Exploration leads in a proven petroleum system - Offshore Northern Perth Basin

Gareth O'Neill[1], Karyna Rodriguez[1] and David Eastwell[1*] discuss the evidence for a viable petroleum system on the West Australian continental margin.

The Offshore Northern Perth Basin is a north to north-west trending basin located on the West Australian margin. Formed during the separation of Australia and Greater India in the Permian to Early Cretaceous, it includes a series of NW - SE trending sub-basins and structural highs (Figure 1). Exploration success in the basin has been sparse to date with the exceptions of the Cliff Head Field, three non-commercial discoveries and numerous hydrocarbon shows (Figure 2). Despite limited success, evidence from exploration to date provides invaluable information of a working petroleum system and the key risks to be addressed.

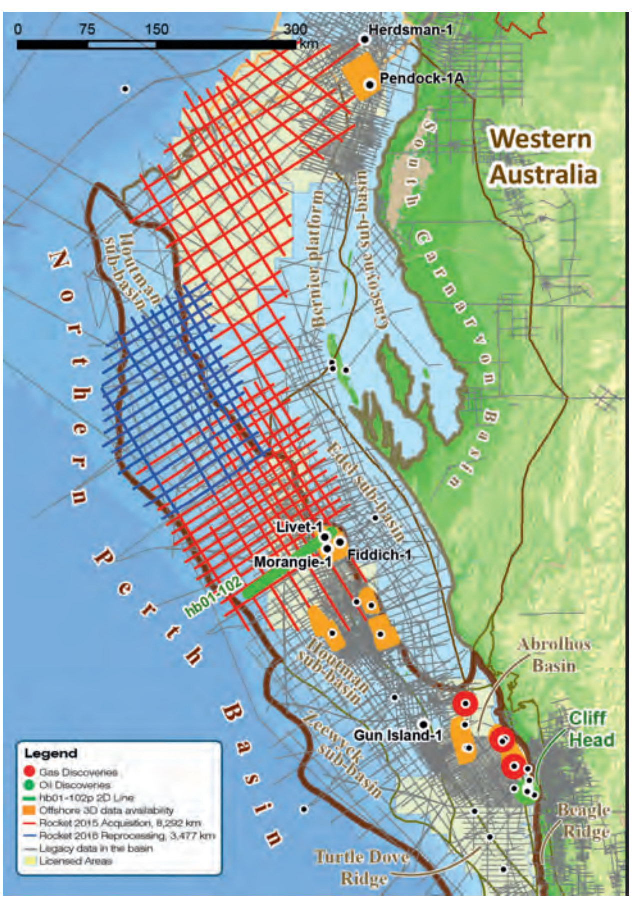

Figure 1 The North Perth Basin and its sub-basins, key wells, legacy seismic data and 2015 Rocket 2D survey.

In 2015 Spectrum acquired the modern long offset 'Rocket' 2D seismic survey, covering the majority of the Houtman sub-basin and extending northwards into the South Carnarvon Basin, providing further seismic coverage within licensed blocks and open acreage (Figure 1). Improved seismic imaging obtained from this dataset is expected to form an integral part in reviving interest in this basin and in helping operators to exploit this underexplored portion of the Australian margin. Integrating new modern seismic data with information provided by key wells within both the Abrolhos sub-basin and the South Carnarvon basin, points to the presence of an extensive, viable, petroleum system within the province.

Exploration summary

The first 2D seismic acquisition campaign began in 1965, prior to initial drilling and has increased gradually to the current coverage. Publically available legacy 2D seismic data is therefore multi-vintage and highly variable in quality. In 2003 Apache Energy Limited commissioned the first 3D survey (Macallan) across the structural high at the northern limit of the Abrolhos sub-basin (Figure 1). This was followed by two 3D surveys in the latter half of the same year and a further three surveys which were undertaken between 2004 and 2008, resulting in the current 3D coverage of 2705km^2, equivalent to only 2.7% of the area of the offshore basin. Spectrum undertook acquisition of the Rocket 2D survey in 2015, consisting of 8292 km of new 2D lines augmented with 3477 km of reprocessed seismic data.

Stratigraphy and hydrocarbon discoveries

The Offshore Northern Perth Basin contains a Permian to recent succession of sediments (Jones et al., 2013) overlying Palaeozoic terranes (Hall et al., 2012). The Mesozoic succession is coarse clastic rich (Figure 3) with regional marine incursions represented by the Kockatea Shale and Cadda Formation (Norvick, 2003).

The West Australian Petroleum & Geothermal Information Management System (WAPIMS) database currently holds records for 42 wells drilled within the Offshore Northern Perth Basin, the majority (33) having

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Figure 2 Offshore Northern Perth Basin exploration map.

tested the petroleum potential of the Abrolhos Sub-Basin. The Houtman Sub-Basin, Beagle Ridge and Turtle Dove Ridge have each been penetrated by three wells and drilling has yet to be undertaken in the deep water Zeewyck Sub-Basin. Geoscience Australia (Jorgensen et al., 2011) released a folio of information compiled from the well completion reports and revised the stratigraphic boundaries recognised in the wells during drilling, as summarised in Table 1 (development wells excluded).

Triassic-Jurassic play

The succession from the Lower Triassic Woodada Sequence to the Upper Jurassic Yarragadee has been penetrated by a number of wells and the presence of coarse-grained sediments has been confirmed. Traps include a hanging wall rollover fold (Houtman-1), anticlines (Wittecarra-1 and Leander Reef-1) and tilted horst blocks sealed by intra-formational shales. Indications of residual oil columns indicate the potential for effective sealing and highlights the danger of fault reactivation and trap breach after charging, indeed, successes have been recorded onshore at Mount Horner and North Yardanago. This Triassic-Jurassic Play is likely to be limited to the Abrolhos sub-basin and the southern margins of the Houtman sub-basin due to erosion and a regional southerly dip.

Upper Permian play

The Wagina/Dongara sandstones have been a key target within the province due to their location immediately below the Kockatea Shale, however they are not always encountered due to local erosion or non-deposition. Older, Permian reservoirs with potentially no onshore analogue, may also sub-crop and are commonly truncated beneath the regionally sealing Kockatea Shale due to the presence of an Upper Permian unconformity within the basin. This Permian Play (e.g. Jones and Hall, 2002) has been tested in 19 of the 21 wells and was successful at Cliff Head (Figure 4). The traps are structural and are described as faulted anticlines (Geelvink-1A, Cliff Head-1) or structural highs with anticlinal reservoir closures and/or bounding fault seals. The Kockatea Shale provides a top and lateral seal where fault juxtaposition places it adjacent to potential reservoirs. The majority of wells targeting the Permian play have been unsuccessful with trap breach most commonly cited as the cause of failure (Figure 2). A working petroleum system is demonstrated by non-commercial discoveries at Frankland-1, Dunsborough-1 and Perseverance-1, illustrating the potential for further exploration successes within this play.

Lower Permian play

Only four wells (Cliff Head-1, Twin Lions-1, Mentelle-1, Vindara-1) have penetrated the lower Permian section beyond the High Cliff Sequence, testing reservoirs on top of fault bounded horsts. The lower Permian sediments (Figure 5) are thought to have been deposited during the first period of syn-extensional deposition in the basin, during activation of major NNW trending faults (e.g. Harris, 1994). The lack of exploration within these sediments likely reflects their limited geographical extents and their depth which makes them difficult to map on the existing 2D seismic lines. Excepting Cliff Head-1, the wells were not successful with failure attributed to unfavourable trap and charge timing or poor reservoir quality. The identification of a palaeo-oil column in Mentelle-1 points to trap breach after charging as the cause of failure.

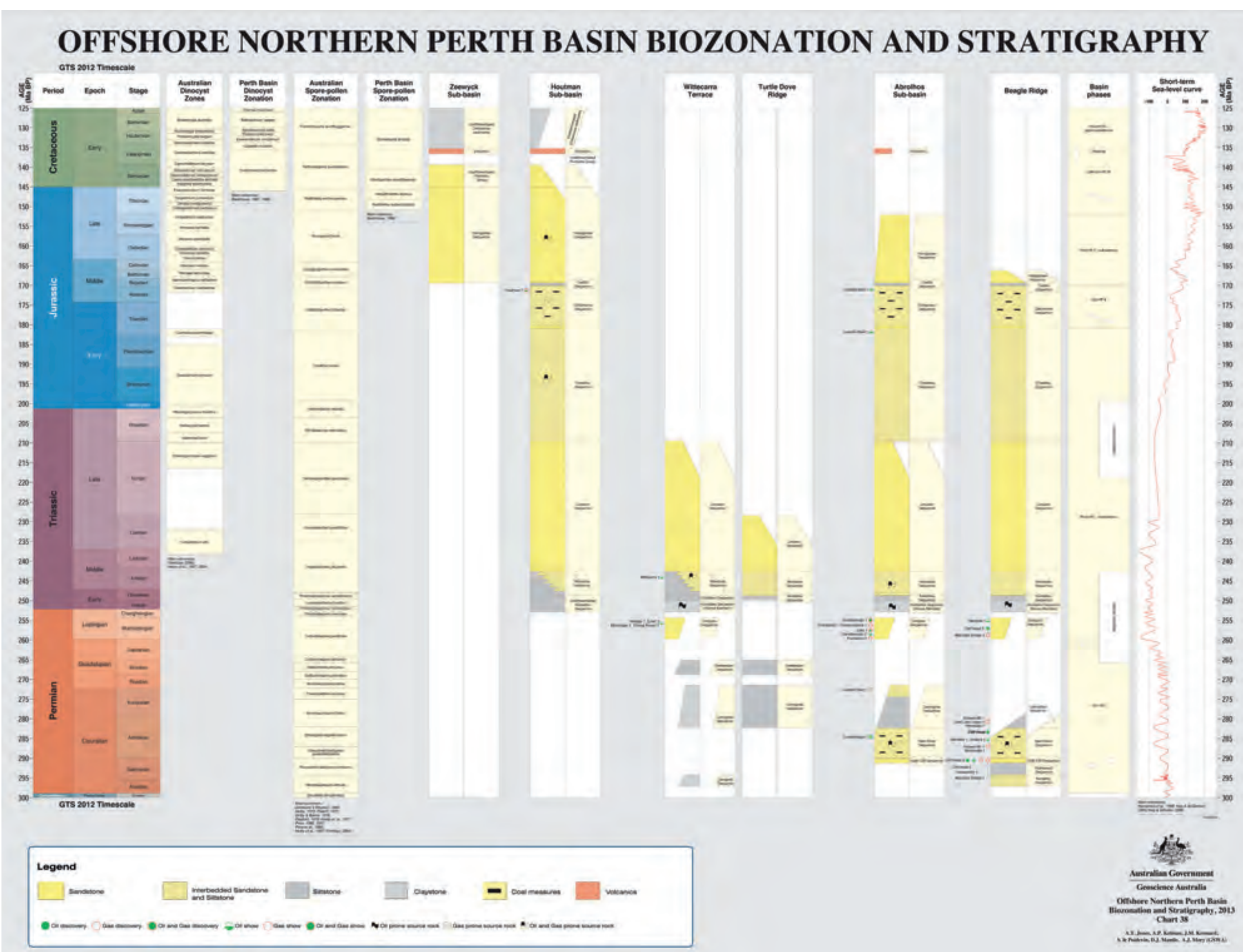

Figure 3 North Perth Basin stratigraphy and hydrocarbon discoveries (Geoscience Australia website).

Well	Sub-basin	Well Completion	Geology															Primary Target Sequence	Secondary Target	Trap Style	Shows	Failure	Palaeo-oil (Kempton et al, 2011a)	Triassic-Jurassic Play	Permian Play
			Yarragadee	Cadda	Cattamarra	Eneabba	Lesueur	Woodada	Dongara	Beekeeper	Caryngiania	Irwin River	High Cliff	Holmwood	Nangetty	Tumblagooda	Basement								
Gun Island 1	Houtman	22/06/68	x	x	x	x												Stratigraphic Test		N/A	No	N/A	Residual oil in Cadda, Cattamarra, Eneabba *	N/A	N/A
Houtman 1	Houtman	06/06/83	x	x	x													Jurassic		Collapsed hanging wall rollover anticline	Oil=basal sst of Cadda, Gas=upper Cattamarra	Non-connected pores-space in reservoirs, no valid trap, source migration to west of structure (Gorter et al 2004), lack of cross fault seals (Cadda seal downthrown past reservoirs)	Cadda	x	
Geelvink 1A	Abrolhos	10/09/83	x	x	x	x	x	x	x		x					x		Dongara		N-S trending faulted anticline	No	Poor seismic meant that 4 way dip closure may not exist, reservoir drilled on hw rather than footwall so no seal (Crostella, 2001)	Dongara		x
Batavia 1	Abrolhos	01/11/83	x	x	x	x	x	x	x		x	x					x	Permian		Upthrown (tilted) fault block	No	Fault throws greater than Kockatea Sequence thickness so no sealing, low porosity due to qtz overgrowths also observed			x
Wittecarra 1	Abrolhos	16/12/86				x	x	x		x	x							Cattamarra, Eneabba, Lesueur	Dongara	NNW trending anticline, 4 way closure	Oil show = Woodada below intraformational seal	No effective seals in post Kockatea sediments, no Dongara Sst		x	x
Leander Reef 1	Abrolhos	23/08/87		x	x	x	x	x			x	x						Dongara	Cattamarra, Eneabba, Caryngiania	Leander Reef: large faulted anticline	Gas peak=upper Cattamarra, Oil show=lower Cattamarra, high water saturation	Lack of effective seals other than Kockatea (high sand:shale ratios), local faulting not observed on seismic as possible leakage paths, breaching of palaeo-collumns by cross fault seal failure or fault reactivation	Caryngiania below Kockatea and beneath intraformational seal in lr Cattamarra	x	x
South Turtle Dove 1B	Turtle Dove Ridge	07/08/90					x	x		x	x							Dongara	Caryngiania, Irwin River, Tumblagooda	Structural high	No	No reservoirs, poorly defined structure, lack of structural seal by Kockatea			x
Livet 1	Abrolhos	12/10/98					x	x	x							x		Dongara	Woodada	Tilted block	Oil show=Dongara	Fault reactivation lead to trap breach	Dongara	x	x
Cliff Head 1	Abrolhos	05/02/04	x	x	x	x	x	x				x	x	x			x	Permian		Faulted anticline with NW-SE bounding faults	OIL DISCOVERY 4.8m oil collumn in Irwin River Coal Measures beneath Kockatea Sequence	N/A	Permian below Kockatea		x
Morangie 1	Abrolhos	04/11/04					x	x	x									Dongara	red beds above basement	Tilted horst, dip closure to south	Oil show=Dongara sequence but not moveable	Trap breach (fault reactivation)	Dongara Sequence, sourced from Yalthoo Trough in Houtman Sub-basin		x
Twin Lions 1	Beagle Ridge	10/03/05	x	x	x	x	x	x	x			x	x	x	x		x	Irwin River	High Cliff	NNE-SSW fault bounded, rotated fault block	N/A	Lack of charge, late trap development	N/A		x
Mentelle 1	Abrolhos	18/03/05	x	x	x	x	x	x	x			x	x	x			x	Irwin River	High Cliff	Fault bounded, rotated fault block	Minor gas/ fluorescence in Irwin River	Trap breach (well orginally thought to be beyond spill point of closure)	Dongara Sequence oil present during qtz intergrowth		x
Vindara 1	Beagle Ridge	28/03/05		x	x	x	x	x	x		x	x	x	x				Dongara, Irwin River, High Cliff		NW-SE horst block (N and S dip closure)	Fluoresecence in Irwin River but not moveable	Young trap formation compared to late Jurassic maturation, poor reservoir quality below Kockatea, poor migration pathways, trap breach	below intra-formational seals in Dongara & Irwin River Sequences		x
Fiddich 1	Abrolhos	10/12/06					x	x	x		x							Dongara		Three-way dip closure and fault closure in tilted horst	No	Preferential charge to North and Northwest, immature Hovea within capture area of trap			x
Hadda 1	Abrolhos	29/03/07				x	x	x	x							x		Permian		West tilted fault block, 2 crests against eastern bounding fault	No (patchy fluorescence)	Trap breach (late Jurassic charge) causes fault dilation or cross-fault migration, timing? Poor reservoir quality.	Dongara		x
Flying Foam 1	Abrolhos	28/11/07					x	x	x						x			Permian		Tilted fault block with three-way closure	100m tight sands with shows but tight	Trap breach, poor quality reservoir	Dongara		x
Moondah 1	Beagle Ridge	06/09/08	x	x	x							x	x					Permian		Rotated fault block	Fluorescence in lower Kockatea Sequence	Fault reactivation and trap breach, Dongara Sandstone not present.			x
Frankland 1	Abrolhos	09/05/09	x	x	x	x	x	x	x			x	x					Dongara & Irwin River		Faulted anticline	GAS DISCOVERY, many oil shows, 48 pressure tests	N/A	Dongara and Irwin River Sequences, 48m collumn		x
Perseverance 1	Abrolhos	30/05/09	x	x	x	x	x	x	x			x						Dongara & Irwin River		Tilted fault block	NON-COMMERCIAL DISCOVERY	N/A	Dongara		x
Dunsborough 1	Abrolhos	17/06/09	x	x	x	x	x	x	x			x	x					Dongara & Irwin River		N-S rotated fault block trap	OIL DISCOVERY and gas shows in lower Kockatea, Dongara, Irwin River Sequences	N/A	Kockatea to 52m below		x
Lilac 1	Abrolhos	11/02/10	x	x	x	x	x	x	x			x						Dongara & Irwin River		N-S rotated fault block trap	Fluorescence and gas peaks in Kockatea, Dongara and Irwin River. Wireline = no moveable hydrocarbons	Trap breach	Dongara and Irwin River		x
Charon 1	Houtman	24/06/10	x	x	x													Cattamarra		Tilted horst block with E bounding fault	Fluorescence in Cattamarra ssts, no shows	Poor quality (silty) reservoirs in Cattamarra	Cadda and Cattamarra	x	

H = Hovea Member identified
Moondah 1 data from Well Completion Report
** Residual oil interpreted from Quantitative Grain Fluorescence and Extract, may be affectedby coaly fragments (Kempton et al, 2011b)*

***Table 1** Exploration Well summary (After Jorgensen et al., 2011).*

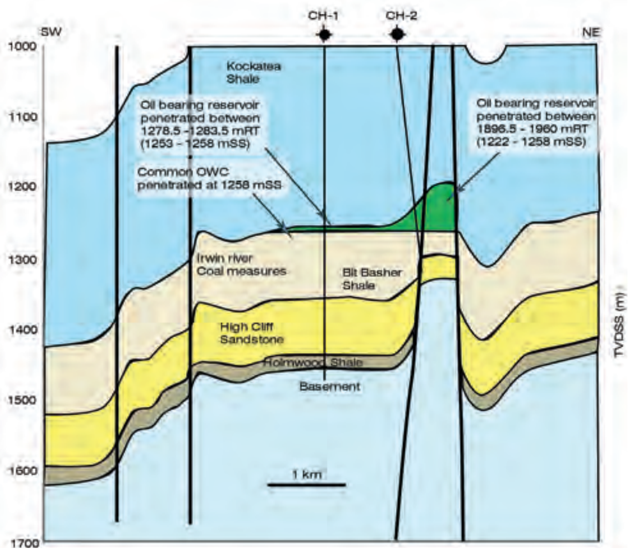

Figure 4 *A schematic section through the Cliff Head Discovery (Jones and Hall, 2002) shows Permian sandstones containing an oil column in a fault bounded anticlinal structure sealed by the Kockatea Sequence.*

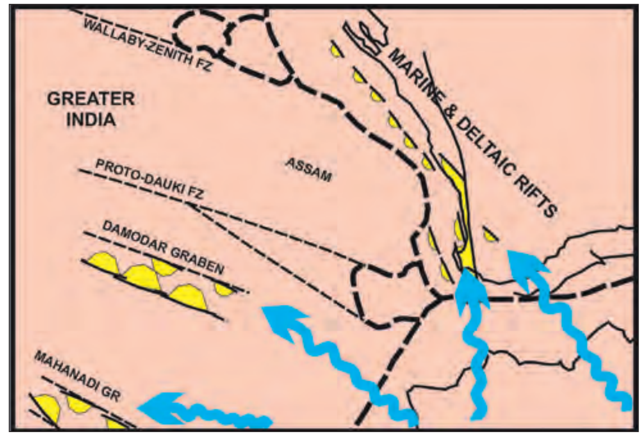

Figure 5 *The breakup of Gondwana is initiated in the Early Permian at the junction of Antarctica, Australia and India (Norvick, 2003). The first extensional phase leads to the deposition of lower Permian sediments (yellow) adjacent to growth faults in the incipient Perth Basin.*

The petroleum system

Sources

Crostella (2001) identified source intervals within the Irwin River, Carynginia, Beekeeper, Dongara and Kockatea Sequences based on geochemistry data from 9 offshore wells. The sapropelic Hovea Member in the basal portion of the Kockatea Sequence is thought to be the source for the majority of discoveries in the northern Perth Basin (e.g. Jones et al., 2011). Re-evaluation of the stratigraphy of the offshore wells by Geoscience Australia (Jorgensen et al., 2011) has identified the Hovea member in the majority of wells (Table 1).Kempton et al. (2011a) note that crude and fluid inclusion oils from the Cliff Head field, Leander Reef–1, Morangie-1 and Livet-1 point to the importance of the Hovea Member as a regional source rock.

The geochemistry compiled by Jorgensen et al., 2011 is summarised in Table 2. The more deeply buried Irwin River – Dongara Sequence rocks (Figure 6) are indicated to be the most mature based on the Vitrinite Reflectance data. Pyrolysis results suggest that the Yarragadee Sequence has the most potential for hydrocarbon generation ($S1 + S2 = 31.26$ mg/g) though its shallow position in the basin fill does not favour maturation. The Cadda, Cattamarra, Eneabba, Kockatea (Hovea Member), Dongara and Irwin River Sequences are indicated to have generation capacities above 5 mg/g.

Reservoirs

Estimation of the bulk sand content of each of the stratigraphic units (Figure 7) in the basin, based on examination of the lithological logs, reveals potential reservoirs throughout the basin fill. High coarse grained contents (>60%) were recorded within the Yarragadee, High Cliff and Tumblagooda units. The Dongara Sequence, targeted by many of the wells has an average coarse sand content of 48% and fine grained content of 20%.

Table 3 summarises the porosity and permeability measurements from the relevant well completion reports and is based on a combination of lab testing and petrophysical interpretation. Porosity and permeability readings are publically available for 13 wells penetrating the Dongara Sequence revealing good reservoir potential. Fluvial reservoirs of the Yarragadee Sequence demonstrate the highest permeabilities based on data from Charon-1 and Geelvink-1A.

Seals

Shows in Dongara Sequence Reservoirs (Table 1) demonstrate the regional sealing potential of the overlying Kockatea Sequence. The Irwin River reservoirs in the Cliff Head field and Vindara-1 are also sealed by these lower Triassic sediments. Intra-formational seals have local potential within the younger Cadda (Houtman-1), Cattamarra (Leander Reef-1) and Woodada Sequences (Wittecarra-1). The presence of hydrocarbon shows and palaeo-oil columns (Kempton et al., 2011a) indicate that effective seals are present within the offshore province and that the major risk to seal integrity is fault reactivation and trap breach.

Traps

The structural evolution of the Northern Perth Basin includes three periods of rifting associated with the post-Carboniferous break-up of the Gondwana supercontinent (e.g. Jones et al., 2011). Incipient rifting beginning in the Lower Permian was characterised by NE-SW extension and movements on NW trending basement lineaments. The second extensional event began in the lower Jurassic with a similar extension direction and re-activation of similar fault trends. Upper Jurassic NW-SE oriented extension was documented by Harris (1994) and may be the result of oceanic spreading at Argo Ridge in the NW Shelf (Gibbons et al., 2012). Jones et al. (2011) recognised N-S trending faults within the offshore Houtman Fault System that formed in reaction to this change in extension direction. These rifting episodes are separated by sag phases characterized by parallel seismic reflectors and minor localised fault movements. Drilling to date has concentrated on testing Permian reservoirs within structural highs, sealed by the transgressive Kockatea Sequence. These highs formed during one or more of the rifting events detailed above and there is clearly a risk of reactivation along the bounding faults of these structures during later rift periods. Palaeo-oil columns in a number of wells point to fault reactivation and the potential for block rotation and spill-point adjustment after secondary charge migration. Geomechanical modelling undertaken by Langhi et al. (2012) identified NNW and ESE trending faults as being at risk of breaching during the Upper Jurassic extension event. Miocene inversion due to collision between the Indo-Australian plate and the Eurasian plate (Jones et al., 2011; Crostella, 2001) resulting in the reactivation of normal faults constitutes a further risk. Shows in Jurassic reservoirs and evidence of hydrocarbon migration in the Cattamarra Sequence at Leander Reef 1 indicate that younger seals are also susceptible to breaching by fault reactivation.

Timing

Modelling of thermal maturation in the onshore northern basin undertaken by West Australia Petroleum Pty Ltd

Geology	Average VR	VR Samples	Petroleum Generation	Average Tmax	S1 avg (mg/g)	S2 avg (mg/g)	S1avg + S2avg (mg/g)	No of samples	Depositional Environment	Oil/ Gas Prone
Valanginian	0.38	4	Immature	421.20	0.37	7.81	8.18	10	N/A	N/A
Yarragadee	0.47	61	Immature	427.02	1.18	30.07	31.26	141	Fluvial	N/A
Cadda	0.59	18	Early Oil Generation	430.42	0.47	5.35	5.82	138	Marine shales	Oil
Cattamarra	0.58	51	Early Oil Generation	437.14	0.43	5.93	6.36	122	Deltaic	Gas
Eneabba	0.64	19	Early Oil Generation	459.59	0.88	14.53	15.40	70	Sabkha	Oil/ Gas
Lesueur	0.46	21	Immature	458.00	0.13	0.78	0.91	18	Fluvial with marine in north	N/A
Woodada	0.56	27	Early Oil Generation	435.57	0.18	2.55	2.72	72	Marine and fluvial	Oil
Kockatea	0.65	80	Early Oil Generation	436.01	0.20	1.53	1.73	121	Marine shales	Oil
Hovea Member	0.70	21	Early Oil Generation	431.06	0.62	12.33	12.95	67	Marine shales	Oil
Wagina	0.94	1	Early Condensate	456.42	0.26	1.16	1.42	4	Marine Mudstones	Oil
Dongara	0.98	10	Early Condensate	445.75	0.50	4.84	5.35	16	Terrestrial	N/A
Caryngina	0.91	21	Early Condensate	457.04	0.27	1.48	1.75	28	Marine mudstones	Oil
Irwin River	0.85	28	Early Condensate	438.22	0.95	8.27	9.22	55	Coals	Gas
Holmwood	0.54	3	Early Oil Generation	435.33	0.10	0.99	1.09	3	Marine shales	Oil

***Table 2** Source potential of the basin lithologies summarised from the geochemical data in Jorgensen et al. (2011).*

Table 3 Summary of porosity and permeability ranges from publically available completion reports.

Sequence	Average Porosity (-)	Permeability (mD)	Wells
Yarragadee	17.93 - 25	1324.9 - 1454.65	Charon-1, Geelvink-1A
Cadda	8.82 - 25	0.26 - 16.57	Charon-1, Geelvink-1A, Houtman-1
Cattamarra	3.12 - 30	0.12 - 9.5	Batavia-1, Charon-1, Geelvink-1A, Houtman-1
Eneabba	18 -24	N/A	Batavia-1, Geelvink-1A
Lesueur	15 - 30	N/A	Batavia-1, Geelvink-1A, South Turtle Dove-1B
Woodada	15 - 30	N/A	Geelvink-1A, South Turtle Dove-1B
Kockatea	6 - 17	N/A	Geelvink-1A, Livet-1, Perseverance-1
Dongara	2 - 25	0.9 - 65.76	Cliff Head-3 & 10, Batavia-1, Dunsborough-1, Fiddich-1, Flying Foam-1, Frankland-1, Geelvink-1A, Hadda-1, Livet-1, Perseverance-1, Twin Lions-1, Vindara-1
Beekeeper	11 - 18	N/A	South Turtle Dove-1B
Carynginia	5 - 12	N/A	Batavia-1
Irwin River	5 - 26.2	0.03 - >1000	Cliff Head-1 - 5, 8, 9 , 11 - 13, Dunsborough-1, Frankland-1, Geelvink-1A, Mentelle-1, Twin Lions-1, Vindara-1
High Cliff	9.2 - 19	1.3 - 243	Cliff Head-1 - 6, Dunsborough-1, Frankland-1, Mentelle-1, Twin Lions-1, Vindara-1
Tumblagooda	18.9 - 19.4	118 - 124	Hadda-1

(1996, unpublished report in Crostella, 2001) indicated that maturation of Permian sources began in the early Jurassic and continued until the present day. Jones and Hall (2002) describe thermal modelling undertaken during development of the Cliff Head field which indicated peak generation (likely from Kockatea and Irwin River Sequences) occurred in the late Jurassic however further details are not provided. These examples from the literature indicate that secondary migration may have begun in the Jurassic, after the first phase of rifting/trap formation and could have led to charging of fault bounded structures. If widespread maturation did occur in the Jurassic then it's possible that structural traps may have been reactivated during the second (Lower Jurassic) and third (Upper Jurassic) rift events.

Seismic imaging breakthroughs

Legacy seismic data in the basin suffers from several limitations, including issues with subsurface imaging related to complex ray paths and velocity trends resulting in poor

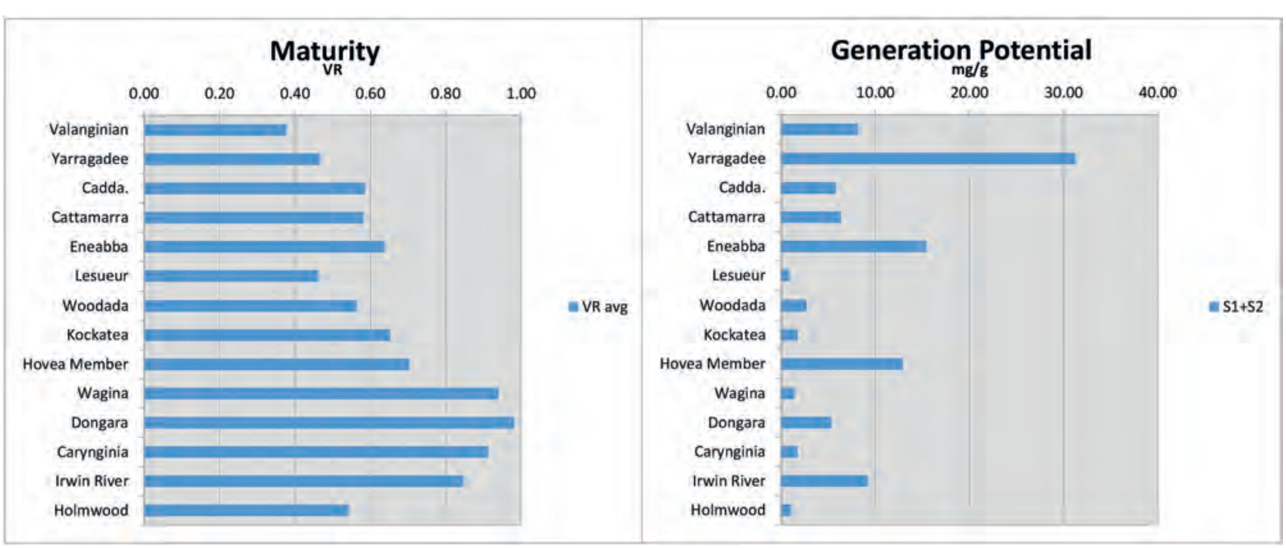

Figure 6 VR and (S1+S2) compiled from geochemical data in Jorgensen et al. (2011).

first break volume 34, June 2016

Imaging Issue	Solution
Intrusive and basalts	• Reduced gun size • DUG Broad processing • Streamer depth modelled for optimum response
Complex structures, faulting and migration pathways	• PSDM processing • Wells used for velocity model calibration • Dense 2D survey though multi-phase shoot
Deep targets	• Long off set cable • Deep tow for improved low frequency recording and reduced noise
GA Survey Ties	• Both surveys processed in conjunction • 2 km full fold overlap on lines • Phase and amplitude tie
Interpretation	• 10 well ties across survey • Basin scale seismic frame work

Table 4 *Rocket survey design considerations.*

data quality, hampering structural analysis and evaluation of potential migration pathways. Legacy data is relatively sparse over the source kitchen for the basin as well as over the likely location of Mesozoic drilling targets, also suffering from lack of resolution at target depths. Considering all the limitations and taking advantage of all applicable modern technologies, the Rocket 2D survey was carefully designed in order to address known issues (Table 4) and provide a tool suitable to identify future exploration targets applying all the lessons outlined above from exploration to date.

Rocket Phase 1 was acquired over the South Carnarvon Basin largely to establish the poorly imaged subsurface structure and geometry of the offshore section of the basin, thereby proving the presence of a sedimentary basin and attempting at the same time to define its age. Preliminary results to date are already showing very encouraging outcomes (Figure 8A and 8B).

The South Carnarvon Basin has a very different geological evolution to the Abrohlos and Houtman sub-basins. The onshore section of the basin consists of an Ordovician to Permian section overlain by the Neocomian regional angular unconformity which was caused by the breakup of Australia from greater India. Clearly visible even on legacy seismic data, it is a significant regional seismic marker which can be used to constrain interpretation in areas with limited well control. Above this unconformity is a thin Cretaceous to Present section resulting from limited sedimentation post-rift.

Not much is known about the subsurface in this basin, predominantly due to the presence of what have been believed to be shallow basalts providing a major barrier to seismic imaging (Figure 8A). Many have suggested that either shallow basement or perhaps very thick basalts underlay the main Cretaceous unconformity. However, gravity

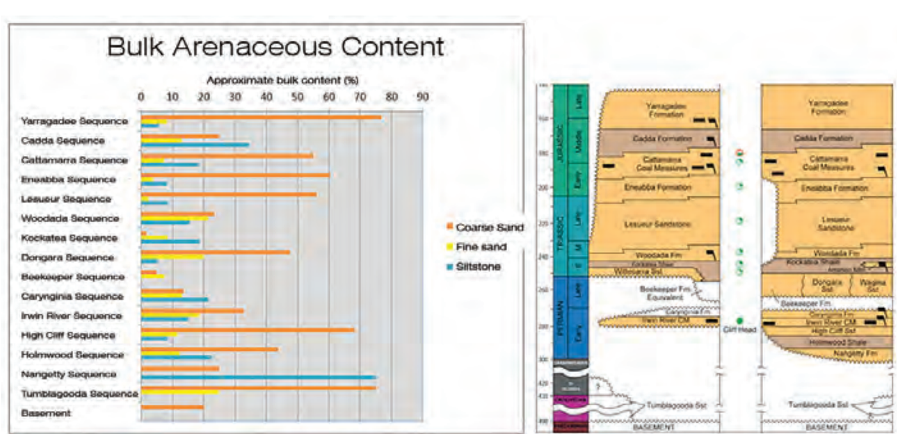

Figure 7 *Bulk sand content of basin fill.*

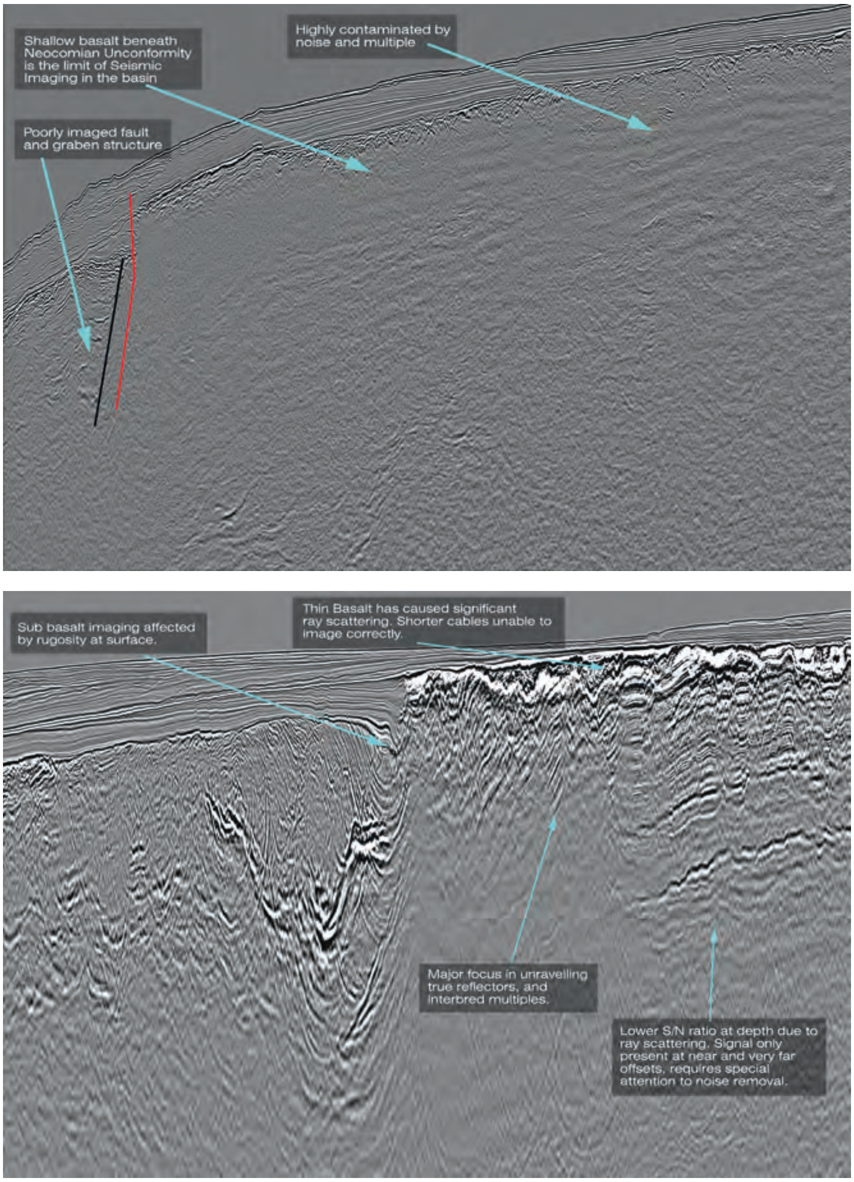

***Figure 8** Comparison of preliminary Rocket Survey data with Legacy seismic.*

A

B

mapping has suggested the presence of a sedimentary basin, perhaps several kilometres thick, which had not been imaged before. Preliminary results from Phase 1 strongly support the presence of a basin as large rotated fault blocks are imaged below a “thin” and very rugose basalt layer.

Similar improvements in imaging are expected for Phase 2. At this stage of processing, available seismic data from the Phase 2 survey is confirming future exploration targets.

Future exploration in the Houtman sub-basin

The Houtman sub-basin is currently penetrated by three wells (Figure 1) which have tested Jurassic reservoirs underneath the regional seal of the Cadda Formation (Figure 2). The presence of palaeo-oil in all three wells and shows in Houtman-1 and Charon-1 prove that charge has moved though the basin and was temporarily preserved within these tested structures. Extensive uplift and erosion during the Valanginian separation of the Indian plate likely restricts this play to the southern margins of the Offshore Northern Perth Basin.

The deeper, sub-Kockatea Shale play is more geographically extensive since it has not been subjected to Valanginian erosion and there is potential for further successes similar to the Cliff Head field discovered in the Abrolhos sub-basin. This play has yet to be tested in the Houtman Sub-basin. Geomechanical modelling of fault reactivation risk suggests that the orientation of bounding faults is the key to understanding the risk of Upper Jurassic trap breaching. The Rocket 2D survey will aid in the

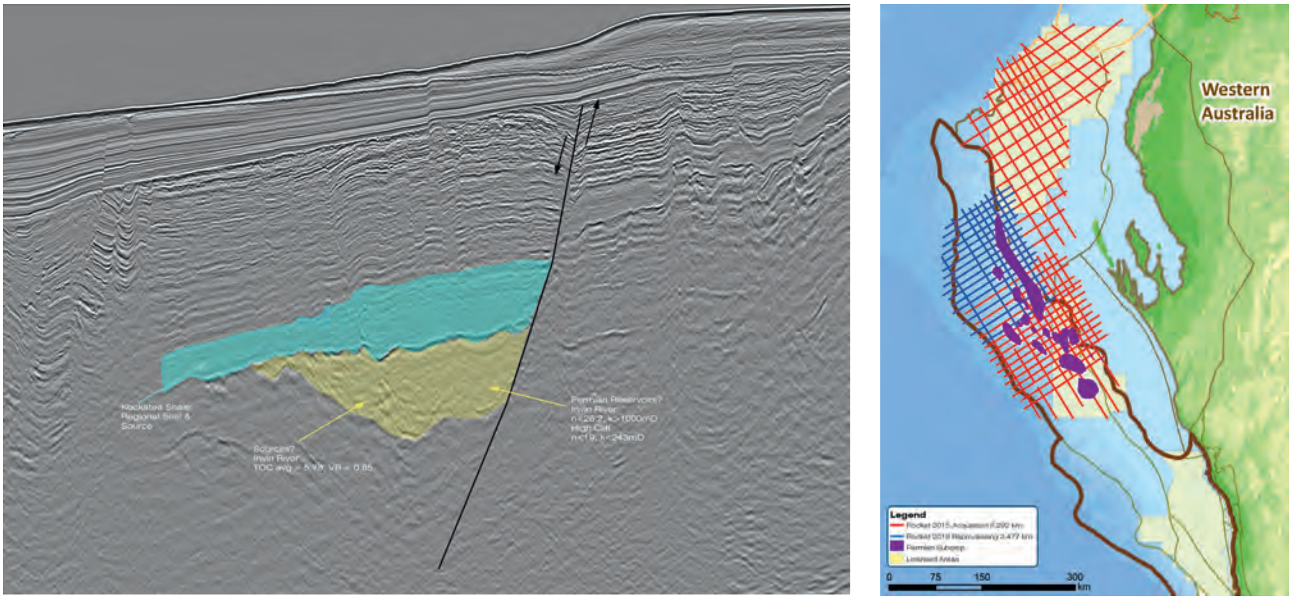

Figure 9 Preliminary results from Rocket Phase 2 seismic confirming a new untested play in which Permian reservoirs and source rock deposited in Permian growth wedges are overlain by the Kockatea Shale regional source. Tentative mapping of Permian subcrops highlights locations where this play may be investigated.

identification of leads and help to better define the orientation of trap-bounding faults. Testing of this play in the Abrolhos sub-basin has focused on reservoirs on the tops of structural highs, sealed above and laterally across bounding faults by the Kockatea Shale (Figure 4).

To date, no wells have tested the lower Permian syn-extensional wedges deposited locally on major fault hanging walls. These localised depocentres (Figure 9) have the potential to contain reservoirs such as the Irwin River and High Cliff sandstones which have been found to possess good reservoir properties elsewhere within the offshore province (Table 3). These sands have the potential to receive charge from fine-grained materials within the lower Permian succession (e.g., Irwin River coals, Holmwood Shale) or from the overlying Kockatea Shale. The geometry of the potential reservoir reflectors indicates that charge would accumulate on the up-dip margins of the structure, distal to the listric growth fault and therefore far from any trap breaching event. Tentative mapping of the Permian subcrop on legacy seismic reveals a number of depocentres warranting further investigation.

Conclusions

Drilling in the Offshore Northern Perth Basin has identified a number of promising reservoir sections. A number of source rocks that may have contributed to a mixed charge from terrestrial and marine sediments have been proven. Numerous shows throughout the sedimentary record prove the occurrence of secondary migration and the integrity of a number of seals including the regional Kockatea Shale.

Palaeo-oil columns in many of the wells provide further evidence for secondary migration and also highlight the risk of fault reactivation. Understanding the orientation of trap bounding faults and the axis of regional extensional events may allow the risk of trap breach to be evaluated and ranked.

Modern seismic has revealed offshore basin geometry beneath a 'thin rugose basalt layer' in the unexplored sector of the South Carnarvon basin.

The Houtman sub-basin has only been tested by three wells that have penetrated to the base of the Jurassic. There is running room for further testing of structural highs, sealed vertically and laterally by the Kockatea Shale and for further discoveries, similar to the Cliff Head field.

A new play concept, consisting of Permian growth wedges sealed by the Kockatea Shale is proposed and is yet to be tested.

The Rocket 2D survey will contribute to further exploration success through high-quality subsurface imagery, leading to the identification of leads and improved understanding of the timings of fault movements.

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