Kraken 3D – acquisition to interpretation on the edge of the Browse

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SUMMARY

The broadband Kraken 3D Marine Seismic Survey was acquired during 2013 in the outer Browse Basin exploration permit WA-314-P with the specific goal of assessing risk and volumes at the Elvie prospect. The survey was acquired over a highly rugose sea floor, comprised of deep slump canyons that overlie a steeply prograding Miocene carbonate sequence.

Multiple attempts at processing the seismic data have already been made; including a post-stack time migration (a fast-track volume), pre-stack time and pre-stack depth migration. Conventional processing and pre-stack depth migration approaches were unable to fully resolve short-wavelength velocity anomalies below the sea floor that cause obvious residual imaging problems and impact upon depth conversion and seismic amplitude interpretation. A geomechanical pre-stack depth migration now underway to hopefully address the remaining imaging concerns.

Overall, the Kraken 3D is considered to be a significant improvement over the pre-existing 2D seismic. Interpretation was performed largely in the depth domain, although ties to nearby wells were made in the time domain using legacy 2D and 3D seismic. Mapping has further matured the Elvie prospect, which is a robust 4-way dip closure located on the divide between the Caswell and Seringapatam Sub-basins. The survey provides strong evidence for a thick top seal in the form of deep-marine muds of Miocene age, although there is evidence of minor seepage through a thin flank of the sealing unit. These shallow amplitude indicators, nearby surface seeps and pockmarks near the sea floor provide additional support for a working petroleum system. The Elvie structure appears to be draped by potentially high quality turbidite reservoirs of most-likely Paleocene age.

Key words: 3D marine seismic acquisition, broadband, pre-stack depth migration, rugose sea floor, turbidites, Browse basin, Seringapatam Sub-basin, Caswell Sub-basin.

INTRODUCTION

The Browse Basin is a northeast-southwest trending, Palaeozoic to Cainozoic depo-centre located entirely in the offshore Timor Sea region north of Western Australia. The basin has been divided into a number of structurally defined features including the Caswell Sub-basin, which forms the main depo-centre and the Seringapatam Sub-basin, which is a deepwater basin located to the northwest. A tectonostratigraphic framework for the Browse Basin has been defined by Struckmeyer et al (1998) with several phases of extension, thermal subsidence and inversion noted during the evolution of the basin (Blevin et al, 1998).

Acquisition of the Kraken 3D was constrained by the Australia-Indonesia maritime boundary, but was otherwise uncompromised in its design specifications and operational performance. The main acquisition innovation was to employ a slanted streamer broadband solution (Soubaras and Dowle, 2010) with a view to improve the temporal resolution at the original Jurassic target level.

It is quite rare to reprocess a new seismic survey that was acquired using the latest technology, effectively three times in as many years! The initial processing of the Kraken 3D was driven by turnaround considerations, as is often the case due to permit commitments (and the time it now takes to obtain approvals to shoot seismic). Expectations were not high for the post-stack time migrated volume to succeed with the survey goals. A pre-stack depth migration was commissioned immediately because it was well known that the bathymetry in the survey area would likely lead to imaging problems in time-domain processing. Pre-stack depth migration techniques have not changed that much in three years. So if we see a clear improvement then there must be something to learn from this exercise in perseverance.

Regrettably, this PSDM project was also driven largely by the need for rapid turnaround and only some modest improvements in the imaging were achieved. Nevertheless a robust structural and stratigraphic interpretation of the permit was achieved. The remaining data quality issues were noted later in the interpretation cycle during depth conversion and amplitude studies. Upon recognizing the impact of the remaining imaging problems in the Kraken 3D, the permit was renewed with a clear focus on improving data quality before progressing drilling plans. This has increased the scope for trialling more sophisticated imaging methods such as a geomechanical approach to pre-stack depth migration (Birdus, 2008) and non-parametric tomographic updating (Fruehn, et al., 2014).

The Elvie prospect is located on the western edge of permit WA-314-P and sits on the divide between the Caswell and Seringapatam Sub-basins. The latter sub-basin is almost entirely unexplored, with the nearest relevant wells being Snarf-1 and Warrabkook-1 to the south. Jurassic source rocks are expected to exist on both sides of the basin divide although maturity is expected to shift towards being more oil-prone (relative to the central part of the gas-prone Caswell Sub-basin) driven in part by the greater water depth.

Ahead of acquiring the Kraken 3D it was thought that the Jurassic Plover formation would be the primary reservoir target, albeit with the possibility of greater marine influence than seen within central Browse basin wells. It was also feared that volcanics might occlude reservoir development, as had been the case in the nearest wells (Maginnis-1, Buffon-1, Kontiki-1 and Grace-1). A separate magnetics data interpretation study was commissioned to address this risk (Dunne, *et al*., 2015). The primary top seal was thought to be the marine Jamieson Formation, a known over-pressured unit (and drilling hazard) of Aptian age. In the overburden, a thick prograding Miocene carbonate wedge was noted on 2D seismic with very steep progrades formed on the western side of the Elvie prospect. The sea floor above Elvie also represents a prominent shelf break and some 2D seismic lines revealed deep slump canyons.

After briefly discussing the survey design and acquisition, I show the evolution of the processing to date by highlighting how and where image improvements were achieved. Fortunately imperfect data did not stand in the way of developing an intriguing prospect. I then show how the Kraken 3D has completely reshaped our thinking on the main elements (reservoir, seal and charge) of the Elvie prospect. Further reprocessing (underway) may enable more advanced interpretation methods to achieve further de-risking of what appears to be the largest undrilled 4-way dip closure remaining in the Browse basin.

ACQUISITION

The Kraken 3D Marine Seismic Survey was acquired by CGG using the seismic vessel Geo Caspian on an exclusive basis over eight days during August 2013. The survey area was located approximately 345 km northwest of the Kimberley coastline (Western Australia) in Australian Commonwealth Waters (Figure 1). A total of 26 prime lines were acquired to achieve a full-fold area of 328 km^2 up to the Perth Treaty Area Border (green line in Figure 1). The vessel was allowed to operate (turns and soft starts) outside the Perth Treaty Area, on the proviso that it did not acquire full-fold data. This explains the odd shape of the survey and the need to acquire in a NE-SW azimuth that represents the dominant strike direction.

The objective of the survey was to image the Middle Jurassic to Tertiary formations, at target depths of between 1500 m and 5500 m. The data were acquired in a broadband mode, using a variable streamer depth (Soubaras and Dowle, 2010). The source and recording parameters could be considered standard (for the time). The streamer configuration could also be considered a typical setup, with 12 streamers used at 100 m separation with an active length of 6600 m.

PROCESSING

The Kraken 3D was initially processed by CGG, with some tight time constraints set as a result of looming permit commitments. An initial fast-track volume was produced using post-stack time migration. The image quite clearly shows large areas of poor data quality that immediately underlie areas of extreme sea-floor topography. A fast-track hybrid PSDM was then applied to deliver significant improvements in these problem areas by addressing ray-bending at the rugose sea floor and using PSTM below. Meanwhile a full time-domain processing sequence was applied including 3D SRME and tau-p deconvolution to suppress multiples. The subsequent full anisotropic Kirchhoff hybrid PSDM improved vertical resolution in the image but did not appear to change the structural interpretation.

Starting from the CGG pre-migration gather archive, a PSDM project was contracted to ION-GX Technology and this was completed during the latter part of 2014. After the 6^{th} tomographic update it was felt that the image was not improving any further and so a Kirchhoff TTI anisotropic migration was performed using the velocity model from the 5^{th} iteration. Some careful post-processing was also applied with interpreter guidance to produce an image that appeared more coherent in the deep section. However, the lack of structural difference to what was effectively a PSTM (in the final hybrid PSDM volume) suggests that lateral velocity contrasts in the deep section could be quite benign.

The full PSDM did not change the image significantly in the shallow section. If anything, it was now better highlighting problems with the shallow velocity model. These problems appear as pull-ups and push-downs in the basal part of the Miocene carbonate section, where the sequence of reflections should appear flat or gently dipping when viewed in the strike direction. Problems in the shallow velocity model were also confirmed upon inspection of the final interval velocity model subtracted from a regional overburden velocity trend (taken below mudline). The areas of greatest discrepancy (between these two velocity models) were found directly underneath the largest sea-floor slump canyons. In these areas it appears the tomography was unable to find the very low velocities required beneath the canyon, possibly because of the constraints applied; the lack of offset information to work with; or perhaps if the starting model was too different from the true model.

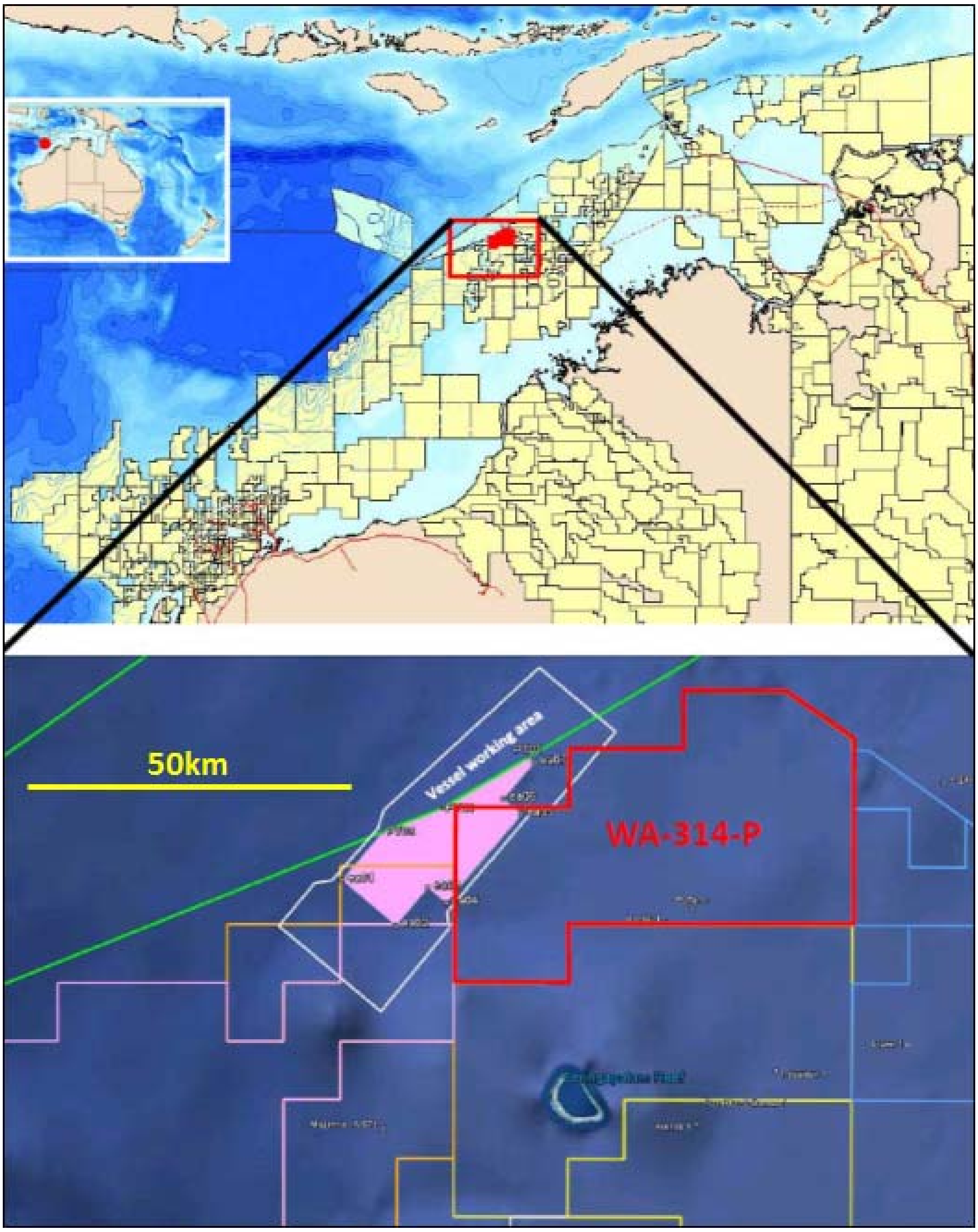

Figure 1 - Broad-scale image detailing the location of the Kraken 3D MSS.

Despite these concerns, the final image is certainly an improvement over the pre-existing 2D seismic (Figure 2). Co-located comparison sections are shown although the 2D image (BR98- survey) has two-way time as the vertical axis, while the Kraken 3D is shown in depth. These images appear quite different in a structural sense as a result of removing the distortive depthing effect of the large shelf-slope break that runs across the middle of the surveyed area. The 3D image also shows much improved fault resolution, particularly in the targeted Jurassic section from 2800-3000 ms. The broadband character reveals previously unseen detail (paleo slump canyons) in the shaley section overlying the Elvie horst.

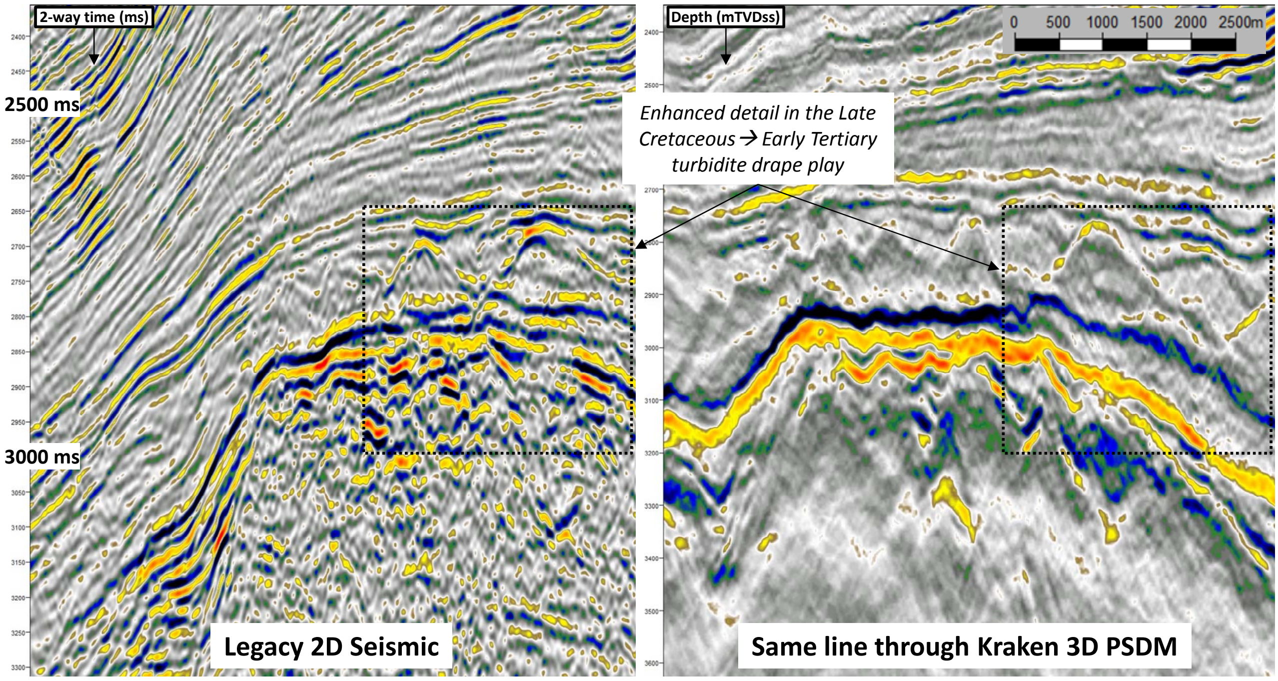

Figure 2 - Kraken 3D data quality vs legacy 2D seismic (co-located) revealing wholesale differences resulting from the combination of broadband, 3D and PSDM.

INTERPRETATION

The Kraken 3D was acquired to improve the subsurface assessment of the Elvie prospect that had been identified on pre-existing 2D seismic data in this area. It was hoped that better imaging under the known seafloor canyons present in the area would reveal Jurassic Plover formation half-grabens similar to those at the Poseidon field to the southeast. The seismic would also help to validate the expected 4-way dip closure; the expected Jamieson Formation top seal; and provide accurate depth and stratigraphic information for charge modelling support.

There are no wells located within the area of the Kraken 3D seismic survey. Some key wells used to interpret significant horizons into the 3D area included Buffon-1, Kontiki-1, Grace-1, Argus-1 and Maginnis-1. It was possible to verify wavelet phase and polarity using the water bottom event in places where it could be isolated. As a result of the dephasing applied during processing, the interpretation dataset is very close to zero-phase, with a negative number (black event as shown in Figure 3) representing a hard acoustic impedance interface. Events were interpreted directly in "raw" depth using the PSDM seismic.

Eight seismic horizons were mapped throughout the 3D dataset, as tabulated below:

Horizon Name	Abbreviation
Sea Floor	WB
Mid Miocene Marker	MMIO
Mid Miocene MFS	MMIO MFS
Near Base Miocene	NBMIO
Paleocene Sand 1	PAL
Cenomanian	CEN
Near Top Triassic	TRIAS
Near Top Permian	PERM

3D seed events were generally picked with a regular inline/crossline spacing, then auto-tracked, edited/infilled, gridded, smoothed and re-snapped as required. Some of these horizons were mapped to aid in depth conversion, rather than act as potential exploration targets. There exists considerable uncertainty in deriving anisotropy (depth calibration) factors from nearby wells because the overburden sequences at the Elvie horst are not well represented by logs or checkshot data from the inboard wells. Also, given the velocity issues discussed, a reference event (MMIO) that could be safely assumed to possess a gently dipping structure was used to generate a depth correction map. Additional smoothing was also applied to other interpreted events to reduce the imaging influences and produce more geologically sensible depth grids.

A primary (exploration) target horizon was the "Paleocene Sand 1". Figure 3 shows a typical dip section through the Kraken 3D with each of the 3D horizons noted and it also provides a representative example of the three sets of faults mapped.

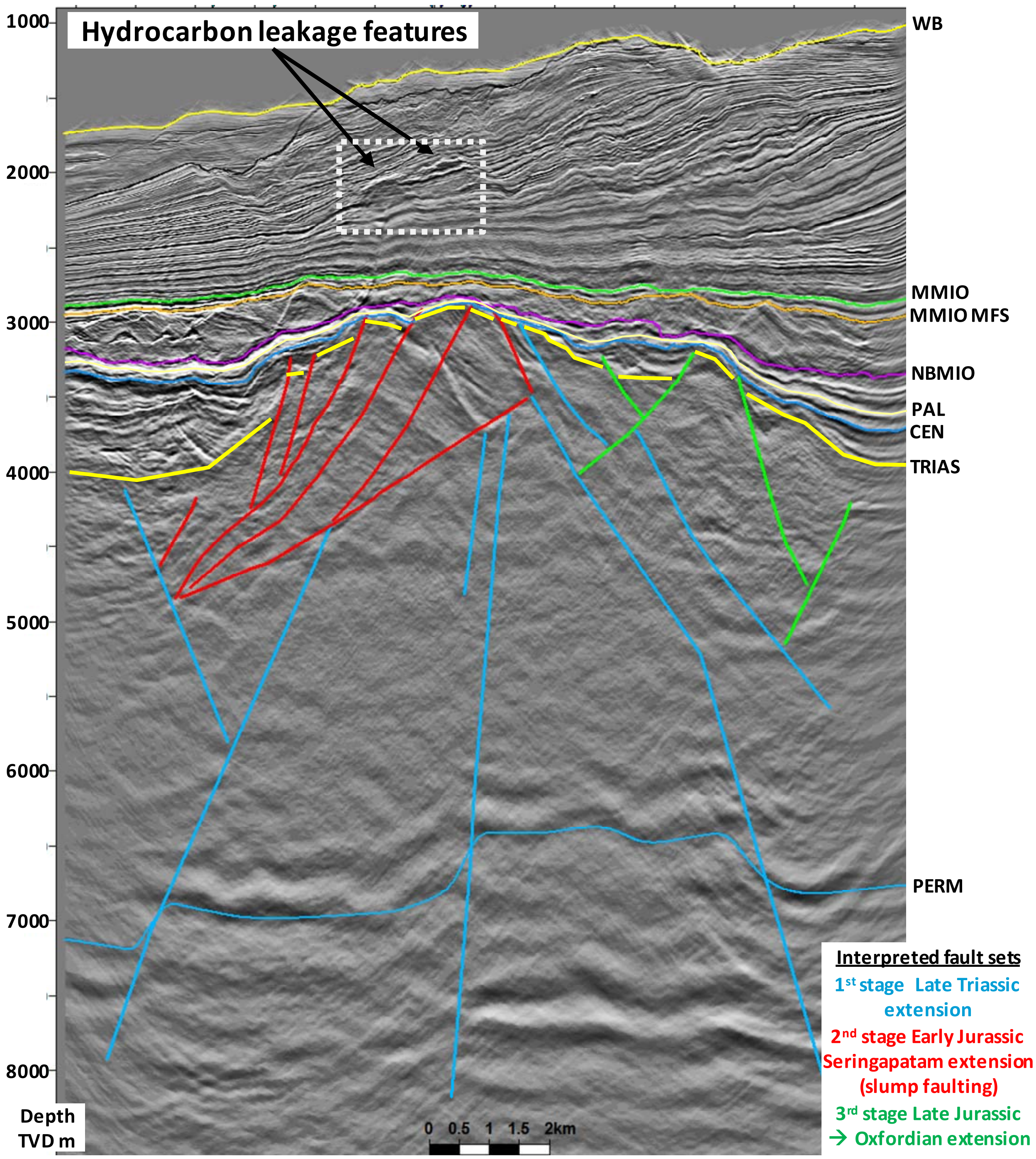

Figure 3 - Fault and horizon mapping on the Kraken 3D PSDM depth "structural" volume (PSDM reprocessing). Strong evidence for hydrocarbon seepage is visible between 2000-2500 m near the centre of this image.

The three sets of faults mapped were colour-coded to represent their most likely timing, bearing in mind the well-documented structural history of the Browse Basin. The light blue set represents a phase of extension towards the end of the Triassic, in which large horst and graben structures were formed across the Browse basin, with faulting observed through the entire Triassic and Permian sections.

The red set of faults most likely occurred in the Early Jurassic and it represents a phase of extension that does not appear to have been previously noted in the literature and is perhaps revealed by the improved fault imaging delivered by the Kraken 3D. Using palinspastic reconstruction it is possible to show how the Seringapatam basin extended by a modest amount (at this point in time) while the Caswell Sub-basin remained locked in position. In this way, the Red faults can viewed as single-sided slumping, of what is presumably a shale-dominated Late Triassic interval, from the western (distal) side of the Elvie horst.

The green set of faults represents the well-documented phase of Jurassic extension in the Caswell Sub-basin, which probably ends during the Oxfordian period (Late Jurassic). These faults can be viewed as antithetic systems to the Permo-Triassic horst blocks that are quite regularly-spaced throughout the Caswell Sub-basin. It is this phase of extension that creates accommodation space for deposition of the prolific Plover formation.

A high confidence pick was obtained at the hard sea floor using a sparse seed-grid and extensive auto-tracking with only minor editing required (Figure 4). The sea floor slopes from approximately 800 m in the northeast to 1800 m in the southwest of the survey area and contains several highly rugose slump canyons. The remaining imaging problems in the Kraken 3D tend to underlie these slump canyons. Further reprocessing in the renewal phase of this permit will make use of this detailed sea floor interpretation to build a geomechanical model to constrain velocities during tomography in the shallow overburden.

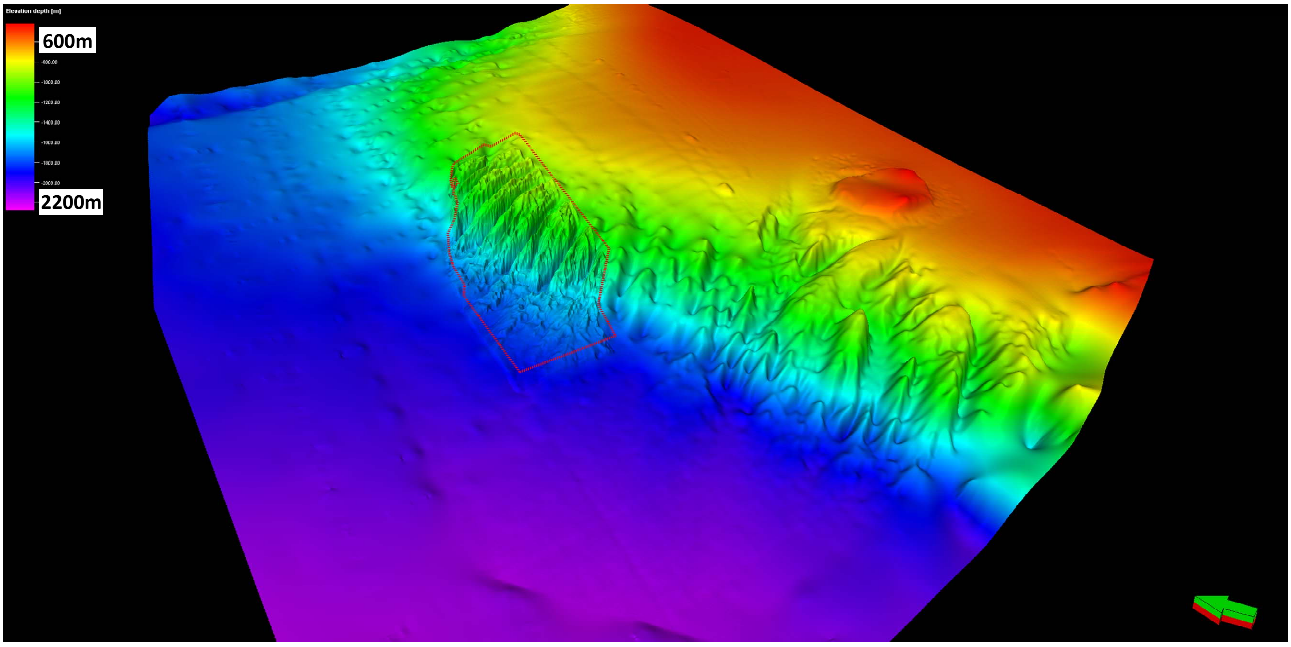

Figure 4 - Sea floor depth map for the Kraken 3D appended to a regional 2D bathymetric grid showing the highly rugose sea floor in the survey area (red outline).

Three Miocene seismic horizons were mapped in the overburden. The Mid Miocene Marker (MMIO) was picked primarily for depth conversion purposes as outlined earlier. It represents an early distal toe-set of the prograding Miocene carbonates, also known as the Oliver Formation. Progradation is oriented approximately perpendicular to the dominant structural nose, as visible on the sea floor map (Figure 4).

The next trough below sits at the base of the Miocene prograding carbonates and is considered to represent a maximum flooding surface (MMIO MFS). Its interpretation was extended onto nearby 2D lines and the accompanying paleo-shelf-slope break was noted well into the centre of the Caswell Sub-basin. This event represents the top of the proposed regional seal for the Elvie prospect. It is believed to represent the culmination of the marine transgression initiated in the Oxfordian.

A prominent trough was mapped to demarcate the base of what appears to be a thick interval of deep marine muds (Figure 5). The interval between the Near Base Miocene and Mid Miocene events shows strong evidence of slump canyons and debrites when visualised in 3D. These canyons also have present-day analogues noted within the southwestern corner of the Kraken 3D.

The Cenomanian event can be confidently mapped from several wells in the Caswell Sub-basin into the Kraken 3D area where it can be shown to onlap the Permo-Triassic Elvie horst. It was picked on a distinctive decrease in acoustic impedance (Peak) known to represent the onset of hard overpressures in the Cretaceous Jamieson Formation.

A number of distinct soft events were noted in the interval between the Near Base Miocene and Cenomanian event (Figure 5). Their drape over the Elvie horst can be shown to extend substantially further than the Cenomanian onlap and therefore represents a relative sea-level fall. It was possible to map the “Paleocene Sand 1” event over the entire Kraken 3D survey. Its crest lies at approximately 2900 m.

Younger soft events appear to downlap the “Paleocene Sand 1” event in more proximal positions, so it is thought that the mapped event represents the maximum extent of a low-stand system that could stretch from the Turonian to the Eocene. Sea level curve data suggests the Paleocene Johnson Formation as the most likely time equivalent for the mapped event. Ties to inboard wells also place the main mapped event at approximately this age.

Other key observations (on the Paleocene sand events) based on 2D seismic ties to Caswell Sub-basin wells and mapping within nearby 3D surveys include: 1) clear incision and channeling in a lower slope setting; 2) quartz sands recorded in cuttings and apparent in available logs from some nearby wells; 3) isopach mapping supporting transport directions and ponding into the eastern side of the Elvie horst. This supports the notion that relative sea-level falls during the Paleocene have triggered the reworking of coarse clastics ('stored' on the shelf) into a deep-water setting where they were captured within structurally formed topographic lows and ultimately fill and spill beyond the Elvie structural trend into the Seringapatam Sub-basin.

Interpretation of the Top Triassic has proven difficult and to date only a sparse seed grid has been attempted in order to guide interpretation of the shallower sequences. In contrast, the Near Top Permian event was mapped quite easily on a prominent, low frequency hard event that most likely represents a regional limestone marker in the Hyland Bay Formation. This event proved very helpful in establishing the overall fault framework.

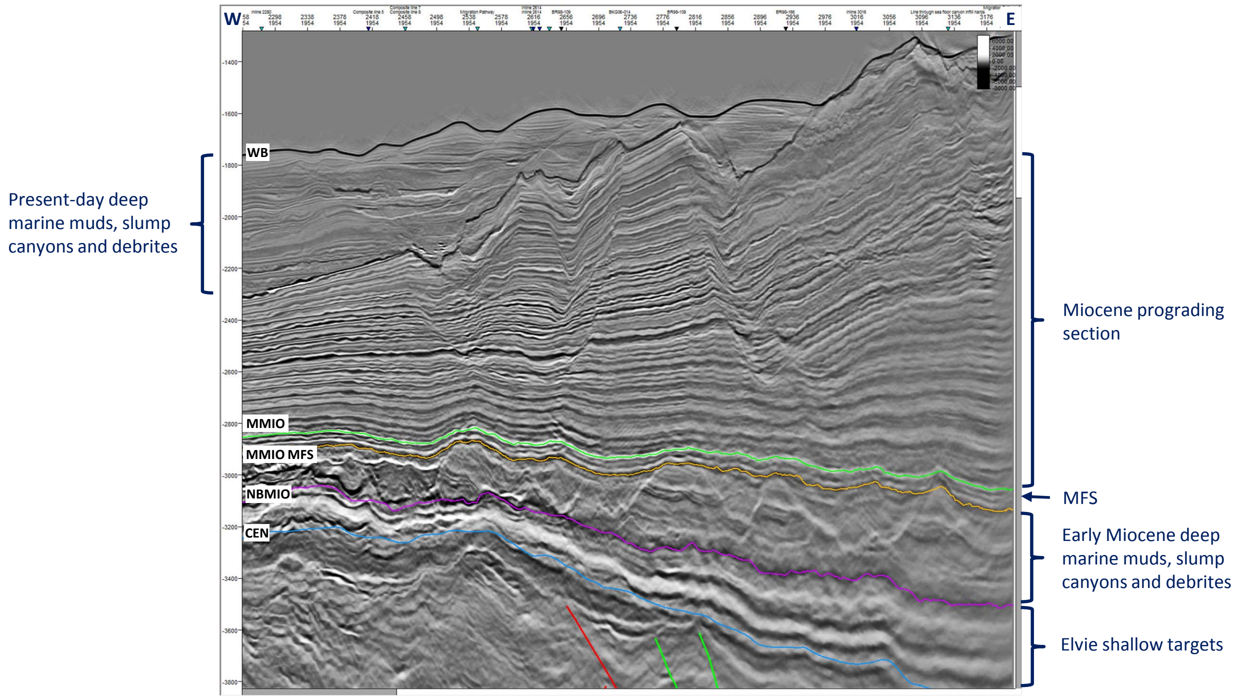

Figure 5 - Miocene event mapping and evidence for a deep marine seal above a sequence of soft events that drape the predominantly Permo-Triassic Elvie horst.

PROSPECTIVITY

Upon completion of the mapping it became clear that the original concept for the Elvie prospect was not fully supported by the seismic. The proposed Jamieson Formation top seal was either very thin or not present and the Plover Formation half-grabens were very thin and located down-flank of the Permo-Triassic horst that forms the Elvie anticlinal trend.

Nevertheless, Elvie remains a robust 4-way dip closure that is genetically related to the Buffon-Scott Reef-Brecknock anticlinal trend. Deep marine muds of Miocene age, presenting as paleo slump canyons and distal carbonates, provide a thick top seal, although there is evidence of minor seepage through a thin part of the sealing unit and on the flank of the structure (Figure 3). These shallow amplitude indicators, nearby surface seeps and pockmarks near the sea floor on the Kraken 3D provide additional support for a working petroleum system. Charge modelling suggests a good chance for oil fill at Elvie due to the reduced overburden above Jurassic source kitchens on both sides of the structure.

The Elvie structure appears to be draped by potentially high quality turbidite reservoirs of most-likely Paleocene age. These appear as soft draping low-stand events that can be mapped into time-equivalent sands encountered in incised settings in several wells on the shelf. Seismic amplitude support might further derisk reservoir but is currently hampered by the remaining imaging problems linked to the rugose sea floor.

CONCLUSIONS

The Kraken 3D survey in WA-314-P was successfully acquired; processed; and interpreted over a period from August 2013 to December 2014, with further reprocessing underway and further interpretation anticipated in 2017. The primary objective of the survey was to provide subsurface coverage of the western portion of WA-314-P, where a high potential structural prospect had been identified within the Tertiary and Jurassic sections.

The Kraken 3D is considered good quality overall and most certainly an improvement over the pre-existing 2D seismic data. It has allowed maturation of the Elvie prospect, by providing strong evidence for a valid trap (4-way dip closure); charge and migration (in the form of shallow seeps); reservoir (soft onlapping Paleocene low-stands tied to shelfal wells); and seal (paleo slump canyons and distal carbonates).

Further reprocessing in the form of geomechanical PSDM with non-parametric tomographic updating is underway to address the difficult imaging problem of a rugose sea floor that currently limits attempts at seismic amplitude interpretation at the Elvie prospect.

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A very large number of individuals have been involved in the design, operations, processing, reprocessing and interpretation of the Kraken 3D. The effort stretches back to long before my employment at Karoon and I hope I haven't left anyone out. Key contributors at Karoon included Jorg Bein, John Steel, Ian Reid, John Cant and Ian Ward. I'd also like to acknowledge the efforts of many processors at CGG (Hao Zhang, Sam Koh) and Ion (Ed Lewis, Paul O'Neill), as well as Matt Zengerer from Gondwana Geoscience for helping me to build the geomechanical model that underpins the latest reprocessing effort. Thanks also to Rick Smith for reviewing this paper at short notice.

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