# Improved Subsurface Imaging and Interpretability through Broadband Reprocessing of Legacy Seismic Data. Examples from North West Shelf Australia

**Stephen Malajczuk***
*Geotrace Technologies*
*23 Altona St. West Perth, Australia*
*Smalajczuk@geotrace.com*

**Rajesh Saklani**
*Geotrace Technologies*
*Unit A-8-1, 6 Jalan P. Ramlee, KL, Malaysia*
*Rsaklani@geotrace.com*

**Dean Clark**
*Geotrace Technologies*
*Unit A-8-1, 6 Jalan P. Ramlee, KL, Malaysia*
*Dclark@geotrace.com*

**David Eastwell**
*Spectrum*
*Lvl 1, 105 St. Georges Tce. Perth, Australia*
*David.eastwell@spectrumgeo.com*

## SUMMARY

The reprocessing of legacy seismic data can be a time and cost effective means of obtaining an improved image of the subsurface, particularly when compared to the acquisition of new seismic data. The investment that has been made over the years in acquiring the many thousands of kilometres of seismic data offshore Australia has been preserved by Geoscience Australia, which houses an extensive collection of petroleum data including seismic survey data. Much of this data is available to the petroleum industry for reprocessing, facilitating the potential to enhance the data's value for regional reconnaissance and interpretation.

Two marine examples are shown from North West Shelf Australia where reprocessing was performed on seismic data from two different surveys acquired in 1993. The first example is from the Northern Carnarvon Basin, and the second example is from the Browse Basin.

These two examples demonstrate how the uplift attained from a modern broadband processing flow can yield a vastly improved subsurface image, which in turn can assist with interpretation. The reprocessing workflow (which was similar for both surveys) is discussed, as well as some insights into how the improved data benefit the interpretation and understanding of subsurface geology.

**Key words:** Broadband Seismic, Processing, Deghosting, Legacy Seismic Data, Australia.

## INTRODUCTION

There are a large number of legacy marine seismic survey datasets from offshore Australia which may be suitable for modern broadband reprocessing. This could yield more information than previously obtained, leading to a better understanding of the subsurface geology. Reprocessing of seismic data is more time and cost effective than acquiring new seismic data and depending on the objectives of the organisation may well be fit for purpose when used for regional reconnaissance, or to support basin-scale interpretation.

Most legacy marine seismic datasets have been acquired using a "conventional" flat cable, hydrophone-only configuration, usually towed at a constant depth below the sea surface. The seismic bandwidth and resolution of conventionally acquired data suffers from the source and receiver ghosts in the form of spectral notches in the amplitude spectrum.

A successful reprocessing workflow applied to two typical legacy datasets is described in this paper. The workflow has a focus on the deghosting methodology in particular, using the Geotrace Technologies HDBand™ suite (an example of this technology being used in another region is described in Saunders *et al*., 2015). This is because deghosting is a more recent addition to the modern processing workflow and has been shown to provide greater signal content at the low end of the frequency spectrum, vital for better deep data imaging and interpretation. The deghosting methodology is an evolution of the broadband processing of conventional streamer data workflow applied by Yu *et al*., 2014.

Two seismic datasets in the Northern Carnarvon Basin and the Browse Basin respectively are shown as examples. The parameterisation for these two datasets differed depending on geological and survey-specific issues, but nevertheless the overall workflow was the same. The intention is not to focus on individual issues but broadly demonstrate that with a robust reprocessing workflow, improved interpretability can be obtained from legacy datasets.

## METHOD

A reprocessing workflow was designed based on current methods as well as extensive testing on the available datasets. An outline of the workflow is shown in Figure 1.

| |
|---|
| Preliminary processing |
| Designature and deghosting |
| Demultiple |
| First iteration velocity analysis |
| Pre-migration demultiple |
| Migration velocity analysis |
| Kirchhoff pre-stack time migration |
| High density automated velocity analysis |
| Post-migration demultiple |
| Post-migration processing |
| Output |

**Figure 1: Basic outline of the PSTM reprocessing workflow which was undertaken on the legacy conventionally towed marine seismic datasets.**

While new broadband processing technologies are brought to bear in this workflow, it's important to note that there isn't one single processing stage that results in the overall improvement in the data. Instead a multi-faceted approach is needed which deals with each processing challenge whether it be reflection ghosts, multiple energy, velocities or imaging. Furthermore, the effectiveness of each processing step is connected to the other processing steps. The early application of the HDBand™ technology suite, therefore, facilitates higher quality results and more precisely tailored parameter decisions for the subsequent incremental processing steps.

Legacy seismic field data is often missing supporting information like acquisition reports and observer logs. So the preliminary processing begins with obtaining the correct acquisition parameters, identifying any issues with the data and establishing the survey configuration. This also includes performing amplitude spectrum quality control on all shots across the line to confirm the source and receiver depth, as this can be variable and needs to be taken into account during deghosting processing. This challenge of having accurate source and receiver depth information has also been described in Zhou *et al*. (2015). An example of amplitude spectra quality control is shown in Figure 2 at the end of this section. It is important to get these oft-overlooked basic items correct otherwise the more sophisticated processing steps will fail to work properly.

In conventionally towed marine acquisition, ghost reflections can be caused from acoustic signals travelling upwards and reflected by the air-water interface before reaching the receiver. Through constructive and destructive interference, this well-known interference phenomenon manifests itself as a series of notches in the amplitude spectrum which narrow the seismic bandwidth of the usable data. In particular, the "zero-Hz notch" results in a significant loss in low frequency information. This low frequency content is highly beneficial for improved structural interpretation, interpretation of deep basin structures, as well as seismic inversion of data into rock properties. Traditionally for seismic inversion it has been necessary to infer low frequency information from other sources, such as well log information (Lindseth, 1979) or migration velocity models (Oldenburg, *et al*. 1984). However these sources can only produce a crude estimate of the information required, whereas the recovered low frequency information in the seismic itself is more optimal. The advent of modern Full Waveform Inversion methods has also been a driver for the recovery of low frequencies.

The ghost G(kz) can be formulated in frequency domain as:

$$G(kz) = 1 + re^{2ikz} \tag{1}$$

Where r is the reflectivity of the free surface, k = ω/v is the wavenumber, ω is the angular frequency, v is the water velocity and z is the source/receiver depth.

By accounting for these ghost reflections through the utilisation of an inverse ghost operator, more signal and a broader frequency bandwidth can be recovered from the data. Theoretically, an inverse ghost operator D(gz) would be given as:

$$D(kz) = \frac{1}{G(kz)} \tag{2}$$

The deghost operator is often expanded to 3D, which is given as (Yu *et al.,* 2014):

$$D(k_z z) = \frac{1}{(1+re^{2ik_z z})} \tag{3}$$

Where $k_z = \sqrt{k^2 - k_x^2 - k_y^2}$ is the vertical wavenumber. The obliquity effect is represented in the $k_z$ term, which is dealt with in the deghost processing and described more fully below.

The deghosting process usually involves firstly extracting an estimate of the source signature from the near channel data, because a modelled source signature is not often available for legacy seismic data. Once this statistically-derived wavelet has been obtained, it can be used within the trace-by-trace calculation of the inverse ghost operator.

The data is transformed to tau-p space to account for the obliquity effect (this phenomena has been described previously in Masoomzadeh *et al,*. 2013), where the ghost time depends on the emergence angle. The deghosting is then performed where an inverse ghost operator is created for each trace as a function of angle (p) using both statistical and deterministic methods depending on the signal component. Header information like water velocity, reflection coefficient of the water/air interface and notch frequencies are also determined for each trace to further constrain the result. The deghosting and designature processing is performed before the demultiple processing, whereby the rationale for applying the processing at this stage of the workflow is described in Brookes *et al.* (2014).

In many legacy marine seismic surveys, a harsh low cut filter was normally applied during the acquisition. For example, the Carnarvon Basin survey had a low cut filter of 6Hz at 18 dB/oct. Nevertheless there can still be some low frequency content that can be recovered which may not have been visible in previous processing efforts, which is shown in the case study examples.

Significant attention was also placed on the demultiple part of the reprocessing workflow. The north west of offshore Australia has a well-known issue with multiples (Ramsden, 1991), which pose a challenge for both processing and interpretation. The multiple energy can be difficult to attenuate, and can mask primary events. In this workflow, Shallow Water Demultiple (SWD), Surface Related Multiple Elimination (SRME) and tau-p deconvolution were applied prior to the first iteration of velocity analysis. The SWD was applied prior to the SRME, and utilised a double-gap deconvolution approach which is described in Verschuur (2006). The SRME was undertaken by building a multiple model over three iterations, and then performing the adaptive subtraction in tau-p space. While also in tau-p space, predictive deconvolution was undertaken to remove further short period multiple.

After the first iteration of velocity analysis, a suite of demultiple methods were employed prior to migration. The first method was high resolution Radon demultiple. With an accurate velocity model the Radon demultiple polygon cut can be less mild which will in turn remove more multiple. Targeted Apex Shifted Elimination Routine (TASER™) demultiple was then applied. This method utilises the expected time of multiple events to create a model which can be removed from the data. This is especially useful for removing remnant diffracted multiples and shifted apex events. Finally a pass of frequency-dependent noise attenuation was applied, which as the name suggests discriminates primary and multiple by frequency.

With better signal content due to the deghosting and demultiple, a more optimum velocity model could be obtained. This more accurate velocity model was then used within the pre-stack time migration processing. After pre-stack time migration, another pass of high resolution Radon demultiple was applied for further removal of residual multiple.

All of these main processing steps work together to create an overall improved image which can then aid in interpretation. Furthermore, another benefit of reprocessing legacy data is that the interpreter is able to obtain more output datasets which are either not available as open-file data or were never created before. These include conditioned pre-stack time migrated CMP gathers and dense velocity fields.

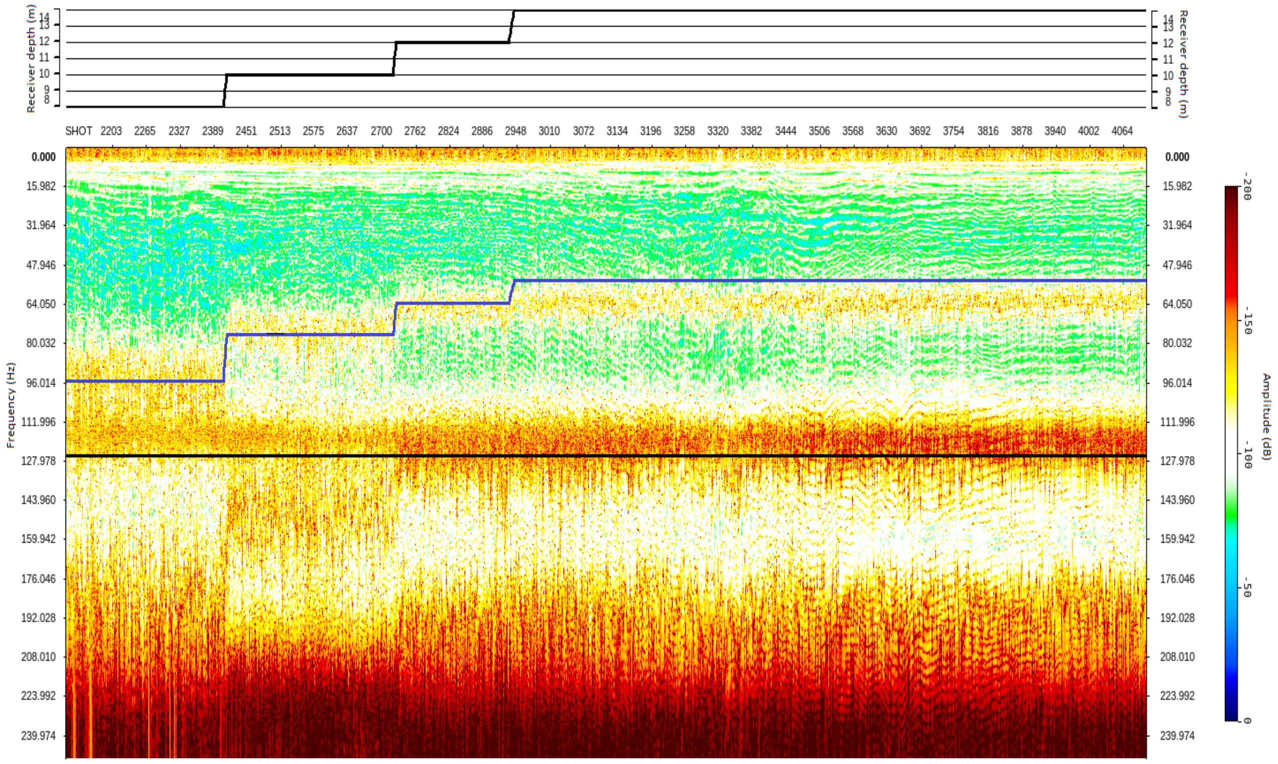


**Figure 2: Amplitude spectra map display where each trace is an individual shotpoint. The bands on the amplitude spectra map denote areas where source and receiver notches reside. The black and purple overlays are shown on the map display which correspond to the theoretical notch frequency in a vertical plane where the source and receiver depth values are provided by the observers logs and the water velocity is 1531m/s. The receiver depth provided by the observers logs is also plotted on the graph above the map display. It is noticeable that the theoretical receiver notch overlay (in purple) differs from what was provided in the observers logs from shot points 2948 onwards. Because of this, a receiver depth of 12m was used instead for those shot points in the deghosting which produced a more accurate result.**

## RESULTS – NORTHERN CARNARVON BASIN CASE STUDY EXAMPLE

The first case study example is from the Northern Carnarvon Basin, which has been very well explored. The basin contains nearly all of the producing fields in Western Australia, and is a key region for present-day hydrocarbon production development projects. A more detailed geological overview of the basin as well as the exploration and production history can be found in the Northern Carnarvon Basin prospectivity report by the Department of Mines and Petroleum (2015).

The seismic data which was reprocessed was acquired using a conventional flat cable arrangement by Geco-Prakla in 1993. Three wells intersect the reprocessed line, namely Maitland-1, North Gorgon-1 and Achilles-1. Table 1 shows a summary of the acquisition parameters. Note the relatively sparse shot point interval, variable cable depth and harsh low cut filter parameterisation. The acquisition parameters shown here are typical of legacy marine seismic surveys from this era.

| | | | |
|---|---|---|---|
| **Survey** | GPTC93 | **Streamer depth (m)** | 8-12* |
| **Year** | 1993 | **Streamer length (m)** | 6000m |
| **Source depth (m)** | 6 | **Record length (ms)** | 11264 |
| **Shot point interval (m)** | 37.5 | **Sample rate (ms)** | 2 |
| **Near offset (m)** | 152 | **Low cut filter** | 6 Hz (18 dB/oct) |
| **Number of groups** | 480 | **High cut filter** | 180 Hz (70 dB/oct) |
| **Group interval (ms)** | 12.5 | | |

**Table 1 – Summary of acquisition parameters of the Northern Carnarvon case study example dataset. The streamer depth was verified by use of amplitude spectra displays as shown in Figure 2.**

Figure 3 shows a comparison between the reprocessed stack and the vintage processed stack, which had a similar PSTM processing flow but without the deghosting stages. The amplitude spectrum display is also shown to illustrate the broader bandwidth achieved. As can be seen there is a much broader frequency bandwidth at the low and high frequencies as a result of the deghosting.

Figure 4 shows the vintage processed and reprocessed stacks, with the North Gorgon-1 well (with tops) overlaid. There is a sharpening of event terminations in the reprocessed stack, as well as a noticeable improvement in the continuity of the events. The unconformity at the top Mungaroo formation for example is easier to track in the reprocessed stack due to the broader frequency bandwidth. Migrated CMP gathers are also available after reprocessing, and Figure 4 shows these NMO corrected gathers with a 200m spacing around the North Gorgon-1 well area.

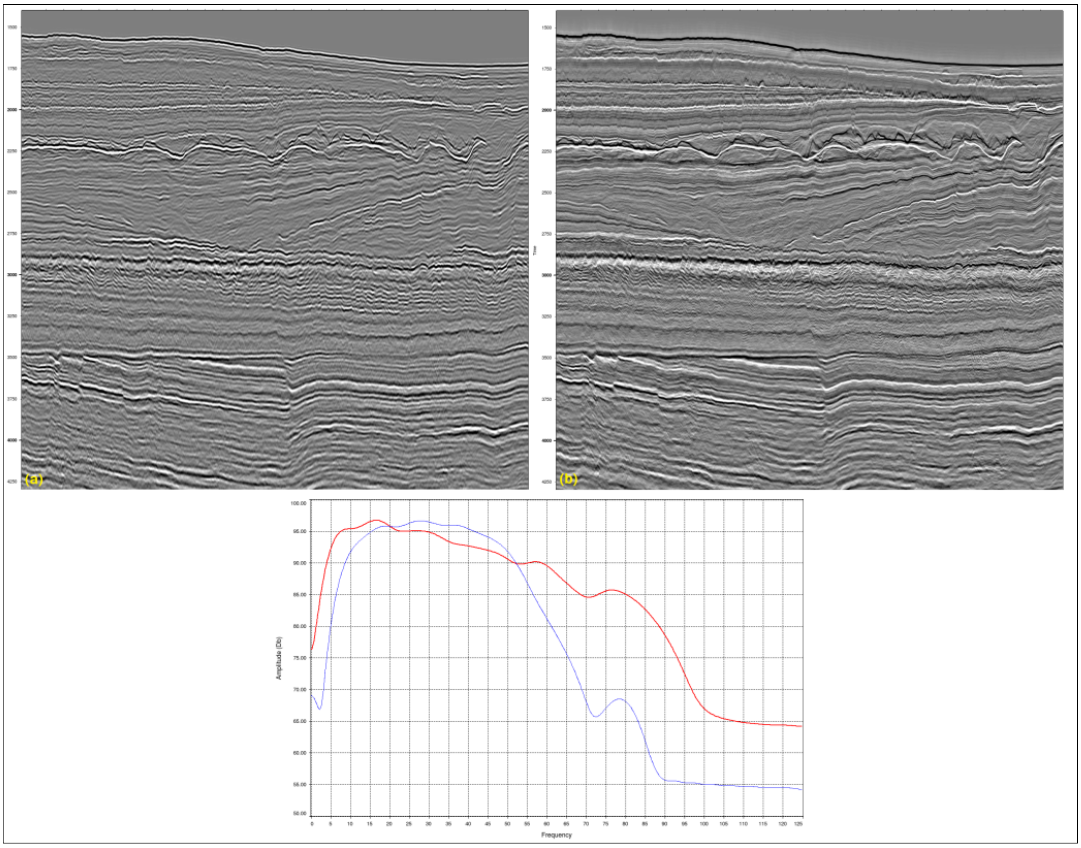


**Figure 3: Comparison of the north-west portion of the survey line, where (a) is the vintage processed stack and (b) is the current reprocessed stack. There is an overall broader frequency range on the current reprocessed stack which could assist interpretation, particularly around the pinchout structures at ~3500ms. The amplitude spectrum for this section is also shown where the thin blue curve is the vintage processed dataset and the thicker red curve is the current reprocessed dataset.**

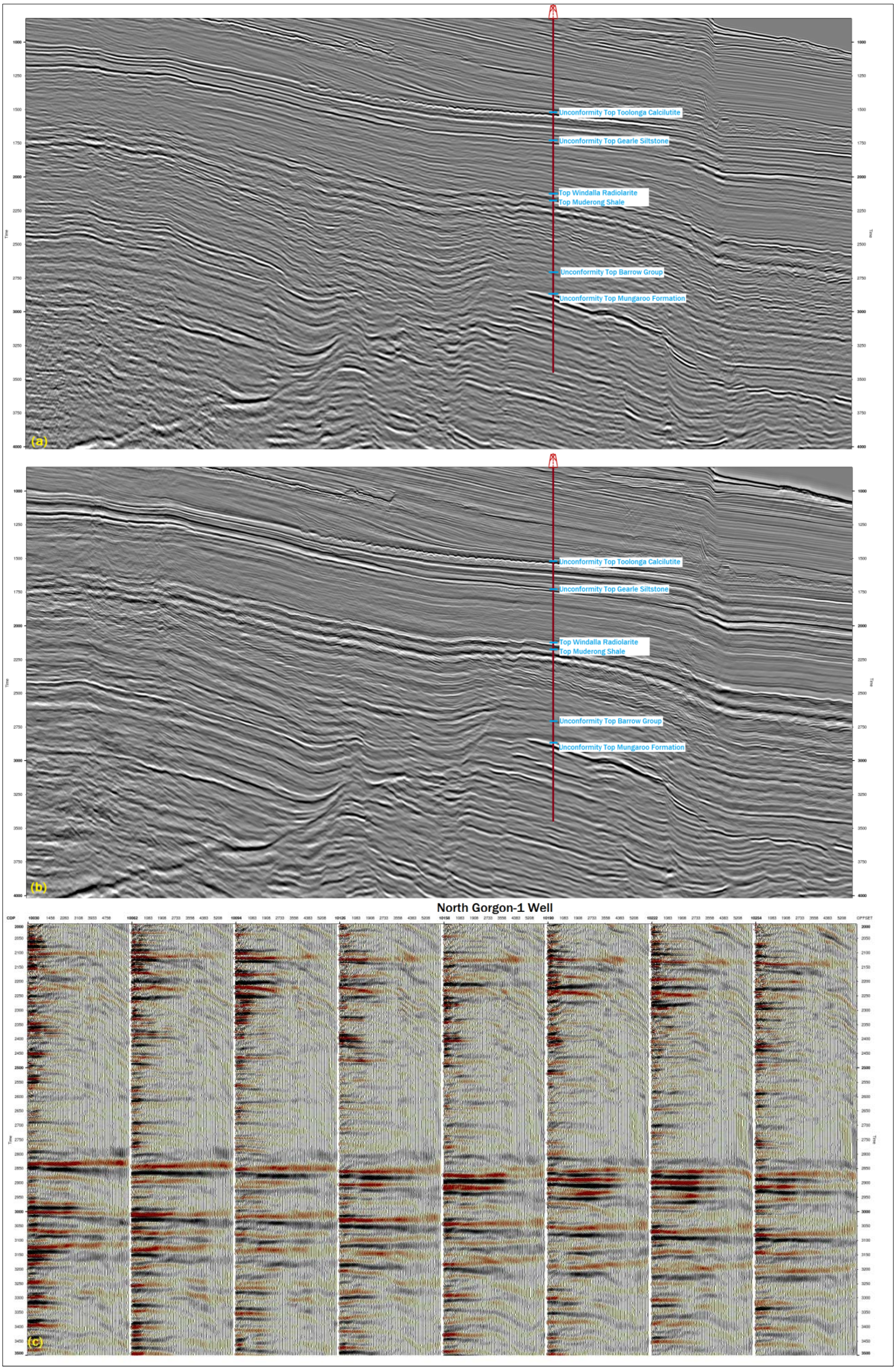


**Figure 4: Comparison of vintage processed stack (a) and current reprocessed stack (b), with the North Gorgon-1 well overlaid with top annotations. The reprocessed stack has better event continuity owing to the broader frequency range which makes it easier to interpret events (for example the Mungaroo formation top). NMO corrected CMP gathers from the reprocessed dataset around the well are also shown in (c) where the spacing between each gather is 200m.**

## RESULTS – BROWSE BASIN CASE STUDY EXAMPLE

The second case study example is in the entirely offshore Browse Basin. More information regarding the geology and exploration history of the Browse Basin can be found in the Western Australian Petroleum and Geothermal Explorers Guide 2014 (pp 31-33). One well intersects the example line, which is called Brewster-1A.

Table 2 shows a summary of the acquisition parameters. As with the Northern Carnarvon example, note the sparse shot point interval and harsh low cut filter parameterisation.

| | | | |
|---|---|---|---|
| **Survey** | AGSO-119 | **Streamer depth (m)** | 10 |
| **Year** | 1993 | **Streamer length (m)** | 4800 |
| **Source depth (m)** | 10 | **Record length (ms)** | 16000 |
| **Shot point interval (m)** | 50 | **Sample rate (ms)** | 2 |
| **Near offset (m)** | 201 | **Low cut filter** | 8 Hz |
| **Number of groups** | 192 | **High cut filter** | 180 Hz |
| **Group interval (ms)** | 25 | | |

**Table 2 – Summary of acquisition parameters of the Browse Basin case study example dataset.**

Figure 5 compares the broadband reprocessed stack with the vintage processed stack. Also included in these displays are amplitude spectrum displays to show the broader bandwidth achieved. There is an overall improvement in imaging the events on this example line, which appear sharper and more continuous. There is also considerably less multiple energy in the reprocessed stack, which allows primary signal to be more easily observed. This uplift in data quality can also be seen in Figure 6, which is a comparison between the vintage processed stack and the reprocessed stack around the Brewster-1A well. There is greater definition and continuity of the events around the well, as well as less multiple content.

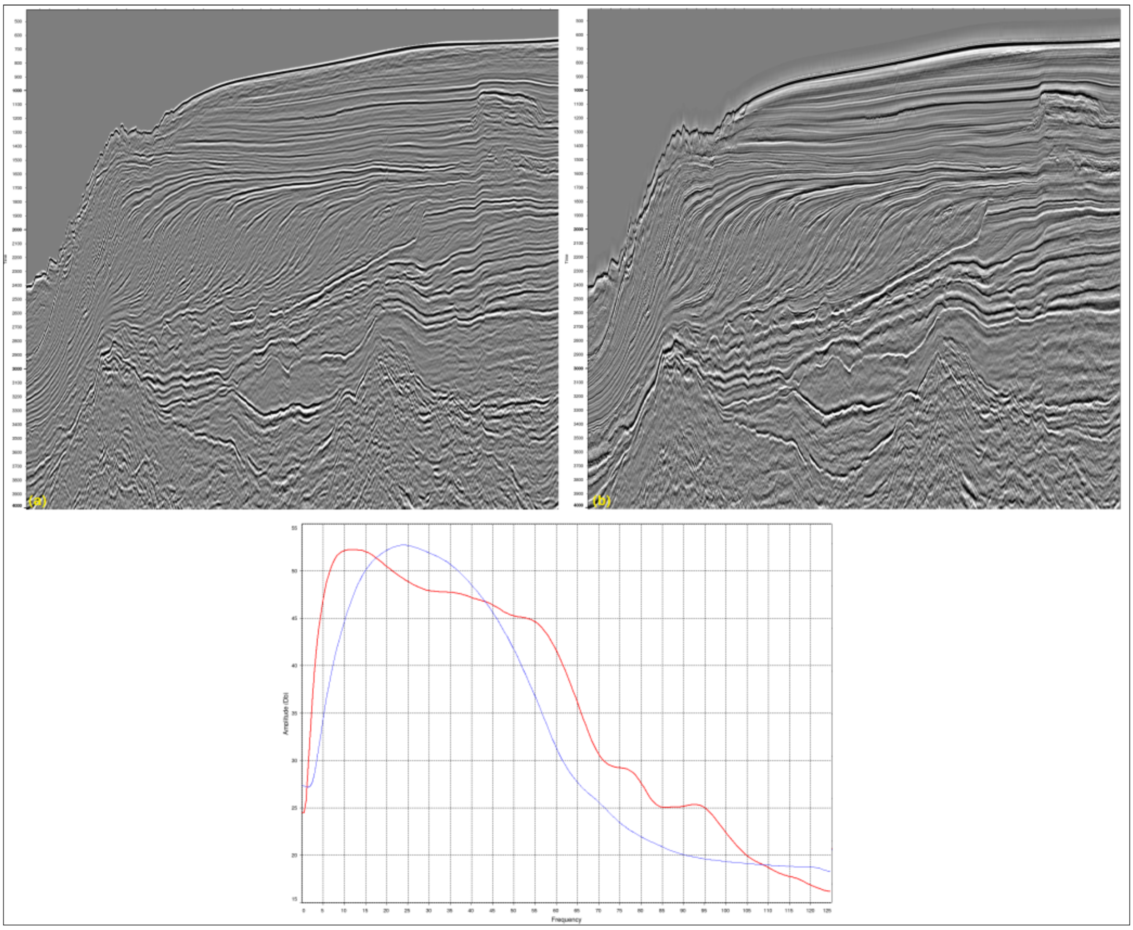


**Figure 5: Comparison between the vintage processed stack (a) and the current reprocessed stack (b). The reprocessed stack has an improved image with less multiple content and a broader frequency range. All of these factors enhance the interpretability of the dataset, particularly for the deeper structures and their flanks. The amplitude spectrum for this section is also shown where the thin blue curve is the vintage processed dataset and the thicker red curve is the broadband reprocessed dataset.**

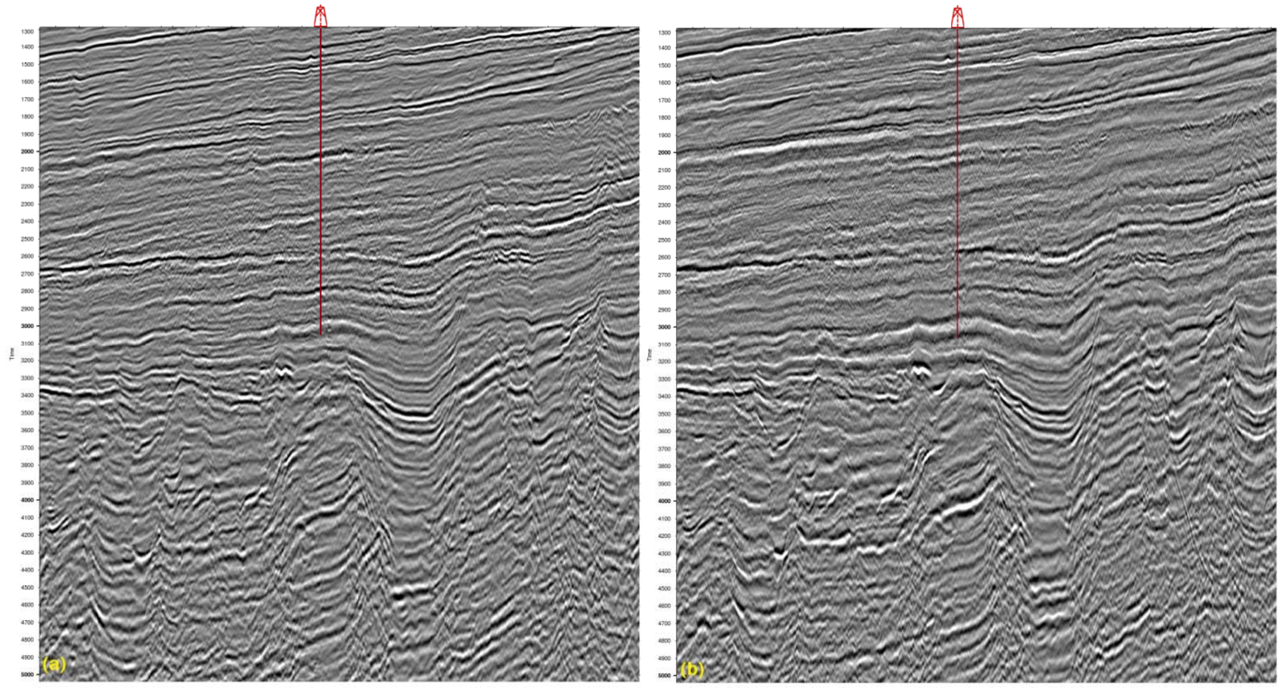


**Figure 6: Comparison between the vintage processed stack (a) and the current reprocessed stack (b), with the Brewster-1A well overlaid.**

## CONCLUSIONS

There are a large number of legacy marine seismic survey datasets from offshore Australia which may be suitable for modern broadband reprocessing. Furthermore, the option of reprocessing available legacy seismic datasets can be attractive given its convenience in terms of turnaround time and cost. Due to this, modern broadband reprocessed legacy data covering potentially huge areas can be made available. The selection of broadband reprocessed data sets can be custom designed from different vintage surveys and used for regional and basin studies in a timely manner to help reduce risk and to aid the decision-making process.

We show two examples from the North West Shelf of Australia where added value is obtained by employing a modern broadband processing flow. In particular, we demonstrate that the recent addition of deghosting to the modern processing workflow can yield significant improvements in recoverable signal bandwidth from legacy data. In both cases we show that the broadband reprocessed data has greater signal content at the low and high ends of the frequency spectrum, and that improved imaging is achieved through careful reprocessing. Additionally, advanced processing workflows that include deghosting technologies such as HDBand™ can yield more robust phase characteristics in the data. The aggregate benefits in such reprocessed datasets allow much improved and more confident interpretations of the subsurface images, which translates to increased exploration successes and lower finding costs.

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