Case Study from N.W. Carnarvon using WEB-AVO Inversion to Map Low Saturation Gas & Unravel Geology Using "Noisy" Seismic

John Coffin
Delft Inversion
Paardenmarkt 1
2611PA Delft,
The Netherlands
coffin@delft-inversion.com

Angie Kelsay
Delft Inversion
Paardenmarkt 1
2611PA Delft,
The Netherlands
kelsay@delft-inversion.com

Shahid Ur Rehman
Chevron Australia Pty Ltd
250 St Georges Terrace
Perth, WA 6000
Australia
srehman@chevron.com

SUMMARY

This case study applies the next generation of seismic AVO inversion technology to a project in the NW Carnarvon Basin offshore Western Australia. The technology is called WEB-AVO (Wave Equation Based – AVO Inversion) and no longer considers the earth as a series of layers with interfaces that create primary only reflections. The difference is that WEB-AVO does not use the reflectivity and convolution model. Instead, it applies the wave equation that considers the total wavefield in the reservoir interval. This includes primaries, interbed multiples, mode-conversions and transmission effects.

The area studied considers the Main Barrow Sand for a blind test and then looks at the Mungaroo which is known to have a complex wavefield in this area. The Mungaroo has significant overburden challenges, and it is not obvious if these are creating AVO false positives.

The results show a robust match to a blind well in the Barrow Sands which confirms the stability of the algorithm. In the Mungaroo we used a technique called Interbed Multiple Investigation (WEB-IMI) to explore the source of the complex wavefield. We studied the progression of the wavefield over the interval and see the compounding effects from the non-primary energy. In the inversion we contrast the results using a conventional inversion (where primaries only are considered) and contrast this with the WEB-AVO results on both "raw" and "conditioned" gathers. We see the greatest uplift between the primaries only and the WEB-AVO results and discuss the conditioning. Finally, using the inversion products; compressibility (κ) and shear compliance (M), we were able to separate the different reservoir sands present within the Mungaroo. We identify unique characteristics in this domain, and this then allowed us to resolve the confusion caused that was caused by the AVO false positive.

Key words: AVO, Inversion, Full Waveform, Gas, Mungaroo, NW Shelf, Offshore, Triassic.

INTRODUCTION

In this case study we will be exploring the practical application of a novel wave equation based AVO inversion (WEB-AVO) method (Gisolf et.al, 2017) to a prospective area of the NW Carnarvon Basin. The zones of interest (ZOI) are from the Cretaceous (Barrow Group) and Upper Triassic (Mungaroo Sands) and we have two wells penetrating the Barrow and just one in the Mungaroo.

The work is a subset of a WEB-AVO technology evaluation with Chevron Australia Pty Ltd which was still active at the time of writing. Three objectives were defined to measure the success of the project in this area.

Objective 1: Demonstrate the reliability of the WEB-AVO inversion technology through a satisfactory blind prediction in the Cretaceous Barrow section
Objective 2: To achieve reliable inversion results even in the presence of coherent noise within the seismic data
Objective 3: Predict AVO false positive (abnormal porosity and/or low saturation gas sands)

To begin the project (Objective 1) we studied the deepest well to produce a well tie, depth trend and set of wavelets to enable the WEB-AVO blind test in the Main Barrow Sand. We then looked at the deeper Mungaroo interval (Objective 2) where we move into the Upper Triassic where and the overall strength of the seismic reflections is lower than in the Cretaceous. We also observe significantly more coherent noise in this interval and suspected a Marl in the overburden was connected. Using WEB-AVO we were able to model the impact of the Marl, and this turned out to be a significant factor in the overall result. The focus then shifted to the deeper sands of interest in the Mungaroo and to understand the relationship between the AVO response observed, through the WEB-AVO inversion products of compressibility (κ) and shear compliance (M), and exactly how this was uniquely linked to the measured porosity and gas saturation in the deeper well (Objective 3).

Throughout the work we have looked at the impact of low frequency models (LFM) and seismic data conditioning on the WEB-AVO results. In short, we find that the LFM is of negligible impact provided we stay out of the seismic bandwidth. In regard to the seismic data, we expected that the less conditioned "noisy" seismic would give us the "cleanest" inversion results. This expectation was based on an assumption that the primary reflections, multiples, mode conversions and transmission effects were better preserved. In reality, what we found was that the raw and conditioned seismic data yielded very similar inversion results. Clearly a different conditioning workflow may not produce the same conclusion, however a review of seismic data conditioning for AVO inversion is out of the project scope. It was viewed that the conditioning of the seismic data was mainly cosmetic and that the WEB-AVO inversion results were not significantly impacted as a result.

METHOD AND RESULTS

The WEB-AVO inversion uses plane wave domain (tau/ρ) CDP seismic data. Where tau (t) is the vertical intercept time or travel time contribution due to the vertical component of a plane-wave's slowness, and p is the ray-parameter or horizontal component of a plane-wave's slowness (Snell parameter). Using the interval velocity (Vint) from the migration we calculate the p traces at angle of incidence (θ) using the well-known formula:

$$p(t) = \sin\theta / \mathrm{Vint}(t)$$

To complete the detail of the theory being used we consider the physical laws controlling how medium properties and propagating elastic waves interact. This is using Hooke's Law and the second Newton's law with the connection being made using the stress tensor and the particle velocity vectors. While it is beyond the scope of this paper to go into any more detail it is important to state that the products generated are in the depth domain and consider compressibility κ (inverse of bulk modulus), shear compliance M (inverse of shear modulus) and density ρ. This set of elastic properties is generally three times more sensitive to pore fill and lithology changes when compared to acoustic impedances (Gisolf, 2016).

In this project we created five slowness traces targeting the Barrow and Mungaroo. Considering an average velocity of 3500 m/s the slowness traces correspond to an approximate angle range of 12-45º.

The next step was to understand how the elastic modelling on the Barrow-Mungaroo interval presented as a function of the ray-parameter (p) The Kennett algorithm was applied (Kennett, 1983), this is analogous to the 1.5D integral formulation (Yang et al, 2008) that is used in WEB-AVO. However, this is calculated in a different manner and so provides an independent assessment of the applicability of a WEB-AVO inversion to a specific project. In Figure 1 we show the raw and conditioned gathers for the deeper well placed alongside the primaries only and elastic wave synthetics. We can clearly see the variability in the seismic data (raw and conditioned) however you have to look carefully to notice the difference in the primaries only and elastic wave synthetics.

What we see in Figure 2 are synthetics generated using the elastic wave scheme (Kennett) and a primary only scheme (Shuey) on the deepest well. The idea is to understand if the geology present is generating any non-primary energy and where this non-primary energy will start to interfere in any inversion we are considering. What we see is that until we reach a specific marker (Marl) the elastic and primary results are very similar which tells us there is little to be gained from a WEB-AVO inversion. However, as we go deeper and pass the Marl the effects start to compound, and the elastic and primary synthetics diverge. This means that if we use an inversion scheme that only considers primaries, we are going to introduce error.

With a clear understanding that we have non-primary energy being created it is now important to understand exactly where and how this occurring. In Figure 3 we are show a 'VSP-type display which connects the subsurface properties in depth with the recorded traces in time and is chosen as the most effective way to visualize the wave fields for a specific ray parameter (p), here approximately 45 degrees. We see three panels which show primaries only, primaries with interbed multiple and transmission effects and mode conversions with transmission effect. All displays are in time and the horizontal axis is depth. What is clear is that down to the Lower Barrow sands we are dealing with primaries only, then once we encounter the Marl which is approximately 30m thick significant scattering of the wavefield occurs. This produces interbed multiples and mode conversion and we have highlighted some of the paths they follow. What is very obvious is that in the Mungaroo we have a complex wavefield where multiples and mode conversions are interfering with the primary reflections of the sands. Therefore, it is highly likely that any inversion which does not take this into consideration and derives elastic properties (AI/Vp-Vs) which are then classified to lithology, porosity or saturation estimates will suffer.

The WEB-AVO inversion was undertaken on a small swath of 3D seismic data (60,000 CDP's at 80 fold) which connects the two wells. Two separate runs were completed so that a direct comparison between the results from the "raw" and "conditioned" gathers could be studies. In addition, a primary only (linear style) inversion was undertaken to provide a benchmark product that is similar to what is done with conventional AVO inversion schemes today.

Objective 1 Results

The Barrow interval was successfully recovered in the shallow well in both the compressibility (κ) and shear compliance (M) domains. A 1 Hz depth trend provided the initial incident field, and the broadband seismic data completed the spectrum with energy present below 2Hz. What was apparent was that some of this low frequency energy which would normally be considered noise was being used in the WEB-AVO inversion.

Objective 2 Results

The Mungaroo interval synthetics clearly demonstrated a complex wavefield with constructive and destructive interference being present. It is well known that seismic processing will always face a tough challenge when trying to remove effects caused by geology like the 30m Marl, as the thickness and depth can only be estimated.

The inversion parameters used within the Mungaroo interval followed that of the Barrow. The low frequency model remained a 1Hz depth trend and the WEB-AVO inversion iterated until the elastic properties and wavefield no longer changed (10-15 iterations).

What the inversion shows us is the "raw" and "conditioned" gathers give us broadly similar results. Figure 4 is a comparison of the inversion products at the wells, and we highlighted some areas of difference. What we see is the largest differences are on the shear compliance (M) which is due to miss-alignment of the events in time. This can be further improved by additional seismic processing, however, was not the main purpose of the study.

With Figures 5a and 5b we show the fully inverted WEB-AVO compressibility (κ) and shear compliance (M) alongside a primary only (linear inversion). Here you can see how the WEB-AVO has recovered very well the geology between the wells. With the Barrow sands containing live gas clearly visible in both wells. In the deeper well we can easily identify the Marl and then the Mungaroo sands below. It is obvious just by looking at the compressibility (κ) that these sands have differences and when we start also investigating the shear compliance (M) there are different patterns visible. These products are then used in the classification (Objective 3) as we understand these patterns are related to the lithology and fluids present.

Objective 3 Results

A detailed analysis of Mungaroo interval in the deeper well was undertaken at seismic resolution to characterize the different sands present in the compressibility (κ) vs shear compliance (M) domain. Figure 6 shows us the results for the Mungaroo sands, we show the true log data filtered to the seismic bandwidth (0-0-40-60Hz), then the WEB-AVO inversion results at the well location and with 5 adjacent locations. It is clear that we are able to separate what we know as different sands as a function of porosity and saturation. When we contrast this against a similar display in Figure 7 using a conventional AVO inversion scheme where we use as AI vs Vp-Vs we clearly see the benefit of compressibility (κ) and shear compliance (M).

This is logical because compressibility (κ) is the inverse of the bulk modulus. Similarly shear compliance (M) is the inverse of shear modulus. These properties are significantly more sensitive to changes in physical properties than our traditional Acoustic Impedance (AI) and Vp-Vs attributes. On a final note, it is important to say that WEB-AVO can invert for density (rho) as well at compressibility (κ) and shear compliance (M). This does however rely on the seismic data having high enough angles of incidence at the target interval to be robust; unfortunately, this was not the case in this project.

CONCLUSIONS

In this case study we have applied the next generation of AVO inversion technology (WEB-AVO) to a challenging dataset from the NW Carnarvon Basin offshore Western Australia.

What we found was that conditioning pre-stack seismic data for the purposes of AVO modelling and inversion is somewhat unnecessary. We produced very similar WEB-AVO products whether or not the seismic was conditioned. This is because the WEB-AVO algorithm is engineered to fit the seismic data, which is inherently non-linear due to “noise” which always exists in recorded seismic data. This fundamentally differentiates WEB-AVO from the other approached which rely on a primary only assumption.

We demonstrated the importance of considering the geology above your reservoir interval and the effect it can have on an inversion result.

Finally, we showed how compressibility (κ) and shear compliance (M) provided a way for us to extract fluid and lithology information hidden within the seismic data.

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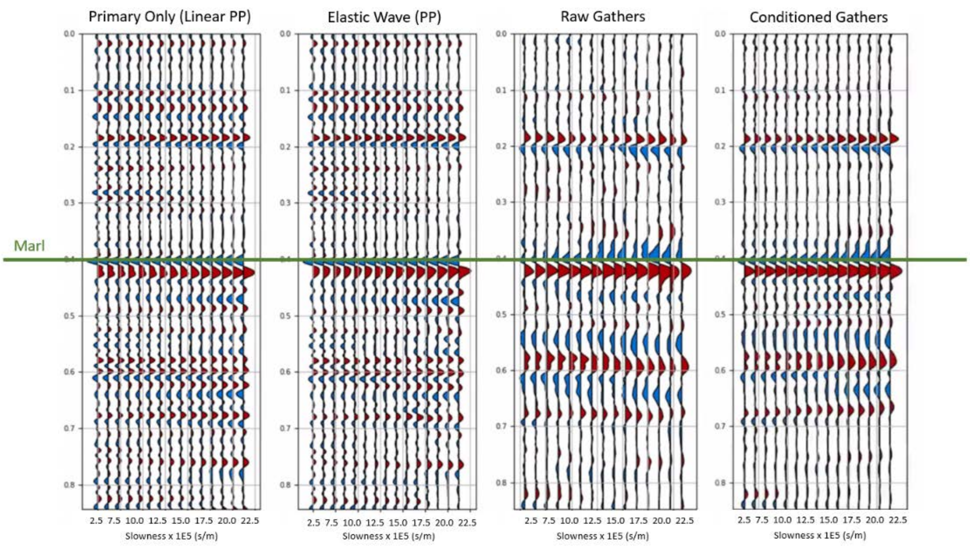

Figure 1. Raw & Conditioned Gathers from Deep Well Location with Primary Only and Elastic Wave Synthetics

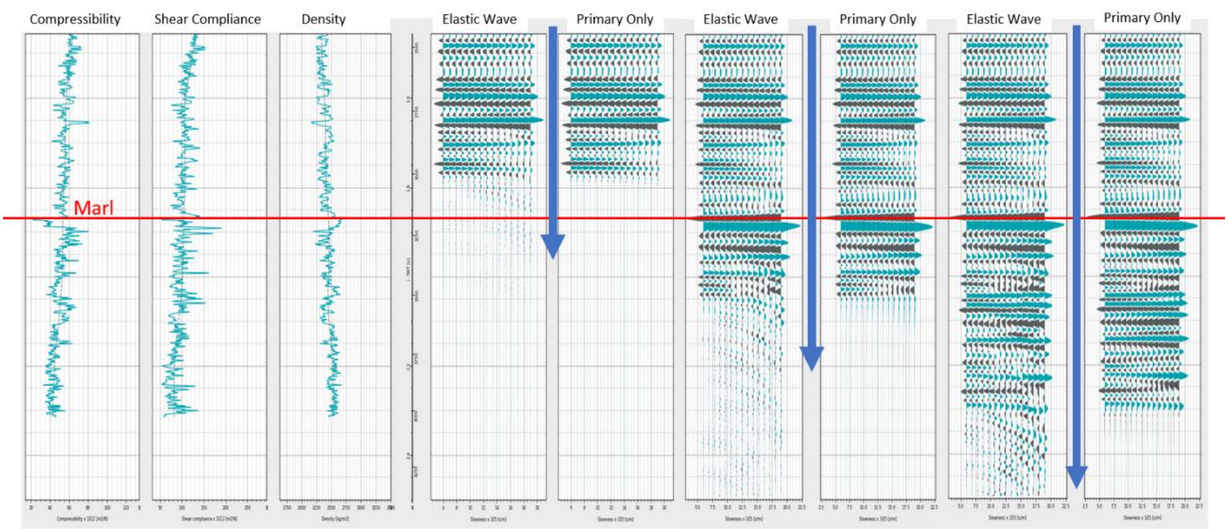

Figure 2. Elastic Wave (Kennett) & Primary Only (Shuey) Synthetics

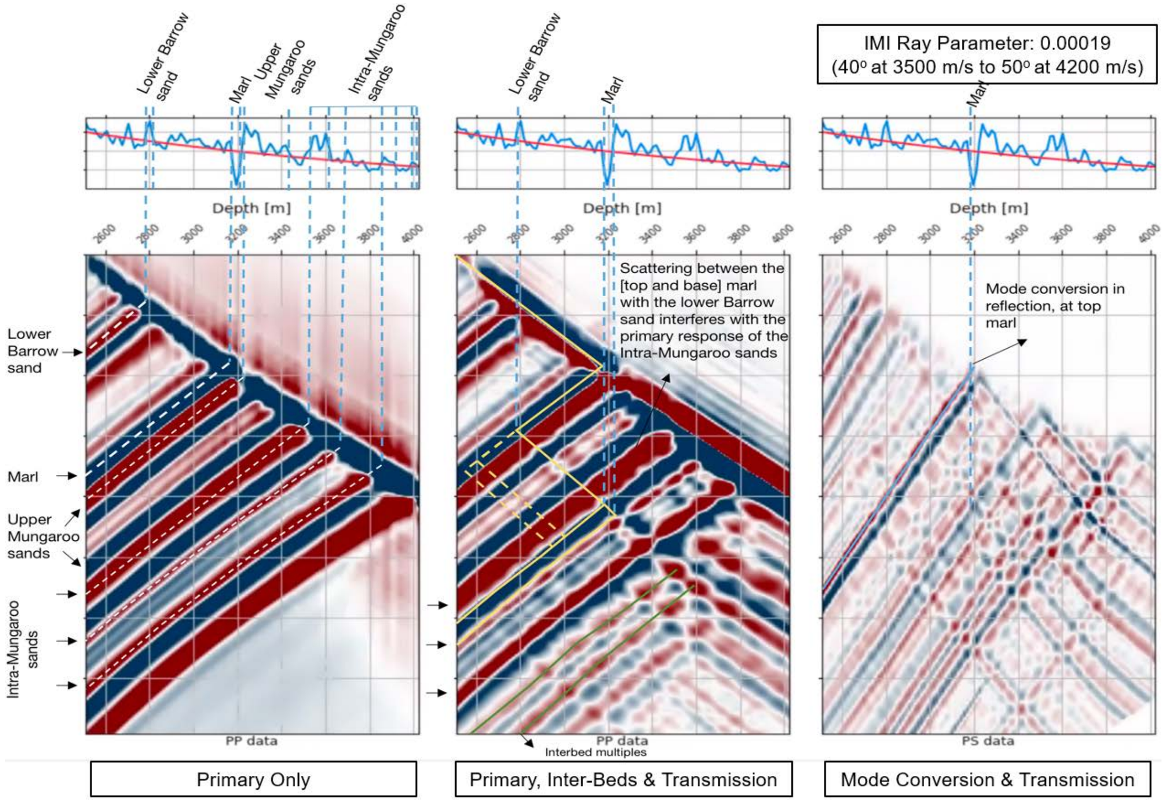

Figure 3. WEB-IMI Modelling for the Barrow-Marl-Mungaroo Interval in the Deep Well

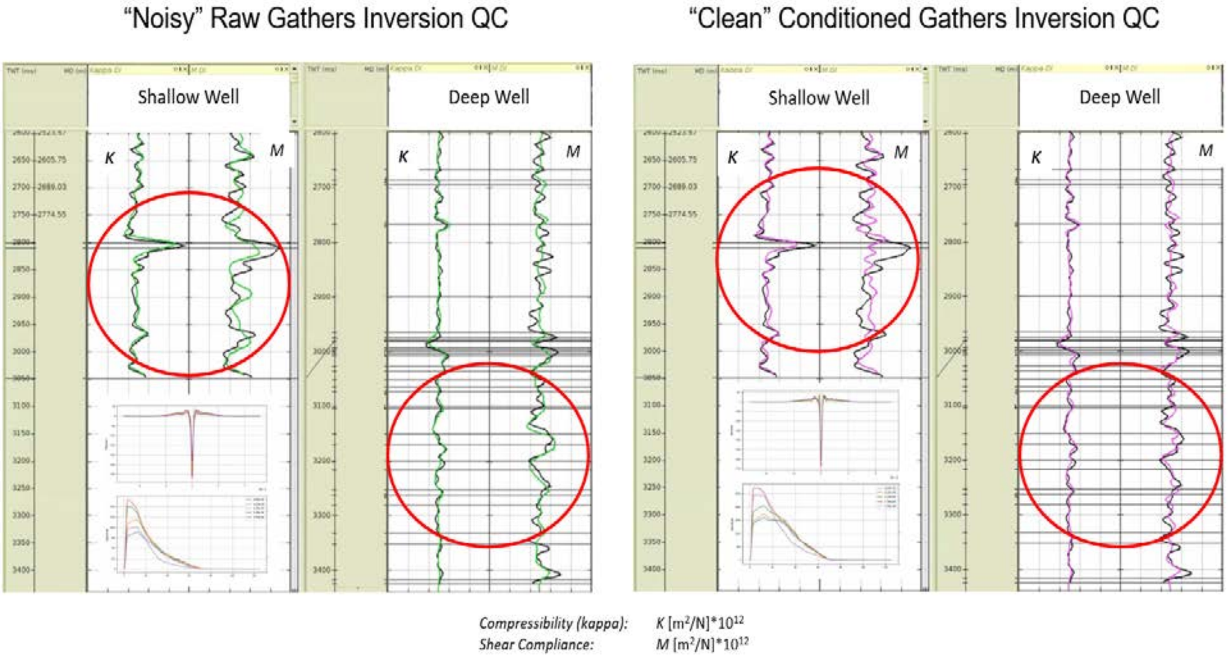

Figure 4. Relative kappa and M inversion QC for "Noisy" & "Clean" Gathers

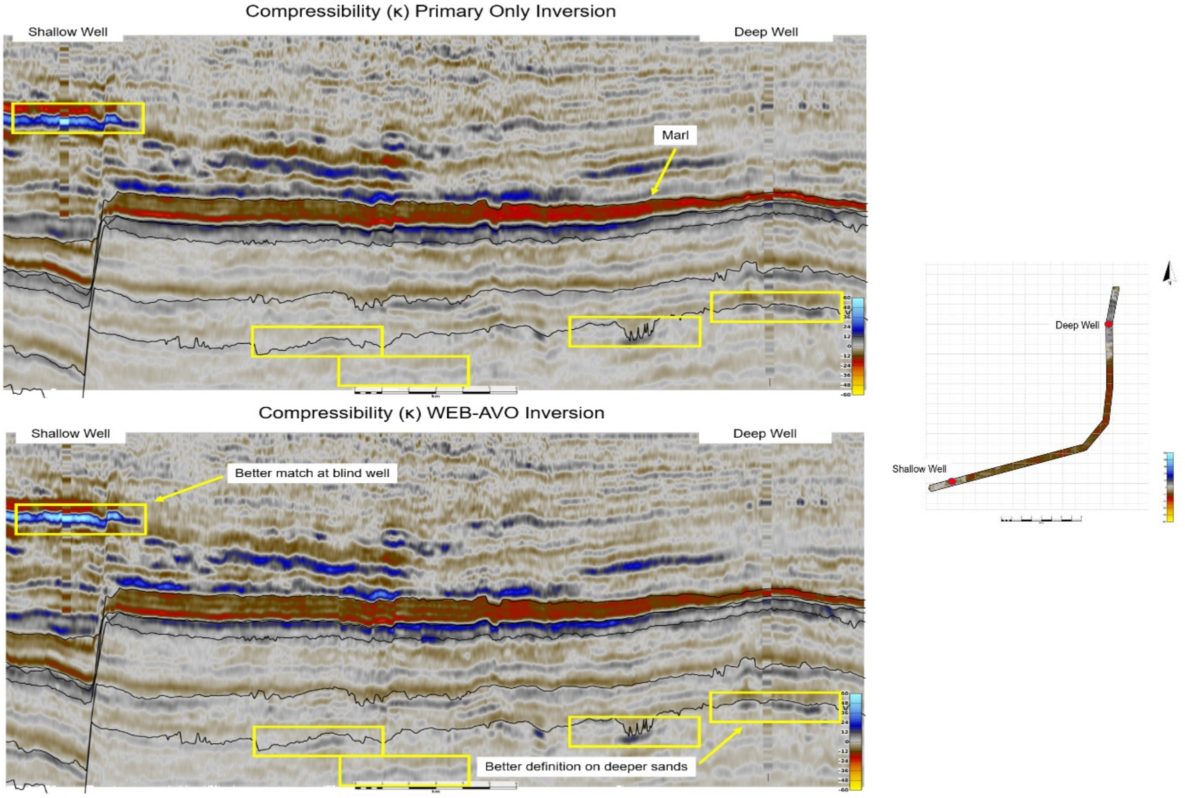

Figure 5a. Compressibility (κ) WEB-AVO Inversion and Primary Only Inversion (Linear Inversion)

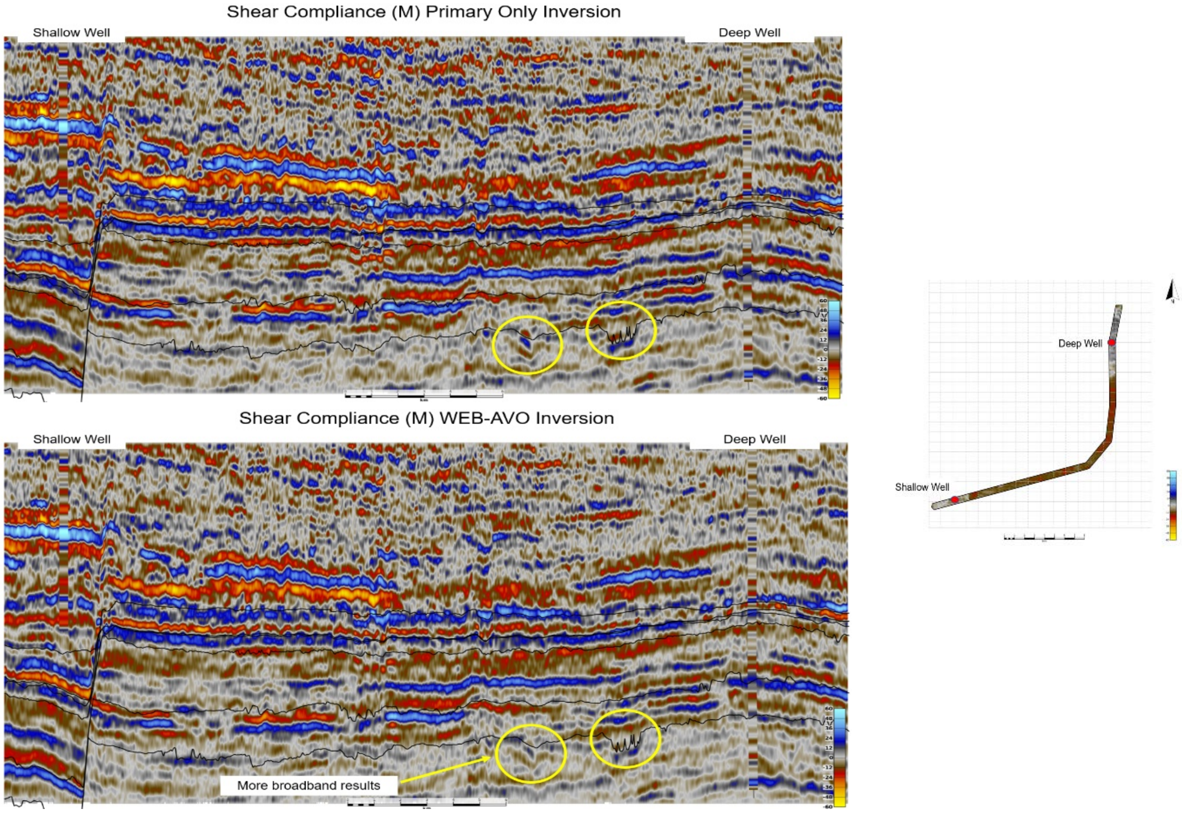

Figure 5b. Shear Compliance (M) WEB-AVO Inversion and Primary Only Inversion (Linear Inversion)

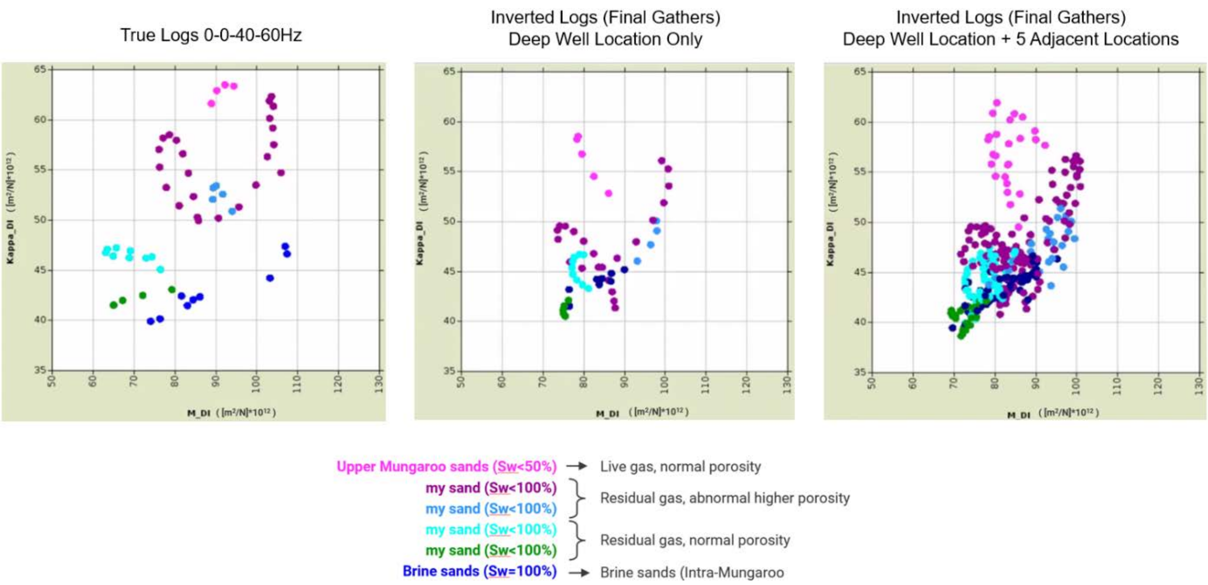

Figure 6. Compressibility (κ) vs Shear compliance (M) Analysis of the Mungaroo Sands

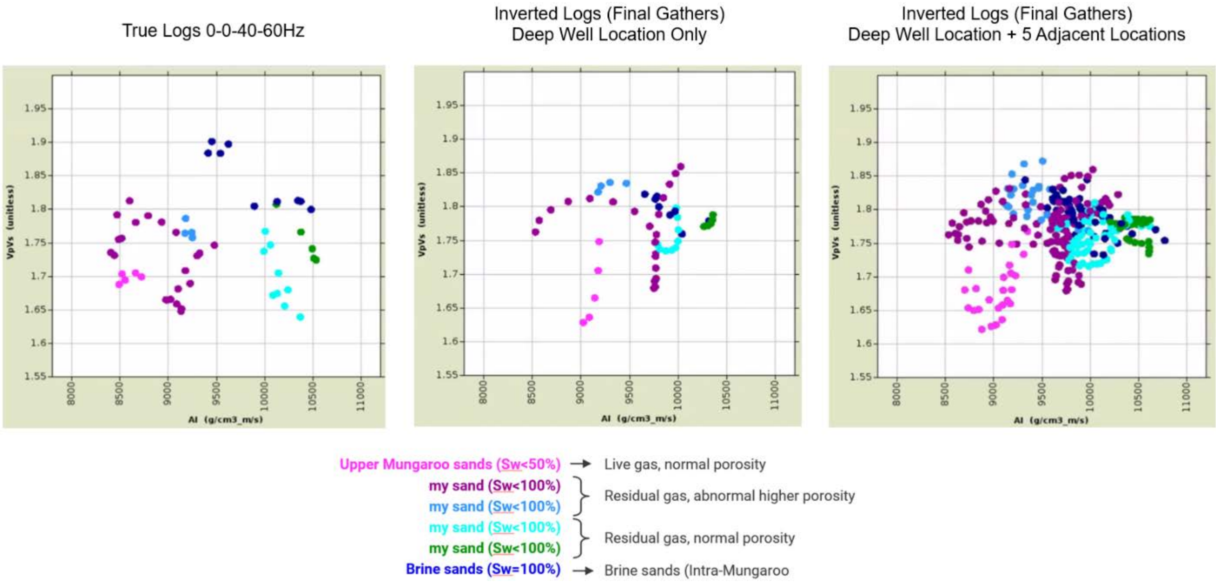

Figure 7. Acoustic Impedance (AI) vs Vp-Vs Analysis of the Mungaroo Sands