# OVERCOMING SHALLOW WATER IMAGING CHALLENGES IN AUSTRALIA’S NORTH WEST SHELF

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## Summary

The North West Shelf, situated in Western Australia, is a world-class offshore hydrocarbon province. The presence of hard water bottom, near water bottom reflectors and shallow Tertiary carbonates not only generates strong multiples but also distorts the ray-paths for deeper reflectors. Seismic data quality is severely deteriorated due to residual multiples, limited bandwidth, and poor signal-to-noise ratio, impeding reservoir delineation and further AVO/QI analysis. With the recent advancement of seismic imaging technologies, we propose an integrated workflow including (1) comprehensive demultiple and (2) hybrid tomography and Time-lag Full-Waveform Inversion (TLFWI) to overcome these long-standing imaging challenges. The significant uplift of the reprocessed image provides deeper insights into the subsurface geology and improves confidence of prospect mapping for exploration.

## Introduction

The North West Shelf, located in offshore Western Australia, is a world-class gas province with significant oily sweet spots (indicated by the green box in Figure 1). It has been operating for more than 30 years and delivered one-third of Australia's oil and gas production with investments of more than $150 billion to date. Exploration work of lower Cretaceous to Triassic reservoirs in this shallow water area requires high-quality seismic images. Unfortunately, the rugose and hard water bottom generates strong multiples, which leads to difficulty for the demultiple process. Moreover, the shallow fast layer Tertiary carbonates further reduce the penetration depth of diving waves and increase illumination issues. Image quality thus deteriorates severely at the reservoir due to the distortion of the ray-paths caused by shallow anomalies and residual multiples.

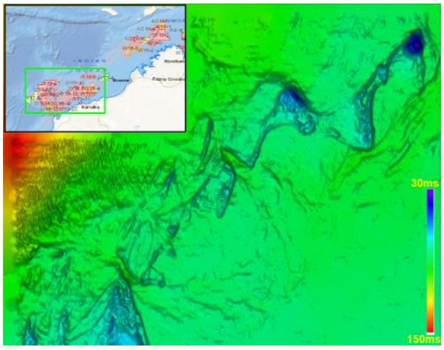

***Figure 1** Davros water bottom map*

The legacy Davros 3D survey was acquired in 2015 and is located on the North West Shelf. The acquisition configuration included 12 streamers with a cable length of 8 km and a cable spacing of 100 m, and a nominal near offset of 200 m. The wide-tow acquisition in this shallow water environment poses further imaging challenges including multiple attenuation and velocity model building. Tremendous processing efforts have been conducted, but the results are not yet satisfactory. Thanks to the evolution of imaging technologies, more advanced workflows, including multiple attenuation and velocity model building, can now be integrated to overcome the imaging challenges. We demonstrate the value added from using these technologies during the reprocessing of the legacy dataset.

## Advanced multiple attenuation flow

Effective water-layer-related multiple attenuation is very challenging for shallow and rugose water environments such as the North West Shelf. Adding to the difficulties is the wide-tow acquisition, with sailline spread of 1200 m, which limits near-offset coverage. Different techniques have been implemented to rectify these issues. Wave-equation-based water-layer demultiple (MWD) has been proposed and proven to be an effective tool to facilitate water-bottom-related multiple attenuation (Wang et al., 2011). In our work, the accuracy of the rugose water bottom can be further enhanced by multiple migration (Yang et al., 2013). This improved prior water bottom knowledge resulted in more accurate amplitude and phase of the MWD model, which led to better subtraction. However, MWD was unable to model the multiples generated by near seabed reflectors, indicated by the blue arrows in Figure 2a. In this regard, a data-driven modelling method like shallow-water demultiple (SWD) (Yang et al., 2013) can predict the multiple model without prior information. However, for shallow water data, near offset extrapolation is typically difficult as the curvature of primaries and multiples can change dramatically. Hence, the inverted SWD operator is commonly contaminated by severe stretching or unreliable near offset information. In this study, the MWD and SWD models were utilized simultaneously to optimize the final subtraction. Figure 2b shows the subtraction result of an outer cable near channel (offsetx: ~300 m; offsety: ~550 m). The auto-correlation (full window, Figures 2c and 2d) shows the statistical improvement: the wavelet became sharper once the clusters of multiple ringing in the near offsets were eliminated. The weak primary signal was effectively revealed, as illustrated by the green arrows in Figure 2d.

Strong velocity contrasts are present in the North West Shelf sedimentary sequence, where pre-rift Triassic intracratonic sediments are overlain by Jurassic to Cainozoic syn- and post-rift successions. These reflectors generate strong long-wavelength surface-related multiples. The tuning and cross-talk between different orders of multiples hinder the amplitude accuracy of the predicted multiple model, which negatively impacts the subtraction. In addition, the dips of the weak primary signal and multiples are difficult to discriminate in the channel domain. Together, these issues result in either primary damage or residual multiples. In our work, recursive SRME modelling was conducted to correct the amplitude prediction, followed by one extra pass of residual SRME after offset binning to model the amplitudes of higher-order multiples more accurately. Similar to what Chua et al. (2019)

suggested, we extended the crossline dimension for subtraction to preserve weak primaries by increasing the sparseness of the dip separation in crossline direction. Figure 3 illustrates the PSDM full stack results comparison (0-35° in depth) between conventional SRME and our proposed flow. The new flow resulted in less residual multiples and increased signal-to-noise ratio (S/N).

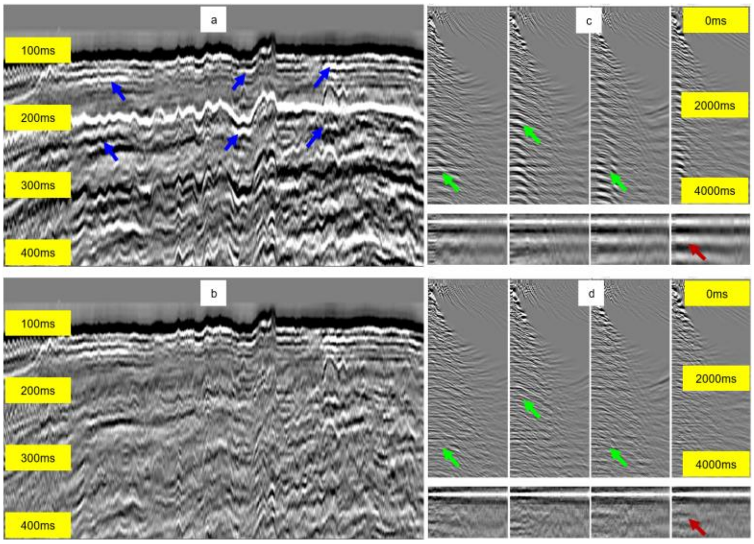

***Figure 2*** *Outer cable near channel display: (a) input and (b) after SWD+MWD; NMO CDP gathers with auto-correlation at bottom: (c) input and (d) after SWD+MWD*

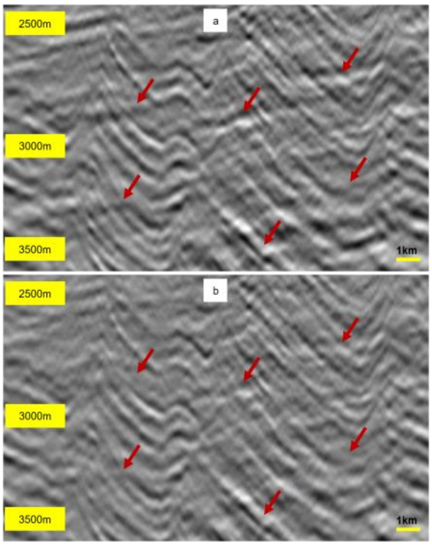

***Figure 3*** *Kirchhoff PSDM full stack: (a) after conventional SRME (b) after recursive SRME + one pass of residual SRME after binning*

## Advanced velocity model building flow

The presence of a shallow carbonate layer in the area not only generates strong multiples but also constructs complex ray-paths, which causes unreliable curvature picking and inhibits tomography from producing meaningful shallow velocity updates. Conventional application of full-waveform inversion (FWI) on this dataset is also limited due to low S/N at low frequencies. Zhao et al. (2018) propose a hybrid velocity model building flow by iterating FWI and tomography to stabilize the model update in complex areas with shallow overburden. In addition, the shallow carbonate layer generates complex wavefield and amplitude variations caused by velocity inversion, leading to cycle-skipping issues with conventional FWI. To overcome this challenge, Zhang et al. (2018) propose a new FWI approach, Time-lag FWI (TLFWI), which uses a traveltime-based cost-function. This new cost-function has the potential to mitigate cycle-skipping and amplitude-discrepancy issues, leading to more reliable updates than conventional FWI.

The starting model for FWI was from the legacy 2016 reprocessing after a multi-iteration tomography update. The existing well log data indicate that the shallow carbonate can be as fast as 4200 m/s, and the thickness of the carbonate layer varies from nearly one hundred meters to a few hundred meters. The legacy model did not capture these features, resulting in the gather curvature highlighted by the green arrows in Figure 4c. With proper noise attenuation, we were able to run TLFWI from 3.5 to 8 Hz. Tomography was then employed to fine-tune the model. The updated model managed to capture the fast carbonate layer and also revealed velocity variations underneath the carbonate, as highlighted by the red arrows in Figure 4b. Figures 4c and 4d show that the gather curvatures caused by the previously incorrect carbonate velocity are now corrected. As a result, the carbonate events become more focused and continuous.

## Final imaging and inversion results

It needs to be pointed out that the legacy dataset had the latest technology at the time applied, such as MWD with curvelet-domain subtraction. Aggressive subtraction had to be conducted to attenuate the strong multiples, which led to image damage (pink box and red arrows in Figure 5a). Figure 5 shows the traverse line passing through the depicted prospects. Compared with the legacy stack, Figure 5b illustrates the crucial improvements and added value from our reprocessing flows: higher resolution in shallow images (indicated by pink box); more focused and continuous/coherent events at the reservoir level (red arrows); sharper fault delineation (green arrows); and greatly improved S/N (highlighted by blue oval). This provides the assurance of reliable interpretation and AVO for inversion analysis. Appreciable uplifts were also observed in the inversion domain. Figure 6 illustrates the inverted Vp/Vs ratio extracted from the interpreted reservoir formation. The lower value indicates sands bearing fluid. Overall, the new results are cleaner and the delineation of the prospects is sharper and clearer. Local geology studies show that the prospects are mainly stratigraphic traps overlapping with complex faults or channels at the reservoir level (Watkins et al., 2015). The legacy results could not identify these small-scale geological features. Conversely, the geological features are clearly visible on the new images, as highlighted by the blue arrows in Figure 6b. The false AVO response was caused by residual multiples as shown by the pink circle in Figure 6a, while that noise is supressed by our revised processing, resulting in more reliable AVO response. The new data instils higher confidence for further mapping of prospects and future detailed reservoir engineering work, such as compartmentalization analysis and flow study.

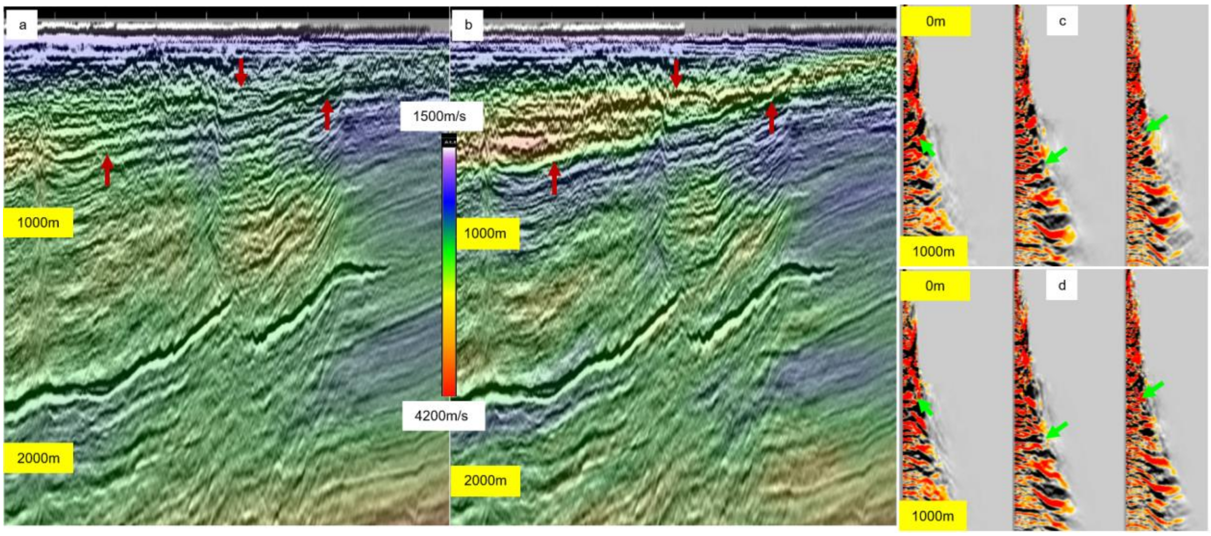

***Figure 4*** *Kirchhoff PSDM section passing through the shallow carbonate: (a) overlaid with legacy model (b) overlaid with 8 Hz TLFWI model; (c) and (d) corresponding CIGs around shallow carbonate area*

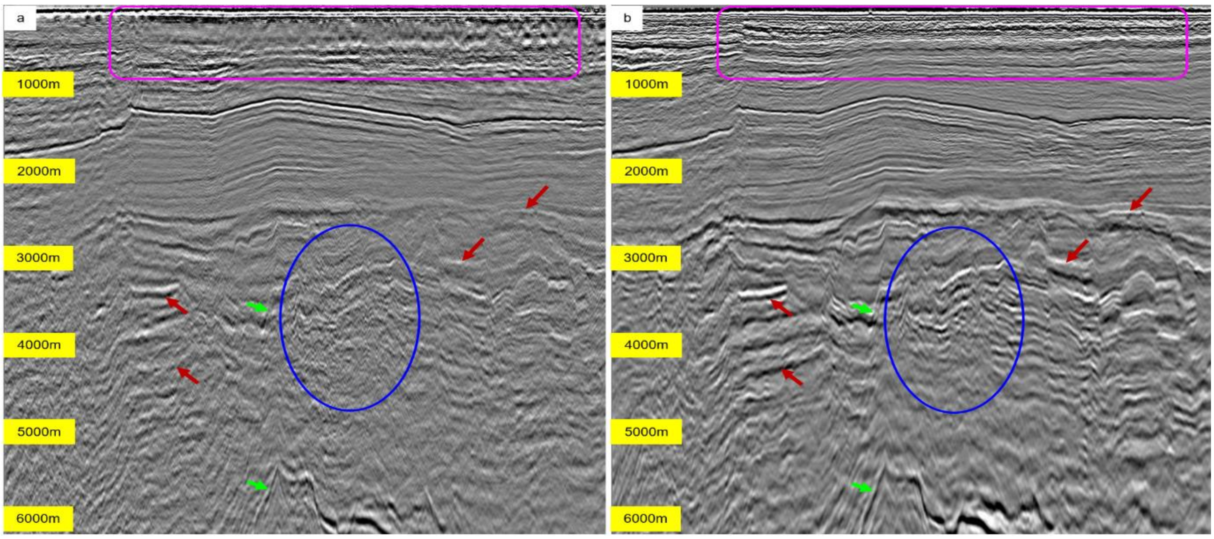

***Figure 5*** *Traverse line (far stack in depth) passing through key prospect: (a) legacy final PSDM and (b) reprocessed PSDM.*

## Conclusions

The North West Shelf has proven highly challenging due to its unique geological complexity. The poor quality of existing legacy seismic imaging has been a significant barrier to reducing exploration risk. With the advancement of high-end imaging technologies, an integrated demultiple and hybrid velocity model building flow was adapted to overcome the existing challenges. Compared with legacy images, the newly reprocessed data not only yield substantial improvements in imaging but also add further insights into subsurface geological understanding. This work can be extended to adjacent North West Shelf areas or potentially other geologically similar shallow water environments.

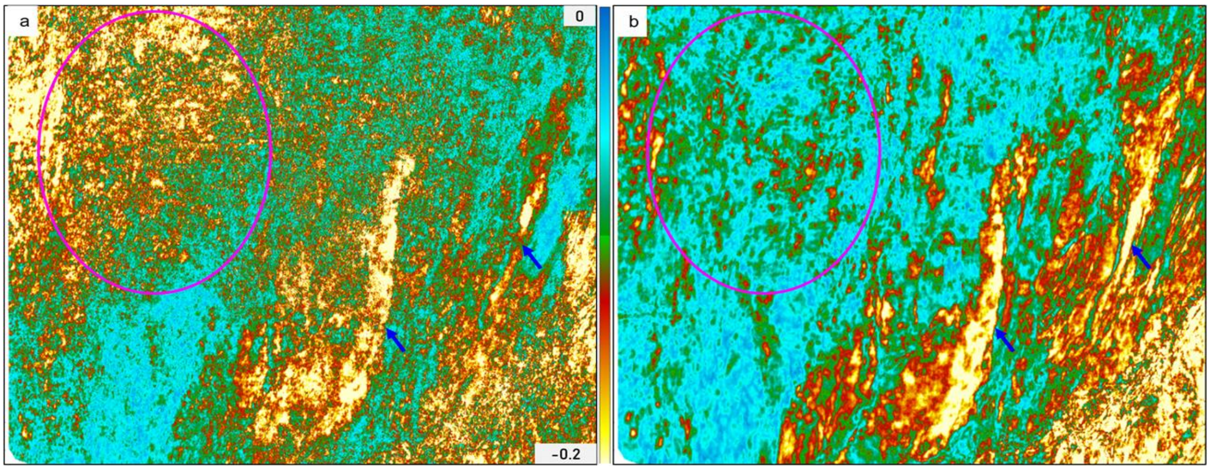

***Figure 6*** *Map view of extracted Vp/Vs ratio from reservoir inversion results: (a) inverted using legacy data; (b) inverted using reprocessed data.*

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