Mesozoic Rift Onset and its Impact on the Sequence Stratigraphic Architecture of the Northern Carnarvon Basin

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Abstract

Ages varying from Late Triassic to Early Jurassic have been proposed by different authors for the onset of rifting in the Northern Carnarvon Basin. Seismic sections from the Exmouth Sub-basin and outer Exmouth Plateau demonstrate significant growth strata associated with displacement on normal faults starting at least the base of the R. rhaetica zone (Rhaetian). This tectonic event coincides with a marked change in sequence architecture and a large landward shift (~300km) of the paleo-shoreline to the vicinity of the Rankin and Alpha Arch trends. Rapid creation of accommodation space in the inboard narrow rift basins (Exmouth, Barrow, Dampier Sub-basins) is the most likely cause of this major transgression. The preferential development of associated carbonate build ups during the Rhaetian on the footwall side of active tilted fault blocks provides additional evidence for the onset of significant extensional faulting occurring during this time. However, an earlier more subtle initiation phase of rifting is interpreted during the Norian, from around the middle part of the H. balmei biozone time, above which a change in stratigraphic architecture from aggrading to retrograding occurs. The observed structural and stratigraphic transitions can be related to typical phases of evolution described in many rift basins around the world. The work highlights the importance of integrating regional structural geology, sequence stratigraphy and depositional systems observations in order to provide robust constraints for basin evolutions.

Introduction

Sequence stratigraphy studies changes in depositional trends (i.e. progradation, retrogradation, aggradation, erosion) and the resulting stratal stacking patterns through time. These changes are controlled by variation in the balance between accommodation creation or destruction and sedimentation rate (Weimer and Posamentier, 1993; Emery and Myers, 1996; Posamentier and Allen 1999, Catuneanu, 2002, 2006; Catuneanu et al., 2009; Martins-Neto and Catuneanu, 2010). Sequence stratigraphy is a powerful exploration tool as it characterises the spatial and temporal distribution of depositional systems, allowing more reliable prediction of reservoir, source and seal facies distribution and properties. Classic sequence stratigraphy was developed in the context of passive margin settings, which are tectonically stable areas where accommodation is primarily controlled by global eustatic sea-level variations on a background of longer term thermal subsidence (e.g. Vail et al., 1977). More recently sequence stratigraphic studies have emphasised the role of tectonism in particular, as well as climate, as major external forcing mechanisms (e.g. Hunt and Tucker, 1992; Posamentier and James, 1993; Martins-Neto and Catuneanu, 2010). However, despite the fundamental differences in sequence development in tectonically stable versus active basins, many studies are performed applying the passive margin model. Ignoring the effects of tectonism can lead to major errors in the sequence stratigraphic model, and hence, poor characterisation of petroleum systems, plays and prospects.

Structural geology and sequence stratigraphy have an intimate complimentary relationship where observations from each discipline can be combined to improve the understanding of the other in order to reconstruct the geological evolution of a region. Rift basin around the world display typical structural evolution and associated stratigraphic responses. These relationships can be used to help refine structural histories and, once a clear link is established, can be used to constrain the timing and extent of structural events where the data is more ambiguous. Similarly, understanding the structural architecture and evolution at the time of deposition can help the construction of palaeographic maps and depositional models for play evaluation.

The North West Shelf margin has undergone multiple phases of extension and continental break-up punctuated by several important phases of compression and inversion linked to the disintegration and dispersal of Gondwanaland. These tectonic events and associated deformation have shaped the margin and played a major role in controlling its stratigraphic architecture, petroleum systems and plays (Fig. 3).

The Northern Carnarvon Basin encompasses the Paleozoic to Cenozoic depocentres of the southern end of the North West Shelf (Fig. 1; Stagg and Colwell, 1994). It is a broad passive margin basin over 500 km wide in some places bound by the Precambrian Pilbara Craton to the east and the Curvier, Gascoyne and Argo Abyssal Plain oceanic crust to the south, west and north. The main internal tectonic elements comprise of a series of inboard "failed" rift basins (Exmouth, Barrow, Dampier, Beagle Sub-basins) and a broad relatively undeformed platform (Exmouth Plateau) that contains some additional structural sub-elements (e.g. Investigator Sub-basin, Dixon Sub-basin, Wombat Plateau, Alpha Arch-Rankin Trend, Victoria Syncline; Figs. 1 & 2).

The dominant NE-SW trending rift architecture was initially established during Late Paleozoic (Late Carboniferous to Early Permian) extensional phase (e.g. Etheridge and O'Brien, 1994). N-S and E-W trending structural elements are also observed due to reactivation structural fabrics inherited from the basement. Extension during this time resulted in an extensive system of rift basins as part of the Westralian Superbasin system that underpins the entire NW Shelf margin (Yeates et al., 1987). Breakup of the SIBUMASU continental block, which is now docked in SE Asia (e.g. Veevers, 1988), is thought to have occurred in the Early Permian (e.g. Audley-Charles, 1988). Extensive thermal sag basin development ensued throughout much of the Triassic, during which pulses of regional compression occurred (Fitzroy Movements, e.g. Forman and Wales, 1981; Smith et al., 1999; Figs. 2 & 3).

A major Mesozoic phase of rifting followed which ultimately resulted in the breakup of the Argoland (Late Jurassic) and Greater India (Early Cretaceous) continental blocks and the development of the oceanic abyssal plains. The timing of these breakup events is now relatively tightly constrained by oceanic magnetic anomaly analysis, ODP wells and correlation with major regional stratigraphic events (e.g. JO, KV; Fig. 3). However, no firm consensus for the onset of Mesozoic rifting or demonstrated link to the sequence stratigraphic architecture has been established in the Northern Carnarvon Basin. For example Bradshaw (1994) and Etheridge and O'Brien (1994) consider the onset to have occurred in the latest Triassic (Rhaetian). In contrast, times in the Early Jurassic are suggested by several other authors including Tindale et al. (1998, Pliensbachian), Longley et al. (2002, Sinemurian) and recently Marshall and Lang (2013, Pliensbachian). The various interpretations are influenced by the focus area of interest being worked on by the different authors and the tectonostratigraphic model used. Furthermore, these efforts are often hindered by removal of sedimentary section on the uplifted basin flanks and crests of fault blocks where the majority of wells are located (e.g. in the Dampier Sub-basin).

The aim of this paper is to combine structural geology with sequence stratigraphic and depositional systems observations to better constrain the timing of Mesozoic rift onset in the Northern Carnarvon Basin. The Falcone-1A well in the Exmouth Sub-basin is one of the few basinal wells in the region that penetrates the Jurassic section into the Triassic Mungaroo Formation. This area is covered by good quality open-file 3D seismic, providing the opportunity to link detailed structural and stratigraphic observations from the seismic and well data. Further evidence for the timing of Mesozoic rift onset has come to light due to more recent exploration of the outer reaches of the basin targeting Rhaetian carbonate build ups (Grain et al., 2013) and further analysis of the regional depositional architecture (Adamson et al., 2013; Marshall et al., 2013).

Rift Basin Structural and Stratigraphic Evolution

Rift-basin stratigraphy commonly records an early stage of slow subsidence followed by an abrupt increase in subsidence rate (Gupta et al., 1998). Prosser (1993) termed these stages in rift-basin development the "rift initiation" phase when the rate of fault displacement is relatively low and the "rift climax" phase when the rate of fault displacement increases markedly (Fig. 4A). The very early stages of rift development are sometimes represented by broad downwarps or sags (e.g. Gregory Rift, East Africa, Karroo Rifts, Okavango Delta; Lambiase and Bosworth, 1995). Physical modelling studies show that during the rift initiation phase extension is largely accommodated by ductile thinning and a distributed array of minor faults, which results in subtle downwarping at the surface (Fig. 4B; Gartrell, 1997). This stage is characterised by low displacement, non-rotational normal faulting (sub-seismic resolution in some cases) and syn-rift sediment packages that thicken towards the centre of the basin (Fig. 4 B & C). Rift shoulder and accommodation topography is absent or poorly developed, and therefore, their influence on sedimentation is relatively minor. In the absence of these structural barriers, sediment transport directions tend to sub-orthoganal to the rift axis. The relative rate of topographic rejuvenation is also relatively low compared to regional sedimentation and erosion rates (Lambiase and Bosworth, 1995). An increase in accommodation space occurs, but the rate generated during the rift initiation stage is relatively low and sedimentation tends to keep pace with subsidence. Consequently, fluvial, shallow lacustrine or shallow marine deposition are usually associated with this stage, depending on the palaeogeography at the time of deformation.

As extensional strain increases, rheological contrasts in the mechanical layering of the lithosphere result in the development of necking instabilities (Fig.4 B & C; e.g. Gartrell, 1997; Gartrell, 2000). The stronger more plastic layers within the crust and upper mantle deform by necking, while the weaker ductile layers flow to fill spaces. As the necks develop, faults in the brittle upper crust begin to link up to form longer faults capable of accommodating greater displacements, resulting in the development of discrete fault controlled rift basins. Deformation is progressively localised onto the larger faults in the system and displacement on the smaller faults decreases or eventually ceases (Fig. 4 B & C). This process results in the development of half graben and graben where the syn-rift sediments thicken towards the basin bounding fault systems. Rift bounding faults become increasingly rotational, creating wedge shaped syn-rift packages and unloading of the footwall results in flexural-isostatic rebound and uplift of the rift flanks where significant fault displacement has occurred.

Once fault bound rift basins are established, episodic pulses of extension rapidly create accommodation space for sediment accumulation, leading to rapid transgression, increasing water depths and deposition of deep lacustrine or deeper marine systems. In addition, rift shoulder uplift initially alters drainage systems and restricts fluvial access to the basin resulting in sediment starvation. These phases of rapid tectonic subsidence are typically followed by longer periods of tectonic quiescence, when sediment supply gradually consumes and fills the available accommodation. The erosion of the uplifted rift shoulders and increased differential topographic gradient results in sediment rejuvenation and increased supply to the basin, usually entering along the axis or via relay zones. The change in the balance between accommodation and sedimentation results a change to fluvial-deltaic and eventually fluvial deposition if the basin is completely filled (Lambiase and Bosworth, 1995).

This cyclicity results in depositional sequences that display overall progradational trends and coarsening-upward vertical stacking patterns (Fig. 5). Sequences are often marked by sharp flooding surfaces at the base related to the transgression of lacustrine or marine systems in response to tectonic subsidence. In the early phases of rifting this transgression will be less dramatic than in the later phases when rapid subsidence may cause 'instantaneous' generation of accommodation. As such, a typical rift depositional sequence starts with a flooding surface overlain by a relatively thin transgressive systems tract and a much better developed highstand systems tract (Fig. 5). A renewed subsidence pulse leads to the drowning of the previous deposits and the start of a new depositional sequence. Lowstand systems tracts tend to be poorly developed due to strong background subsidence and reworking by the next transgression (Catuneanu, 2006). Fining-upwards trends may be observed at the end of a cycle due to a decrease in the efficiency of sediment supply to the basin due to denudation of the source area and a decrease in the differential relief between the source areas and the basin (Fig. 5; Martins-Neto and Catuneanu, 2010).

Mesozoic Rift Development in the Northern Carnarvon Basin

Here structural and stratigraphic observations are linked to investigate the timing of Mesozoic rift onset and its effect on the sequence architecture in the Northern Carnarvon Basin. The focus is on two areas, the Exmouth Sub-basin and Outer Exmouth Plateau, which provide relatively clear constraints on this question compared to other parts of the basin.

Figure 6 shows an arbitrary seismic section from the open file Indian 3D Survey (acquired in 2000 by WesternGeco on behalf of Woodside) that intersects the Falcone-1A well (drilled by Woodside in 2005) towards the southern end of the Exmouth Sub-basin. The interpreted seismic events were tied to tops constrained by biostratigraphic data from Falcone-1A and seismic observations that can be related to regional geological observations.

A set of strong reflectors towards the base of the section, below which poorly imaged growth strata are observed, are interpreted to be (Early?) Permian carbonates capping the Permo-Carboniferous rift phase section (Fig. 6). Indications of inversion and reverse faulting are probably associated with the Late Permian (Bedout Movement) and Triassic (Fitzroy Movements) compressional events, with possible further reactivation during subsequent compressional events (e.g. JO & KV breakup events). These deep reflectors are overlain by a relatively bland seismic package interpreted to represent thick ?Late Permian and Early Triassic shales. Normal faults associated with the overlying Mesozoic rift sole out into the shale-prone layer indicating that this layer is ductile and allowed mechanical decoupling and/or detachment to occur in some areas. In other parts of the basin direct linkage between the Palaeozoic and Mesozoic rift structures occurs.

Seismic reflectivity progressively increases upwards in the Triassic section (TR10 and TR20) towards the H. balmei event (Fig. 6). This interval (i.e. below H. balmei) is characterised by fluvial-deltaic and alluvial (coastal plain/nonmarine) deposition with intermittent marine transgressions in the inboard and medial parts of the basin. Shallow marine deposition becomes prevalent in the outboard parts of the Exmouth Plateau where the shoreline trajectory shows an overall aggradational stacking pattern (Figs. 7). Relatively uniform thickness across the basin is observed for this interval.

Subtle thickening towards the centre of the Exmouth Sub-basin occurs between the H. balmei and TRR events (upper TR20, Fig. 6). Minor thickening across some faults (fault A in figure 6) and subtle onlap are also observed. A marked change in log motif and biostratigraphic facies associations indicate a change to coastal plain to shallow marine depositional environments (Fig. 8; Hooker, 2005). Regional depositional environment mapping (e.g. Adamson et al., 2013; Grain et al, 2013) indicate that a major regional transgression and marine incursion during H. balmei flooding event resulted in the shoreline shifting landwards to the vicinity of the Alpha Arch-Rankin Trend and widespread deposition of marine shales. Subsequently, a change to backstepping delta front/shoreline stacking pattern with large, high frequency, shifts in the position of the paleo-shoreline between the inboard and outboard areas and increased marine influence is observed through to the end of the Norian (Fig. 7).

Distinct sediment growth and development of wedge-shaped synrift package occurs between TRR and TR (TR30/Brigadier Formation), including subtle onlap at the base of this unit, is observed in the seismic section shown in Figure 6. This indicates the onset of fault block rotation in the Exmouth Sub-basin. The base of the unit is marked by another rapid major transgression that again forced the shoreline landwards to the vicinity of the Alpha Arch-Rankin Trend (Fig. 9). In contrast to the previous major flooding events in the upper part of TR20, the shoreline stayed within the inboard domain throughout the remainder of the Triassic and Jurassic, indicating a major break in the stratigraphic development of the basin (Fig. 7). A series of progressively backstepping, but internally coarsening upwards transgressive-regressive cycles, dominated by offshore, offshore transition, pro-delta and delta front to lower delta plain siliciclastics occur in the inboard domain (Figs 6 & 7). An overall upwards increase in marine influence is observed based on evidence from both biostratigraphy and sedimentology (Figs. 6 & 7; Adamson et al., 2013).

Further outboard the TR30 section changes from mixed deltaic sediments to fine grained marine carbonates and associated reefal build-ups (Figs. 7 & 9; Adamson et al., 2013; Grain et al., 2013). Rhaetian pinnacle and platform carbonates, drilled at Tiberius-1 in the outer Exmouth Plateau (Grain et al, 2013) and in ODP sites 761 and 764 on the Wombat Plateau (von Rad et al., 1992), developed preferentially on faulted highs (Fig. 9). The seismic section shown in figure 10 from Grain et al, clearly shows a Rhaetian aged reefal build-up growing on the high side of a rotated fault block coincident with sediment growth in the adjacent fault block.

Only minor fault related growth occurs during J10 (i.e. between TR and JP1 events) in the seismic section shown in figure 6. A period of more rapid growth and syn-rift wedge development is observed after JP1 (Fig. 6). This structural event is also associated with a major regional transgression followed by an overall coarsening upwards trend associated with the progradation of a major Jurassic delta system during the J20 interval (Fig. 3). A further pulse of extension follows a period of erosion at JP2, with a highly condensed J20 section was deposited above this unconformity in the vicinity of the Falcone-1A well (Fig. 6). Minor fault related growth and an overall fining upwards depositional trend is developed after LDM15.

A major period of uplift and erosion is observed at the JO event, followed by renewed phase of extension (after JK, Fig. 6). In contrast to the previous phase of Mesozoic rifting, sediment thickening developed towards the centre of the basin, as opposed to the margins occurred. Subsequently, the axis of the Exmouth Sub-basin has undergone significant inversion, uplift and igneous intrusion/extrusion associated with the Valanginian breakup event (KV, Fig. 6). Similar inversion is also observed in the Barrow and Dampier Sub-basins. Post-rift thermal sag and passive margin development followed with intermittent pulses of regional compression (e.g. Aptian, Campanian) associated with plate-scale events.

Discussion

Based on the observations above and comparison to tectonostratigraphic evolution of other rift systems it is possible to construct a geological model for the onset of Mesozoic rifting as shown in figure 11.

The Triassic section below the H. Balmei event is interpreted to represent pre-rift section wrt Mesozoic rift phase (post-rift wrt Paleozoic rift phase) due to the observed relative uniform thickness (gradual thinning towards the basin margins) and lack growth/thickening across faults (Fig. 11A). Low depositional gradient and decreased rates of subsidence during TR20 results in sensitivity to higher order variations in relative sea-level and large shifts in the position of the shoreline. Consequently, multiple sequence cycles bound by sequence boundaries were developed (Figs 3 & 7), probably driven by a combination of eustacy, climate and tectonism (e.g. TRC1 related to compressional deformation during the Fitzroy Movement, Longley et al., 2002). Deposition during this interval is typical of low accommodation “shelf type” settings dominated by fluvial and alluvial sedimentation during lowstands and estuarine deposition during transgressive system tracts. Highstand systems tracts are poorly developed or preserved, due to the lack of accommodation.

The overall backstepping depositional stacking pattern developed between the H. Balmei and TRR events (i.e. upper TR20) is consistent with a 2nd order global eustatic sea level rise (Fig. 3). However, thickening towards the centre of the Exmouth Sub-basin and minor fault growth at this time may represent sag during the earliest initiation phase in the inboard rift basins, as observed in other rift basins and predicted by the models shown in figure 4. Hence, the TR26.5_MFS major regional flooding event and associated shift in position of the shoreline to the vicinity of the Rankin-Alpha Arch trend suggests some additional structural control on the sequence architecture. Relatively slow rates of subsidence and increase in accommodation space in the inboard area during this initiation phase, resulted in a gradational change in depositional architecture. The shoreline tended to return to the outboard area after successive transgressive events, such that fluvial and alluvial deposition dominated in the inboard region (Fig 11B).

The development of discernible syn-rift wedge packages during the Rhaetian (at TRR) in the Exmouth Sub-basin is interpreted to represent the start of the “rift climax” phase in this part of the basin with the formation of discreet graben (Fig. 11C). Increased rates of subsidence and accommodation generated once the inboard rift basins were established was enough to drive a major, long-lived transgression. Subsequently, the shoreline/delta front remained in vicinity of Alpha-Arch-Rankin Trend as the delta system was captured due to the increased accommodation and water depths in the inboard rift. As is typical of rift sequences, cycles during this interval are characterised by rapid basal transgressions and longer lived coarsening upwards highstand deposits, while sequence boundaries and associated lowstand deposits are poorly developed due to the relatively strong tectonically driven subsidence. However, accommodation remained relatively modest and sediment supply was generally sufficient to maintain deltaic or shallow marine shelf conditions across the inboard region (Marshall et al., 2013), suggesting that the rift basins were not yet fully developed. Rift segmentation may have contributed to the development of a number of separate delta lobes in and around the inboard rifts (e.g. Fig. 9). Further outboard the sudden cut off in clastic sediment supply due to “capture” of the delta(s) in inboard rifts resulted in the development of a drowned shelf and promoted carbonate deposition and buildups on fault blocks on the Exmouth Plateau (Fig. 11C). An overall rise in eustatic sea level continues from the end of the Norian into the lower part of the Rhaetian (Fig. 3), however, the rapid change in depositional architecture and stacking patterns is consistent with a significant tectonic overprint.

It is more difficult to constrain timing of rift onset further north in the Barrow, Dampier and Beagle Sub-basins, due to greater amounts of uplift and removal of the Late Triassic and Early Jurassic section on the rift flanks and the lack of basinal wells penetrating into the Triassic section. However, the basin wide (and margin wide) change in depositional response and landward shift of the shoreline/delta front to the vicinity of the inboard rifts strongly suggests that accommodation due to rift development also occurred at this time in the Barrow, Dampier and Beagle Sub-basins (Fig. 9). Although, it is possible that the stage of deformation may have varied from basin to basin (e.g. timing of rotational fault development).

The seismic data from the Exmouth Sub-basin suggests that that lower rates of syn-rift growth occurred during the J10 interval, suggesting a period of relative tectonic quiescence (Fig. 6). This stage is characterised regionally by deposition of low accommodation progradational deltas (North Rankin Beds; Marshall et al., 2013), with overall strong coarsening upwards log motifs (Fig. 3). Unlike the other syn-rift cycles, this interval is bound at the base by a sequence boundary (Fig. 3).

A major pulse of extension in the Sinemurian resulted in another tectonically driven regional flooding event at JP1 (Fig. 3). This stage is interpreted to represent a progression to fully established inboard narrow rift systems with high rates of subsidence that were only partially matched by sediment supply. The large scale stacking patterns for J20 are largely bound by transgressive surfaces and maximum flooding surfaces and displays an overall coarsening upwards depositional trend through J20 (Fig. 3). Further north, where the effects of the inboard rifts die out, this interval develops into a major progradational delta system (e.g. Fig. 12 in Longley et al., 2002) indicating rejuvenation of the sediments source areas to the north (i.e. onshore Canning Basin). Previous authors have placed the onset of rifting at this time due to clear development of syn-rift wedge packages (e.g. Marshall et al., 2013). Here we interpret this stage as a renewed pulse of extension and the peak stage of Mesozoic inboard rift development in the Northern Carnarvon Basin. It is important to note that in a broader context the timing of this peak phase varies along the North West Shelf margin. For example the equivalent phase occurred during J30 in the Browse Basin (e.g. Fig. 13 in Longley et al., 2002) and J40 in the Bonaparte Basin (e.g. Fig. 14 in Longley et al., 2002)

Late phase rift development (J30, J40, J50) in the Northern Carnarvon Basin tend to show fining upwards depositional trends that may represent decrease in sediment supply due to denudation of the sediment source areas (Fig. 3). After the erosional Oxfordian breakup event (JO), a combination of thermal subsidence and extensional faulting resulted in the observed sag and basinward sediment thickening in the inboard rift basins.

Subsequent coarsening upwards depositional trends during the K10 interval indicates a rejuvenation of sediment supply, probably due to reactivation of the inboard rifts associated with extension between Greater India and Australia (Fig. 3). This change is particularly marked in the south (Exmouth and Investigator Sub-basins) where major uplift and erosion resulted in high sediment supply and rapid progradation of the Barrow Delta (e.g. Fig. 16 in Longley et al, 2002. Finally the breakup between Australia and Greater India resulted in basin inversion, erosion and development of the KV breakup unconformity (Figs. 3 & 6). Subsequently, post-rift thermal sag was the dominant subsidence and accommodation mechanism.

Breakup unconformities such as the JO and KV events develop during the transition from rifting to drifting (Falvey, 1974). A number of mechanisms can produce the uplift and erosion commonly associated with this type of unconformity including: (1) lateral heat flow from rift centers (e.g., Steckler, 1981), (2) dynamic support by small-scale mantle convection (e.g., Keen,1985; Steckler, 1985; Buck, 1986), (3) rebound associated with stress relaxation during the rift–drift transition (e.g., Braun and Beaumont, 1989), (4) igneous underplating (Brodie and White,1994), and/or (5) crustal shortening and inversion after rifting due to ridge push (Withjack et al., 1998, 2002). Hence, breakup unconformities should be represented as sequence boundaries, as is the case for JO and KV (Fig. 3), due to the associated loss of accommodation and increase in sediment supply from erosional reworking. Subsequent transgression and backstepping depositional system occur once thermal subsidence outpaces the uplift associated with breakup.

Previously, however, Longley et al 2002 related the TRR and JP1 events to continental breakup of the Lhasa and “West Burma I” blocks respectively. As transgressive surface these events are inconsistent with both the expected tectonostratigraphic response to breakup and syn-rift growth patterns observed in seismic data. This raises the question of timing of breakup with the Lhasa Block. Palaeomagnetic data suggests that Lhasa broke away from Gondwanaland sometime in the Late Triassic or Early Jurassic, suggesting that the TR or JP2 sequence boundaries may be better candidates to relate to this phase of breakup.

Conclusion

Data from the Exmouth Sub-basin and outer Exmouth Plateau provide important constraints on the timing of Mesozoic rift onset in the Northern Carnarvon Basin. Structural and stratigraphic observations suggest a progressive rift evolution common to many rift basins around the world.

The early initiation phase of rifting may have started towards the end of the Norian, around the middle part of the H. balmei biozone time. This phase is characterised by subtle downwarping and sediment growth across small faults in the inboard rift zones (i.e. Exmouth, Barrow, Dampier, Beagle Sub-basins) and coincides with a change from aggrading to retrograding stacking patterns in the upper part of the TR20 play interval. Fluvial and alluvial deposition dominate in the inboard rift area as in the earlier TR20 times, however increasing marine influence occurs. The change in stacking pattern is interpreted to be driven by a relatively minor increase in accommodation in the inboard proto-rift basins in combination with an overall eustatic sea-level rise.

The start of the "rift climax" phase is interpreted to occur at the beginning of the Rhaetian (TRR) when discernible syn-rift wedge packages are observed. This change in structural architecture resulted in a further increase in the rate of accommodation space development in the inboard rifts that was sufficient to cause the major, rapid and long lived transgression observed at this time. A significant change in sequence architecture occurs during this interval with depositional cycles characterised by rapid basal transgressions and longer lived coarsening upwards highstand deposits, typical of syn-rift sequences. The sudden cut off in clastic sediment supply to the outboard region, due to "capture" of the delta(s) in inboard rifts, resulted in the development of a drowned shelf and promoted carbonate deposition and buildups on fault blocks on the Exmouth Plateau. Global sea-level charts suggest an overall sea-level rise continued from the Norian into the Rhaetian, however the rapid changes observed are more consistent with additional structural control.

Progression to fully established rift development and the peak of the "rift climax" phase in the inboard basins occurred in the Early Jurassic to early Middle Jurassic J20 play interval, the base of which corresponds to the JP1 major regional transgressive event. High rates of subsidence that were only partially matched by sediment supply during this phase, resulting in deep water deposition in the axial parts of the inboard rifts.

The timing of Mesozoic rift onset in the Barrow, Dampier and Beagle Sub-basins is more difficult to constrain, however, the same depositional responses (e.g. shoreline shifts and changes in stacking patterns) occur across the basin. This indicates that the timing of rift onset is common to all the inboard rifts, although the phase of rift evolution may vary.

All of the tectonostratigraphic events discussed from the Northern Carnarvon Basin (and others not discussed) represent major play boundaries across which the nature and distribution reservoirs, seal and source rocks may change dramatically. For example marine shales deposited during rift-related transgressions form important sub-regional seals, sequence boundaries are often associated with better reservoir development, source rocks may be developed during periods were subsidence is greater than sediment supply during peak or waning phases of rift development. Hence, understanding the structural control on these stratigraphic events is not simply an academic exercise as it aids in the prediction of the distribution of these play elements.

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Figure Captions

Figure 1. Tectonic elements map of the Northern Carnarvon Basin.

Figure 2. Schematic crustal cross section of the Northern Carnarvon Basin. See figure 1 for location.

Figure 3. Chronostratigraphic chart for the Northern Carnarvon Basin (Modified from Marshall et al., 2013).

Figure 4. Subsidence behaviour and structural evolution of narrow rift basins based on observations from nature and analogue modelling. A) Backstripped tectonic subsidence curve from the Suez rift (from Gupta el al., 1998). B) Schematic cross sections showing rift basin evolution. (after Gartrell, 1997). C) Surface view of rift basin development from an analogue modelling experiment from Gartrell, 1997.

Figure 5. A) Schematic stratigraphic column of the rift succession of the Proterozoic Espinhaço basin, southeastern Brazil, showing dominantly coarsening-upward depositional sequences. B) Conceptual stratigraphic column showing the coarsening-upward vertical stacking pattern that is typical of sequences accumulated in rift basins.

Figure 6. A) Interpreted seismic section through Falcone-1A across the Exmouth Sub-basin from the Indian 3D survey. B) Zoomed in section showing detail of the western flank of the Exmouth Sub-basin. See figure 1 for location.

Figure 7. Schematic depositional model showing conceptual geological interpretation and key sequence stratigraphic surfaces for TR20 and TR30 (from Adamson et al., 2013).

Figure 8. Interpreted well logs and biostratigraphy from the Falcone-1A well.

Figure 9. Palaeogeographic maps for TR20 and TR30 highlighting the major landward shift in depositional facies between these intervals (modified from Adamson et al., 2013).

Figure 10. Seismic section from the outer Exmouth Plateau showing Rhaetian carbonate buildups that grew on active tilted fault blocks (modified from Grain et al., 2013).

Figure 11. Schematic cross section showing the interpreted structural and stratigraphic evolution associated with the onset of Mesozoic rifting in the Late Triassic.

References

Adamson, K.R., Lang, S.C., Marshall, N.G., Seggie, R.J., Adamson, N.J., and Bann, K.L., 2013, Understanding the Late Triassic Mungaroo and Brigadier Deltas of the Northern Carnarvon Basin, North West Shelf, Australia. *in* Keep, M. and Moss, S. J. (eds), The Sedimentary Basins of Western Australia IV: Proceedings of the Petroleum Exploration Society of Australia, Perth, 1-29

Audley-Charles, M.G., 1988, Evolution of the southern margin of Tethys (north Australian region) from Early Permian to Late Cretaceous. *in* Audley-Charles, M.G. and Hallam, A. (eds), Gondwana and Tethys: Geological Society of London Special Publication, 37, p. 79-100.

Bradshaw, M.T., Bradshaw, J., Murray, A.P. , Needham, D.J., Spencer, L., Summons, R.E., Wilmot, J., and Winn, S., 94, Petroleum systems in west Australian basins . *in* Purcell, P. G. and Purcell, R. R. (eds), The Sedimentary Basins of Western Australia: Proceedings of the Petroleum Exploration Society of Australia, Perth, 93-118

Catuneanu, O, 2006, Principles of Sequence Stratigraphy, Amsterdam, Elsevier. 375.

Catuneanu, O., 2002, Sequence stratigraphy of clastic systems: concepts, merits and pitfalls. Journal of African Earth Sciences, v. 35, p. 1-43.

Catuneanu, O., V. Abreu, J.P. Bhattacharya, M.D. Blum, R.W. Dalrymple, P.G. Eriksson, C.R. Fielding, W.L. Fisher, W.E. Galloway, M.R. Gibling, K.A. Giles, J.M. Holbrook, R. Jordan, C.G.St.C. Kendall, B. Macurda, Martinsen O.J., A.D. Miall, J.E. Neal, D. Nummedal, L. Pomar, H.W. Posamentier, B.R. Pratt , J.F. Sarg, K.W. Shanley, R.J. Steel, A. Strasser, M.E. Tucker, C. Winker, 2009, Towards the standardization of sequence stratigraphy. Earth-Science Reviews, v. 92, p. 1-33.

Emery, D, K J Myers, 1996, Sequence Stratigraphy, Oxford, Blackwell. 297.

Etheridge, M.A., G.W. O'Brien, 1994, Structural and tectonic evolution of the Western Australian margin system. PESA Journal, p. 45-63.

Forman, D.J., D.W. Wales, 1981, Geological evolution of the Canning Basin, Western Australia. Bureau of Mineral Resources, Geology and Geophysics Bulletin, v. 210, p. 91.

Grain, S.L., Peace, W.M., Hooper, E.C.D., McCartain, E., Massara, P.J., Marshall, N.G., and Lang, S.C., 2013, Beyond the deltas: Late Triassic isolated carbonate build-ups on the Exmouth Plateau, Carnarvon Basin, Western Australia. *in* Keep, M. and Moss, S. J. (eds*)*, The Sedimentary Basins of Western Australia IV: Proceedings of the Petroleum Explora-tion Society of Australia Symposium, Perth, 1-19

Gupta, S., P.A. Cowie, N.H. Dawers, J.R. Underhill, 1998, A mechanism to explain rift-basin subsidence and stratigraphic patterns through fault-array evolution. Geology, v. 26, p. 595-598.

Hooker, N. 2005, Palynology of well Falcone-1A, Carnarvon Basin, Western Australia. In: Falcone-1 & 1A Well Completion Report (unpublished).

Hunt, D., M.E. Tucker, 1992, Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall. Sedimentary Geology, v. 81, p. 1-9.

Lambiase, J.J., W. Bosworth, 1995, Structural controls on sedimentationin continental rifts. *in* Lambiase, J.J. (ed), Hydrocarbon habitat in rift basins: Geological Society of London Special Publication: 80, p. 117-144.

Marshall, N.G. and Lang, S.C., 2013, A new sequence stratigraphic framework for the North West Shelf, Australia. *in* Keep, M. and Moss, S. J. (eds*)*, The Sedimentary Basins of Western Australia IV: Proceedings of the Petroleum Exploration Society of Australia, Perth, 1-32

Martins-Neto, M.A., O. Catuneanu, 2010, Rift sequence stratigraphy. Marine and Petroleum Geology, v. 27, p. 247-253.

Posamentier, H.W., G.P. Allen, 1999, Siliciclastic sequence stratigraphy: concepts and applications. SEPM Concepts in Sedimentology and Paleontology, v. 7, p. 210.

Posamentier, H.W., D.P. James, 1993, Sequence stratigraphy - usesand abuses. *in* Posamentier, H.W., Summerhayes, C.P., Haq, B.U., and Allen, G.P. (eds), Sequence Stratigraphy and Facies Associations: International Association of Sedimentologists Special Publication: 18, p. 3-18.

Prosser, S., 1993, Rift-related linked depositionalsystems and their seismic expression. *in* Williams, G.D. and Dobb, A. (eds), Tectonics and seismic sequence stratigraphy: Geological Society of London Special Publication: 71, p. 117-144.

Smith, S.A., P.R. Tingate, C.M. Griffiths, J.N.F. Hull, The structural development and petroleum potential of the Roebuck Basin. The APPEA Journal, v. 39, p. 364-385.

Stagg, H.M.J. and Colwell, J.B., 94, The structural foudation of the Northern Carnarvon Basin. *in* The Sedimentary Basins of Western Australia: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 349-364

Vail, P.R., R.M. Mitchum Jr., R.G. Todd, J.M. Widmier, S. Thompson III, J.B. Sangree, J.N. Bubb, W.G. Hatlelid, 1977, Seismic stratigraphy and global changes of sealevel. *in* Payton, C.E. (ed), Seismic Stratigraphy – Applications to Hydrocarbon Exploration: AAPG Memoir, 26, p. 49-212.

Veevers, J.J., 88, Morphotectonics of Australia'snorthwestern margin - a review. *in* Purcell, P. G. and Purcell, R. R (eds*)*, The North West Shelf, Australia: Proceedings of Petroleum Exploration Society of Australia Symposium, Perth, 19-27

Weimer, P., H.W. Posamentier, 1993, Siliciclastic Sequence Stratigraphy. AAPG Memoir, v. 8, p. 292.

Yeates, A.N., Bradshaw, M.T., and Dickins, J.M., 87, The Westralian Superbasin, an Australian link with Tethys. *in* McKenzie, K. G. (eds*)*, ShallowTethys 2, International Symposium on Shallow Tethys 2 Proceedings, Wagga Wagga, 199-213

Biographies

Anthony Gartrell obtained his degree in geology and geophysics from the University of Western Australia in 1993. He then worked WMC Resources Petroleum Division in 1995. After completing his PhD. in Geology and Geophysics at UWA he joined CSIRO Petroleum Division in 2000 where his work focussed on the effects of fault reactivation on fault seal and trap integrity. He then joined Shell working in Brunei (2007) and then Australia (2011) where he played a lead role in major regional and Play Based Exploration projects. Since 2013 he has been working as a consultant specializing in structural geology, sequence stratigraphy and play based exploration. Currently he is also an Adjunct Senior Research Fellow at the University of Western Australia.

Jose Torres obtained a degree in geology from the University of Barcelona (Spain), a MSc in the French Institute of Petroleum of Paris and a PhD in Marine geology from the University of Barcelona in 1995. He worked for Repsol for almost 9 years with different assignements in Spain, South America and the US mostly in New Ventures. He joined Shell in 2007 in Brunei working as a regional geologist and sedimentologist. He moved to Shell Australia in 2012 with a similar role where he has been involved in several regional studies covering the totality of the North Western Shell.

After studying at UWA, Matt Dixon was a consultant palynologist with Morgan Goodall Palaeo for 6 years, specialising in the Cretaceous to Triassic of NW Australia to PNG (over 70 wells). For the later four years of this time, he worked concurrently as a Biostratigrapher for Shell Australia. Since 2013 he has been an Explorer / Stratigrapher with Shell Australia, where he is located in the Regional Team.

Myra Keep is Professor of Structural Geology and Tectonics at the University of Western Australia. Her research interests include reactivation and inversion of fault systems, dynamics of collisional margins, neotectonics and seismicity. She has worked extensively on reactivated systems on the NWS, and since 2003 has also had an active research program in Timor-Leste. Myra holds degrees from London (BSc., UCL), Vancouver (MSc., UBC) and Texas (PhD). After leaving Mobil in 1995 she worked at Royal Holloway University of London and the University of Aberdeen before commencing at UWA in 1997. She is a recipient of a WA Premier’s Science prize, being named Science Ambassador of the Year 2013-14.