Northwest Canning Basin Top and Fault-seal Potential

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**Overview**

James Price Point (JPP) 55km north of Broome is the chosen location for a LNG facility to exploit the gas fields of the Browse and other northern NW Shelf Basins. The purpose of this study is to analyse existing well data to identify suitable sedimentary sequences and hence potential sites for CO2 sequestration within 200km of JPP. 200km being the maximum feasible distance for any pipe line to deliver CO2 to an injection site in the basin.

The well information was downloaded from the DMP WAPIMS online database. There are 65 wells within 200km of JPP in the database. It should be noted that 22% of Canning Basin wells lie within 200km, whereas an additional 40% lie within 200 to 300 km, a considerable increase in the data and knowledge of the reservoir sequence. As such the survey has been extended beyond 200km to investigate wells in areas such as the Lennard Shelf, Mowla Terrace and Willara Sub-Basin. Data from 81 wells was downloaded from the database and received preliminary analysis. Not all of the wells intersect the Permian and Carboniferous sequence, many have no potential local top-sealing units, several do not have suitable wireline information and several of the wells were drilled from the same locality and as such contained similar data.

Within 200km of JPP the broad structure of the tectonic elements can be subdivided from the NE to the SW as the northern flank of the Fitzroy Trough (Pender Terrace, Lennard Shelf), the trough itself, the southern flank of the trough (Jugurra and Mowla Terraces), the Broome Platform and the Willara Sub-basin (figure 1).

Kennard & al. (1994) presents a standard summary of Canning Basin deposition, petroleum systems and their interrelation with basin tectonics, this is modified in figure 2. The paper summarises three Palaeozoic depositional megasequences, each of about 70 -80 million years duration (Ordovician-Silurian (OSM), Devonian-Early Carboniferous (DECM) and Late Carboniferous-Permian (LCPM)) whose deposition is punctuated by basin-inversion events (Early Devonian Prices Creek Movement, Mid Carboniferous Meda Transpression and Early Jurassic Fitzroy Transpression). The paper identifies four petroleum systems which are related to the megasequences (Larapintine 2 (OSM), 3, 4 (both DECM) and Gondwanan (LCPM)).

Various publications have described the geographical distribution of the Palaeozoic megasequences (e.g. Kennard & al. 1994, Mory, 2010). In summary, the most complete OSM sequence occurs in the Willara Sub-basin. The sequence is truncated across the Broome Platform, but also has reasonable thickness in the terraces on the southern flank of the Fitzroy Trough. The DECM after its earliest-most units is restricted to the Fitzroy Trough and its flanks. The LCPM sequence is again at its most extensive in the Fitzroy Trough. However certain LCPM units, such as the early Permian Grant Group have basin-wide distribution. In areas on the Broome Platform Jurassic Wallal Sandstone overlies Grant Group which in turn overlies mid Ordovician Goldwyer Formation. The columns in figure 2
Figure 1. Map illustrating the tectonic elements of the Canning Basin in relation to Jame Price Point (JPP), Broome (B) and Derby (D). Tectonic elements labelled are the Lennard Shelf (LS), Pender Terrace (PT), Fitzroy Trough (FT), Jugurra Terrace (JT), Mowla Terrace (MT), Broome Platform (BP), Willuna Sub-basin (WS) and Munro Arch (MA). The red circle illustrates the 200km radius from JPP.

Figure 2. Schematic cross section to illustrate relative thickness and age of the fill of the NW Canning Basin at the end of the Palaeozoic. The section might represent a composite section indicated as the yellow line in figure 1. The Ordovician-Silurian megasequence (OSM) is green, the Devonian-Early Carboniferous megasequence (DECM) blue and the Late Carboniferous-Permian megasequence (LCPM) in orange and gold. The top gold layer represents sediment thickness removed by erosion resulting from uplift and basin inversion prior to Mesozoic sedimentation. Sedimentation in the Fitzroy Trough is generally estimated as exceeding 12km, the section length would be approaching 400km, as such it should be noted that the schematic has a vertical exaggeration of about x20.
attempt to summarise this geographical distribution. It should be noted that the Canning Basin stratigraphic column presented (figure 2) is indicating the length of time of sedimentation, rather than indicating sedimentary thicknesses. The schematic cross section in figure 3 attempts to illustrate the relative Palaeozoic sedimentary megasequence distribution and thicknesses related to the elements of the basin.

Initial extension and sedimentation in the Canning Basin began just after 500 Ma. Extension, sag and periodic pulses of basin inversion are commonly inferred to have occurred orthogonally to the ~NW-SE axes of the basin’s troughs, terraces and platforms (e.g. Forman & Wales 1981). However, it should be noted that the Canning Basin is young in the greater scheme of Australian tectonics and that the basin orientation may reflect Proterozoic lineaments rather than the orientation of the initial early Palaeozoic extension. Earlier events are occasionally alluded to in literature describing the Fitzroy Trough (Smith 1968, Kennard & al. 1994).

Mesozoic deformation in the Fitzroy Trough has since the 1960s been envisioned as a ‘wrench’ or ‘transpression’ indicated by synchronous NNW-SSE compression indicated by ENE-WSW striking anticlinal fold axes and ENE-WSW extension indicated by NNW-SSE striking normal faults (Rattigan 1967, Smith 1968). The fold axes and to a lesser extent the fault orientations on inspection are far from being uniform. However between them a tectonic regime of synchronous extension and roughly perpendicular compression is evident and best explained by a transpressional event. Structural deformation, anticline formation, reactivation and formation of new faults, associated with this transpression is restricted to the Fitzroy Trough and Gregory Sub-basin and their flanking structures. However erosion exceeding 1km occurred across the whole Canning Basin at this time (Horstman, 1984).

Kennard & al. 1994 identifies and provides geochemical properties for source intervals in all four of the Palaeozoic Canning Basin petroleum systems (Larapintine 2, 3, 4 and Gondwanan 1). The oldest, Larapintine 2 system sources identified occur in the Early Ordovician Nambeet Formation, then Mid Ordovician Goldwyer Formation and Late Ordovician Bongabinni Formation. Larapintine 3 system sources occur throughout the Late Devonian. Source units in the Larapintine 3 system comprise shale units associated with the formation of Frasnian and Famenian reef complexes (Gogo, Mellinjerie, Clanmeyer and Luluigui formations). Kennard & al. 1994 include shalier units of the Lower and Middle Carboniferous in their Larapintine 4 system, the most notable of which being the Laurel Shale. Units within the Grant, Poole and Noonkanbah Formations comprise potential sources within the Gondwanan 1 petroleum system.

Figure 4, taken from Carlsen and Ghori (2005), indicates the ages of known Canning Basin Reservoir units. It is evident that reservoirs occur in every unit from the Mid Devonian to the Mid Permian.
Figure 3. Tectonostratigraphic column for the Canning Basin (simplified from Kennard et al. 1994). Columns represent the tectonic elements of the basin, the southern Canning Basin margin (SCBM), Willare Subbasin (WSB), Broome Platform (BP), Fitzroy Trough southern flank (FTSF, i.e. Jugurra, Mowla and Barbwire Terraces), Fitzroy Trough (FT) and Fitzroy Trough northern flank (FTNF, i.e. Pender Terrace and Lennard Shelf). The Ordovician-Silurian megasequence (OSM) is green, the Devonian-Early Carboniferous megasequence (DECM) blue and the Late Carboniferous-Permian megasequence (LCPM) in orange, brown and gold colours (the dark gold colour represents undifferentiated LCPM, pale gold is late Permo-Carboniferous, yellow is Poole Sandstone, brown, Noonhanbah Fm and grey Blina Shale). Timing of the Gondwanan (G) and Larapintine (L) 2, 3 and 4 petroleum systems are indicated on the right. The horizontal red bars indicate the timing of the principal tectonic compressional events, the early Devonian Prices Creek Movement, the mid Carboniferous Meda Transpression and the end Palaeozoic Fitzroy Transpression. It should be noted that length of deposition not thicknesses are indicated and periods of no deposition are not differentiated from gaps in the sequence caused by erosion.
Figure 4. Canning Basin generalised time-stratigraphy with hydrocarbon occurrences (Carlsen and Ghori, 2005). The wide range of ages of the sediments hosting the hydrocarbon occurrences is notable.
**Sequences Analysed**

The Lower Permian sequence underlying the potentially top sealing Noonkanbah Fm is the main focus of the investigation, most specifically the Permian Poole Sandstone unit. In addition to stratigraphic relationships it is associated with high TOC. It has potential for both hydrocarbon reservoir and sequestration sites, given the occurrence of a suitable structure. However for the purposes of the fault seal study a much wider range of units can be assessed at the same time and as such the fault sealing discussion has been extended beyond just the Poole Sandstone. There follows a brief description of the sequences analysed, with focus being given to the early-mid LCPM units of the Noonkanbah Formation, Poole Sandstone and the Permo-Carboniferous.

**Post Noonkanbah Fm Sequences**

There is a gap in preserved Canning Basin sequences of over 60Ma from the early Triassic to the middle Jurassic. This is a result of the major Fitzroy Transpression. Post Fitzroy Transpression, Jurassic and Cretaceous sediments are immature and sealing lithologies are uncommon, these units are not described further in this study.

Remnant post Noonkanbah Fm (i.e. upper) LCPM sequences commonly is on the order of a km thick. The upper Permian Liveranga Group is a succession of silicilastic and carbonates rocks with thin coal seams, which may exceed 600 m in the Fitzroy Trough. The remnant early Triassic sediments comprise conglomerates, sandstones, siltstones, shales and claystones. Bioturbation is common indicating coastal environments with seasonal flooding alternating with fluvial and restricted marine facies. Analysis of vitrinite reflectance indicates that in excess of a km, locally more than 2.5km, of mid-late Triassic sediments were removed from the Canning Basin sequence by the end of the Fitzroy Transpression (Horstman, 1984).

**Noonkanbah Formation**

In the sub-surface the Noonkanbah Formation is arguably the most easily recognized Permian unit in the basin, as it is dominated by mudstone with thin sandstone beds. In this study, the Noonkanbah Formation represents the regional seal for the Lower Permian reservoirs. Resistant sandy carbonate beds dominate outcrop, which is usually poor, but in general these beds comprise only a small part of the succession. Cored intervals are available from just 11 petroleum wells. Of these cores the longest is 6.1 m (core 3, BMR 01 Mount Anderson). The only fully cored section through the formation is in BHP PND 1 (137–311 m), drilled on the northeastern edge of the Fitzroy Trough (and 36 km east of the type section). Palynomorphs from the Noonkanbah Formation indicate a mid-Sterlilamakian (late Sakmarian) to mid-Kungurian age (~280Ma to ~273Ma) (Mory, 2010).

The unit is up to 640 m thick in Myroodah 1 and in exposures along the southern limb of the Grant Range. The main depocentre for the formation is in the Fitzroy Trough, with secondary depocentres in the Gregory and Kidson Sub-basins (based on Bindi 1, 361 m, Betty Terrace, Kidson 1, 321 m, Point Moody 1, >343 m, and Wilson Cliffs 1, >288 m). The formation is absent west of the Kidson Sub-basin and south of the Jurgurra Terrace, and possibly was never deposited in that area. There are no complete sections along the southern margin of the Fitzroy Trough, so it is unclear whether the formation thins gradually (as it does onto the Lennard Shelf to the north) or abruptly as might be expected in this strongly faulted region (Mory, 2010).
Poole Sandstone

The Poole Sandstone is a Lower Permian (mid-Sakmarian to earliest Artinskian, ~286Ma to ~280Ma) deltaic to marine siliciclastic unit possibly up to 160 m thick, with a basal carbonate member (Nura Nura Member) and thin coaly beds. The lower contact with the Grant Group is abrupt, implying a disconformable relationship; rootlet beds characterize the base of the formation in the eastern outcrops (figure 5). In the western and central parts of the basin the unit contains distinct coarsening upward cycles (assigned to the Tuckfield Member in outcrop). By comparison, such cycles are not as obvious in the easternmost part of the basin as the unit is far sandier, indicating a greater fluvial influence. The localised Christmas Creek Member is marked by a prominent basal cross-bedded pebbly sandstone, about 8 m thick (Hocking et al., 2008), which terminates against a channel 100 m to the northwest. Whereas channel-fill facies are relatively common in the upper part of the Poole Sandstone, in the absence of a distinct basal bed or a clear crosscutting relationship it is not easy to differentiate them lithologically from the underlying part of the formation (Mory, 2010).

The unit is most easily observed in outcrop in the exposed flanks of anticlines in the centre of the Fitzroy Trough, which approximate the depocentre of the unit. Additional poor exposures occur near all the margins of the basin. It is clear that the formation extends along the Fitzroy and Gregory Sub-basins as well as onto the flanking sub-basins, especially the Lennard Shelf, and Kidson Sub-basin and onto the margins of that region. There are no intersections of the unit west of 123° east or south of the Jurgurra–Mowla Terrace; therefore, it is uncertain if the formation was deposited across this area (Mory, 2010).

Marine fossils are rare apart from those in the Nura Nura Member and its equivalents at the base of the Poole Sandstone on the southern limb of the St George Ranges anticline, and in the ‘Cuncudgerie Sandstone’ along the southern margin of the basin. Plant fossils are more common throughout the formation and include distinctive rootlet beds. Wave generated ripples are common, and Crowe and Towner (1976a) invoked a lagoonal depositional environment. That interpretation is here considered consistent with the low-energy, shallow-marine environment favoured by Goldstein and Hubbard (1984) as part of a dipmeter study of Hakea 1. By comparison, Adkins (2003) identified a series of regressive systems tract cycles in dominantly shore-zone to supra-tidal facies. However, many of the vertical burrow trace fossils she identifies are likely to be rootlet beds, although Hocking et al. (2008) were ambivalent about distinguishing vertical burrows from root traces.

The Nura Nura Member (Guppy et al., 1952; originally ‘Nura-Nura Limestone’, Wade, 1937) contains up to three distinct, fossiliferous, sandy limestone beds, and appears to be no more than 10 m thick. Ammonoids indicate a likely Sterilitamakian (upper Sakmarian; Glenister et al., 1993) age, possibly to extending into the lower Aktastinian (earliest Artinskian) based on brachiopods (Archbold, 2002a), ~286Ma to ~284Ma.

Permo-Carboniferous Glacial Sequence (PCGS)

The Permo-Carboniferous, around 300 million years ago, was a period of globally widespread glaciation. An extensive PCGS sequence forms the lower part of the LCPM in the Canning Basin (~325 to ~290Ma). Parts of this sequence exist over almost the entire basin. In description and well completions the sequence is referred to as the Grant Group (Crowe and Towner, 1976b). Initially the Grant Group was informally divided into upper and lower parts. However the Upper Carboniferous
Figure 5. Exposures of the Poole Sandstone: a) onlap across slump in the Grant Group, Mt Hutton (outcrop gamma is indicated); b) large channel, Poole Range; and c) rootlet bed near top of Mt Hutton section (from Mory, 2010).
Reeves Formation was formally differentiated from the Lower-Permian Grant Group by Apak and Backhouse (1998, 1999) due to the presence of an Asselian (~299 to ~294Ma) disconformity. In well completion reports the Grant Group is commonly undifferentiated. It should be noted that the Poole Sandstone is commonly not defined in well completions, potentially as it is undifferentiated from the much thicker Grant Group.

In outcrop, the upper contact of the PCGS is abrupt; a disconformity is indicated by a local breccia (Crowe and Towner, 1976a), and a rootlet bed at the base of the overlying Poole Sandstone, which is clearly onlapping a slump at the top of the group. The contact of the Mid-Carboniferous to Early-Permian Sequence on the underlying Lower Carboniferous Anderson Formation is probably a major erosive surface related to the Mid-Carboniferous Meda Transpression.

The PCGS is an Upper Carboniferous - Lower Permian fluvial to marine glacigene succession dominated by siliciclastic strata that exceeds 1000m thickness in the NW part of the Fitzroy Trough. Exposures are dominated by clean, massive to crossbedded sandstone of likely fluvio-deltaic origin (figure 6 and 7), but also include diamicrite, mudstone with erratic clasts (some striated), contorted beds, probable varves, and striae typical of glacial deposition in both marine and non-marine environments (figure 8) (Crowe and Towner, 1976a). The group onlaps striated pavements along the basin margin, thereby providing direct evidence of sedimentation after glaciation. Resedimentation, while possibly related to fault movements, is just as likely to be due to rapid deglaciation and high sedimentation rates, and these processes can effectively rework glacial deposits and hinder identification of the primary depositional mechanism. The presence of glacial indicators, such as striated dropstones in marine claystone and siltstone, at the top of this member in St George Ranges is in direct contrast with the lack of such features in the thick, predominantly coarse-grained facies at the same stratigraphic level in the Grant Range to the northwest. These latter facies are interpreted as rapid fluvio-deltaic outwash, which at times overwhelmed marine sedimentation.

Lithological differences between the Reeves Formation and the Grant Group are minor and as such the differentiation is based on the perceived presence of the Asselian disconformity. Although the paucity of Asselian ages suggests that the Grant Group potentially disconformably overlies the Reeves Formation. Rare Gzhelian–Asselian M. tentula palynofloras (e.g., from Fraser River 1, Grant Range 1, Lawford 1, and Point Moody 1) imply that in the centre of the Fitzroy Trough deposition may have been continuous. As such Mory (2010) suggests there is a case for reintegrating the Reeves Fm into the Grant Group.

There is little direct evidence for significant fault activity during deposition of the Grant Group due to the discontinuous nature of outcrops and variable seismic quality. However, there is some thickening of the Grant Group into the Fitzroy Trough and the Kidson and Willara Sub-basins implying at least local penecontemporaneous fault movements, although not as dramatic as for the Carboniferous. The available seismic data in the Canning Basin suggests that significant fault movement had mostly ceased by the Early Permian, when thermal sag became the dominant subsidence mechanism. Thinning of the Grant Group across features such as the Munro Arch, and the Broome–Crossland Platforms imply these areas were relative highs during deposition, even though younger Permian units are largely missing across the platforms.
NW Canning Basin Seal Potential
Figure 6. Panoramas of the Grant Group: a) sandstone filled channels, Poole Range; b) large, low-angle foresets (cliff 50 m high), Grant Range; c) general view of south limb of Grant Range anticline; and d) large channel in Wye Worry Member, Carolyn Valley with outcrop gamma superimposed (from Mory, 2010).
Figure 7. Exposures of Grant Group: a) large slump overlain by massive to cross-bedded sandstone, Grant Range; b) Deeadeea Sandstone and Ngumban Claystone Members, Deeadeea Cliff with outcrop gamma superimposed; and c) erosional contact between Millajiddee Sandstone and Wye Worry Member, Carolyn Valley (from Mory, 2010).
Figure 8. Glacial features in the Grant Group: a) diamictite, Lauris Range; b) contorted bedding, Lauris Range; c) mictite, Lauris Range; d) stone, Mount Wynne, Grant Group:
a) dia; and d) striae in sandstone, Mount Wynne (from Mory, 2010).
DECM
The DECM is thickest and most extensively preserved in the Fitzroy Trough and Gregory Sub-basin, extending across the shelves and terraces forming the classic Devonian reef complexes. The sequence is at least 4km thick in the Fitzroy Trough, but is probably 6km thick in western parts of the trough. Early DECM sedimentation comprised marginal marine carbonates and clastics to the north and Aeolian and playa deposits to the south. Later DECM sequences are more completely preserved in the northern parts of the basin and comprise two depositional cycles. The first consists of the classic Pillara-Nullara reef cycle. The second consists of peritidal carbonates and shoreface clastics (Yellow Drum Fm), shallow-marine to shoreface carbonates and shales (Laurel Fm) and fluvio-deltaic sandstone and siltstones (Anderson Fm). The organic-rich marine shales of the Laurel Fm are thought to be the most promising source rock in the Fitzroy Trough / Gregory Sub-basin structure (Kennard et al., 1994).

OSM
The base of the OSM marks the initiation of sedimentation in the Canning Basin. Parts of the OSM are preserved in almost all the structural elements of the basin, though it rarely outcrops. It is at least two km thick in most parts of the basin, though it is likely that the full sequence is only preserved in the southern tectonic units. The lower half of the OSM is composed initially of coarse clastics, then fine-grained marine clastics, shallow-marine carbonates and finally the widespread cyclic subtidal to intertidal platform carbonates and shales of the Goldwyer and Nita Fms. These mid Ordovician formations are the last units of the OSM to have basin wide distribution and are considered to contain the main source rocks within the OSM. The upper part of the OSM comprises the Carribuddy Group, fine-grained red-bed clastics and carbonates with rare algal coals. Widespread evaporates are preserved at least two stratigraphic levels. It is unclear how far this group extends northwards into the Fitzroy Trough / Gregory Sub-basin structure (Kennard et al., 1994).

Methodology
Fault seal prediction in mixed clastic sequences can be derived from knowledge of the clay content of the lithology. Wireline logs from the wells in the vicinity of JPP were downloaded from the DMP WAPIMS database. Gamma logs were extracted and converted into a shale volume (Vshale) for the sequence intersected by the well using methodology derived from Larionov (1969). It should be noted that as the focus of the investigation was to identify areas with the best sealing potential the conversion utilised was set up to err towards an underestimate Vshale to minimise potentially over-optimistic sealing results.

To assess the sealing capacity of sand on sand faulted juxtapositions, a number of different fault-seal algorithms may be utilised. Shale Gouge Ratio (SGR), defined in publications by Fristad et al. (1997), Yielding et al. (1997) and Freeman et al. (1998), is an attempt to predict the proportion of shale incorporated into a fault zone. At each point on the fault, the algorithm calculates the net content of shale / clay in the volume of rock that has slipped past that point on the fault. The implicit assumption in this algorithm is that material is incorporated into the fault gouge in the same proportions as it occurs in the wall rocks in the slipped interval (Figure 9). If this assumption is true,
Figure 9. Schematic diagram showing defining of Shale Gouge Ratio, after Yielding et al. (1997). At any point on the fault surface, the SGR is equal to the net shale (or clay) content of the interval (t) that has slipped past that point.

\[ \text{Shale Gouge Ratio} \quad \text{SGR} = \sum (\text{Vcl.} \Delta z) / t \]

\( \text{Vcl} = \) volumetric clay fraction
\( \Delta z = \) bed thickness
\( t = \) fault throw

Figure 10: Empirical approach to fault-seal calibration (after Yielding 2002) showing the comparison of Shale Gouge Ratio and in situ across-fault pressure difference for faults in a variety of extensional basins. Data points are colour-coded by burial depth (blue, <3.0 km; red, 3.0-3.5 km, green, >3.0 km). Dashed lines represent the maximum across-fault pressure that a specific SGR could support without leaking (the seal envelopes).
then SGR can provide a direct estimate of the up-scaled composition of the fault zone as a result of the mechanical processes of faulting. A high SGR value corresponds to more phyllosilicate in the fault zone and therefore to higher capillary threshold pressure and lower permeability. Case studies (e.g. Yielding 2002; Sperrevik et al. 2002; Dockrill and Shipton 2010; Bretan et al. 2011; Manzocchi et al. 2010) have shown that there is a general correlation between the measured clay content of a fault zone and the calculated SGR value, higher SGR values being derived for fault zones containing a higher observed clay content. In many basins in particular the Brent Province (Yielding 2002), it is observed that SGR > 15% corresponds to faults that are sealing to hydrocarbons (figure 10).

The sealing properties of a sequences lithology thus can be predicted for various fault displacements. For simple ‘layer-cake’ stratigraphy, fault seal potential can be expressed as a variety of standard attributes such as SGR. Triangle, throw or juxtaposition diagrams are a 1D graphical technique that can be used to quickly evaluate uncertainty in the stratigraphy and in the Vshale log. The plots are essentially a ‘template’ on which to visualise the likely juxtaposition relationships at different throws and what kind of fault-seal properties might be generated when a Vshale curve and well sequence slips past itself (Figure 11). Such diagrams are very useful for a first stage analysis of likely juxtaposition relationships and computed seal attributes for Vshale logs at different throws. It is useful to analyse sparse 2D data or where the structure is not reliably mapped and can also be used to investigate sensitivity issues arising from 3D fault seal analysis. A 3D structural model is not required for a triangle analysis and seal potential can be quickly assessed based on different well logs. In hydrocarbon exploration it has become standard practice to use fluid densities to convert SGR into column height supported (Yielding 2002), a practice which has recently been applied to CO2 sequestration, for this the density of the CO2 in the supercritical state (475 kg/m3) is substituted (Bretan et al., 2011).

**Triangle Plot Analysis**

**North - Pender Terrace / Lennard Shelf**

The Pender Terrace forms the northern margin of the Fitzroy rough at that margins closest point to JPP. The terrace is equivalent to the Jugurra Terrace on the southern margin. Several of the closest wells to JPP are located on the Pender Terrace, which as defined, is about 70km from JPP at its closest point. Wells discussed are up to 200km away by which point they are located on the Lennard Shelf (Fig. 1). The wells generally intersect extensive LCPM stratigraphy, including Noonkanbah Fm, Poole Sandstone and PCS. The Poole Sandstone is relatively clay-rich (commodity 15-20%) across the Pender Terrace, with questionable sequestration potential.

The most westerly wells on the Pender Terrace analysed are the offshore, Kambara 1, Minjin 1 and Perindi 1 wells (figure 12). The Noonkanbah Formation in this area, where recorded, is thin, with low shale content or non-existent. These wells have little potential for sequestration. The next three wells, Curringa 1, Moongana 1 and Pender 1 are located immediately onshore, approximately 35km east of the offshore wells. Curringa 1 and Moongana 1 intersect Noonkanbah Fm with good potential for top-seal. The Poole Fm and upper Grant Group have not insignificant shale content and as such have some potential for self-juxtaposition fault-seal. The Pender 1 well sequence, the most northerly thus far assessed, has middle Jurassic units sitting directly on mid-Grant Group. Rather anomalously for the onshore Pender Terrace sequence there is little sealing potential.
Figure 11: Analysis of the impact of simplistic fault on a "layer cake" stratigraphy. (a) block diagram to illustrate the relative movement of the upthrown and downthrown blocks. The grey area in (a) corresponds to the triangle diagram in (b). The triangle diagram comes from the well named Moogan _1 (Pender Terrace) and has been modelling with the SGR, the juxtaposition type and with an offset of 100 m.
Figure 12. Triangle-juxtaposition plots for wells on the Pender Terrace. In the interpreted interval column the Grant Group is red and the Poole Sst yellow, the Noonkanbah Fm is brown. The log plotted is derived Vshale. Wells shown are one representing the western, central and eastern grouping, Kambara 1, Ka; Moogana 1, M; and Padilpa 1, P; respectively, on the Pender Terrace and Kora 1 on the Lennard Shelf. Significantly the shale content of the sequence and the thickness of the Noonkanbah increases eastwards, hence increasing amounts of orange and red appear indicating greater SGR and thus fault-seal potential. The sequences at Padilpa and Kora have excellent potential for top and fault-seals.
Figure 12 cont. The final triangle-juxtaposition plot labelled Ko – CO₂ is again for the Kora 1 well, focussing in on the LCPM units. The plot is now coloured for column height supported, the densities used to generate the columns heights are those for CO₂. On this plot the yellow indicates columns of around 40m will be supported, the small patches of blue indicate fault surfaces capable of supporting columns of over 100m. The most notable aspect of the plot is that significant sealing is generated by the intra-Grant shales.
The most easterly Pender Terrace wells assessed, Puratte 1 and Padilpa 1 are very promising in terms of both top and fault-sealing. Both wells intersect thick (300-400m) Noonkanbah Fm and Poole Fm and Grant Group sequences which contain interbedded clean reservoir and shalier units. Given association with suitable structural geometries and the reservoir qualities of the units there is good potential for trapping in this sequence. Continuing eastwards onto the neighbouring tectonic element, the Lennard Shelf, the LCPM sequence maintains its potential for top and fault-sealing. Examples such as Kora 1, located just east of Derby, penetrate up to 400m of Noonkanbah Fm and well developed, intra-formational shale units occur in the Grant Group, interbedded with low Vshale sands. The Poole Sandstone unit though is dominantly shaley.

Mafic Intrusives
Three of the wells analysed on the Pender Terrace intersect mafic intrusives at the base of, or in the Lower Grant Group. Minjin 1 and Perindi 1 intersect ‘Dolerite’, below the Grant Group in Minjin 1, in the lower-middle Grant Group in Perindi 1. These two wells are within 15km of each other in the western Pender Terrace so it is probably safe to assume that these were contemporaneous intrusions. The Padilpa 1 well is logged as terminating in ‘Early Carboniferous Gabbro / MicroGabbro’ below the Grant Group. This well is at the eastern end of the Pender Terrace, 90km from the wells which intersect dolerite. The thickest, upper intersection of gabbro is 233m after which the well penetrated ‘metasediments’ of ‘unknown age’, before terminating after reencountering gabbro. No evidence for the Early Carboniferous age of the intrusion is given in the well completion report other than it being below the Grant Group. But assuming that the Gabbro would have been intruded at depth the pre-Grant Group timing would infer an erosional event prior to Grant Group deposition.

Potentially the Padilpa gabbro could have been introduced in the same extensional event as the mafic intrusives further to the west. Timing for this intrusion event could possibly as late as the end of the Carboniferous, coinciding with the suggested ‘Upper Carboniferous’ age for intrusion reported in other well completion reports, e.g. Pudovskis (1960). Thus potentially the intrusive of the Pender Terrace are contemporaneous with a single extensionally induced intrusion event which occurred across the whole Fitzroy Trough. Such an event would have implications for the timing and amount of extension and hence impact on sedimentation. In addition there are implications regarding heatflow and maturity for at least the Pender Terrace sediments depending on what scale of intrusive event is inferred.

Fitzroy Trough
A number of analysed wells are located within the Fitzroy Trough tectonic unit. These wells however are sparsely distributed, with only eight wells representing an area of 50,000km² (figure 13). The first point that should be noted is that the wells summarised form a disparate group. The Fitzroy River 1 and Frazer River 1 onshore wells and the Wamac 1 and Lacepede 1 offshore wells are axially located with respect to the trough, thus highlight lateral variations and consistencies along the structure. Whistler 1, Pearl 1, Barlee 1 and the Yulleroo wells are on the southern margin, but still within the Trough tectonic unit as defined, though they may potentially be thought of as representing a transitional sequence moving onto the southern terraces.

No Poole Sandstone occurs (or is recorded) in any of the axially located wells and little Noonkanbah Fm top seal. This observation is biased, however, as the anticlinal structures targeted have been
Figure 13. Triangle-juxtaposition plots for wells located near the axis of the Fitzroy Trough. For the plots on this figure the red in the stratigraphic column on the left of each triangle plot indicates general LCPM units. The Lacepede 1 well (L) red unit is not differentiated beyond ‘late Permian’. In the Fraser River 1 (FrR) and Fitzroy River 1 (FiR) wells the red unit equates to Permo-Carboniferous and in these cases Late Carboniferous. The significant points from the latter two plots are that all but the earliest LCPM units have been removed by erosion in these localities, but internally the Grant Group is typified by containing some internally significant shalier units, which result in fault-seal potential (especially in Fraser River 1). The white box approximates an area of 15,000km² around Jame Price Point (JPP) which is devoid of well data.
eroded. The onshore wells do however record PCS, which in the Fitzroy Trough is characterised by the occurrence of thick (on the order of 100m), internal shales.

The Fitzroy River well is at 311km outside the immediate area of interest, but has been investigated due to its axial position within the Fitzroy Trough; partially to help in an attempt to assess variations along the trough and also the central parts of the trough do not contain many wells. Reasonably thick (> 100m), shalier intervals occur within the PCS in the Fitzroy River well, leading to minor potential for self-juxtaposition fault-sealing. The PCS is very shallow and has no top seal in Fraser River 1. However the Grant again contains shale units exceeding 100m thick, with potential for minor, localised sealing.

Wamac 1 and Lacepede 1 are located in the offshore continuation of the Fitzroy trough, at approximately 80km (WNW) are two of the closest wells to JPP. The wells are located axially with respect to the Fitzroy Trough and would be ideally located to give some indication of the sealing potential of the western part of the Fitzroy Trough depocentre. However, Lacepede 1 well only just reaches into the Permian and Wamac 1 stops in Jurassic. No particularly shaly units are intersected and there is only minor potential for self-juxtaposition fault-sealing in Cretaceous units. Additionally the sequences would indicate that there is also little possibility for accompanying top-sealing. The wells though are too shallow to draw any definitive conclusions with regard to seal potential in the deeper parts of the offshore Fitzroy Trough.

**Fitzroy trough Southern Margin / Outer Jugurra Terrace**

Whistler 1, Pearl 1, Barlee 1 and the Yulleroo wells are drilled into the crests of anticlinal structures located within 6km of the defined southern edge of the Fitzroy Trough tectonic unit (figure 14). These wells are grouped for analysis and theoretically represent the transitional from the deep trough to the Jugurra Terrace. The Jugurra Terrace forms the southern margin of the Fitzroy Trough at that margins closest point to JPP. Whistler 1 is near the eastern end of the defined Jugurra Terrace, 210km from JPP. The other wells are considerable closer, between 40 and 90km from JPP.

Whistler 1 and Pearl 1 display similar characteristics to the more axially located Fitzroy River and Frazer River 1 well sequences, lacking significant top seals due to Fitzroy Transpression related erosion, but having internally significant shalier units in their Permo-Carboniferous sequences. The internal shales in both sequences suggest some potential for trapping given the presence of suitable structures.

The degree of basin inversion related to the anticlines into which the Yulleroo 1 and Barlee 1 wells were drilled has resulted in Permian units being brought up to very shallow levels in the anticlinal structures and are either completely eroded or largely removed. The sliver of Permo-Carboniferous sediment that remains in Yulleroo 1 has no evidence of internal sealing potential, however it is far from diagnostic. There is minor sealing potential in the early Carboniferous Anderson Fm. However there is good potential sealing in deeper units (Ordovician, exceeding 3500m depth) where drilled in Yulleroo 1.

**Fitzroy Trough Sequence Between Anticlines**

The wells available for analysis in the Fitzroy Trough tectonic unit do not necessarily allow definitive representation of the entire LCPM as drilling has been restricted to the crests of the anticlines within the trough. As such none of the wells displays the entire LCPM. However the sequence was

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Figure 14. Triangle-juxtaposition plots for wells on the Southern Margin of the Fitzroy trough / outer Jugurrra Terrace. In the interpreted interval column the LCPM units are red. Blue units above the LCPM are various Jurassic, Pink is upper Anderson Fm (DECM), blue units below the red LCPM are undifferentiated Anderson Fm and the brown unit the LCPM is sitting on in Whistler 1 is Ordovician. Wells shown are Pearl 1, P (the closest well to JPP at 43km); Barlee 1, B; Yulleroo 1, Y and Whistler 1. Between the wells there is obvious variability in the LCPM present. Pearl 1 and Whistler 1 have well preserved early LCPM sequences, with quite well developed internal shales (especially in Whistler 1). Conversely Barlee 1 and Yulleroo 1’s LCPM have been locally removed by erosion.
Figure 14 cont. The final triangle-juxtaposition plot labelled W – CO₂ is for the Whistler 1 well’s LCPM units. The plot is again coloured for column height supported, the densities used to generate the columns heights are those for CO₂. On this plot the yellow indicates columns of around 40m will be supported, the small patches of blue indicate fault surfaces capable of supporting columns of over 100m. Again the most notable aspect of the plot is that significant column heights are supported by faulting of the intra-Permo-Carboniferous shales.
deposited throughout the trough and is present where not eroded. One observation can be made though, that in all wells where a significant Permo-Carboniferous sequence is present, clay rich units are developed within the formations which are at least as shaley as the dirtiest Permo-Carboniferous sequences on the troughs flanking terraces. This observation is in accordance with sedimentological theory, wherein finer grained deposition is commonly more associated with the centre of basins with coarser clastic deposition dominating on the basin margins. Following this logic further it might be fair to predict that the Permian units in the Fitzroy Trough likewise are more clay-rich than their flanking counterpart sequences.

**Inner Jugurra Terrace / Northern Broome Platform**

Four wells will be discussed which have been drilled in the transition between the Jugurra Terrace and the Broome Platform, just east of the town of Broome (figure 15). Freney 1, the nearest, is 80km from JPP. This sequence of wells form an approximately, east-west, 25km transect. The series shows westerly increase in Noonkanbah thickness and clay content. Additionally the Poole and Grant Fms are present across the section. The Poole Fm remains constant across the area but the Grant Fm changes from monotonously, clean quartzites in the east to containing thick shaley units in the west.

In the vicinity of Cow Bore 1 and East Crab Creek there is no potential for self-juxtaposition fault-sealing. The Noonkanbah Formation has some potential for sealing the Poole and Grant Fms. However, around Freney 1, the Permo-Carboniferous sequence with its thick shaly components has very good potential for self-juxtaposition fault-seal in addition to having 200m of Noonkanbah Fm top-seal. Large fault structures (>100m) cutting this sequence will have potential for sealing traps given suitable top-seal geometry. The Permian units are only just marginally reach depths suitable for CO₂ sequestration in this area.

**Broome Platform**

Moving south onto the Broome platform five wells form a group on the Broome Platform, 90 to 110km south of JPP (figure 16). Generally there is an erosional unconformity between the Grant Group and the middle Jurassic, however Poole Fm is recorded in the Hilltop 1 well, the most south easterly well. No significant top seal is ever present above the Permian.

The first three wells Goldwyer 1, Kanak 1 and Hilltop 1 have very clean Permian sequences, so additionally self-juxtaposition fault-seal is unlikely. However, the Sharonn Ann 1 and Hedonia 1 wells, the furthest SW and NE respectively have significant shale content within their Grant Group units, with potential for internal traps given suitable structural geometries. Hedonia 1 is only 12km from Goldwyer 1, Kanak 1 and Hilltop 1, which gives some indication of the localised potential for variation within the Grant Fm.

Sunshine 1 is 60km further inland than the other Broome Platform wells, approximately 130 kilometres SE of James Price Point. The Permo-Carboniferous sequence again sits between unconformities, below Jurassic and above Ordovician, but in the vicinity of Sunshine 1 the Permo-Carboniferous sequence contains thick (> 50m) shaley beds. Additionally significant faults are evident on the local seismic lines with throws exceeding 100m.

All the wells analysed from the Broome Platform have the Grant Group directly lying on relatively shallow (<1km) Ordovician units. These earlier sequences all would have significant potential for trapping based on the shale content of their top-seals and the SGRs predicted given a suitable
Figure 15. Triangle-juxtaposition plots for the sequence at Freney 1, F; Crab Creek 1, CC; East Crab Creek 1, ECC; and Cow Bore 1, CB; wells. These wells located on the transition between the Jugurra Terrace and the Broome Platform. Their location is indicated on the insert map, these wells are lined up approximately east-west, paralleled to the major basin structures. The Permo-Carboniferous is red in the interval column, Poole Sst is yellow and the Noonkanbah Fm, brown. In this area there is thick LCPM, with significant Permo-Carboniferous shale content increasing to the west, Freney 1 and Crab Creek 1 illustrate significant top and fault-sealing potential.
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Figure 15 cont. In the interpreted interval column the Permo-Carboniferous Grant Group is red, Poole Sst yellow, Noonkanbah Fm brown. Freney 1 and Crab Creek 1 have a thin white Nura Nura Fm interpreted between the Pool Sst and Grant Group. East Crab Creek 1 as a blue ‘Nura Nura +’ unit in the same position. DECM Fairfield Gp is Green. The log plotted is derived Vshale.
Figure 16. Triangle-juxtaposition plots for wells on the Broome Platform. Hilltop 1, Hi; Hedonia 1, He; Goldwyer 1, G; Kanak 1, K and Sunshine 1, S; are plotted. None of the wells have significant LCPM top-seals. Hilltop 1, Kanak 1 and Goldwyer 1 have relatively clean Permo-Carboniferous units. However, Hedonia 1 to the NE, Sharon Ann 1 to the SW and Sunshine 1 to the E have significant shale interbedded in the Grant Group, which locally could have some sealing potential. Most significantly all these plots indicate good top and fault-sealing potential in the Ordovician units.
Figure 16 cont. The Permo-Carboniferous Grant Group is again red, Poole Fm, yellow, only occurs in Goldwyer 1 in this area, with an associated sliver of blue Nura Nura. Brown indicates various mid-Ordovician formations. The top thick blue is Jurassic Wallal Sst.
structural geometry. All across the Broome Platform the LCPM is too shallow for CO₂ sequestration, however Ordovician units are potentially better sequestration targets in this area.

**Willara Sub-basin – Great Sandy 2, Cudalgarra 1**
The transition from the Broome Platform into the Willara Sub-basin occurs within 200km from JPP, 160km at the nearest point (Figure 17). In this area, the later LCPM (Noonkanbah Fm, Poole Sst) is again absent, however a notably dirty Permo-Carboniferous sequence does occur. Shale units have thicknesses exceeding 200m. There is good potential for traps to be associated with the lowest most sands of the Grant Group interacting with faults associated with the northern margin of the Willara Sub-basin.

**Summary of Triangle Plotting**
The localities which have LCPM sequences which have the most potential for fault-sealing and hence sequestration are on the eastern Pender Terrace (Padilpa 1, Puratte 1, Kora 1, West Kora 1) / Lennard shelf (>110km from JPP) and on the inner Jugurra Terrace in vicinity of Freney 1 (80km SE of JPP). Though, actually at Freney 1 the LCPM sequence is marinally too shallow for CO₂ sequestration.

Localised trends within groups of wells demonstrate that there is variability within even the closely spaced wells (closely spaced for the Canning Basin). Such localised variations should be kept in mind should be taken when extrapolating into less explored parts of even the Fitzroy Trough.

Historical drilling into the crests of anticlines in the Fitzroy Trough has biased the data against sealing potential in the deeper parts of the sub-basin. Using geological intuition it almost certainly can be inferred that the LCPM in the middle of the Fitzroy trough will be the more clay-rich than on the flanks of the trough. The partial information for the Permo-Carboniferous sequence from the trough’s wells (Fitzroy River, Whistler 1, Fraser River 1, Pearl 1) supports this inference.

The LCPM on the Broome platform is generally truncated in the Permo-Carboniferous. Occasionally the sequence is dirty enough to produce potential fault-seals. However in the wells analysed the LCPM is too shallow for sequestration. If Ordovician reservoirs are considered then the Broome platform wells have good potential for sequestration sites if they are associated with suitable structural geometry. Sunshine and more onshore Broome Platform.

The northern flank of the Willuna Sub-basin also has where analysed, a dirty Permo-Carboniferous sequence, even better developed than on the Broome Platform. The sequences analysed around Great Sandy 1 and Cudalgarra 1 are 100-200km from JPP. However as an alternative to potential LCPM reservoirs in the Fitzroy Trough and adjacent terraces the older megasequences, the DECM in the Fitzroy Trough and Ordovician units of the Broome Platform and especially the Willuna Sub-basin might provide suitable fault related traps for sequestration.
Figure 17. Triangle-juxtaposition plots for the Great Sandy 2 well on the Northern Margin of the Willuna Sub-basin. In the interpreted interval column the LCPM units are red. Blue units above the LCPM are various Jurassic, light grey is Worral Fm (lowermost DECM), black units are Silurian Carribuddy Gp (OSM). The sequence penetrated has excellent potential for fault sealing in both the LCPM and Silurian. The wells on the northern margin of the Willuna Sub-basin are just within the 200km radius of JPP and are potentially worth assessing further with respect to sequestration.
**Faults in the Seismic**

After assessing the fault seal potential of the Canning basins sequences it is worth briefly identifying whether there is faulting associated with the sequences and localities studied.

On a cursory inspection of the 2D seismic dataset (figure 18) it is evident that there is very little movement on major, tectonic unit, bounding faults, such as the Dampier and Fenton Faults with relation to LCPM (occasionally reactivation of tens of meters).

Rattigan (1966) and Smith (1967) proposed a simple wrench model for the Mesozoic transpressional deformation of sediments in the Fitzroy Trough. A series of ~E-W trending shallow anticlines are cut by contemporaneous normal faults extending along the fold axes, defining the ‘wrench’ system. It perhaps should be noted that the orientation of the anticlines throughout the trough are far from being uniformly oriented, however the normal faults temporal relationship with the folding supports the model by accounting for the synchronous compression and perpendicular extension. From field mapping and analysis of 2D seismic surveys it is seen that these faults occasionally have displacements on the order of 100m. These faults constitute the most likely location for trapping structures associated with the LCPM sequence, especially given their association with the trough’s anticlinal structures (figure 19).

Unsurprisingly there are however big displacements, often >300m, on the major, tectonic unit, bounding faults displacing the older OSM and DECM units. As an alternative to potential LCPM reservoirs in the Fitzroy Trough and adjacent terraces the older megasequences of the Broome Platform and Willuna Sub-basin might provide more suitable fault related traps for investigation.

**Discussion**

The wells available for analysis in the Fitzroy Trough tectonic unit do not necessarily allow definitive representation of the entire LCPM as drilling has been restricted to the crests of the anticlines within the trough. As such none of the wells displays the entire LCPM. However the sequence was deposited throughout the trough and is preserved undrilled in synclinal structures. One observation can be made, in all wells where a significant Permo-Carboniferous sequence is present clay rich units are developed within the formations which are at least as shale-rich as any PCS on the troughs flanking terraces. This observation is in accordance with the sedimentological inference, wherein finer grained deposition will have a greater predominance in the depocentre of a given basin as opposed to the basin margins which will have a larger coarse clastic component. There is potential for predictive sedimentological modelling to be undertaken for the LCPM in the Fitzroy Trough.

After assessing the fault seal potential of the Canning basins sequences it is worth briefly identifying the relationship between faulting associated with the megasequences analysed. Firstly it should be pointed out that the movement on the major, tectonic element bounding, extensional faults finished during early LCPM deposition. As such the most likely targets for fault sealed traps associated with the LCPM should be structures related to the Fitzroy Transpression, i.e. in the Fitzroy Trough. However as an alternative to potential LCPM reservoirs in the Fitzroy Trough and adjacent terraces the older megasequences, the DECM in the Fitzroy Trough and Ordovician units of the Broome Platform and especially the Willuna Sub-basin might provide suitable fault related traps for sequestration.
Figure 18. 2D Seismic Line W-82-122_MIGR_083W, south is left towards the Broome Platform, north is right towards the Jugurra Terrace and Fitzroy Trough. The part of the line shown is about 5km, therefore vertical exaggeration is ~x2. The fault shown in yellow is interpreted as the Dampier Fault, i.e. The major structure delineating the northern edge of the Broome Platform. The throw in the LCPM section is 30 ms, so a few 10s of meters. Freney 1 well is located about 1km west of the vertical white line. Red is base Jurassic and orange, base LCPM.
Figure 19. 2D seismic line W-82-100_MIGR_083W. This line runs E-W along the Fitzroy Trough. This section of the larger line is 10km long and the vertical exaggeration is ~×3. Red is base Jurassic and orange, base LCPM. Faults shown in yellow are cutting the limb of an anticline whose axis runs parallel to the line. Throws are 200ms, i.e. considerably better targets for fault sealed traps than the main tectonic element defining structures.
**Summary**

- Sequences in all of the tectonic elements of the NW Canning Basin have potential for fault-sealed traps.

- The localities with well-sampled, lower-LCPM sequences which have the most potential for fault-sealing and hence sequestration are on the eastern Pender Terrace / Lennard Shelf (Padilpa 1, Puratte 1, Kora 1, West Kora 1 – 110-200km NE of JPP) and on the inner Jugurra Terrace (Freney 1 - 80km SE of JPP).

- Localised trends within these groups of wells demonstrate that there is variability within even the closely spaced wells (closely spaced for the Canning Basin). Such localised variations should be kept in mind should be taken when extrapolating into less explored parts of the basin, such as the Fitzroy Trough.

- Drilling into the crests of anticlines in the Fitzroy Trough has biased the data against sealing potential in the deeper parts of the sub-basin. Geological intuition would suggest however that the LCPM in the middle of the Fitzroy Trough has good potential to be the more clay-rich, hence more sealing than on the flanks of the trough. The partial well information for the PCS in the trough supports this inference (Fitzroy River, Whistler 1, Fraser River 1, Pearl 1).

- The LCPM on the Broome platform is generally truncated in the PCS. This sequence is commonly clay-rich enough to produce potential fault-seals. In the wells analysed however the LCPM is shallow (<1km). The northern flank of the Willuna Sub-basin also has where analysed, a clay-rich PCS sequence, even better developed than on the Broome Platform.

- Anderson Formation interbedded reservoirs in the Yulleroo 1 well also indicate that there is potential for sequestration in DECM units in the Fitzroy Trough.

- If Ordovician reservoirs are considered then the Broome platform and especially the Willara Sub-basin have good potential for sequestration sites if those units are associated with suitable structural geometry.

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