Fault Seal Analysis:

Constraining fault seal risk using seismic velocities

Tobias Colson

Supervisor: Prof. Myra Keep
Co-Supervisor: Adj. Prof. David Castillo

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GLOSSARY

**Checkshot** - Seismic Velocity Checkshot Survey - Used to calibrate time-depth curves by conducting a series of sound shots with a receiver at various depths in the well.

**CFF** - Coulomb Failure Function.

**FIT** - Formation Integrity Test - used to test the strength of a formation by increasing the bottom hole pressure in a well. Where LOT tests are conducted and 'Leak off' not achieved, a FIT test has been conducted, often quoted as 'Max Pressure'.

**LOT** - Leak Off Test - A test to determine the strength or fracture pressure of the open formation, usually conducted immediately after drilling below a new casing shoe. During the test, the well is shut in and fluid is pumped into the wellbore to gradually increase the pressure until the fluid enters the formation, or leaks off, either moving through permeable paths in the rock or by creating a space by fracturing the rock. The results of the leak-off test dictate the maximum pressure or mud weight that may be applied to the well during drilling operations.

**NCB** - North Carnarvon Basin.

**NWS** - North West Shelf, Western Australia.

**RFT/FIT** - Repeat Formation Tester/Formation Interval Test - Tool/measurement used to assess formation fluid pressure, density and other fluid properties (FIT is used in older Wells).

**Sonic Log** - Well Log used to measure interval transit time by sending out a high-frequency sound signal and receiving a return signal at a receiver in the same tool. Resolution and frequency are far higher than with a checkshot, so it has important scale dependent differences compared with the checkshot.

**Stacks** - Stacking Velocities. Once seismic traces are collected according to a common mid-point (CMP), their velocities are corrected for the normal hyperbolic moveout, and combined/stacked to improve the signal-to-noise ratio. Stacks can be interval velocities, RMS or average velocities.

**\( Sh_{\text{max}} \)** - Maximum horizontal stress

**\( Sh_{\text{min}} \)** - Minimum horizontal stress
ABSTRACT

Fault seal capacity is an important component in the conventional petroleum system. Assessing the capacity for a fault to seal or leak can be difficult, particularly where well constraint is lacking. In the frontier basin, in a marine setting, seismic velocities may be the only data available. However, useful constraints on a fault’s sealing capacity can be extracted from this data alone. This study investigates the robustness of a number of empirical relations that can assist in extracting useful constraints from seismic velocities and amplitudes. Reliable estimates on maximum and minimum stress tensors and pore pressures can be calculated and combined with basic fault architecture analysis, to place practical constraints on fault risk. In this study of an area on the Rankin Trend found good correlation between well-based and seismic velocity-based pore pressures and stress magnitudes allowing a coulomb failure function based only on stacking velocities to be calculated. Faults separating the Rankin 1 well block from the Dockrell/Keast Field, were shown to be within a stable stress regime. Calculated pore pressures match known RFT measurements and show that overpressure can be assessed using basic time-migrated velocity stacks. Furthermore, theoretical capillary pressure and hydrocarbon column calculations correlate with known values and highlight the capillary seal potential of sand-sand juxtaposition seals which can support 100 to 200 m column heights within the Triassic play. They suggest that many traps on the Rankin Trend within the Triassic play are limited by a combination of pore pressure and stress orientation. However, deeper intra-formational seals are likely to have increased seal capacity by virtue of overburden stress and reduced porosity exceeding any capacity for shear stress failure. Well data for this area confirms a Sh_max orientation of approximately 110° +/− 10° and calculations show that faults striking within 20° of this direction may be at high risk of failure within the neotectonic setting, where pore pressures and dip predicate fault slip.
1. INTRODUCTION

The primary components of a petroleum system include source, seal, trap, reservoir and a mechanism for migration of petroleum. These factors must all be assessed, not just for their presence, but for the degree to which they are associated and the sequence in which they were formed. Key to the effectiveness of a petroleum system is the extent to which secondary migration and charge access can facilitate the linking of these primary components. An element of assessing the risk factors associated with secondary migration and charge access is the capacity for faults to inhibit or facilitate secondary migration, as well as their capacity to contribute to trap formation.

Many petroleum exploration targets that are drilled on faulted traps and fail to return positive results have a lack of petroleum accumulation attributed to charge access. Charge access relates to the capacity for secondary migration to facilitate the 'filling' of a defined trap. However, the contribution that fault seal has played in this is poorly understood. Advancement in reservoir petroleum management, particularly with 4D time-dependent seismic monitoring, has advanced our understanding of why faults fail when they do. However, the ability to make predictions of fault seal capacity from the geometry and seismic velocities alone allows more accurate risk factors to be applied in the 'green fields' stage of oil and gas field exploration.

This study addresses some key constraints used in assessing whether a fault is likely to seal or leak. Principal to these constraints is the typical lack of well control in frontier exploration. A first-pass methodology based on seismic data alone enables better defined risking parameters to be placed on the fault component of the petroleum system analysis where well control is lacking.
2. BACKGROUND

2.1 THE FAULT AND CAPILLARY SEAL

Secondary migration refers to the movement of petroleum from its source rock (in the 'kitchen') to a site where it accumulates (the trap). Secondary migration (movement through a carrier bed) differs from primary migration (out of the source rock) via the porosity, permeability and pore size distribution in which the petroleum migrates.

The process of secondary migration is essentially one of fluid movement. Density and viscosity differences notwithstanding, the fundamental principles of fluid mechanics are applied equally, whether the migration of gas, oil or water is being assessed. These principles have being applied in studies on migration and seal capacity by Hubbert (1953), Smith (1966), Berg (1975) and Schowalter (1979). Watts (1987) further developed cap (top seal) and fault rock seal capacity based on capillary leakage in which cap rock seals are divided into those that fail by capillary leakage and those that fail by hydraulic fracturing due to capillary entry pressures being higher than the tensile strength of the sealing lithology.

Capillary leakage refers to interstitial pore pressure exceeding the capillary pressure of the formation and subsequently leaking. Capillary pressure exists whenever two immiscible phases are present in a fine bore tube or analogous void or pore space in a rock. Capillary pressure is then defined as the pressure drop or differential across a curved liquid interface.

Watts (1987) shows how capillary pressure $P_c$ in a pore space can be calculated if the fluid interfacial tension $\gamma$, rock-fluid contact angle $\theta$ and the pore radius, $r$, are known:

$$P_c = \frac{4\gamma \cos(\theta)}{r} \quad \ldots \text{Eqn. 1}$$

Alternatively, capillary pressure can be expressed as a hydrostatic head. It is equal to the product of the height of the liquid (column height) the density difference between the two liquids and the gravitational constant $g$:

$$hc = Hg(\rho_w - \rho_c) \quad \text{(Watts, 1987)} \quad \ldots \text{Eqn. 2}$$

For capillary seals, Watts (1987) noted that cap-rock thickness becomes unimportant once the capillary slug pinch-off length is exceeded. The seal capacity of a hydraulic seal on the other
hand is highly dependent on thickness, together with the in-situ stress state of the sealing layer and the degree of overpressure development.

The concept of cap rock failure by capillary leakage or hydraulic fracturing is directly transferable to our understanding of whether a fault will seal and inhibit, or leak and/or facilitate secondary migration. Sealing faults can thus be thought of as a capillary cap rock at an angle.

Fault related seals may be further divided into those where the fault plane itself acts as a seal and those where the sealing unit is laterally juxtaposed against reservoir sands (‘juxtaposition seals’). Most if not all fault seals will preferentially leak via capillary leakage rather than hydraulic fracture (not including leakage along the fault) (Aydin, 2000; Bailey et al., 2006; Dodds et al., 2007; Shipton et al., 2005; Tueckmantel et al., 2010; Watts, 1987; Shepherd, 2009)

The concept of capillary pressure or membrane seal potential and associated pressure differential is a direct reflection of the permeability of the fault in question. The permeability is known to be highly dependent on the clay content of the fault (Aydin, 2000; Berg, 1975; Bretan et al., 2003; Busch and Amann-Hildenbrand, 2013; Dehandschutter et al., 2005; Dewhurst et al., 2002; Fisher et al., 2001; Fisher and Knipe, 2001; Kachi et al., 2005; Ngwenya et al., 2000; Schowalter, 1979; Shipton et al., 2005; Watts, 1987) and clay content in particular is a primary control on seal behaviour of faults in mixed clastic sequences (Ngwenya et al., 2000; Torabi et al., 2013; Tueckmantel et al., 2010).

There are a number of empirical based algorithms that are widely used to attempt to predict seal capacity based on the clay component of a fault. These include, the Shale Gouge Ratio (SGR), the Smear Gouge Ratio (SMGR), the Shale Smear Factor (SSF) and the Clay Smear Potential (CSP) (Allen and Allen, 2005; Childs et al., 2009; Kachi et al., 2005; Yielding et al., 1997). The shale gouge ratio (SGR) is one of the more widely used algorithms and is based on the assertion that the sealing capacity of a fault is directly related to the number of shale beds and therefore amount of clay material within the slipped interval. If clay is incorporated in the fault gouge, the clay will increase the membrane seal potential of the fault and increase the chances of an effective seal.
The studies by Fisher and Knipe (2001) directly attributed increased clay percentage in the fault gouge to decrease in permeability of the fault. However, the concept assumes a homogeneous distribution of the percentage of clay within the fault, an assumption that develops an inherent weakness in this approach for predicting seal potential. Studies have shown consistently that there will generally be a high degree of variability in the amount of clay within a fault (Bailey et al., 2006; Bretan et al., 2003; Fisher et al., 2001; Fisher and Knipe, 2001; Torabi et al., 2013). Furthermore, this method inherently requires an understanding of the amount of clay that has been incorporated within the fault gouge. Whilst mature basins, where core analysis is available, benefit from a deterministic petro-physical constraint placed on SGR estimates, new exploration fields generally lack this information. Without robust clay component estimates, SGR parameters can become misleading. SGR estimates suggest that faults with shale gouge of <15% clay component will tend to leak (Yielding et al., 1997). However, quartz dissolution-related diagenetic processes can contribute up to 2 orders of magnitude in permeability reduction in faults (Fisher and Knipe, 2001; Ngwenya et al., 2000; Tueckmantel et al., 2010). SGR estimates do not take this into account, nor do they take into account increasing confining pressures with depth. The greater a cap rock of any kind is buried, the greater the compaction and cementation contribution to permeability reduction will be.

Empirically derived equations that attempt to incorporate factors such as cementation and increased confining pressures are highly dependent on the data set from which they are based and have limited applicability to different tectonic settings, fault types and lithologies. Nonetheless the SGR and SMGR, where reliable estimates of clay content are available, can provide a first pass assessment, and studies that show a reduced permeability in fault gouge with increasing clay content suggest that higher clay content should indicate higher Pc. A higher Pc alone, on the other hand, will not necessarily be indicative of a sealing fault, because if the pressure differential, ΔP, across the fault exceeds Pc, the fault will still leak (Fig. 1) (Fisher and Knipe 2001).

Thus, if the capacity for cross fault migration depends on the pressure differential, it then depends on how well a trap on one side of the fault is charged as to whether a trap will equilibrate on both sides of the fault (Fisher et al., 2001). Studies also show the sealing capacity of a fault should be calculated from the difference in pressure between the
hydrocarbon and pore-water at the position along the fault where leakage is most likely to occur (Fisher et al., 2001).

Figure 1 Representation of a typical fault zone with fault gouge in the damage zone depicted as varying from siliceous cataclastic gouge to shale smear gouge with a higher clay content (from Shipton et al., 2005). Pc denotes the capillary pressure of the gouge, and p\(_1\) and p\(_2\) denote the host rock or reservoir pressure, where \(\Delta p\) is the difference in pressure from one side of the fault to the other.

The pressure differential can therefore provide an indication as to whether there is fluid communication on one side of the fault to the other. However, as (Fisher and Knipe, 2001) and Fisher (2001) note, pressure differences and heights of hydrocarbon columns are often more likely to be controlled by factors such as the capillary entry pressure differences of the undeformed reservoir lithologies and the amount of hydrocarbons entering the reservoir than...
by the actual capillary entry pressure of the fault rock itself. So whilst the pressure difference will not necessarily reflect the capillary entry pressure of the fault gouge, it may provide an indication of a potential effective fault seal. This can be complicated since a lack of pressure difference does not necessarily mean that the fault is leaking. Without knowledge of absolute hydrocarbon column height potential of the cap rock, a $\Delta P$ of zero may mean that there has been sufficient charge to fill the trap up to the maximum capillary pressure of the fault gouge, and leakage has occurred whenever the pressure exceeds $P_{c\text{ max}}$. This would present a repetitive leak-seal sequence analogous to a ‘fill to spill’ scenario. Given such a scenario, an assessment would ideally be made on pressure differences between hydrocarbon and pore water pressures in areas with minimum shale/clay component as this would have minimal capillary pressure potential and be where the fault was most likely to leak.

There are numerous studies (Aydin, 2000; Bense et al., 2013; Losh, 1998) that ascribe fault gouge acting as a fluid conduit for hydrocarbon migration without providing significant direct evidence. Rather, they conclude that fault formation and trap formation are related and typically infer that fluid conduit migration ‘probably’ facilitated the migration pathway. Studies do show that fault-related dilatant fractures can increase permeability (Aydin, 2000; Dewhurst and Hennig, 2003; Dewhurst et al., 2002; Færseth et al., 2007; Ngwenya et al., 2000; Shepherd, 2009), which, along with mode II failure, places a dependency of fluid migration on the seismicity of the fault and a dependency on conditions necessary for reactivation.

The magnitudes of the maximum principal stress and the minimum cohesive shear strength necessary for reactivation sensitively depend on the orientation of the horizontal intermediate principal stress. The reactivation becomes easiest when the intermediate principal stress axis is rotated out of strike by 45°. Here it requires only one third of the minimum cohesion and little more than half of the maximum compressive stress necessary for pure dip-slip reversal (Mandl, 2000). This implies that the axis of maximum horizontal stress, $\sigma_{H}$, during reactivation is unlikely to coincide with that of the earlier axis of minimum horizontal stress, $\sigma_{h}$. Hence, most inversion episodes for example, are non-coaxial, with oblique-slip or strike-slip kinematics being the important modes of fault reactivation. In such a setting, shortening strains will often be partitioned between faults displaying dip-slip, oblique-slip and strike-slip kinematics (Turner and Williams, 2003).
The Coulomb Failure Function provides an assessment on the likelihood of mode I and II failure where shear stress on a fault plane exceeds the effective normal stress. This function takes into account the effect pore pressure has on the effective stresses on a fault plane. If such a failure mode is prevalent, the in-situ stress field needs to be assessed and fault seal reactivation risked (Castillo et al., 2000; Jones and Hillis, 2003; Reynolds et al., 2005; Zoback, 2010; Zoback and Healy, 1984).

2.2 THE APPLICATION OF SEISMIC DATA

One of the principal indicators of fault seal potential is the pressure differential across the fault. How then can we attempt to measure petro-physical properties such as pore fluid pressure, rock strength and porosity? We know that when external forces are applied to a body, balanced internal forces are set up within it. Stress is a measure of the intensity of these balanced internal forces. The stress acting on an area of any surface within the body may be resolved into a component of normal stress perpendicular to the surface, and a component of shear stress in the plane of the surface. A fluid does not shear stress however, so no shear stress is developed in a fluid. A body subjected to stress undergoes a change of shape and/or size known as strain (Brown, 2004; Kearey et al., 2002; Yilmaz, 2008).

Up to a certain limiting value of stress, known as the yield strength of a material, the strain is elastic and directly proportional to the applied stress. The linear relationship between stress and strain in the elastic field is specified for any material by its various elastic moduli, each of which expresses the ratio of a particular type of stress to the resultant strain.

It is the bulk elastic properties of a material that determine how much it will compress under an external pressure. The ratio of the change in pressure to fractional volume compression is referred to as the bulk elastic modulus (Bulk Modulus) and it is the bulk modulus that influences the speed of sound such as seismic waves in a material, as well as being a factor in the amount of elastic energy or stress that is built up in a solid. This bulk modulus can be thought of as the state of incompressibility of a solid and it is this incompressibility that allows the propagation of sound.
Seismic waves can then be thought of as parcels of elastic strain energy that propagate outwards from the seismic source. Since rocks differ in their elastic moduli and densities, they differ in their response to seismic waves measured through differing seismic velocities and energy propagation. Information on the compressional P (Primary) and S (shear) wave velocities, $V_p$ and $V_s$, of rock layers measured through seismic wave response can therefore provide an indication of the lithology of the rock through which they propagate and the nature of the pore fluids contained within it. Because shear strain will not develop either in the pore space or in the pore filling fluid, it is only the $P$-wave velocity that is influenced by pore fluids. Thus, in principle, a variation in pore fluid type as well as pore fluid pressure should be detectable through $P$-wave velocity variation (Brown, 2004; Kearey et al., 2002; Yilmaz, 2008).

Because the velocity of seismic waves is highly dependent on the density of the medium they propagate through, subtle velocity changes can also give an indication of the densities and pressure through which they propagate. This enables $P$ wave velocity changes to give an indication of not only the relative pressures and densities but also the bulk modulus and subsequently the stress states of a rock (Hatchell and Bourne, 2005). The change in reservoir pore-fluid properties due to pressure depletion such as gas coming out of solution can also have a large impact on the seismic velocity, and studies show subtle variation in $P$-wave velocities depending on whether the pore fluids are brine (water) or gas (Dvorkin, 2008; Hatchell and Bourne, 2005).

The bulk modulus can be calculated from shear wave velocities based on empirically derived relationships between $V_p$ and $V_s$ (Castagna, 1993). However, $V_s$ can also be derived from porosity velocity relationships (Castagna, 1993; Castagna et al., 1985; Dvorkin, 2008). Where known porosity trends are available, this allows further deterministic assessment of the elastic moduli response of a stress regime, as well providing comparison with bulk moduli determined from the empirical relationship between $V_s$ and $V_p$. Furthermore, we see that since the pore fluid type should not affect the shear wave response, this would also allow a further assessment on the impact on $V_p$ by the pore fluid, independent of any anisotropic effect on the $V_s$. The inter-relationship between $V_p$ and capillary pressure becomes apparent when we consider the empirical equation relation of porosity to pore throat radius (Pittman, 1992; Torabi et al., 2013). Torabi et al. (2013) also show a porosity permeability power law relationship that relates a lower porosity and permeability to fault core in relation to host rock.
However, apart from the exponent, the empirical relationship is the same, such that the hydrocarbon column height can then be related to pore throat radius via;

$$hc = \frac{2\gamma}{Rg(\rho_w-\rho_c)}$$  \hspace{1cm} \text{Eqn. 3}

and where;

$$hc = \frac{\Delta P}{g(\rho_w-\rho_c)} \implies \Delta P = \frac{2\gamma}{R} = P_c$$ \hspace{1cm} \text{Eqn. 4} \hspace{0.5cm} (Hasegawa et al., 2005; Shipton et al., 2005)

where $P_c$ is the capillary pressure, $\Delta P$ the pore fluid pressure differential across the fault, $g$ gravitational constant, $R$ the pore throat radius, $\gamma$ fluid viscosity, $\rho$ the density of w (water) and c (hydrocarbon). Pore throat radius can be estimated from porosity through Pittman's (1992) empirical relationship. Thus, through equations 3 and 4, an empirical determination of capillary pressure for a given lithology can be assessed (Hasegawa et al., 2005; Pittman, 1992; Shipton et al., 2005; Torabi et al., 2013; Watts, 1987).

Stacking velocities in a seismic survey is related to the normal-moveout (NMO) velocity which in turn, is related to the root-mean-squared velocity from which the average and interval velocities are derived. Interval velocity is the average velocity in an interval between two reflectors. Pore shape, pore pressure, pore fluid saturation, confining pressure and temperature all influence the interval velocity within rock unit (Yilmaz, 2008).

One of the most prominent factors influencing velocity in a rock of given lithology and porosity is confining pressure. This type of pressure arises from the overburden and increases with depth. It is generally true that velocity increases with depth, however, because of factors such as pore pressure, there may be inversion in the velocity within a layer (Yilmaz, 2008). There are a number of empirically derived equations relating the effect of overburden stress and pore pressure to the $V_p$. Amongst the more robust relationships are the relationship of pore pressure to vertical stress, first proposed by Terzaghi (1923) in 1923;

$$\sigma_v = \sigma_v - \alpha P_p$$  \hspace{1cm} \text{Eqn. 5}
and

\[ \sigma_v = \rho_w g z_w + \int_{z_{sb}}^{z} \rho(z) g dz \]  

...Eqn. 6  

where \( \sigma_v \) is the vertical stress field, \( z \) is the depth or amount of overburden, \( g \) gravitational constant and \( \rho \) the density of \( w \); water, for the water column, or a density as a function of depth below mudline. Density of the lithology is the dominant petrophysical property affecting the velocity and Gardner et al.'s. (1974) equation \( \rho = 1.741 V_p^{0.25} \) is typically used. However, Castagna's (1993) separate empirical relations for sandstone, limestone and shale \( \rho = a V_p^2 + b V_p + c \) show a closer relation to typical trends. The coefficients provided by Castagna (1993) provide good results, notwithstanding the fact that if sonic log data is available, these should always be corrected (Castagna et al., 1985; Gardner et al., 1974; Tingay et al., 2003).

### 2.3 Geometrical structure of the study area - Dampier Sub-basin and Rankin Trend, North West Shelf

The Dampier Sub-basin forms part of the North Carnarvon Basin (NCB) which itself constitutes one of the four main basins of the North West Shelf (NWS) of Australia. The NWS is a collection of marginal and offshore rift basins along the northern Australian margin (Fig. 2). It is a marginal rift with pre-rift Permo-Triassic intracratonic sediments overlain by Jurassic to Cenozoic syn- and post-rift successions deposited in response to rifting and seafloor spreading throughout the Paleozoic and Mesozoic (Keep et al., 2000; Keep et al., 2007; Longley et al., 2002). The NWS has pervasive NNE-SSW trending faults, some of which show reactivation (Etheridge et al., 1991). The primary faults that influence the structural trends are inherited from the final stages of rifting and breakup of Gondwana throughout the Jurassic and early Cretaceous (Keep et al., 2007).
Figure 2. Regional geology of the North West Shelf showing the four main constituent basins (Bonaparte, Browse, Canning and Carnarvon). Modified from (Keep and Moss, 2000).

Tectonic collision during the Neogene modified the pre-existing rift architecture, causing localised fault reactivation (Longley et al., 2002). The change in tectonic regime from one of overall extension to one of overall shortening, manifested as pulses of deformation during the Miocene and Recent (Harrowfield et al., 2003). Bulk strain, estimated at less than 1% shortening, was strongly partitioned on to a small number of favourably orientated structures (Harrowfield et al., 2003; Keep et al., 2007). Areas of discrete reactivation/inversion occur in some parts of the Bonaparte, Browse and Carnarvon basins (Keep et al., 2007). These plate boundary forces continue to have an impact on the present day stress field and neotectonic intraplate deformation of Australia (Fig. 3) (Hillis et al., 2008; Longley et al., 2002; Müller et al., 2012).
Differences in neotectonic activity along the NWS reflect rift-related compartmentalisation which resulted in the division of the major basins. The compartmentalisation takes place along NW-trending features that have been shown to be Proteozoic fracture systems. The basement involvement in this compartmentalisation has resulted in the compartments responding to regional stress fields in different ways (O'Brien et al., 1997). As a result, there is a marked change in structural orientation on the NWS in the Carnarvon Basin from a northeast orientation in the north (Dampier Sub-basin) to a north-northeast orientation in the south (Exmouth Sub-Basin) (Baillie and Jacobson, 1995). Muller et al. (2012) modelled the $\sigma_H$ (horizontal stress) regime which changes considerably in the late Miocene with the onset of collision at the Papua New Guinea margin. Late Miocene $\sigma_H$ orientations rotate in a
clockwise direction from east–west in the Carnarvon Basin to northeast in the Timor Sea, correlating with structural observations.

The NCB which forms the westernmost basin of the NWS has undergone multiple deformation episodes including Late Permian extension (Cathro and Karner, 2006), Late Triassic inversion and further localised extension in the Early Jurassic (King et al., 2010) (see Appendix A for tectonostratigraphic column of the NCB).

The two final phases of extension in the Mesozoic resulted in continental breakup and formation of oceanic crust in the Argo (Callovian) and Gascoyne-Cuvier abyssal plains (Cathro and Karner, 2006). Minor inversion at this time is interpreted to be the result of a major plate re-organisation as India moved northwest and break up commenced between Australia and Antarctica (Cathro and Karner, 2006; King et al., 2010).

Extensive faulting in the Jurassic produced the five main structural elements of the Dampier Sub-basin, including the Rankin Platform, the Madeline-Dampier Trend, the Lewis Trough, the Legendre-Rosemary Trend and the Enderby fault zone (Fig. 4). The Rankin Platform is a relatively high structural platform of Triassic rocks between the Rankin Fault and the shelf edge.

Since the Neogene, collision of the Australian Plate with the Java-Banda arc system to the north has dominated tectonism along the NWS (Keep and Harrowfield, 2008; Keep et al., 2007). As a result, present day stress fields (Fig. 3), determined from modelling, borehole breakouts and seismicity, indicate that maximum horizontal stress trends NE-SW across the Bonaparte, Browse and Canning basins, reflect the dominant control by plate collision in the PNG region (Hillis and Reynolds, 2003; Hillis et al., 2008; Hillis and Williams, 1993a; Hillis and Williams, 1993b; Müller et al., 2012). However, in the Carnarvon Basin the modelled stress field changes orientation, with maximum horizontal stress oriented ESE, suggesting dominant control by far field stress generated from the plate collision in the Himalayas (Hillis et al., 2008; Revets et al., 2009).
Cretaceous inversion concentrated along major boundary faults of the northeast–southwest orientated Rankin, Madeleine, and Rosemary–Legendre trends, with the locus of Miocene inversion located adjacent to the northwest limits of the Rosemary–Legendre Trend (Fig. 5). Inversion has critically controlled the major structures for trapping hydrocarbons within the Dampier Sub-basin (Cathro and Karner, 2006).

The Dampier Sub-basin can be divided broadly into two structures, flanking either side of the main Oxfordian depocenter. Fields along the western flank include the large rift-related horst block traps such as the Goodwyn, North Rankin, and Echo-Yodel wet gas fields, the single unique Perseus lowside saddle trap and numerous other smaller horst and tilted fault block traps such as the Searipple field beneath Perseus. Subcrop of different Early Jurassic and Late Triassic sands within many traps at the level of the base regional seal produce complex fields containing oil and dry gas and wet gas phase combinations (Longley et al., 2002).
The accumulation of significant volumes of hydrocarbons at multiple stratigraphic levels along both the flanks and within the main basinal area demonstrates the laterally drained high-impedance nature of the petroleum system within the central Dampier Sub-basin (Longley et al., 2002). In the Dampier Sub-basin and Rankin platform in particular, the complex charge history is reflected in at least 5 distinct fluid families, ranging from oil accumulations in the Jurassic to dry gas accumulations suspected to have undergone a component of vertical migration from the Triassic (Longley et al., 2002).

Figure 5 schematic cross-section of the West Dampier Sub-basin (Bennett, 2005) (see Appendix B for typical stratigraphic column of the Dampier Sub-basin).

So we see the structural history of the Rankin platform, along with the numerous well-defined, yet complex hydrocarbon fields, provide the ideal setting to better understand the implications that the regional stress field and multiple episodes of fault reactivation have had on sealing faults. The deep seated faults penetrating the Triassic are well suited as they have typically been formed during the early stages of the Gondwana breakup and have undergone multiple phases of reactivation. This is particularly relevant as industry now more actively pursues the Triassic Play of the NWS.
3. AIMS (AND OBJECTIVES):

This study assesses parameters that can be used to define risk factors on fault seal when well data is scarce. Fault seal risk analysis is not only important in the assessment of petroleum reservoirs, but also in the assessment on the impact of any type of fluid flow within the ground. The cross-discipline implications none more apparent than in the assessment of fluid flow in ground water. Ground water management continues to of immense importance to the broader economy and livelihood of those that depend on it. The developing science of CO$_2$ sequestration is yet another discipline where fault seal capacity can have significant implications. The assessment of CO$_2$ reservoir storage potential, relies on the accurate assessment of the impact that pre-existing faults and future potential seismicity may have on its integrity.

The principle objectives focus on:

- Identifying the degree to which fault architecture and stress regime can contribute to fault seal capacity assessment.
- Endeavouring to link fault seal capacity to formation pressure and seismic velocity.
- Evaluation of capacity to make passive evaluation (no wells) of fault seal risk factor.

Fundamental to these objectives is the assertion (hypothesis) that the risk factor on fault seal can be better defined using seismic velocities alone, to a practical level, where well log data is unavailable. This study aims to test this hypothesis.
4. METHODOLOGY:

The study involved the analysis of the Demeter 3D survey. Acquired in 2004 by Woodside Pty Ltd on behalf of the North West Shelf Joint Venture, it is a SEG normal polarity pre-stack time migrated volume. The survey covers approximately 3590 square km over the Echo-Yodel, Rankin, Dockrell/Keast, Goodwyn and Perseus fields, to name a few, which sit on the northern end of the Rankin Trend (Fig. 6). The survey has an inline bin spacing of 6.25m and crossline bin spacing of 25m with a fold of coverage of 133. The survey was reportedly optimised for maximum bandwidth to improve imaging of shallow targets (Bennett, 2005).

Figure 6 Map showing the blocks comprising the NWSJV and outline (red line) of the Demeter 3D survey area, on the western edge of the Dampier Sub-basin, NCB (modified from Bennett, 2005).

A small subset of the area was selected, covering the Rankin and Dockrell/Keast fields and associated fault blocks (Fig. 7). The subset area (summarised in Table 1) was selected as it covers some well known fault blocks which could be used for assessment. Furthermore, the associated stacking velocity file had to be small enough in size to be loaded on the software in use, which has a 4GB restriction. Seismic analysis was conducted using the Landmark software suite V5000.0.2 and final maps were generated using the Petrosys mapping software.
suite. The stacking velocities were High Density Velocity Analysis (HDVA) ‘unsmoothed’ pre stack time migrated CMP stacks of a 12.5 m x 25 m grid. HDVA stacks were generated to create a velocity field with higher spatial resolution for final NMO correction, rather than the 500m x 500m sparse array that may typically be generated. The stacking velocities are sampled on every shotpoint at a spacing of 12.5 x 25 m with a vertical sampling of 32ms.

**Table 1** Survey Subset details

<table>
<thead>
<tr>
<th>Survey</th>
<th>Inlines</th>
<th>Crosslines</th>
<th>Depth Range (ms)</th>
<th>Bin Size</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Demeter 3D - subset</strong></td>
<td>1800</td>
<td>1400</td>
<td>0 - 6000</td>
<td><strong>6.25 x 25</strong></td>
<td>394</td>
</tr>
<tr>
<td><strong>HDVA Vels</strong></td>
<td>900</td>
<td>1400</td>
<td><strong>32 sampling interval</strong></td>
<td><strong>12.5 x 25</strong></td>
<td>394</td>
</tr>
</tbody>
</table>

Checkshot survey data was available for 32 wells in the Rankin Trend and Exmouth Plateau. Exmouth Plateau wells were analysed for comparative purposes in a tectonic area with a 'similar' history. The checkshot data, sometimes referred to as the 'poor man’s’ sonic log, provide accurate time depth conversion, as well as interval velocities that are based on Dix's Equation (Dix, 1955). This allowed calculations to be compared to well-based data at common depths. A quality check of the data was also performed, comparing HDVA, checkshot and sonic velocities. Sonic logs have a vertical resolution greatly exceeding that of the seismic velocities, thus, these were not used in calculation checks, rather the checkshots represent a far more realistic approach to qualifying the validity of using the various empirical relationships that may be employed on the stacking velocities.
Figure 7 Base Oxfordian regional unconformity that intersects the Horst Graben structure of the Rankin Trend. The escarpment fault which bounds the eastern edge of the Rankin Trend is also indicated. The study area is bounded in the green box (modified from (Bennett, 2005)).

The empirical relationships used rely on established properties in standard rock physics models. In basin analysis, the overburden stress $S_v$ can be calculated as a function of thickness $Z$ and density $\rho$ of the overlying rocks multiplied by gravity $g$.

$$S_v = Z \rho g \quad \text{... Eqn. 7}$$

The bulk density was calculated using the empirical relationship of (Castagna, 1993). This polynomial fit allows density to be determined in the absence of sonic log, core sampling, or locally calibrated trends:

$$\rho = aV_p^2 + bV + c; \quad \text{...Eqn. 8}$$

Here, $a = -0.0261$, $b = 0.3730$ and $c = 1.4580$. These constants match the fit for shales and feldspathic sandstones, and best approximate the marls, claystones and clay and shale inter-
bedded sandstones that dominate the lithology in the study area. The appropriateness of Catagna's (1993) relationship was compared to (Gardner et al., 1974) relationship;

$$\rho = 0.23 + 3.2808Vp^{0.25}$$  ...Eqn. 9

as well as a porosity based empirical relationship (Swarbrick and Osborne, 1998) relating porosity to density;

$$\rho = \rho_{ma}(1 - \phi) + \rho_{fl} \phi$$  ...Eqn. 10

where $ma$ and $fl$ refer to the matrix and fluid density respectively. Equation 10, based on (Wyllie et al., 1956) relationship, had the advantage of comparing density trends from two different sources, thus comparing not just the closeness of 'fits'. Here, porosity is related to depth via a porosity depth trend for the NCB (see Appendix C for details). The resulting density allows Terzaghi's (Terzaghi, 1923) equation to calculate overburden stress;

$$\sigma = S_v - P_p;$$  ...Eqn. 11  where $P_p$ is the pore pressure.

Pore pressure can be measured in the well via a Repeat Formation Tester (RFT) tool and RFT pressure data was collected from publically available Well Completion Reports (WCR) for 28 Wells along the Rankin Trend. This allows the effective stress to be calculated for depths corresponding to the RFT measurement points. However, this also allows a QC check to be performed on an empirical relation between seismic velocity and pore pressure. The common pore pressure relationship given by Eaton (1969) relates stress measured to pore pressure from the ratio of measured seismic velocities to the normal velocity trend for the basin. Although, it is noted that a ‘normal’ trend can be difficult to confirm in many instances and possibly erroneous where for example, as is the case for the Rankin trend, overpressure is so consistent that the overpressure trend is 'normal'.

There are a variety of additional empirical relationships that reportedly provide good results where good well calibration is available (Sayers, 2006; Soleymani and Riahi, 2012; Zhang, 2011). This study uses Bower's (1995) method, which required less calibration compared to some others and was therefore considered more readily applied to the frontier basin. Bower's (1995) modification relates velocity to pore pressure based on a virgin pressure curve (see Appendix D) taken from a reference well, Rankin 1 in this case, and subtracts this from the lithostatic pressure gradient;
\[ P = (3.958 * z) - \left( \frac{V_{\text{int}} - 1250}{16.5} \right)^{1/0.6} \] ...Eqn. 12

where \( z \) is depth in meters, \( V_{\text{int}} \) the interval velocity in m/s.

As the stacking velocities only contained the P-wave velocities. Shear wave velocities are calculated using the empirical relationship of Castagna (1993);

\[ V_s = bV + c \] ...Eqn. 13

where \( b = 0.77 \) and \( c = -0.867 \). Again this is for a lithology that best fits the dominant rock type in the formations being studied (see Appendix E for the 'goodness of fit' for this empirical relation). This allows Poisson's ratio to be calculated through the relationship;

\[ \nu = \left( \frac{V_s^2 - 2V_P^2}{2(V_P^2 - V_s^2)} \right) \] ...Eqn. 14

And Poisson’s ratio can be used to equate the horizontal stress \( S_{h\text{min}} \) extent via;

\[ S_{h\text{min}} = \left( \frac{S_N}{(1/\nu) - 1} \right); \] ...Eqn. 15

A range of different empirical relationships to calculate \( S_{h\text{min}} \) are available (Zoback, 2010). Those employing an effective stress ratio consistent with Byerlee’s (Byerlee, 1978) range of values for constant of internal friction are compared (Eaton, 1969; Hubbert and Willis, 1957; Zoback and Healy, 1984). Figure 8 summarises the work flow utilising the relationships described above.

This allows a range or properties to be assessed; importantly the Coulomb Failure Function (CFF):

\[ CFF = \sigma_s - \mu_s (\sigma_n - Pp) \] ...Eqn. 16

where, \( \sigma_n \) is the normal stress, \( \sigma_s \) the shear stress and \( Pp \) pore pressure. Appendix F describes the three dimensional calculation of the normal and shear stress from the principal stress vectors.

The CFF measures the difference between shear stress and effective normal stress. The effect of increased pore pressure is to decrease the effect of overburden stress such that shear stress is greater and Mode I and II failure is of higher risk.
If we know the normal and shear stress, we can calculate the angle of internal friction, or angle at which the ratio of shear and normal stress puts the rock in a critical state of stress through

$$\frac{\tau}{\sigma} = \mu = \tan \theta \quad \ldots \text{Eqn. 17}$$

$\mu_s$ on the other hand refers to the coefficient of sliding friction, equal to;

$$\frac{s_s}{s_n} = \mu_s \quad \ldots \text{Eqn. 18}$$

This is essentially Amontons’ law (Amontons, 1699), who had expanded on experiments on friction that had first been conducted by Leonardo da Vinci (Gao et al, 2004). The coefficient of sliding friction describes the ratio of shear to normal stress in a fault that will initiate slip or movement. Byerlee (1978) found that for a range of rock types, the ratio of shear stress to effective normal stress required to initiate slip was between 0.6 and 1, a phenomenon known as Byerlee’s law. Further studies (Jaeger et al., 2007), also showed that the ratio, or $\mu_s$ was remarkably consistent and approximate to 0.6. Some mudstones and clays have been shown to have a $\mu_s$ of less than 0.6 and as low as 0.2 at low effective pressures (Lockner et al., 2011; Moore and Lockner, 2004; Moore et al., 2009; Zoback, 2010). Low $\mu_s$ in the fault gouge of some rock types is attributed to a high concentration of certain phyllosilicates, of which the more common minerals have been shown to range between 0.2-0.5 (Moore and Lockner, 2004). However, aside from these minerals and the fault gouge that is comprised of them, most rocks typically adhere to Byerlee's law thus, where $\mu_s$ is applied in this study, it is assumed to be 0.6. This carries forward into the various empirical relations for $S_{\text{min}}$ employed, where an Effective Stress Ratio (ESR) of 0.32 is equivalent to a value of $\mu_s$ of 0.6.
Figure 8 Workflow diagram summarising the process of assessing the validity of select empirical relationships used to relate velocity to fault seal properties.
5. Results

5.1 Structural Characteristics of the Rankin Dockrell Keast Blocks - Rankin Trend

Spudded in July 1971, Rankin 1 (Fig. 9) tested a structural culmination on the Rankin Trend structural high. The Rankin 1 well drilled through Pleistocene to Upper Triassic formations with Cretaceous rocks lying unconformably on the Triassic with the entire Jurassic and much of the Neocomian absent. The Triassic sandstones contained significant hydrocarbon accumulations with 63m of gas/condensate pay underlain by a 3.4m oil column and an oil/water contact at approximately 2955m, 274m higher than at North Rankin.

Figure 9 The study area with main oil and gas fields and well locations. Inset: tectonic map highlighting the Sub-basins and Rankin Trend in the NCB. The blue box over the inset relates to the area covered by the larger picture (inset: Geoscience_Australia, 2010).
The Dockrell Field was discovered in 1973 with the Dockrell 1 well intersecting a stacked reservoir of three hydrocarbon accumulations of gas and oil, with approximately 88m of oil and gas in the top Brigadier reservoir, and 15m of gas/condensate in the lower two Mungaroo Triassic intersections.

The Keast Field was discovered in 1996 and has two penetrations. Keast-1, drilled in 1996, encountered a stacked reservoir with five hydrocarbon accumulations with the fluid intersected being gas. Keast-2, drilled in 1997, was a dry hole. Whilst both Keast and Dockrell penetrated the Upper Triassic, core data is limited to the Brigadier formation.

Together, the three wells, which are not under production, provide pressure information across two faults separating the Rankin High, from the Keast Graben and Dockrell high (Fig. 10). The fault blocks of the Rankin High, Keast Graben and Dockrell High are comprised of extensional graben, half graben blocks separated by moderately dipping (40-50°) planar normal faults. These normal faults show differential offset in the strata indicative of continuing reactivation throughout the Jurassic age (Figs. 10-12). The main southern bounding Rankin Escarpment fault has been reactivated well into the middle Neogene with hard and soft linkage between the Triassic and Cretaceous/Cenozoic overburden, alternating along the NE-SW strike of the fault. The faults show significant throw in the Triassic strata with the Rankin Keast fault and Keast Dockrell faults showing more than 300 ms TWT (approximately more than 400 m). Pre-kinematic strata fill the Keast Graben within the Triassic and along the Rankin Escarpment (Figs. 12-13).

Figures 10 and 11 both show two-way time slice through 2920 ms in the Triassic. Figure 11 displays amplitude variation across the time slice with red (negative) amplitudes principally reflecting a shale-dominant lithology with a resulting high impedance contrast. The amplitude time slice shows horizontal separation in the NW-SE faults, which, when considered with the relative dip of reflectors suggests that a dextral strike-slip or oblique slip movement has occurred.

Most of the Jurassic is missing with the reported Oxfordian sub-aerial exposure resulting in the erosion of these sequences. The upper part of the Oxfordian is dominated by claystones which form a seal over the underlying lowstand sands. This in turn is overlain by regional transgressive and highstand marine claystones of the Early Cretaceous period.
Figure 10 TWT structure map of the base Norian Late Triassic surface showing the main structural elements in the study area. Triassic fault blocks have undergone extensive faulting and reactivation with the southern bounding Rankin escarpment fault representing the southern boundary of the Rankin Trend high. The Rankin, Keast and Dockrell wells have all been drilled in fault bounded structural highs with recorded hydrocarbon accumulations.

These Oxfordian and Neocomian claystones dominate the seismic cross sections with high impedance contrast. Only extensive and continual reactivation of the Rankin Escarpment and Goodwyn fault block offset these regional claystone seals. However, whilst Neogene reactivation is hardlinked to the escarpment fault, many Triassic fault blocks show some minor evidence of reactivation, with soft-linking through the Jurassic and Cretaceous
claystones (Figs. 12-13). The claystone horizons themselves are dominated by classic polygonal faulting that is typically associated with compaction and dewatering, but without clear evidence of hardlinks through the more ductile shale dominant lithology (Fig. 13).

The semblance attribute time slice at 2910 ms TWT in figure 14 shows faulting within the main fault blocks. The Keast Graben and Dockrell high have small faults cross-cutting the blocks at an angle of approximately 60° to the bounding faults and with small vertical offsets, typically less than 10 ms TWT. These cross-cutting faults terminate at the bounding faults. The E-W faults within the Rankin/Echo-Yodel fault block are somewhat different, with very little vertical offset and a E-W striking trend. The E-W faults also indicate horizontal separation (Fig. 15). These E-W faults comprise a small horst and graben set cross-cutting the Rankin/Echo-Yodel fault block and offsetting some N-S faults at an angle of approximately 60°.

Figure 11 2910 ms TWT amplitude time slice of the study area. The principal faults in the study can be seen, along with horizontal separation in the east-west faults cross-cutting the Rankin block.
**Figure 12 a)** NE-SW cross section (inset shows location (inset: red lines show correct spatial location of inline and crossline, but are not to scale in length) showing the Rankin High and well bounded by the escarpment fault to the SW and Keast Graben to the NE. Both faults are reactivated normal faults with fault bend folds in the upper Triassic and reactivation up into the middle Neogene horizons. 

**b)** showing principal stratigraphic boundaries (TWT, v/h x 2 and x 4 respectively).
Semblance images show time slices in the Eocene, Middle Cretaceous and Base Cretaceous respectively. They highlight the reactivation of the Rankin Escarpment fault throughout, however, no reactivation of the underlying horst-graben architecture is evident within the geomorphology above the regional unconformity which is controlled by the depositional setting of the area.

Eocene: Rankin Escarpment still present. Shore line depositional features dominate with no further evidence of reactivation of underlying . . .

Shoreline channels in siliciclastic-dominated depositional sequence

Rankin Escarpment shows Neogene reactivation

Rankin Escarpment fault

Goodwyn/Dockrell fault

Middle Cretaceous: Rankin Escarpment still apparent with the geomorphology revealing little about underlying structure in this calcilutite and carbonate-dominated depositional sequence.

Base Cretaceous: Classic polygonal faulting in the shale sequence with the Rankin escarpment evident, but underlying architecture hidden under the unconformity.

**Figure 13** Semblance images show time slices in the Eocene, Middle Cretaceous and Base Cretaceous respectively. They highlight the reactivation of the Rankin Escarpment fault throughout, however, no reactivation of the underlying horst-graben architecture is evident within the geomorphology above the regional unconformity which is controlled by the depositional setting of the area.
Figure 14 Semblance attribute of the 2910 ms TWT slice (Late Triassic Carnian) through the study area highlighting the fault array. The main Rankin Escarpment fault bounds the Rankin, Keast and Dockrell blocks to the south and the smaller East-West faults cross-cutting the Rankin Block can be seen.
Figure 15 Cross section through E-W striking faults that manifest within the upper Triassic of the Rankin block. These faults show small vertical offset (approx. 10 ms TWT) but 100s of metres of horizontal separation (v/h x8).

The Keast/Graben and Rankin and Dockrell Highs are underlain by a large listric fault that terminates at the escarpment and strikes along the uplifted basement structure that constitutes the greater Rankin Trend (Fig. 16). Figure 16 shows that any tilting of the horst graben fault blocks will not occur without influence from the underlying Rankin Trend structure.

Figure 17 also shows the Keast Graben displaying subtle strike slip features indicative of fault reactivation with an oblique slip component, with strata peaking across offset (pseudo teepee). Horizons with varying angle of dip and some reverse offset are also possible indications of oblique slip. The regional base Cretaceous unconformity (Figs. 19 and 20) shows that whilst the horst-graben bounding faults do not offset the shale, the geomorphology is still controlled by the oblique slip reactivated horst-graben architecture. This architecture is also shown in figure 18, which again exhibits oblique slip features on what would otherwise be considered a classic extensional horst graben array.
Figure 16 Inline cross section of the Keast Graben highlighting listric faulting underlying the horst graben architecture (v/h x 2).
Figure 17 The horst graben architecture can be seen with transpressive/transtensive reactivation generating teepee and inversion rollover along the main horst-graben bounding faults. Varying angle of dip also indicate block rotation (oblique slip) rather than a simple strike-slip sideways movement (v/h x8).
Figure 18 An inline cross section across the Keast Graben showing features indicative of fault reactivation with an oblique slip component, with strata peaking across offset (pseudo teepee). Horizons with varying angle of dip and some reverse offset suggest that horizontal movement may be associated with the episodes of fault reactivation that have occurred (v/h x8).

Figure 19 Map of the regional Cretaceous unconformity: a deep marine shale deposited on top of the erosional Jurassic unconformity. Whilst only the main reactivated escarpment faults offset the horizon, the horizontal movement and rotation of the Triassic fault blocks are reflected in the geomorphology of this surface.
Figure 20 Dockrell a) shows the Dockrell horst fault block along strike NE-SW (inset: red lines show correct position of inline and crossline, not to scale) which has NE dipping strata from the northerly tilt of the fault block. b) NW-SE cross-section on the edge of the escarpment again shows the reactivation into the Neogene (v/hx2).
The implications of this fault reactivation on lithology and subsequently, pressure communication across faults, may be further assessed from consideration of the velocity profile across this fault array. Figures 21 to 25 show the stacking velocities as colour overlaying the amplitude cross-sections for the fault blocks being studied. The cross sections through the Rankin closure show significant velocity variation though the Triassic fault blocks. In the Upper Triassic, velocity differential can be seen across the Rankin escarpment fault, and interestingly within the Rankin High itself, where a small fault appears to be delineating the southern and northern parts of the Rankin Closure (Fig. 21). Beyond 3000 - 3200 ms TWT, the velocity differential is too poor to make any significant observations regarding relevant variation.

The Keast Graben and Dockrell High show distinct velocity shifts from the Cretaceous to Triassic lithology (Fig. 22-23). Low velocities persist at greater depths around the bounding faults. The velocity also shows a significant increase at the base of the Norian. In all the velocity overlays, a low velocity zone can be seen dominating the Cretaceous formation. This is a region consisting of a mixture of marls, claystones and calcilutite. The velocity increases again over the claystone shale layers that make up the regional unconformity above the Triassic. Lateral variation in velocity is minimal above the regional claystone seals and relatively high below the seal within the Triassic fault blocks. Low velocities focus around bounding faults and at the 'up dip' section of dipping strata (Figs. 22- 25). A distinct differential in relative velocity across the faults is not evident. However, as figure 25 illuminates, the velocity gradient is highly sensitive to formation boundaries. The shift from one major formation to another can almost be picked from the velocity gradient shift alone.

The velocity distribution map, for the base Norian surface (Fig. 26), shows how the velocity is principally dependent on density and therefore depth, with the deeper parts of the surface correlating with higher velocities. The surface is within the Mungaroo formation, and shows lateral variation in lithology that is not seen in the TWT surface.
Figure 21 Cross section (location inset) showing velocity variation across the Triassic fault blocks of the study area. A velocity differential is observed between the minor fault transecting the Rankin structural high. This variation may suggest a pressure differential associated with fault seal. This delineates the Rankin accumulation from the south-bounding escarpment, however, little differential is evident between the Rankin block and Keast Graben (v/h x2).
Figure 22 Crossline through the Dockrell and Keast Graben. The velocity profile shows relatively low velocities around the main horst-graben bounding faults. The velocities also appear to delineate the main formations with high consistency (v/h x1.5).
Figure 23 Inline and crossline across the Dockrell accumulation showing significant velocity variation across the Triassic fault blocks of the study area. The Rankin escarpment fault displays a velocity differential across it, however, again there is little variation between the Keast Graben and Dockrell high. Both the inline, B, across the Dockrell Horst and the crossline A, aligned with the strike of the horst show evidence of slow velocity patches within the Carnian which may suggest fluids or gas within the Middle Triassic (v/h x4).
Figure 24 This crossline across the Rankin, Keast and Dockrell fault blocks shows evidence of inversion, principally through the structural culmination within the greater Keast, Dockrell Graben where sediment has been deposited prior to extension, extensionally listrically faulted and inverted. The varying dip within each fault block is itself a possible result of fault block rotation associated with oblique slip. Unlike the inlines, this cross line at a smaller scale does show some velocity variation across the Rankin/Keast fault, however in this instance, it is difficult to separate this from fault shadow effects (v/h x4).
Figure 25 Whilst velocity differential across faults is ambiguous, the velocity profile shows remarkable consistency with the formation boundaries. ‘Formation’, as being distinct from ‘lithology’ (such as shale or sandstone), means the overall gross lithological properties that define a formation such as the Haycock Marl or Mungaroo Formation (v/hx2).
Figure 26  a) Base Norian Horizon in TWT showing the principal fault blocks of the study, including Goodwyn 6 and the eastern edge of the Goodwyn fault block. b) showing the P-wave velocity profile of the Base Norian horizon. The velocity profile is a good indicator of lithology and density, and therefore the fault block architecture, however, lateral resolution is too poor to infer any pore pressure differential.
Figure 27 shows the Depth Structure map of the Base Norian Horizon. It shows that the general structural geomorphology is consistent with the TWT maps with no culminations or depressions removed during depth conversion. The depth map is used in the pore pressure calculation for the base Norian horizon.

Figure 27 Depth Structure map of the base Norian (Triassic) horizon. The structure remains consistent with the time structure maps.
5.2 Velocity Analysis

The velocity profile of the Rankin Trend is broadly consistent along its entirety (Fig. 28). However, when compared to a similar region within the same basin; the Exmouth Plateau, each displays a different rate of increase with depth. The exception is Gorgon 1, which is known to sit over an anomalous 'hot spot' within the basin (see Appendix G). In addition, the interval velocities (Fig. 29) as opposed to the instantaneous velocity, show a velocity reversal at approximately 2000 mBML which is also different when compared to the Exmouth Plateau, which has no reversal. The velocity reversal, present over the entire Rankin Trend, is clearly shown in figure 30.

**Figure 28** The velocity profile of 33 wells in the NCB comparing the Rankin Trend to the Exmouth Plateau, two sub-regions of the Basin that are relatively uplifted. Each has a distinct velocity trend of its own.
**Figure 29** Profile of the interval velocity in the Rankin trend and Exmouth Plateau for comparison. Unlike the Exmouth Plateau, the Rankin trend has a distinct change in slope at approximately 1200m and 2500m TVDSS.

**Figure 30** The interval velocity profile of the wells within and adjacent to the blocks of the study area on the Rankin trend. A decrease in interval velocity with increasing depth is seen between approximately 2200m and 2700m.
The $V_p/V_s$ ratio is approximately 2, albeit with a slow decrease (increasing $V_s$) with depth. The first 1000m below mudline has a slow decrease in the ratio in both the Rankin trend and Exmouth plateau. The ratio remains remarkably constant beyond 1000m BML, with the exception of significant lithology variation or overpressure/fluid contact zones.

**Figure 31** The $V_p/V_s$ ratio with depth is rather consistent, at approximately 2, and 2.3 in depths correlating with overpressure.

When comparing the stress and pore pressure differential across a fault block it is important to ensure that the stacking velocities have been 'picked' to sufficient accuracy. Figure 32 shows a comparison between the sonic log and checkshot velocities from four wells within the study area. These well velocities are compared to the stacking velocity over the seismic shotpoint that is nearest to the respective wells (within 75m of the well by horizontal distance). The velocities show a good correlation: however, the sonic logs display vertical resolution of less than 1 m whereas the vertical resolution of the checkshot and stacking velocities are on the order of tens of metres. This is important to consider within the context of differentiating...
individual channel sands or intra-formational seals that may themselves be less than 1m thick. However, within the context of determining gross formation stress and pore pressure variation, the stack and checkshot interval velocities provide a workable resolution.

Hence, we contend that the stacking and checkshot interval velocities are valid data sources for estimating empirically related properties such as pore pressure and stress in a geological formation. Figure 33 shows the relationship between velocity and density, as described in Section 4: (Methodology). The densities were derived from the velocity profiles over the Rankin Trend and Exmouth Plateau. These velocity-based densities broadly match the density trend derived from the NCB porosity trend.

RFT/FIT pressure tests (Fig. 34-35) in the Rankin and Keast/Dockrell field suggests that these accumulations have a pressure differential of up to 750 psi. The Rankin 1 well RFT data is old (1973) and perhaps not as precise as newer tests, however, it suggests that there is capillary seal of at least 750 psi across the Rankin/Keast fault. The Keast 1 and Dockrell 1 Wells indicate a pressure differential of 280 psi, suggesting that the N-S fault separating Dockrell and Keast has a capillary potential of at least 280psi. Most wells follow the hydrostatic gradient with notable exceptions including Zagreus, Orthrus and Gorgon (Fig. 34). With respect to the Rankin Trend wells, Lady Nora 1 and Rankin 1 stand out, both overpressured relative to the hydrostatic gradient at shallower depths. Most wells show a deviation from the hydrostatic gradient around 3500 mTVDSS, with subtle variations, for example, Goodwyn 6 is slightly deeper, around 3600 m, whereas Rankin 1, located structurally on one of the shallowest locations within the Triassic, has elevated pore pressure from 2900m.
Figure 32 Wells from the main fault blocks being studied show a comparison between the interval velocities extracted from the HDVA stacks being examined and the checkshot and sonic log velocities from each respective well. Good correlation supports the validity of using either velocity source to derive stress and pore pressure relationships.
Pore fluid retention leading to overpressure is restricted to the Triassic, below the regional claystone seals. The over pressure can be seen (Figs. 34-36) with the pressure deviation from the hydrostatic trend occurring at approximately 3600 mTVDSS, which is the typical depth of the regional claystone seal within the study area.

The effect of this overpressure can be seen in figure 36 where the effective pressure is not a simple linear trend with depth. Rather, the effective pressure trend is concave downwards with further reduction in effective pressure around 3500 mTVDSS. Further evidence for effective stress reduction being due to overpressure is assessed through the LOT data from the NCB. Figure 37 shows this data including FIT tests that recorded maximum pressures. A linear trend throughout the NCB is evident and the maximum pressure data points scatter with the normal distribution around the actual LOT data. Figure 37b shows just the LOT data and the consistency of the trend. Figure 38 shows the methods based on an empirical Poisson’s ratio (Eqn. 15) and porosity trend underestimate the $Sh_{\text{min}}$ at depth, when compared to values derived from LOT data. The methods of (Hubbert and Willis, 1957; Zoback and Healy, 1984) and (Eaton, 1969) provide a closer fit, with the Zoback and Healy (1984) and Hubbert and Willis (1957) relations underestimating $Sh_{\text{min}}$ at depth and Eaton overestimating the stress. In these relations, Eaton’s (1969) and Zoback and Healy’s (1984) relations use an effective stress ratio of 0.32 (coefficient of internal friction (CIF) of 0.6), whilst that of Hubbert and Willis’ is 0.38 (CIF 0.5). Eaton’s (1969) relationship provides a poorer fit for the Rankin Trend alone (Fig. 39), although may fit better at greater depths.

The difference in $Sh_{\text{min}}$ derived from the velocity and from LOT is plotted in Figure 40. The power law relationship resulting from the underestimation of $Sh_{\text{min}}$ from the velocity allows a 'correction factor' to be calculated. This correction factor assumes a calibration well is present, nonetheless, a clear trend is discernable.

Figure 43a-d show the coulomb failure function described for the principal fault blocks in the study. Described in Section 4, these functions are graphed for a fixed orientation representative of the main graben bounding NE-SW faults that separated Rankin from Keast and Dockrell. A constant coefficient of sliding friction of 0.6 is assumed. The CFF suggests, that under the current stress regime, these fault blocks should not consist of a stress regime that would lead to fault slip for a plane representing the Rankin/Keast/Dockrell N-S faults (Fig. 10). However, when the $Sh_{\text{min}}$ derived from the P-wave interval velocity is employed, an
erroneous data set is found. When the velocity-based CFF with a correction factor applied shows a broad consistency with the LOT-based CFF.

Pore pressures are calculated from Bowers’ (1995) relation with a Biot factor of 0.8 (see Appendix D for details) and pore throat radius calculated from (Pittman, 1992) relation. With empirically derived pore pressure, Eaton’s (1969) or Zoback and Healy’s (1984) equation can be used to calculate the CFF in place of a ‘corrected’, well-dependent CFF. The calculated pore pressure correlate well with the RFT measured pore pressures (Figs. 44-45). The pore pressure variation across the area is broadly consistent, with some scatter coming from the use of checkshot velocities, particularly in the case of Keast (Fig. 46). However, the calculated pore pressures from stacks, mapped on to the base Norian surface in the case of figure 47, suggest there is a lateral variability.

The degree of this lateral variability further is assessed by looking at pore pressure distribution for a constant depth(time) over a time slice of 2300 ms TWT. Eliminating the depth-dependent pressure effects that occur with a depth-varying surface, it shows that a lateral variability in pore pressure remains. However, anomalous velocities (and hence pressures) are observed.

The CFF was subsequently calculated using Bowers (1995) pore pressure and LOT based Sh_{min} and Zoback and Healy (1984) based Sh_{min} (Fig. 49). Both methods suggest that even within the overpressure window there is little risk of reactivation on the modelled N-S fault. Final CFF’s used stacking velocities rather than checkshot velocities (Figs. 50-52). The three primary fault planes representing the Rankin escarpment, Rankin/Keast fault and small East-West Rankin Block faults are modelled. The effects of pore pressure in the overpressure window can be seen. Whereas the Rankin/Keast fault is stable, the escarpment fault has a positive CFF at depths equivalent to the top of the Triassic. Within the current stress regime, the escarpment fault may still be subject to failure in places.
Figure 33 The density relationship with depth for the Rankin Trend, NCB. Scatter in the density derived from interval velocities reflects differing lithologies and pore pressures, whereas Equation 10 (Swarbrick and Osborne, 1998) relates an empirically derived porosity with depth trend to density, hence, the smooth exponential type curve.

Figure 34 The formation pressures of selected wells from the Rankin trend and Exmouth plateau. The lithostatic gradient is based on core measured Rankin trend porosities resulting in the Exmouth plateau well, Jansz 3 exceeding it.
Figure 35  With the exception of the *wells from the Exmouth Plateau, the Rankin Trend wells all show changes in formation pressure gradient associated with the overpressure from disequilibrium compaction. Goodwyn 6 is pointed to as its numerous data points make the gradient change easier to see.

Figure 36  Effective pressures from wells in the study area. They show a concave downwards trend as overpressure at depth of 3400m and below reduces the effective stress and associated stress to depth pressure gradient.
Figure 37 XLOT and ISIP pressures from 47 wells from the NCB show a linear trend between depth and inferred Sh$_{\text{min}}$ at 0 to 4 km depth below sea floor. It suggests a broad consistency in regional Sh$_{\text{max}}$ throughout the NCB and well as a consistent vertical to horizontal stress ratio (data from the CSIRO pressure plot$^{\text{TM}}$ database).
Figure 38 Comparison of the main empirical relationships used to determine $Sh_{\text{min}}$ from interval velocities. Bilateral constraint based relations such empirical Poisson and Porosity based trends underestimate the $Sh_{\text{min}}$ at depth.

Figure 39 Based on the assumed effective stress ratio of 0.32, Zoback and Healy's and Hubbert and Willis' relations provides a good fit to LOT trends, Eaton's tends to overestimate at depth.
Figure 40 The ratio of $S_v$ and $Sh_{min}$ is plotted for the Rankin trend wells in the study area and compares $Sh_{min}$ estimated from LOT data to $Sh_{min}$ calculated from an empirical relation. The green calculated values have an average value of 0.62, however, tend to underestimate the ratio compared to the LOT based data which has an average of 0.64. Apart from a deviation around 3000m, the ratio has a small decrease with depth due to the gradual increase in overburden stress.

Figure 41 plots the difference in $Sh_{min}$ where $\sigma_3$ is derived from shear wave velocity using Castagna's (1993) relation and $\sigma_3$ is inferred from the LOT measurements. This presents a 'correction factor' that can account for the error in the assumption of bilateral constraint. The validity of using shear wave based $Sh_{min}$ may be appropriate where this difference is known, e.g. from a reference well (see Appendix E for validity check).
Figure 42 Comparison between pore pressure and vertical and minimum horizontal stress components. The graph shows effective stress reduction where pore pressure increases. Furthermore, \( \sigma_1 \) remains in the vertical direction, suggesting a normal/strike slip tectonic regime.
Figure 43 Coulomb Failure Function for a fault plane that is representative of the N-S steeply dipping faults that separate the Rankin/Keast and Dockrell blocks (Schematic of the theoretical plane used can be seen in figure 56). The CFF is calculated using Pp and LOT measurements at a depth which has Norian (Triassic) Mungaroo formation geology in the Rankin Trend. a) The shear stress is measured from LOT data, are all below zero suggesting no prevalence for failure. b) The shear stresses are derived from the seismic velocities using Vp to Vs conversion for an estimation of Poissons ration. 
C) a correction factor is applied accounting differences between LOT-based shear stress and Vp based shear stress d) shear stress calculated assuming a fixed principal stress ratio i.e. fixed ESR of 0.32, as per Zoback and Healy (1984) or Eaton's (1969) equations. The figures show the degree to which the 'corrected' c, or calculated d, CFF broadly correlate with a, the LOT based CFF.
Figure 44 Comparison of pore pressure from checkshot interval velocity, RFT and HDVA velocity stack. The velocity picks from the stack closely match the least squares fit of the checkshot.

Figure 45 Comparison between Rankin 1 RFT measured pore pressure and calculated pore pressure using the Bowers’ (1995) relationship with velocity. RFT measurements are biased towards the target reservoir (only measured at the depth corresponding to reservoir), but show a reasonable correlation.
Figure 46 The estimated pore pressure trend based on checkshot velocities from the respective wells in the list is broadly consistent across the different fault blocks within which the wells are located.
Figure 47 Pore pressure variation across the base Norian horizon. Higher pore pressures are focussed around fault boundaries, as well as broadly within the Rankin High and Dockrell Highs and near the Goodwyn block. Pore pressures on the scale bar are in psi. This map does not indicate pressure differential across faults as the horst and graben are at different depths.

Higher pore pressure in the shallower section of the base Norian horizon- localised around the Rankin, Dockrell and Goodwyn 6 blocks.
Figure 48 Observation of lateral variation in a) velocity and b) pore pressure from a time slice at 2300 ms TWT shows good consistency with values for most of the study area. However, anomalous results are evident in the lower corner (see schematic top left corner) of the study area that is south of the Rankin escarpment. This is shown to be due to poorly picked stacking velocities in this part of the study area (inset). Whilst relative variation is useful, absolute values are only as good as the velocity picks.
**Figure 49** a) Coulomb Failure Function using LOT-derived $\text{Sh}_{\text{min}}$ shows the fault plane representing the Rankin/Keast fault should be stable, albeit with relatively reduced stability between 2000 and 3000m BML due to increased pore pressure. The Zoback and Healy (1984) relation is similar, but with reduced variation due to pore pressure.
CFF comparison for three fault planes representing the main fault within the Rankin Fault Block with Rankin Block Pore Pressures

**Figure 50** Coulomb failure function profile using stacking velocities and the empirical relations from Zoback and Healy (1985) and Bowers (1983). The stacks have reduced variability, but are broadly consistent with the checkshot CFF.

**Figure 51** The CFF for three fault planes in the study area. The escarpment fault in the only one within the current stress regime that high risk of mode I or II failure. In this calculation, the intermediate stress is approximated as 0.9σ1.
Further analysis of the possible range of hydrocarbon column heights was made. Based on mercury injection permeability and porosity tests on core sample at STP conditions. Combined with NCB porosity trends for the Norian Mungaroo (Appendix C), it presents a range of possible capillary pressures and HC heights for shale and sandstone. At depths equivalent to typical oil/gas-water contacts, sandstone capillary pressures measure approximately 500 psi, with HC heights up to 126m. Shale on the other hand results in calculated capillary pressure of up to 3700 psi and HC heights of over 1000m. Mixed lithology trend lay somewhere in between and are representative of low Vshale sands due to the statistical bias in the porosity trends (see Appendix C).

**Figure 52** Theoretical capillary pressures for sandstone, shale and sandstone dominant mixed lithologies calculated using mercury injection STP trends and Mungaroo core based porosity trends. Maximum capillary pressures increase with depth and are significantly higher for shale vs. sandstone.
**Figure 53** Resulting permissible HC column heights based on theoretical capillary pressures calculated from Mungaroo porosity trends. This shows that even for moderately porous sandstone, significant HC heights can be sustained at depth.
6. DISCUSSION/ANALYSIS

Structurally, the Rankin and Dockrell/Keast fault blocks show evidence for fault reactivation through to the Neogene (Fig. 12-18). However, whilst multiple episodes of reactivation are evident, this reactivation is highly partitioned, with main horst-graben bounding faults showing differential offset within the Triassic, up to the Jurassic/Cretaceous unconformity. Within the Cretaceous and Cenozoic, reactivation is focused on NE-SW bounding faults of the Rankin escarpment and Goodwyn/Dockrell blocks (Fig. 12-18).

The faults show characteristic features associated with oblique slip which, along with varying dip of strata indicates that oblique slip is associated with fault block rotation during extension. The orientation of fault arrays and classic rhombohedral geometries within the fault blocks also suggests an element of oblique slip associated with seismicity during the formation of the horst-graben architecture (Fig. 14). A rose diagram of the fault orientation also has an array consistent with oblique extension (Fig. 54).

**Figure 54** The fault orientation within the Upper Triassic (Rose diagram) is consistent with a typical array that results from oblique extension. As the range of angles of obliquity shown modelled by (Withjack and Jamison, 1985). The angle of maximum extension shows inversion oblique to extension. The pink line is in the direction of maximum extension, red arrows indicate $S_{max}$ orientation: approx. 110°.
Whilst fault offset maintains net normal displacement, subtle inversion features are evident around the Rankin escarpment which shows evidence of Neogene reactivation. Fault reactivation along the horst-graben bounding faults that separate the fault blocks show signs of late reactivation to be predominately via oblique slip. Stereonets in figure 57 using Angelier's (Angelier, 1979) method, show the likely direction of slip for these reactivated faults is consistent with the right lateral horizontal movement that is evident (Fig. 14, 17, 19, 20). However, this remains comparatively minor and the faults have broadly accommodated very little strain throughout the Cenozoic. This evidence suggests little seismicity along these faults, which are likely to be relatively stable in the present day. Some indication of the validity of this assertion comes from passive seismic data recorded on the NWS. Figure 55 shows all earthquakes recorded at a depth of less than 10km since 1954 (when recording began). The only earthquake measured near the study area was in proximity and likely associated with reactivation of the Rankin escarpment fault.

**Figure 55** Yellow circles are earthquakes recorded since 1954 which were located at depths of 10km or less. Magnitudes 2 or greater (non labelled <2) (data from (Geoscience_Australia, 2014)).

Local borehole breakout data from around the study area show present day $Sh_{\text{max}}$ orientations to be approximately NW-SE. This is relatively consistent with the far field $Sh_{\text{max}}$ for the NCB, reported to be approximately 110° (Hillis et al., 2008; Hillis and Williams, 1993b). The fault array shows a geometry that is suggested to be consistent with far field stress dominance, which is typical for the NCB (Dyksterhuis and Muller, 2008; Hillis et al., 2008; Keep et al., 2002).
Whilst there is lateral variation in velocity within the Triassic, the variation across the faults themselves is subtle, if not typically indistinguishable. A notable exception is within the Rankin Block near the Rankin 1 well, across a small synthetic fault (Fig. 21). Whilst there is little differential across the faults, this is a relative velocity reduction around the fault damage zone. This suggests that there is some change in the petrophysical properties in the lithology immediately adjacent to the fault surface. As that change is likely to be a combination of density and elastic response, it may be indicative of the greater damage zone envelope of the fault. The fact that there is little velocity variation across the faults separating the Rankin High and the Keast Graben is interesting in so far as the Rankin/Keast fault juxtaposes fluvial dominated Mungaroo units with dominantly deltaic Brigadier lithology. This suggests that the two distinct formations must have similar gross petrophysical properties as well as reducing the prospect of the velocities being able to show subtle pressure differences, which the RFT data (Fig. 35) indicates should exist.

However, as figure 25 illuminates, the velocity gradient is highly sensitive to formation boundaries. The shift from one major formation to another can be picked from the velocity gradient shift alone. Particularly prominent is the velocity reversal on the Rankin Trend due to the 'siliciclastic' formation in the Eocene (see Fig 5), which is thin to absent in the offshore Exmouth Plateau, hence no velocity reversal manifests over it. This suggests that whilst the particular stacking velocities used in this study may not have sufficient resolution to detect minor fluid pressure changes, the velocities are sensitive to the contrast between different bulk petrophysical properties of different formations. The $V_p/V_s$ ratio (Fig. 31) is a typical indication of lithology, particularly when correlated with acoustic impedance. Whilst the $V_p/V_s$ ratio approximates 2, it also shows subtle variation, particularly at depths that correspond to overpressure zones and significant lithology shifts such as we see in a formation change.

The 'siliciclastic' formation referred to is part of the Winning Group where claystones at the base of the Wilcox formation grade into limestones of the Walcott formation with a mix of claystones and minor interbedded sandstones (Apthorpe, 1988; Hocking et al., 1987). Whilst this lithology is not likely to be particularly slow, it is in relation to the underlying and overlying lithology, hence the velocity reversal that is evident. This also highlights caution in making simplistic interpretations of lithology based on velocity, because any velocity reversal or increase is going to be relative to the overlying/underlying geology.
Rather than absolute velocities, an understanding of the Poisson ratio extracted from these velocities provides a more robust insight into the type of lithology, be it carbonate, shaly or clean sands. Furthermore, studies have reliably correlated $V_p/V_s$ vs. Acoustic Impedance (AI) correlations to infer general lithology type (Pendrel et al.; Saussus and Jarvis; Vernik et al.). This is also the premise to studies that use impedance inversion to either deterministically match elastic properties of lithology to seismic data, or model seismic data based on lithology type with a stochastic type feedback to acquire a match to a set of calibration wells (Pendrel et al.; Rowbotham et al., 2003; Spikes and Dvorkin, 2003). Lithology determination from a stochastic model-based method is independent of velocity error and far more accurate, although, requires a calibration well in the first place and is computationally demanding. So a simple $V_p/V_s$ vs. AI relation can still be more useful in the frontier basin.

Figure 26 shows the base Norian TWT structure map and associated velocity map of the varying interval velocity for a constant lithology. It shows that within a single formation, there remains significant velocity variation which is highly dependent on depth. The deeper the horizon, such as in the Keast Graben, the faster the velocity. The variation is great enough to exceed any possible distinct observation of a pore pressure differential across a fault, yet again does provide a distinct variation with depth and pressure.

The density can be seen in figure 33 where the variation in lithology creates a significant variation in bulk rock density through the formations. This density is empirically derived from the velocity and broadly correlates with the porosity-based trend of equation 10. The porosity-based trend is derived from core log porosities over the entire NCB. The velocity based densities from the Rankin Trend and Exmouth Plateau reflect the general NCB trend, and confirm a high degree of validity for the density relationships investigated.

It is through these velocity-derived densities that we are able to calculate $S_v$ and $S_{\text{min}}$ to place some preliminary geomechanical constraints on the lithology. This is compared to the LOT measured $S_{\text{min}}$ which, as figure 37 shows, is not only consistent across the entire NCB, but increases linearly. The implications of the linear relation between stress and strain, i.e. the elastic moduli of the material, can be seen in the linear increase in $S_{\text{min}}$ with depth (overburden stress).

Nonetheless, as figure 38 shows, calculating $S_{\text{min}}$ from a porosity-based or velocity-determined Poisson ratio, underestimates the $S_{\text{min}}$ at depth. This is because they rely on bilateral constraint to determine the horizontal stress. Bilateral constraint refers to the
expansion of a material and hence increase in horizontal stress, when it is squeezed. This is the property of elasticity that the Poisson ratio measures, hence the reliance on the empirically determined Poisson ratio to assess the $S_{\text{min}}$. Calculating the stress strain ratio from bilateral constraint relies on a linear relationship, however, as Appendix C highlights, porosity, and therefore density and the associated bulk modulus of a material will depend on a negative exponential relation with increasing pressure (depth). Thus the stress strain ratio appears nonlinear where it is determined from P-wave velocities. Zoback and Healy’s (1984) relation, Hubbert and Willis’s original (1957) relation and Eaton’s (Eaton, 1969) relation result in more accurate values for horizontal stress and generally confirm the coefficient of friction’s nominal value of 0.6, for a vast array of circumstances, hence its validity in use for a frontier region for example. This is because these empirical relations fix the effective stress ratio. This fixed ESR probably begins to break down at depth as the crust transitions from the brittle to plastic elastic moduli regime or where nonlinear viscoelastic solids, such as certain clays and salt, dominate the lithology. However, in sedimentary basin lithology, a constant ESR is shown to remain particularly valid. This is confirmed in figure 40, where the ratio of $S_{\text{min}}$ to $S_v$ is a little over 0.6. The ratio of vertical to horizontal stress is assessed as approximately 0.62 for the Rankin, Dockrell and Keast blocks.

The determination of $S_{\text{min}}$ by bilateral constraint underestimates true values and there is an increased uncertainty in the bilateral-based empirical relation where there is a significant heterogeneity in the lithology or pore fluid (see Appendix E). However, the relation is remarkably consistent. The difference between the LOT-based and bilateral constraint velocity-based $S_{\text{min}}$ shows a power-law relation with depth (Fig. 41). This consistency facilitates the determination of a 'correction' factor to be applied to the velocity-based ratio. $S_{\text{min}}$ can then be calculated using this correction factor, as an alternative method to the ‘assumed’ effective stress ratio of 0.32. However, as figure 30 shows, a distinct difference in the trend between Rankin and the Exmouth Plateau is evident, which suggests that the underestimation will vary according to broad differences in the petrophysical properties area to area.

Furthermore, variation from area to area is likely to be enhanced by the fact that Castagna's (1993) empirical relation used to determine $V_s$ has not had its constants calibrated for the formations being studied. Whilst this correction factor can account for underestimation in certain circumstances, figure 30 shows that care must be taken not to assume a trend over an entire basin; the sub-basins are likely to vary in their shear wave velocity response. If a well
calibration cannot be carried out for a study area, such a method should be avoided, and one of the empirical relations using a fixed effective stress ratio used instead.

The distinct effect of overpressure on the effective stress (Fig. 42) manifests as a sharp effective stress reduction on the Rankin trend at approximately 3000m and 3500 mTVDSS. Whilst the CFF for the Rankin/Keast fault does not suggest any fault instability, it shows a distinct deviation from the trend with depth where overpressures are reported. This is an indication of the effect that overpressure and pore fluid retention can have on the stability of a fault. The capacity to assess this for a range of fault blocks using seismic velocities alone, can provide a useful initial constraint on fault risk and reservoir integrity. As figure 43 shows, for a number of fault blocks, a similar pattern is observed, all being in the stable regime, but with less stability around the 3000m mark where overpressure is reported.

Figure 43b shows the effect of using the incorrect $S_{h_{\text{min}}}$ from equation 15. The underestimation of $S_{h_{\text{min}}}$ result in an incorrect shear stress and an unrealistic conclusion of fault instability. We can apply a correction factor and in so doing acquire a reasonable approximation on the CFF from velocities alone (Fig. 43c). The ‘corrected’ CFF shows similar relative pressures and trends with a deviation around 3000m due to overpressure. As previously noted, however, the problem with the corrected CFF is that the correction factor is highly variable from area to area and cannot be applied on a general basis. Hence, where well calibration for the study area is not available, the constant ESR methods should be applied.

Thus a confidence can be established in the calculated CFF’s used in velocity stacks. Figure 51 shows this for the theoretical planes which are illustrated in the schematic of figure 56. It is important to remember that the CFF is dependent on the relative strike and dip of a fault with respect to the principle stress orientations. Faults will vary in dip and strike and a thorough CFF analysis needs to ‘segment’ a fault to account for this variation. This study only employed a single plane for each fault to establish the validity of the stack-based calculations.
Figure 56 Schematic showing the theoretical planes representing the Rankin Escarpment, Rankin/Keast/Dockrell faults and E-W faults modelled in the CFF plot using the stacking velocities. The CFF plot suggests that the green planes are stable and orange planes have a high mode I/II failure risk in the current Sh_max regime. The escarpment fault, represented by an orange plane, is the only fault to show evidence of reactivation in the Neogene. Maximum pressure differentials are both in the Triassic. b) schematic showing base depths of Rankin, Keast and Dockrell gas columns. Oil-water and gas-water contacts are in blue, depths are mTVDSS. Heights of columns are relative only and not actual heights. Adjacent fault block water contacts at different heights also suggest a degree of sealing capacity to the faults.

Nonetheless, the implications of the stack-based CFF’s are twofold: the capacity to acquire a CFF assessment from seismic velocities alone, and the necessity to have either a correction factor based on a reference well or the assumption of a fixed ESR. It is rare to not have at least one exploration well in a basin, and whilst the comparison between the Rankin Trend and Exmouth Plateau shows that petrophysical properties and seismic anisotropy should not be over-extrapolated, a correction factor from a similar region could be adequate to provide an initial approximate CFF. It is noted that a CFF based on LOT and sonic log data will always provide a superior assessment of the CFF and stress conditions in general, and should not be superseded by an approximation from seismic velocities. However, the contention remains that where well based data is lacking, this framework provides far greater constraints on stress and fault failure assessment than would otherwise be available.
Figure 57 Cross-section across the study area and TWT map of the regional Cretaceous unconformity. The figure shows that with faults orientated NNW-SSE and ENE-WSW at depths between 2500 and 4000 mTVDSS (approximately 1600-3000 ms TWT) there is a higher risk of fault reactivation. Pore pressure plays a large part in making this range unstable. The only faults that show evidence of reactivation in the Cenozoic are the Rankin escarpment and Goodwyn/Dockrell fault: both are in higher risk orientations. Most fault-seal field limitations therefore appear to be due to capillary seal potential which ranges between 500 and 3500 psi depending on the clay content of the fault gouge.
The availability of pore pressure trends is a further constraint that can be made using the seismic velocities. Bowers (Bowers, 1995) formula shows overlap between the RFT pressures and velocity-based pore pressure. This indicates that the use of velocities to infer a pore pressure range or shift may be useful where further constraints are absent. There remains a considerable amount of uncertainty due to the scatter in the velocity data in some locations, be it well location or shotpoint from the stack. This scatter is a product of the lithology varying the velocity, rather than pore pressure, and leads to a standard deviation of up to 1800 psi in the case of Keast 1 (Fig. 44). However, this deviation is lost in the stacking velocities, which are representative of the least square mean value of the interval velocity at any given depth. The checkshot velocities show the standard deviation to vary with depth, a reflection of the level of heterogeneity in different lithological formations.

A pore pressure deviation from the normal trend could be due to overpressure or fluid accumulation or may be a reflection of significant heterogeneity in the lithology. Furthermore, whilst lateral variability is significant, figure 48 shows that poor velocity picks have a significant effect on calculated pore pressure, giving rise to anomalous results. Hence caution is required before taking velocity-based pore pressures as an absolute direct indicator without well constraint. It is noted that good correlation between velocity-based pore pressure and RFT pore pressure was only achieved where the Biot factor was taken into account (Appendix D). This suggests that always assuming the Biot factor to be 1 may be erroneous in many circumstances.

The degree of correlation between RFT and velocity-based pore pressures, LOT-based and velocity-based CFF's, and log-based and velocity-based formation heterogeneity and density variation is high. Using stacking velocities to calculate CCF and pore pressure presents an inherent uncertainty that comes with the method by which they are picked. However, error remains from the empirical relationship utilised to extract density and shear wave velocity. This error could be reduced by calibrating the empirical relationships although this is somewhat difficult in frontier basins. Error could also be reduced by using measured Vs rather than using a calculated Vp:Vs relation, although this is often not available.

These same sources of error place uncertainty in pore pressure prediction, however, resolution is also a key issue. Where vertical sampling of the stacking velocities is, in this case 32ms, this can amount to more than 60m, combined with the half wavelength of the seismic wave; on the order of 30m, single pay pressure differences can be quickly lost. Absolute pore
pressure determination remains important for effective stress calculations and providing useful information for drilling in frontier regions where mud weights and pressure kick tolerance may be poorly constrained. However, capillary seal potential remains dependent on the pressure differential across the seal i.e. relative pressure, rather than absolute pressure. Thus, in the instance that a calibration well was available, theoretical capillary pressures and hydrocarbon column heads can be constrained. Pittman's (Pittman, 1992) equation was used as it enables a constraint to be placed on a possible range in capillary pressures, where fluid type and clay content in fault gouge is unknown. Sand based column heights give an indication of possible sand-sand juxtaposition, arguably the weakest link in the fault seal capacity. Sand capillary pressures based column heights closely match measured values (Fig. 58).

Figure 58A comparison of theoretical HC column heights calculated from mercury-based capillary pressures and NCB Mungaroo (Norian) porosity trends. It suggests that where sand-sand juxtaposition is taken as the ‘weakest’ link in fault seal, significant column heights can still be achieved, assuming geomechanically stable lithology.
One must expect that if the fault is stable, a potential HC column height will sit somewhere between the sand and shale values, depending on the clay content of the fault gouge. Where column heights are less than the sand value, if the fault is stable, charge access may well be an issue. These values are based on mercury capillary threshold pressures, thus whilst they can provide a useful range, once the source rock was defined and fluid type assessed, they could be constrained using relationships that take this into account (Berg, 1975; Busch and Amann-Hildenbrand, 2013; Watts, 1987). Nonetheless they proved a useful first pass assessment, particularly when considered in conjunction with the stress regime and CFF of the fault.

Thus we can see that seismic velocities and amplitudes provide useful constraints on fault seal assessment where good well constraint is lacking. A correlation matrix (Fig. 59) summarises that match between measured values and seismic velocity-based empirically calculated values in this case study. A summary of an effective workflow is presented in figure 60. This shows that depending on the well constraint available, constants can be refined over time to make better predictions of the fault seal capacity.

**Figure 59** Correlation matrix highlights the good correlation between directly measured values and seismic-based empirically calculated values. It supports the applicability of calculating these values where well constraint is lacking.
Figure 60 Recommended work flow for using stacking velocities to calculate CFF, pore pressure and capillary pressure for fault seal constraint.
7. CONCLUSIONS

This study has shown that a number of empirical relationships that are available enable a robust approximation of pore pressures and stress magnitudes to be calculated from seismic velocities. When combined with a basic fault architecture assessment (dip, strike, sense of offset, and evidence of reactivation), an assessment of fault seismicity can be made. This study successfully calculated a coulomb failure function using P-wave seismic velocities as the only source of input. A subsequent porosity evaluation also enabled a theoretical calculation to be made on the capillary pressures which further constrain fault seal risk. A case study of the Rankin and Dockrell/Keast fault blocks shows that there is robust correlation between measured data and empirically derived values. They show that the main faults separating the Rankin and Dockrell and Keast fault blocks are in a stable stress regime and not subject to further reactivation. They have an increased risk of failure around the base of the top-sealing regional Jurassic and Cretaceous unconformity, where overpressure is prevalent and principal stress ratios are large. This highlights the importance of taking all of the following factors into consideration in fault seal risk: pore pressure, stress ratio, and dip and strike of fault. All of these will affect whether a fault is high or low risk for either slip or capillary-based leakage.

*Rankin and Dockrell/Keast faults orientated approximately NNE-SSW in strike, with dips of approximately 50° show no risk of slip, and have a minimum hydrocarbon column head sealing potential of 120m.*

The final uncertainty remains with the clay content of the fault gouge and fluid type, both of which affect capillary seal potential. Whilst these two factors cannot be assessed from seismic data alone, theoretical boundaries can be accommodated through assessment of potential sand-sand and shale-shale potential. In this case, sand-sand capillary pressures were found to be approximately 500 psi in the Late Triassic, corresponding to some capillary pressures measured in the study area. Where source rock presence, maturity and type were all within ideal windows, if the hydrocarbon column head was less than this, charge access should be considered the primary accumulation risk.
8. FURTHER WORK

In using the velocity stacks for CFF and pore pressure range determination, a systematic risk profile could be implemented for an entire region. This is in the spirit of studies such as those conducted by (Castillo et al., 2000; Reynolds et al., 2005). Whilst general strikes and dips may put groups of faults in a high risk or low risk category, this process would need to be refined for prospect-level evaluation whereby trap-relevant faults would need to be segmented. This is because a fault will typically vary in dip and strike and this variation places each respective dip and strike segment under a slightly different stress. In addition pore pressure plays an important role in creating fault instability and, as we have seen, pore pressure also varies both laterally and vertically. Hence, the level of resolution considered in a fault study should be selected based on whether a risk profile is needed for a regional or prospect level.

This should be compared to a mature basin province for a statistical Vs empirical faulted trap comparison. This would allow a statistically robust deterministic Vs empirical comparison to be conducted between faults that have been recorded to have sealed with their risk profile, as calculated from the seismic velocity empirical relations.

$V_p/V_s$ ratio's also lend use for the purpose of lithology determination. Regional velocity cubes can be inverted and $V_p/V_s$ vs. acoustic impedance plots compared with velocity-based Poisson ratio's to allow a relatively robust constraint on lithology in the frontier basin.

Finally, this study presents an example of the potential application of model-based full waveform inversion (FWI) velocity data. The accuracy of FWI velocities can reduce the uncertainty associated with standard velocity picks and present a broader scope for the utilisation of the FWI process in future surveys.
9. **APPENDIX A - TECTONOSTRATIGRAPHIC DIAGRAM**

Overview shows the general stress regime and the main tectonic event association in the NWS (Baillie and Jacobson, 1995; Cathro and Karner, 2006; Keep et al., 2007; Longley et al., 2002).

<table>
<thead>
<tr>
<th>Stress Regime</th>
<th>Epoch (Age)</th>
<th>Tectonic Event</th>
<th>Deposition Event in the Carnarvon Basin</th>
<th>Barrow Sub-basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressional</td>
<td>Pliocene</td>
<td>Generation of Timor Island and Trough</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7 Ma. Miocene (Messinian)</td>
<td>Inversion</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 Ma. Miocene (Tortonian)</td>
<td>Inversion</td>
<td>Delambre Fm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13 Ma. Miocene (Serravallian)</td>
<td>Inversion</td>
<td>Yardie Gp</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18 Ma. Miocene (Burdigalian)</td>
<td>Inversion</td>
<td>Cape Range Gp</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Miocene</td>
<td></td>
<td>Minor siliciclastic deposition</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Oligocene</td>
<td>Australian and Eurasian (Banda Arc) Plates Collide</td>
<td>Carbonate sedimentation</td>
<td></td>
</tr>
<tr>
<td>Extensional</td>
<td>Late Paleogene (Oligocene)</td>
<td>Final Separation of Australia and Antarctica</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Early Paleogene (Paleocene)</td>
<td>Onset of Coral Sea Rifting</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Late Cretaceous</td>
<td>Minor Inversion due to intraplate deformation resulting from AA breakup and India migration. Creation of Barrow Anticline.</td>
<td>Toolonga Calcilutite</td>
<td></td>
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<td></td>
<td>Early Cretaceous</td>
<td>Australia/Antarctica Breakup</td>
<td>Regional Transgression deposits marine (Muderong) Shale.</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Australia/Antarctica Rift Separation</td>
<td>Crust formation of Argo &amp; Gascoyne-Cuvier Abyssal plains</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Australia/Antarctica Rift Onset</td>
<td>Transgressive highstand deltaic complexes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Late Jurassic</td>
<td>West Burma Block III Separation</td>
<td>East and West Gondwana Break up, submarine fans accumulate large volumes of sediment in syn-rift and eustatic sea level rise and fall.</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>West Burma Block III Rift Onset</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>West Burma Block II Separation</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Middle Jurassic</td>
<td>West Burma Block II Rift Onset</td>
<td>Localised extension initiates NCB</td>
<td></td>
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<td></td>
<td>Early Jurassic</td>
<td>West Burma Block I Separation</td>
<td>Interbedded sand and muds deposited in a fluvial deltaic coastal (Mungaroo) complex</td>
<td>Inversion</td>
</tr>
<tr>
<td></td>
<td>Late Triassic</td>
<td>West Burma Block I Rift Onset</td>
<td></td>
<td></td>
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<tr>
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<td></td>
<td>Lhasa Block Separation</td>
<td>Pangea Breakup - Locker Shale deposited in marine settings</td>
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<td></td>
<td>Permo-Triassic Boundary</td>
<td>Regional Transpression Tectonism</td>
<td>Permian sediments comprise marine and marginal marine successions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Compressional</td>
<td>Gondwana and Laurussia collide to form Pangea</td>
<td>Late Carboniferous glacial conditions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Devonian</td>
<td>Uplift and warping, marine conditions.</td>
<td>1 Km of Devonian Sediments with Frasnian reef complex.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ordovician-Silurian</td>
<td>Carnarvon intracratonic basin formation in Gondwana</td>
<td></td>
<td></td>
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</tbody>
</table>
### 10. Appendix B - Stratigraphic Column for the West Dampier Sub-basin

(Bennett, 2005)

![Stratigraphic Column Diagram]

<table>
<thead>
<tr>
<th>Epoch/Stage</th>
<th>Lithostratigraphy</th>
<th>Basis Development</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miocene</td>
<td></td>
<td>Hardgrounds &amp; Calcareites</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Progradational Carbonate Sequences</td>
</tr>
<tr>
<td>Oligocene</td>
<td></td>
<td>Solitary碳酸费布斯, Progradational Sequences</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Carbonate Dominated Calcite Deposition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Deep Marine, fine-grained mixed Clastic - Carbonate Sediments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Regional Mudmor Formation Seal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Angel Turbidite Sandstone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dingo Source Rock</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leganac Delta Sandstones</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thick Basalt Fill - Athol Formation (Seal)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Marginal Marine Early Jurassic Sandstones and Shales</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fiowl Deltaic Mungaroo Formation</td>
</tr>
</tbody>
</table>

Explanation of terms:
- **Mudmor Formation Seal**: Regional mudmor formation that seals the underlying sedimentary sequences.
- **Angel Turbidite Sandstone**: Fine-grained sandstone deposits indicative of turbidite processes.
- **Dingo Source Rock**: Early marine fine-grained deposits indicative of dingo activity.
- **Leganac Delta Sandstones**: Early deltaic deposits forming part of the Leganac delta.
- **Thick Basalt Fill - Athol Formation (Seal)**: Basaltic infill that seals the Athol formation.
- **Marginal Marine Early Jurassic Sandstones and Shales**: Early marine deposits forming part of the Jurassic period.
- **Fiowl Deltaic Mungaroo Formation**: Deltaic deposits formed by fluvial activity.
11. APPENDIX C – POROSITY AND PERMEABILITY IN THE NCB

The porosity and permeability trends for the NCB were acquired from 30 wells within the NCB, biased towards wells along or near the Rankin Trend (Fig. 61). All porosity and permeability data are from core analysis on samples from the Mungaroo formation of the Triassic Period, NCB, NWS. This selection method was chosen so as not to 'skew' trends by mixing formations. The Triassic was most pertinent to this study because fault seal risk uncertainty is targeted in the Triassic. In addition, both mixed and single lithology trends have been acquired, however, due to the core sampling bias towards the 'reservoir', sandstone has the most reliable statistics.

Figure 61 The arithmetic average for 32 Wells in the NCB. 4 Wells were excluded as their inboard and shallow setting mark a statistically significant separation from the rest.

Broad trends in porosity with depth relations are very similar, irrespective of the lithology (Fig. 62). The trends confirm to the typical (Mondol et al., 2007; Weaver, 1989; Wood, 2010) exponential-type relationship between porosity and depth. Shales will tend to have a much faster reduction in porosity with depth as the clay mineralogy dewaters and compacts. This
then slows where further porosity reduction is due to diagenetic reactions. Sandstone compacts much less in the first instance, then slows where further porosity reduction is due to diagenesis and cementation. The Mungaroo Formation is an intra-formational claystone sandstone formation and it is the depositional environment that is by far the greatest determining factor of the ultimate porosity trend and porosity permeability relationship in a formation. Sorting and maturity, along with clay content, have a large impact on the ultimate porosity permeability trend. We see this in figures 63 and 64 for example where the 'slope' of the porosity permeability plot is different depending on well location and its depositional setting, with wells in steep slope setting having coarser and typically cleaner sandstones. Results from this study suggest that good correlation and control should allow depositional setting to be inferred from the porosity permeability trend alone. However, in this instance, the porosity permeability trend used in Pittman’s (Pittman, 1992) relationship was taken from the Rankin Trend only wells, for sandstone lithology, as this lithology type is biased in the RFT data and hence allows for more robust comparison. Capillary pressure determination and subsequent hydrocarbon column height calculation were assessed using sandstone, shale and mixed lithologies for comparison.

Figure 62 Porosity with depth trends show typical exponential curves. Shale porosity reduction occurs quicker than with sandstone, however, broad trends are similar. These relationships are used for the Sh_{min} and capillary pressure relations in the study.
**Figure 63** Porosity vs. Permeability plot showing that lithology is not a primary determining factor in the resulting porosity-permeability relationship.
Figure 64: Porosity/log permeability plot highlighting how well location and associated depositional environment area greater determining factor in the porosity-permeability trend. Inset: Gamma ray and resistivity logs indicating (shale content) and GR trend matching the depositional environment.
12. APPENDIX D - PORE PRESSURE

This study uses Bowers (1995) relation for pore pressure calculations using seismic velocities. Bowers (1995) relation employs constants derived from a so-called ‘virgin’ curve. This describes the increase in velocity effective stress relation with depth where fluids do not affect the trend by reducing the effective stress. The virgin curve constants in this were derived from a corrected sonic log from the Rankin 1 Well (Fig. 65). This sonic log curve was ‘corrected’ to account for hydrocarbon accumulations, hence giving the background or ‘virgin’ relation.

![Virgin Pore Pressure trend based on a hydrocarbon corrected Vp Sonic Log from Rankin 1](image)

**Figure 65** Pore pressure Vs, effective stress from sonic log values, corrected for effects of background fluid pressure. The power regression fit provides constants applied to Bowers pore pressure empirical relationship.

In Bowers’ (1995) relation the mudline velocity is subtracted from the interval velocity and is typically approximated as 1500 m/s; seawater velocity. In this study, the value of 1250 m/s was used, as this relates to the velocity extrapolated to zero pore pressure, because the sea column at the mudline exerts 100's of psi in pressure, depending on depth. The typical water depth in this study was 120 m, relating to 190 psi, so such an extrapolation is considered to better account for the effect of seawater column height on hydrostatic pressure.
Poroelasticity refers to the time-dependant deformation of a porous elastic solid. Poroelasticity results in pore pressure within a porous solid responding to an external pressure applied and affecting the response to that external pressure. Because of this response, the pore pressure can affect the measured bulk modulus of the material. The Biot coefficient attempts to account to the poroelastic effect on the bulk modulus (seismic response) of a material. This study infers this poroelastic response effect on the seismic-based pore pressure calculations by multiplying the seismic-based pore pressure by a poroelastic (Biot) correction factor. This correction factor is estimated by taking the ratio of RFT pore pressure to seismic-based pore pressure. The average correction factor is approximately 0.8. Whilst there is up to a 50% variation in this factor, the results of applying 0.8 across all values provide a very good correlation for wells and fault blocks, whereas assuming a correction factor of 1 leads to erroneous results.

**Figure 66** A value for poroelasticity is taken from the ratio of empirically based pore pressure and RFT based pore pressure. An average is taken as 0.8, seen to be the approximate median in this scatter plot and which results in consistently good agreement between calculated and measured pore pressure.
Figure 67 This pore pressure plot using a Biot factor of 1 does not fit the RFT data, rather it is anomalously high. This is consistent with all the blocks, and the effect of applying the correction factor of 0.8 can be seen in the results (section 5.2).
Figure 68 compares Vs measured from the sonic log of the Rankin 1 well to Vs calculated using Castagna's (1993) Vp relation. The relation is based on an empirical 'fit' from laboratory tests on feldspathic sandstone. The comparison plot shows good correlation with the linear regression fit (pseudo mudrock line) shows a Vp of approximately 1500 m/s where Vs is zero. The correlation plot (Fig. 69) is another qualifier of the appropriateness of using Castagna's (1993) relation. Some scatter persists in the correlation plot, as is expected with heterogeneity in the lithology. More scatter (a poorer fit in the empirical relation) occurs at depths where the Mungaroo formation is penetrated, as well as at depths with significant gas flow is recorded. Considering the lack of calibration of this empirical relation, the correlation was remarkably good, considering the context of having a relation that could be applied in a frontier basin where no calibration well is available.
Figure 69 The correlation plot of calculated vs. measured shear wave velocity. Increased scatter indicates poorer correlation and therefore poorer validity of the empirical trend used. There is a poorer fit at depths correlating with greater lithological heterogeneity and overpressured zones.
14. Appendix F - Shear and Normal Stress

$\sigma_n$ and $\sigma_s$ are the normal and shear stress components of the principal stress tensors $\sigma_1$, $\sigma_2$ and $\sigma_3$. As described in the method, the principal stresses can be determined from a combination of overburden stress, LOT measurements and either mud weight recordings, where well data is available, or constraining the intermediate stress to one that fits the Andersonian tectonic regime, as defined by evidence in the fault architecture. The three dimensional vector components of these principal stress vectors acting on a fault plane, i.e. the normal and shear stress, is calculated via a third order tensor, basis vector transformation, whereby the vectors are rotated to the coordinate system of the fault plane from that of the orthogonal Cartesian system of the principal stress vectors. The equations used in this study for the calculation of $\sigma_n$ and $\sigma_s$, as described by Zoback (2010) and Jaeger et al. (2007) are as follows:

$$\sigma_5 = a_{11} \sigma_1 + a_{12} \sigma_2 + a_{13} \sigma_3 \quad \ldots \text{Eqn. 17}$$

$$\sigma_n = a_{11}^2 \sigma_1 + a_{12}^2 \sigma_2 + a_{13}^2 \sigma_3 \quad \ldots \text{Eqn. 18}$$

where $a_{ij}$ are the matrix components as follows,

$$A = \begin{bmatrix}
\cos \gamma \cos \lambda & \cos \gamma \sin \lambda & -\sin \gamma \\
-\sin \lambda & \cos \lambda & 0 \\
\sin \gamma \cos \lambda & \sin \gamma \sin \lambda & \cos \gamma
\end{bmatrix} \quad \ldots \text{Eqn, 19}$$

where $\gamma$ is the angle between the fault normal and minimum principal stress vector, and $\lambda$ is the angle between the strike of the fault and the plane perpendicular to the minimum principal stress vector.
**15. APPENDIX G – THERMAL GRADIENT FOR NCB**

**Figure 70** A thermal gradient of approximately $29.3 \pm 3.0 \, ^\circ C/km$ is measured from 28 wells in the NCB. This thermal gradient is measured from a least squares linear regression fit excluding values measured within the Gorgon field as it is consistently assessed as being anomalously ‘hot’ compared with the rest of the basin. Larsen Deep 1 off the Exmouth Plateau is another that appears relatively hot in comparison.
16. REFERENCES


Geoscience_Australia, 2014. Earthquakes@GA, Australia.


