due to excellent coverage of diving wave information, which can be used to accurately update the smooth part of the velocity field (Alkhalifah, 2014). However, within the reservoir interval, analysis indicates that the FWI ‘velocity’ closely reflects changes in acoustic impedance. This is not entirely unexpected. At these depths, FWI relies on information from seismic reflections. When using reflection information over a limited offset range, the inversion result is highly non-linear. A reduced sensitivity to changes in velocity leads to multiple combinations of velocity and density being able to produce the same reflection characteristic (shape & amplitude). Hence some degree of leakage is expected within current implementations of FWI.

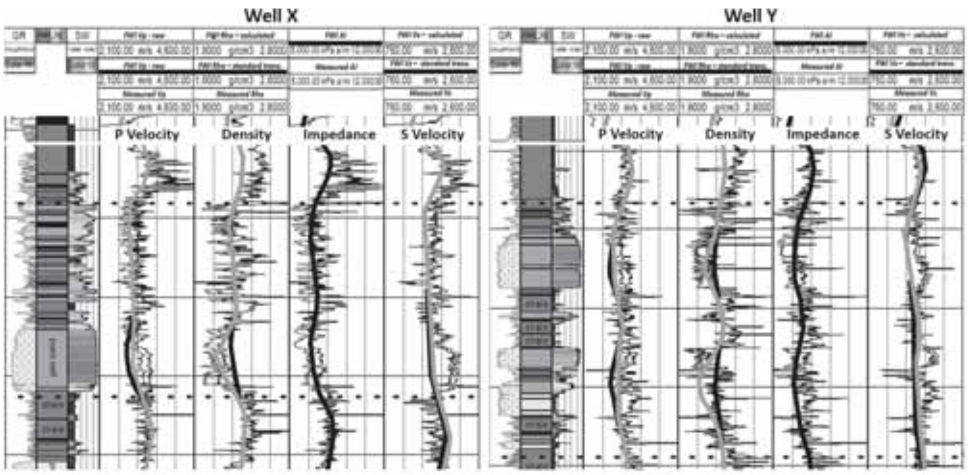

Figure 2 Comparison of FWI derived properties against equivalent well logs (in depth).

Figure 2 compares FWI ‘velocity’ (thick black curve in the left panel for each well) against the sonic log. In most instances, the compressional velocity (V_p) remains reasonably constant, even through gas zones (which only show minor deflections due to gas). As such, a clipped version of this log (thick grey) appears to provide a better match than the raw FWI velocity. Furthermore, when the raw FWI velocity is converted to acoustic impedance (through multiplication with a density log generated from FWI ‘velocity’ via the standard Gardner velocity-density transform), the resulting curve correlates nicely with the acoustic impedance well log (thick black curve in the third panel for each well). All significant acoustic impedance inversions, caused by the presence of gas, are captured. This indicates that the gas affects formation density more than V_p. Such inversions can be observed within the density log in all wells. If the FWI acoustic impedance curve is divided by the clipped FWI V_p curve (thick grey), then the resulting density curve (thick grey curve in second panel for each well) matches the well response nicely.

These observations were used to generate an acoustic impedance and density low frequency model. The underlying assumption is that the FWI model is a representation of both velocity (V_p) & density effects (i.e. acoustic impedance). Estimation of shear velocity (V_s) was achieved via a Greenburg-Castagna type transform using the available well data. As such, Vs is expected to have the greatest error - due to being somewhat decoupled from V_p (and thus reacting differently to the presence of gas). Formation density has an influence on V_p, and exhibits a similar gas response, hence these two parameters/models are expected to be more accurate.

Four FWI constrained deterministic inversions were performed using the FWI models described above. Two inversions were executed using low frequency models with information up to 6 Hz: one using the FWI low frequency models directly (without any well log contribution), and the other using the FWI models only as a spatial guide for the interpolation of the equivalent well logs. This experiment was then repeated using a broader frequency range (up to 15 Hz).

3. Inversion Results

Figures 3 presents representative inversion results. The left curves are the product of a traditional inversion, whereas the curves on the right were produced using only FWI data to build the low frequency models (without well or horizon constraints included). An improved differentiation of the reservoir gas sands (i.e. reduced impedance and density) can be observed within the FWI constrained results – as indicated by the closer match between well log and inversion curves. However, the result still suffers from inaccuracies within the ultra-low frequency component. These depth trends are improved when incorporating well data within the low frequency model building process. In this implementation, the FWI models are used only to assist the spatial interpolation/extrapolation of well logs.

Incorporating FWI models only as interpolation guides, also helps reduce the impact of artefacts contained within the FWI models. Analysis revealed that these artefacts are located predominantly within the south and eastern sides of the study area, and are a function of FWI starting model accuracy. These artefacts materialise as a result of an incorrect starting trend for FWI (the conventional travel-time depth imaging velocity field) and are persistent even down to 6 Hz, albeit not as severe compared to the FWI model filtered to 15 Hz. At these locations, the velocities are either too high or too low for the reservoir. The reduced ability of FWI to update low wavenumbers within the reservoir interval, due to no diving wave penetration at this depth, causes the FWI to become stuck within local minima. These artefacts subsequently lead to larger errors within the FWI based deterministic seismic inversion results in these areas. It is important to note that the velocity guide (depth imaging velocity field) used to build the traditional low frequency models also suffers from the same problem.

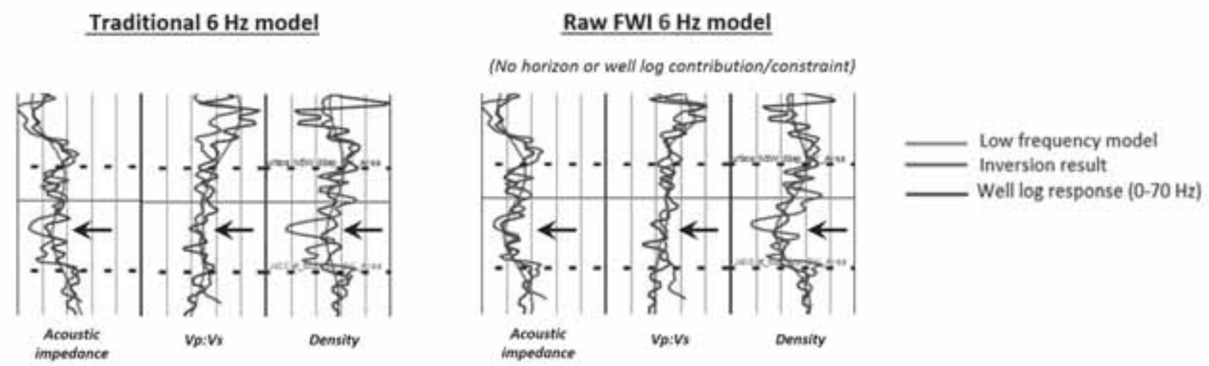

Figure 3 Traditional vs raw FWI inversion results (in 2-way-time) at Well Z.

A fluid and lithology extraction was also performed to highlight changes between inversion results. This was achieved via the definition of fluid and lithology classes within cross-plots of the inversion attributes produced by each inversion, as defined by the well data. This information was subsequently used to create a probability density function for use in a Bayesian lithology classification to facilitate the extraction of gas sand geobodies. Cross sections through the gas sand probability cube are presented in figure 4 for each low frequency model. The results show that all FWI constrained inversion results (figure 4c & 4d) predict a greater spatial gas sand extent compared to the traditional inversion (figure 4a). This is especially evident within the upper two reservoir units (units 1 & 2), which have only been penetrated by two wells. Within these units, the traditional model will likely be less accurate. However, it is also important to recognise the impact of using water saturated logs (rather than in-situ logs) to build a traditional low frequency model. This is especially important for the Pluto field, due to the thick gas column - where an appreciable and important gas effect is recorded within the low frequencies. If this component is neglected, then the gas effect will naturally be reduced. Such a comparison will overstate the improvement FWI provides to reservoir characterisation.

When using traditional low frequency models constructed using in-situ logs (figure 4b), a significant increase in the connectivity and spatial limit of the gas geobodies appears (compared to the water saturated case of figure 4a). The gas effect also does not appear to have been propagated further than the gas-water contact identified from well pressure tests. The distribution and size of the resulting geobodies is also very similar to the FWI guided results (figure 4d). This is positive in two aspects. Firstly, the motivation for using water saturated logs within traditional low frequency models is to prevent propagating local hydrocarbon effects everywhere through the model. In the case of Pluto, this doesn’t appear to have happened, and is likely due to excellent well coverage within the field. This hypothesis is supported by the results obtained when only two wells are used in the creation of the low frequency model (figure 4e). In this case the gas sand geobody volumes are considerably increased, indicating that the gas effect has been propagated too far. This will result in gas volumes being overestimated. Secondly, the ability of FWI data alone to predict similar results to a traditional low frequency model (which has excellent well constraint incorporated) shows the potential power of FWI in locations with limited to no well coverage (i.e. exploration settings). However, the geoscientist will need to be mindful of errors related to the accuracy of the FWI model. With these points in mind, it is thus important to either have good well coverage through all reservoir units, or a good spatial guide model (like FWI data) to help describe the geological variability within the reservoir.

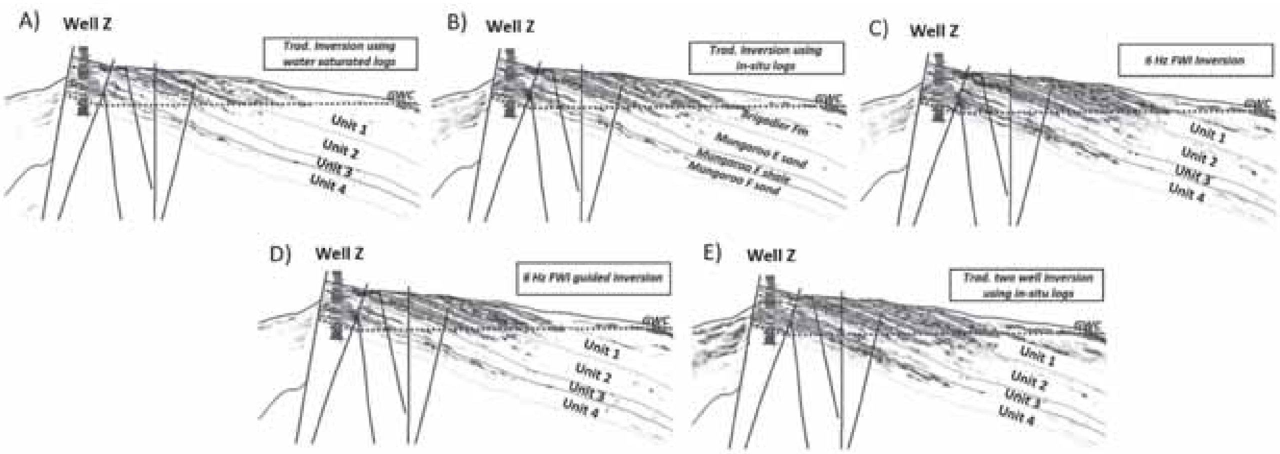

Figure 4 Comparison of gas probability estimates at Well Z. All sections are presented in depth.

4. Conclusions

Incorporating Pluto FWI data into the deterministic inversion workflow has shown encouraging results - however the quality of the FWI starting model appears to still be a major source of inaccuracy. Despite the limitations of current FWI technology, the high resolution FWI model was successfully incorporated into the deterministic inversion workflow with only minor calibration to the wells. For the Pluto gas field, the greatest benefit arises within the uppermost reservoir units (units 1 & 2), which have limited well coverage. However, the benefits vary across the survey area as a function of FWI model quality. The implementation of a 6 Hz FWI guided inversion starting model appears the best method of incorporating FWI data into the Pluto deterministic inversion workflow – as it removes the impact of inaccuracies within the ultra-low frequency component of the FWI velocities. It also limits the effect of FWI artefacts.

Overall, the traditional inversion (using in-situ well logs) results are very similar to the FWI guided inversion, despite the inaccuracies within the FWI model. This is due to the excellent coverage of well information. However, when the number of wells incorporated into the traditional low frequency model is reduced, the gas effect propagates too far and leads to a potential exaggeration of gas sand distribution. This suggests that the greatest benefit FWI may provide to the deterministic inversion workflow is to provide a source of spatial information in areas with minimal well coverage. However, care needs to be exercised when interpreting the results, as any artefacts within the model may falsely predict fluid and lithology classes. Small changes in the absolute values of elastic properties can significantly alter the classification.

5. Acknowledgements

Special thanks to Arturo Contreras, Grant Fryer, Paul Spaans & Chris Hug. Your feedback and software support ensured that this fast-paced project stayed on track.

6. References

Alkhalifah, T. (2014). Full Waveform Inversion in an Isotropic World: Where are the parameters hiding? (Vol. 10). Houten, Netherlands: EAGE Publications.

Heldreich, G., Redfern, J., Gerdes, K., Legler, B., Taylor, S., Hodgetts, D., & Williams, B. (2013, August 18 - 21). Analysis of Geobody Geometries within the Fluvio-Deltaic Mungaroo Formation, NW Australia. Proceedings: The Sedimentary Basins of Western Australia IV: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, Western Australia.

Kneller, E., Ferrer, A., Langlois, J., & Mittaine, F. (2015). Benefits of Broadband Seismic Data for Reservoir Characterisation - Santos Basin, Brazil. Prcoeedings EAGE Workshop on Broadband Seismic - A Broader View for the Middle East, Abu Dhabi, UAE.

Miall, A. (2006). The Geology of Fluvial Deposits. Germany: Springer.

Ozdemir, H. (2009). Unbiased deterministic seismic inversion: more seismic, less model. First Break, 27(11), 43 - 50.

Reiser, C., Bird, T., Engelmark, F., Anderson, E., & Balabekov, Y. (2012). Value of broadband seismic for interpretation, reservoir characterisation and quantitative interpretation workflows. First Break, 30(9), 67 - 75.

Reiser, C., & Ribeiro, C. (2012). Impact of the dual-sensor acquisition on reservoir characterization studies. Proc. SEG Annual Meeting, Denver, Colorado, USA.