The Permian and Carboniferous extensional history of the Northern Carnarvon Basin and its influence on Mesozoic extension

Sam McHarg
Department of Applied Geology
Curtin University
Bentley, WA
sam.mcharg@postgrad.curtin.edu.au

Amy I'Anson
EarthByte Group,
School of Geosciences
The University of Sydney, NSW
amy.ianson@sydney.edu.au

Chris Elders
Department of Applied Geology
Curtin University
Bentley, WA
Chris.Elders@curtin.edu.au

SUMMARY

The North-West Shelf of Australia is a marginal rift system related principally to the fragmentation of Gondwana. Permian-Carboniferous structures along the margin have long been recognised as fundamental events responsible for the formation of the offshore basins that comprise the prolific hydrocarbon producing region. However, the tectonic setting in which this rifting occurred remains unclear.

Detailed mapping of the geometry of Permian and Carboniferous structures on the southern margin of the Carnarvon Basin is possible using regional scale interpretation of publically available 2D and 3D seismic data. Seismic interpretation, combined with 2D structural reconstruction of major faults reveals two distinct orientations of structures. NNE trending faults were initiated in the Carboniferous or Devonian but were underfilled, resulting in erosion of the fault block crest and filling of the remnant rift-related topography by conformable sequences of later Permian and Triassic sediments. By contrast, NE-SW oriented faults experienced a distinct phase of Permian activity and are unconformably overlain by Triassic sediments.

The Paleozoic rift architecture has clearly affected the geometry of the subsequent Upper Triassic to Middle Jurassic rift and can account for the en-echelon style of faulting on the northern margin of the Dampier Basin. Reactivation of the eroded fault block crests results in complex fault geometries and significant deformation of hanging wall strata during Mesozoic extension.

Key words: Carnarvon Basin, North-West Shelf, rifting, seismic interpretation

INTRODUCTION

The North-West Shelf is a term applied to the offshore and marginal basins of Australia's western margin related principally to the fragmentation of Gondwana. It comprises the Northern Carnarvon, Offshore Canning, Browse and Boneparte basins, as well as the Timor-Banda-Orogen (Figure 1A). The sequences of the "Westralian superbasin" are approximately 10 km thick, composed of late Paleozoic, Mesozoic and Cainozoic successions that trend north-east, roughly parallel to the North-West Shelf (Bradshaw et al. 1988).

The Northern Carnarvon Basin is dominated by a north-east trending set of depocenters; the Exmouth, Barrow, Dampier and Beagle Sub-basins (Figure 1B). These broadly defined sub-basins represent the major, predominately Mesozoic depocentres of the Northern Carnarvon Basin and is Australia's premier hydrocarbon province (Geoscience Australia 2015) (Figure 1C).

The major depocentres of the Exmouth, Barrow, Dampier and Beagle Sub-basins are flanked in the landward direction by the Peedamullah and Lambert Shelves, and by the Rankin Platform and Alpha Arc in the seaward direction. The Kangaroo Syncline, Exmouth Plateau, and Investigator Sub-basin lie further offshore, where the outboard limit of the basin is poorly defined. Onshore, the Archean Pilbara Craton defines the inboard limit of the Northern Carnarvon basin (Figure 2).

The marginal Carboniferous to Permian aged structures of the Northern Carnarvon Basin have received relatively limited attention after their original recognition on deep, regional scale seismic sections (AGSO, 1994; Gartrell, 2000; Stagg and Colwell, 1994; Williamson et al., 1990). The focus of regional studies is typically on Mesozoic faulting, which trends north or northeast and defines the large en-echelon rift depocentres (Figure 2). Fault blocks within the Sub-basins have been variably modified by faulting, uplift and rotation. Triassic, Jurassic and Lower Cretaceous sediment thicknesses can exceed 15 km in the depocenters. Paleozoic stratigraphy is typically beyond depths resolved by seismic reflection methods in the main depocentres. However it can be imaged in shallower, inboard areas. The Beagle Sub-basin is structurally distinct from the southern sub-basins with fault blocks and anticlines aligned on a predominantly northerly trend (Longley et al. 2002; Gartrell 2000; Bradshaw et al. 1988).

This study uses several 3D and 2D data sets, extending from the southern portion of the Exmouth Plateau to nearshore areas of the Lambert and Peedamullah Shelves. Structural modelling was used to characterise the marginal Paleozoic fault systems of the Barrow, Dampier, and Beagle Sub-basins. Understanding the Paleozic rift architecture is important as this provides the crustal setting in which the Mesozoic rifts form. Unravelling the structural complexity of the Paleozoic fault system will enhance the understanding of the later Mesozoic deformation.

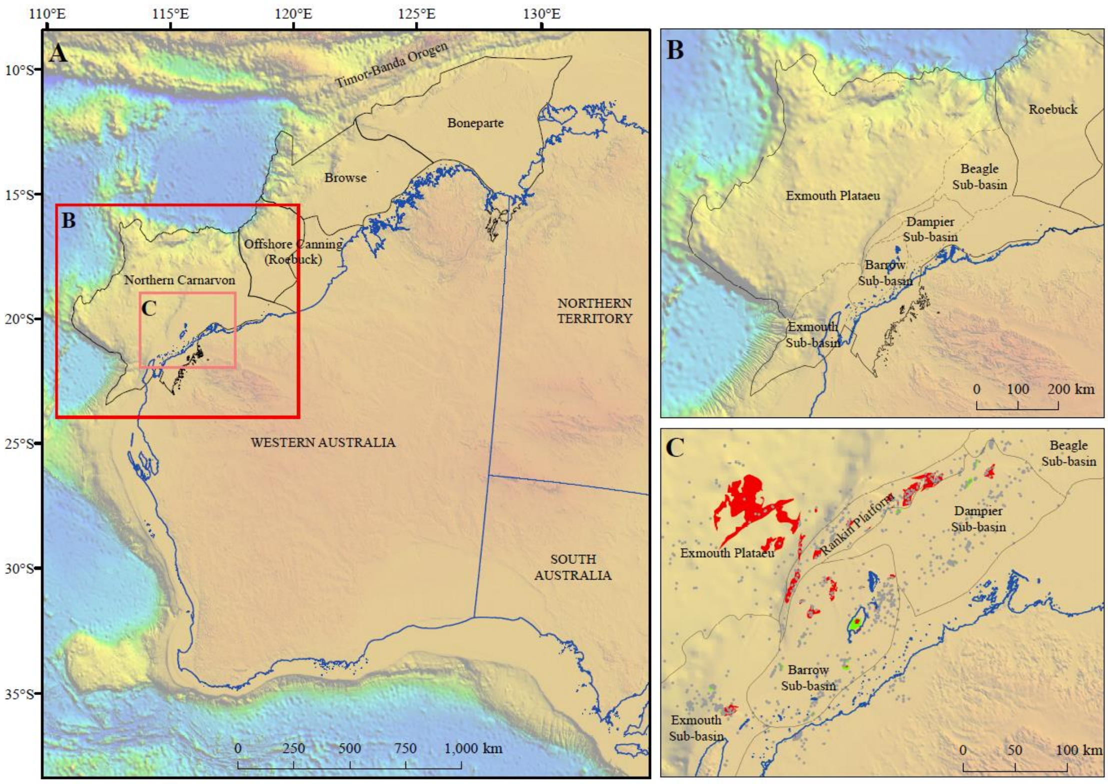

Figure 1 – A) Bathymetric map of Australia showing the offshore and marginal basins that comprise the North-West Shelf. B) Structural sub-divisions of the Northern Carnarvon Basin. C) Study area showing well locations (grey dots) and major oil (green) and gas (red) fields.

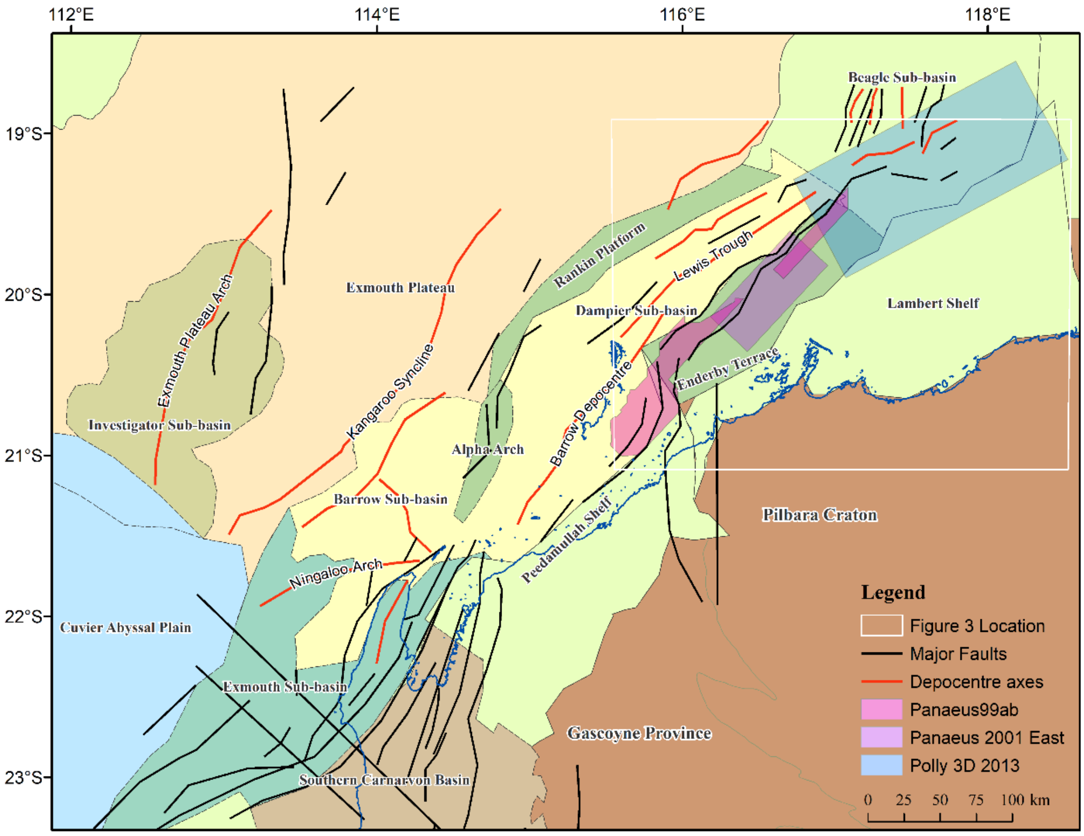

Figure 2 – Detailed structural elements of the Northern Carnarvon Basin, boundaries are approximate only (after Geoscience Australia, 2015), showing the location of the 3D seismic surveys where the inboard Paleozoic section is preserved.

DATA AND METHODOLOGY

Interpretation was completed on time migrated sections, in both DUG Insight and Schlumberger Petrel software. The nearshore 3D surveys Panaeus 99ab, Panaeus East 2001 and Polly 3D 2013 (Figure 2) image the Paleozoic sequences due to thinner Mesozoic sediments, which are better imaged in outboard surveys. Key wells with available well completion reports were used to tie seismic sections and to interpret the stratigraphy.

There are only a limited number of wells ties for Paleozoic aged sediments. In outboard areas, the lower confidence of interpreting some horizons resulted in a number of horizon picks limited to small areas. Cretaceous and younger horizons were typically identifiable across larger areas. Correlation of Lower Jurassic & Upper Triassic sequences was subject to greater uncertainly due to most wells targeting highs where these sequences are generally missing, as well the deterioration of data quality in the deeper parts of the basin.

Several sections were depth converted, where necessary, for structural restoration work using Midland Valley Move modelling software and StructureSolver software. Geometrical data (horizons, faults etc.) were used as inputs for a number of kinematic models with the aim of evaluating the potential of extensional faulting to produce the folding observed in the hanging walls of major marginal faults.

RESULTS

Marginal faults of the Barrow Sub-basin

The marginal faults of the Barrow Sub-basin are primarily orientated north-south and NNE (Figure 2, 3A). The Sholl Island Fault contains more than 6 km of mostly concordant sedimentary fill below the regionally extensive Valanginian Unconformity (Figure 4). In the hanging wall, the oldest stratigraphic horizon intersected by drilling is the Early Carboniferous Moogooree Limestone (Kybra-1 well). The base Triassic horizon is conformable with the underlying thick Paleozoic sequence (Figure 3).

The Sholl Island Fault has a complex geometry. It was initiated in the Carboniferous or Devonian but was underfilled. The observed present day fault plane, where footwall stratigraphy is preserved (Line B, Figure 5), cannot explain the geometry of the base Triassic horizon (Figure 6A). A structural restoration of the fault, at the base Triassic, shows that subtle bends in the gently listric fault plane account for the draping seen in the Permian and older stratigraphy. The observed present day fault geometry can be used to account for the pre-Triassic seismic character but not the younger sequence. To explain this, we interpret erosion of the fault block crest during the early Permian, and later reactivation during Jurassic extension producing the complex fault shape (Figure 5).

Marginal faults of the Dampier Sub-basin

By contrast, the marginal faults of the Dampier Sub-basin, are primarily orientated northeast-southwest (Figure 2 & Figure 3B). The major marginal fault, shown in Figure 7, is the Mermaid Fault. A thinner Paleozoic sedimentary sequence is observed associated with the NE trending Mermaid Fault compared to the N-S trending Sholl Island Fault, which suggests a shift in stresses acting on the basin during this time. Both the Mermaid Fault and the associated Paleozoic sequence is truncated by an angular unconformity at the base of the Triassic. In the hanging wall of the Mermaid Fault, the oldest intersection is the Early Permian Byro Group at Arabella-1 (Figure 7).

While the seismic stratigraphy of the Sholl Island Fault suggests a period of passive sedimentary infill during the Permian, and active fault growth during the Carboniferous (and Devonian?), the Mermaid Fault reveals active fault growth during the Permian, prior to major titling, and peneplanation. The Lower Triassic Locker Shale overlies the base Triassic unconformity. Again, the erosion of the fault block crest, and reactivation of the fault can be seen in the Mermaid Fault (Figure 8). In both the Mermaid Fault and Sholl Island Fault, a 'Basement Anomaly' appears to act as a detachment for Paleozoic faulting while the Locker Shale serves as a detachment surface for much of the Mesozoic faulting (Figure 4, 5, 7).

Marginal faults of the Beagle Sub-basin

At the southern margin of the Beagle Sub-basin (Figure 2), the base Triassic structure map (Figure 3C) shows variable orientations, with north-south and northeast-southwest oriented graben. Like the Mermaid Fault of the Dampier Sub-basin, the major marginal faults contain a thin Permian sequence, which is rotated and truncated by the base Triassic angular unconformity (Figure 9). Carbonate platforms, and their associated talus slopes, are interpreted to be deposited in the Early Triassic. These platforms are buried by the Locker Shale, which again acts as a detachment surface for the Mesozoic faulting (Figure 9). No evidence of fault block crest erosion is evident across the Beagle Sub-basin study area, with Paleozoic faults reactivated during Jurassic extension along the pre-existing fault plane (Figure 9).

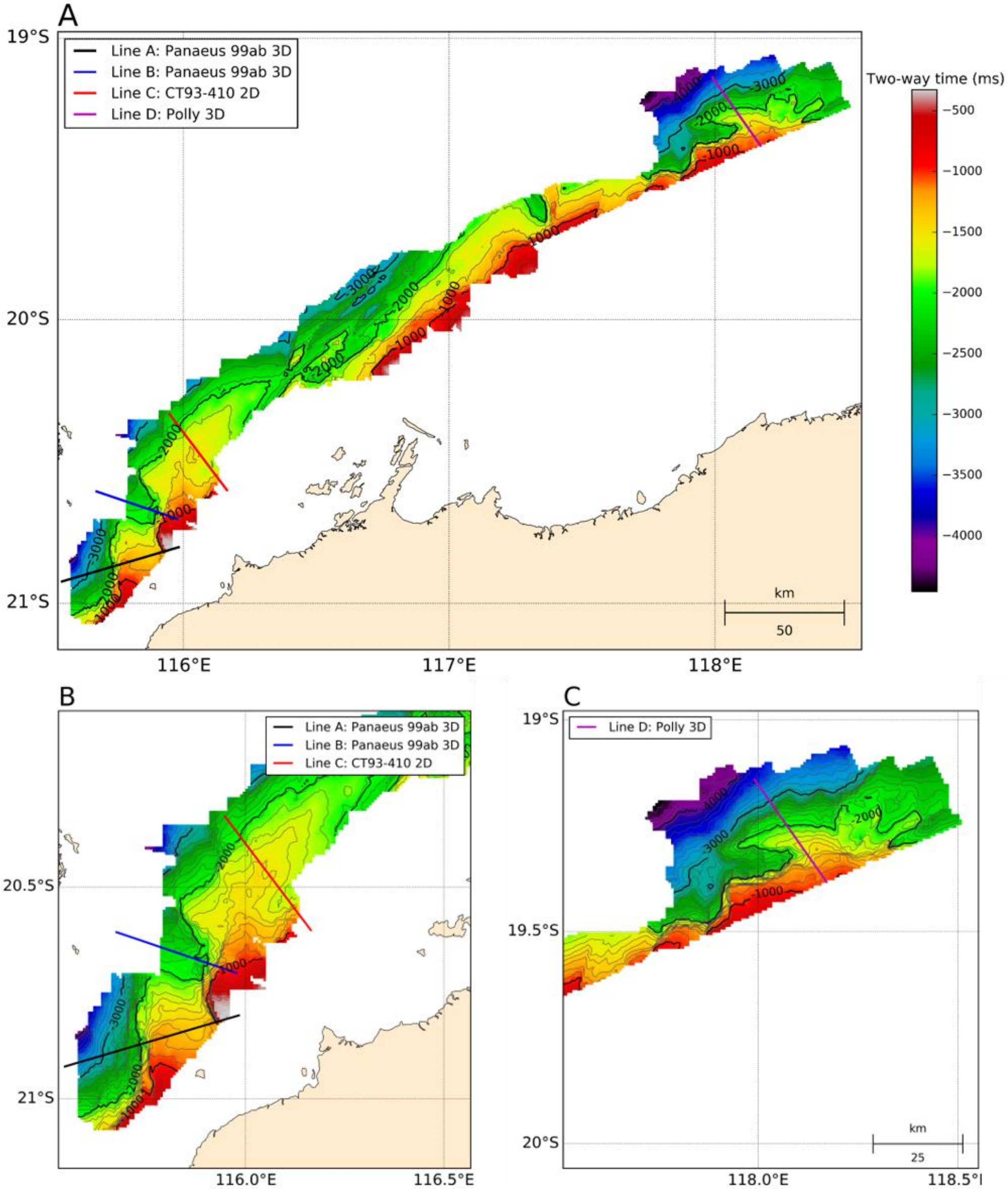

Figure 3 – (A) Interpreted base Triassic horizon structure map for the Barrow, Dampier to Beagle Sub-basins, contour interval of 250 m. (B) The major base Triassic structures are oriented north-south on the Candace Terrace, switching to NE-SW further North on the Mermaid Nose structure, 100m contour interval, and (C) is variable in the southern margin of the Beagle Sub-basin. Location of seismic sections presented in this paper are shown, , 100m contour interval. See Figure 2 location inset.

Influence on Mesozoic extension

The Paleozoic fault system of the Northern Carnarvon Basin is a complex interaction of N to NE trending faults which act as a basal framework for the Mesozoic system. The Mesozoic extension event initiated in the Rhaetian, but was most significant in the Early Jurassic. Vertical propagation of Jurassic aged faults results in a complex set of structures linked to the underlying Permian fault system. The higher displacement faults within the Paleozoic system appear to preferentially hard link with Mesozoic faults. Lower displacement faults within the Jurassic tip out in the Mungaroo formation, but likely maintain a soft link with Permian faults. There is also evidence of some Mesozoic faults detaching onto the base of the Locker Shale Formation.

The resultant Mesozoic fault network on the Rankin Fault Zone comprises NNE to N trending faults which suggests oblique reactivation of the Permian NE trending fabric. In comparison to the models presented by McClay et al., (2002) and Clifton et al., (2000), the fault network closely resembles that produced from E-W oriented extension (Figure 4). Fault-related folding is observed in across the study area has previously been attributed to compression – either from the Fitzroy Movement (Late Triassic) or Neogene collision of Australia and Eurasian plates. Forward modelling of a number of fold systems suggests folding can be attributed to extensional processes, either fault propagation folding or due to hanging wall deformation in associated with ramp-flat fault geometries.

A similar genesis is proposed for the Lewis Trough with the NE trending Rankin Fault Zone forming the Mesozoic expression of a crustal scale Paleozoic fault. Detaching onto the base Locker Shale, the fault then hard links with a Permian aged fault forming a ramp-flat geometry. As extension developed in the Jurassic, the Kendrew Trough, Madeleine Anticline and Lewis Trough developed as hanging wall deformation within Triassic and Jurassic sequences, rather than rotated fault blocks. The variation in growth history as well as structural complexities along the Lewis Trough could be explained by along strike variation in the ramp-flat geometry of the fault, as demonstrated McClay and Scott (1991).

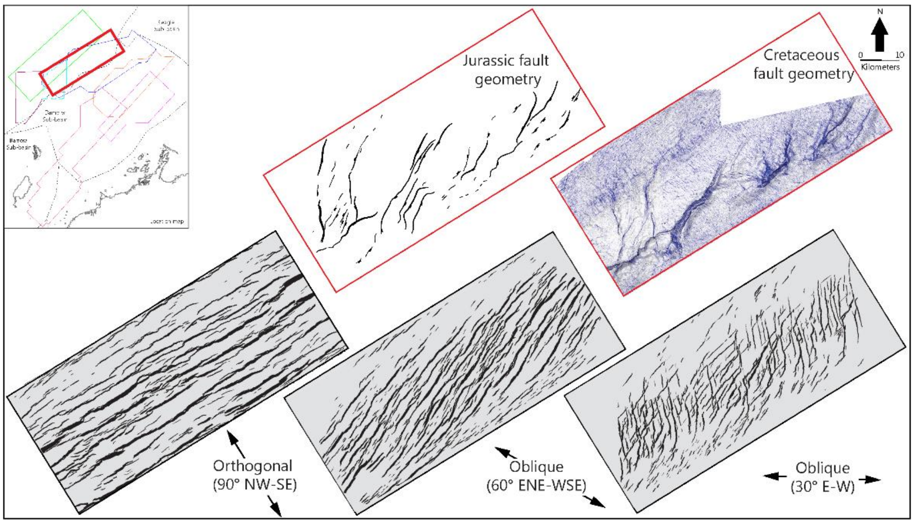

Figure 4 - Jurassic and Lower Cretaceous (variance extraction) fault orientations on the Rankin Fault Zone (upper two diagrams) compared to orthogonal and oblique fault patterns from a series of clay models from Clifton et al., (2000). Lower three diagrams are rotated to the same orientation of the Rankin Fault Zone.

CONCLUSIONS

Permian-Carboniferous structures along the North-West Shelf have long been recognised as fundamental events responsible for the formation of the offshore basins that comprise the prolific hydrocarbon producing region. Detailed mapping of the geometry of Permian and Carboniferous structures across the Barrow, Dampier and Beagle Sub-basins was completed using publically available 2D and 3D seismic data.

Seismic interpretation, combined with 2D structural reconstruction of major faults reveals two distinct orientations of structures. N-S and NNE trending marginal faults were initiated in the Carboniferous or Devonian but were underfilled, resulting in erosion of the fault block crest and filling of the remnant rift-related topography by conformable sequences of later Permian and Triassic sediment. By contrast, NE-SW oriented faults experienced a distinct phase of Permian tilting and are uncomfortably overlain by Triassic sediments. The older rift architecture has affected the geometry of the subsequent Upper Triassic to Middle Jurassic deformation and can account for the en-echelon style of faulting. Reactivation of the eroded fault block crests results in complex fault geometries and significant deformation of hanging wall strata during Mesozoic extension.

ACKNOWLEDGMENTS

DownUnder Geosolutions are kindly acknowledged for their generous provision of DUG Insight for Seismic Interpretation. The StructureSolver company are kindly acknowledged for their generous provision of StructureSolver for structural restoration work.

Schlumberger is acknowledged for the provision of Petrel interpretation software and Midland Valley for the Move modelling software. All data used in this study is open source, available through the National Offshore Petroleum Information Management System (NOPIMS) or Western Australian Petroleum Information Management System (WAPIMS). Amy I'Anson is supported by an Australian Postgraduate Award, and by the Australian Research Council grant IH130200012. Sam McHarg is supported by the BHP Billiton Curtin University Alliance Scholarship.

REFERENCES

AGSO, 1994. Deep Reflections on the North West Shelf: Changing Perceptions of Basin Formation. Sediment. Basins West. Aust. 63–76

Clifton, A E et al., 2000, Influence of Rift Obliquity on Fault-Population Systematics: Results of Experimental Clay Models. *Journal of Structural Geology* 22(10), pp. 1491–1509.

Bradshaw, M.T. et al., 1988. Palaeogeographic Evolution of the North West Shelf Region. In P. G. Purcell & R. R. Purcell, eds. *The North West Shelf, Australia: Proceedings of Petroleum Exploration Society Australia Symposium, Perth*. pp. 29–46.

Gartrell, A.P., 2000. Rheological controls on extensional styles and the structural evolution of the Northern Carnarvon Basin, North West Shelf, Australia. *Australian Journal of Earth Sciences*, 47(2), pp.231–244.

Geoscience Australia, 2015. Regional Geology of the Northern Carnarvon Basin. , pp.1–34. Available at: http://archive-petroleumacreage.industry.slicedtech.com.au//2015/geology/northern-carnarvon-basin/geology.

Longley, I.M. et al., 2002. North West Shelf of Australa - A Woodside Perspective. *The Sedimentary Basisn of Western Australia 3: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, Australia*, pp.27–88.

McClay, K. R. et al., 2002, 4D Evolution of Rift Systems: Insights from Scaled Physical Models. *AAPG Bulletin* 86, pp. 935–960.
McClay, K.R., and A.D. Scott, 1991, Experimental Models of Hangingwall Deformation in Ramp-Flat Listric Extensional Fault Systems. *Tectonophysics*,188(1–2), pp. 85–96.

Stagg, M.J., Colwell, J.B., 1994. The Structural Foundations of the Northern Carnarvon Basin. Sediment. Basins West. Aust., Proceedings of the West Australian Basins Symposium.

Williamson, P.E., Swift, M.G., Kravis, S.P., Falvey, D.A., Brassil, F., 1990. Permo-Carboniferous rifting of the Exmouth Plateau region (Australia): an intermediate plate model. Potential Deep Seism. Profiling Hydrocarb. Explor. Editions Technip, Paris, 237–248.

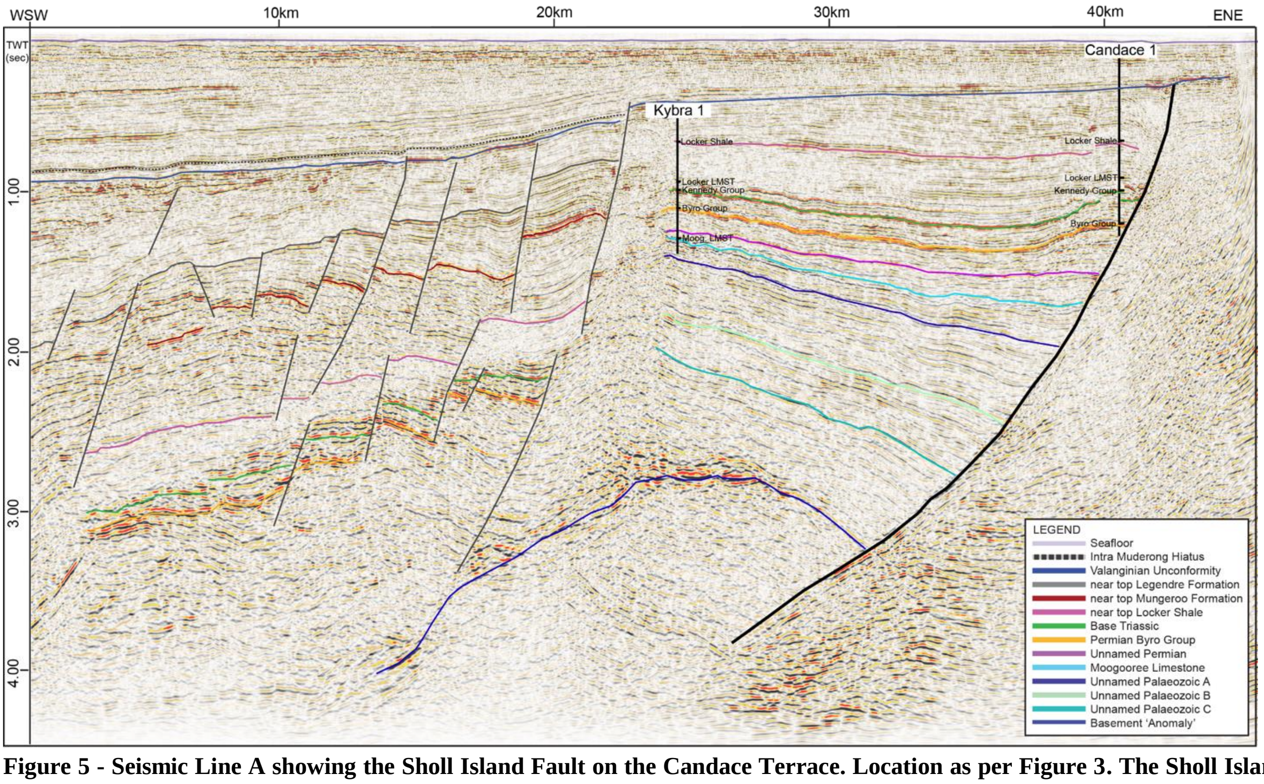

Figure 5 - Seismic Line A showing the Sholl Island Fault on the Candace Terrace. Location as per Figure 3. The Sholl Island Fault is orientated NNE and contains more than 6 km of mostly concordant sedimentary fill below the regionally extensive Valanginian Unconformity. The base Triassic horizon is unconformable with the underlying thick Paleozoic sequence.

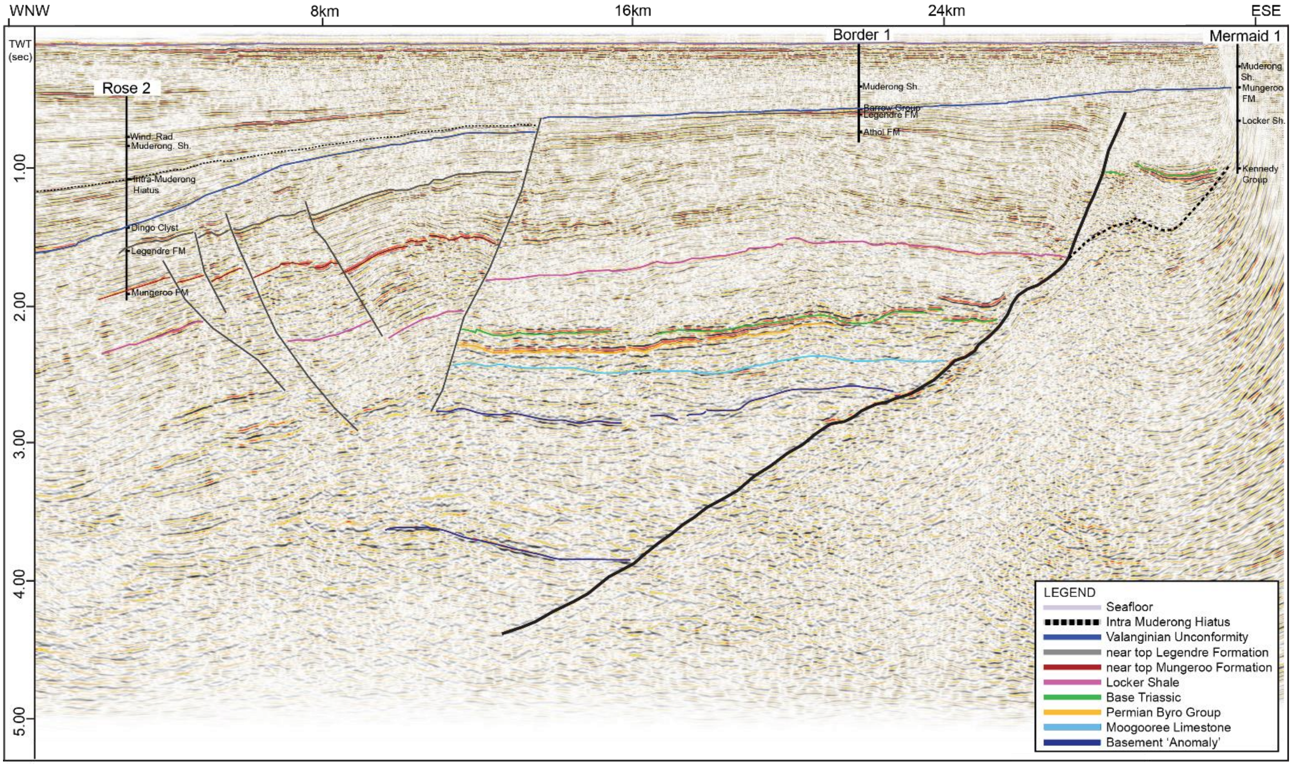

Figure 6 - Seismic Line B showing the Sholl Island Fault on the Candace Terrace. Location as per Figure 3. The Sholl Island Fault has a complex geometry. It was initiated in the Carboniferous or Devonian but was underfilled. The erosion of the fault block crest during the early Permian, and the later reactivation of this unconformity occurred during Jurassic extension, producing the complex fault shape.

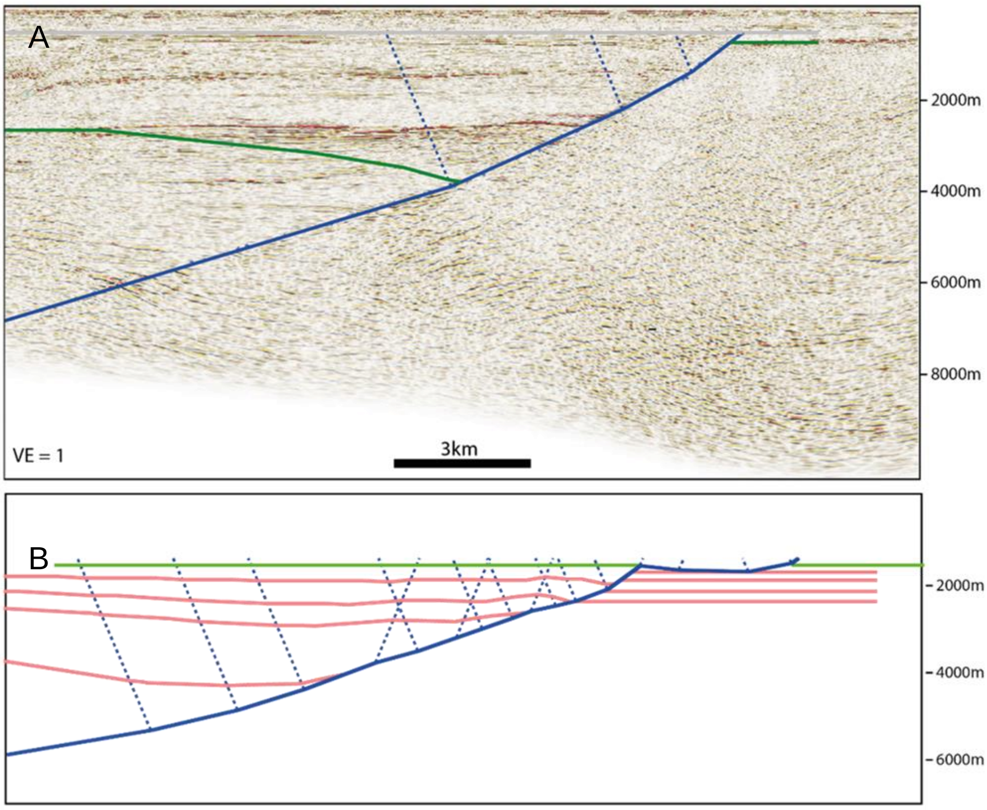

Figure 7 - Structural Restoration of the Sholl Island Fault. (A) The observed present day fault plane cannot explain the geometry of the base Triassic horizon (green). A structural restoration of the fault (B) at the base Triassic (above and below horizon), shows that subtle bends in the gently listric fault plane account for the draping seen in the Permian and older stratigraphy. Synthetic and antithetic shear axes shown.

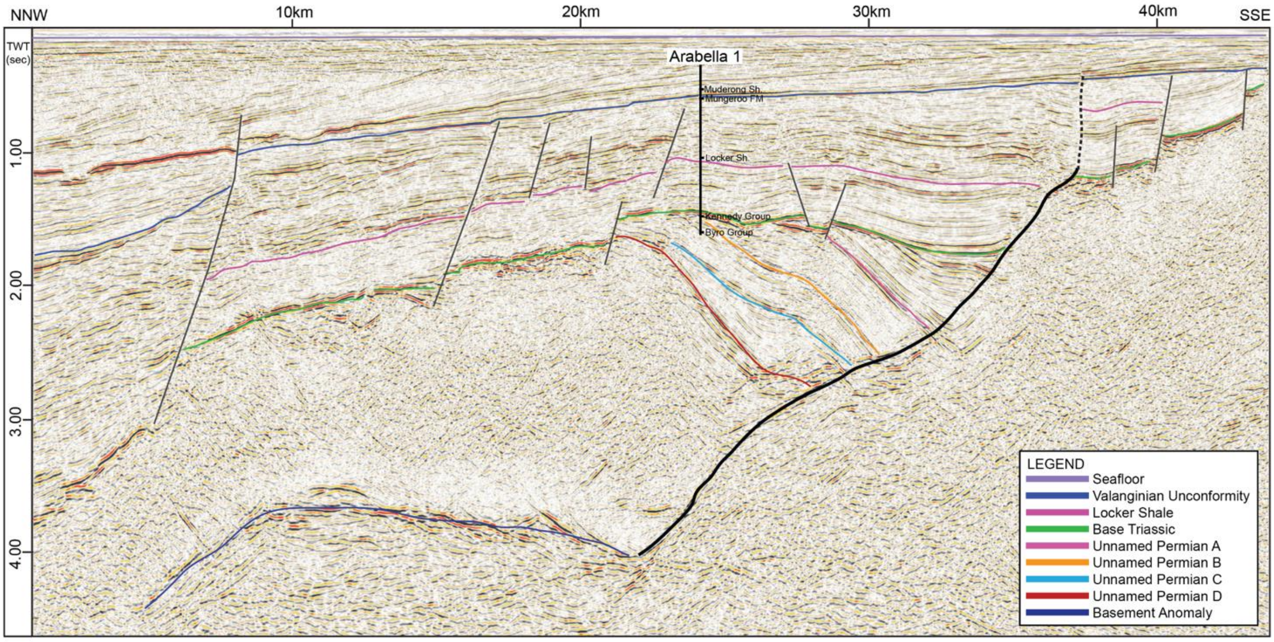

Figure 8 - Seismic Line C through the Mermaid Fault of the Dampier Sub-basin. Location as per Figure 3. The Mermaid fault is orientated northeast-southwest and contains a thin Paleozoic sedimentary fill that is truncated by the base Triassic angular unconformity. The Mermaid Fault reveals the deposition of a thin Permian sequence, subsequent titling and peneplanation, prior to the deposition of the Early Triassic Locker Shale. The erosion of the fault block crest, and the reactivation of the fault at the edge of the erosive surface can be seen. Note the potential detachment of the Mermaid Fault on a 'Basement Anomaly, while the Locker Shale serves as a detachment surface for some of the Mesozoic faulting.

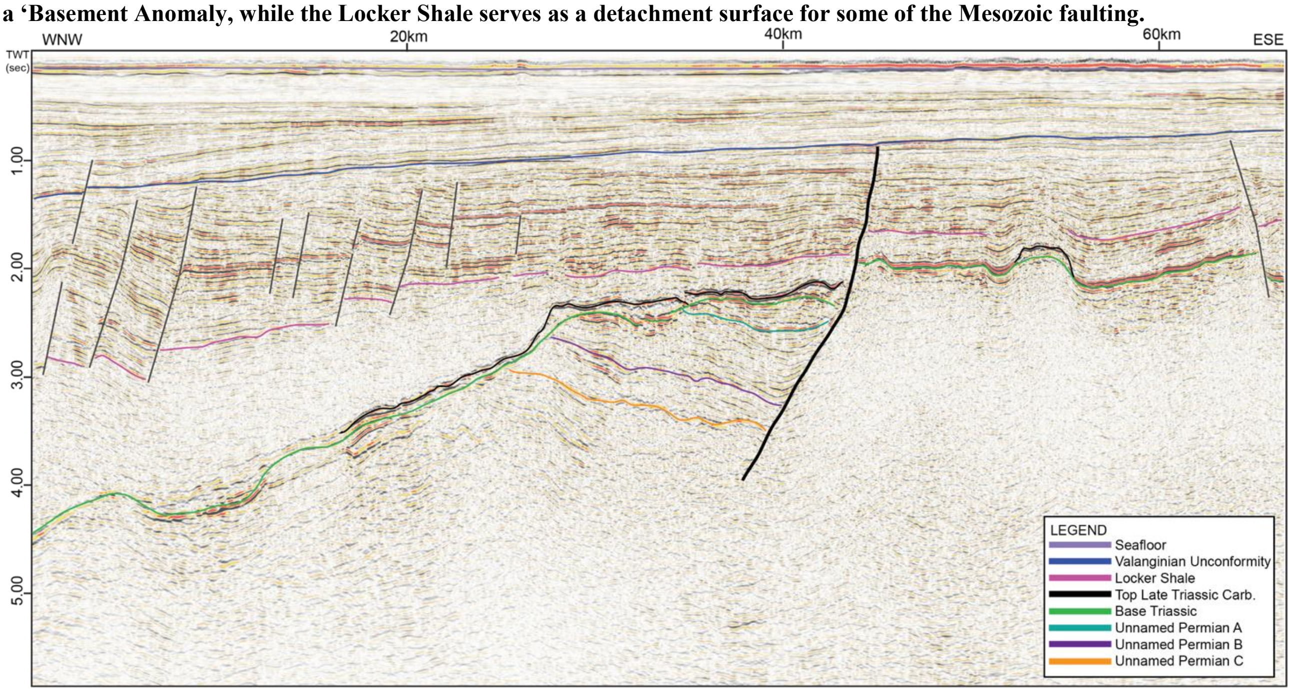

Figure 9 - Seismic Line D on the southern margin of the Beagle Sub-basin, graben structures are oriented variably from north-south to northeast-southwest. The major marginal faults contain a thin Permian sequence, which is highly rotated and truncated by the angular unconformity of the base Triassic horizon. Carbonate platforms, and their associated talus slopes are shown. These platforms are buried by the Locker Shale, which again acts as a detachment surface for much of the Mesozoic faulting. No evidence of fault block crest erosion is evident on the Paleozoic faults of the Beagle Sub-basin. Instead the marginal Paleozoic faults propagate during Jurassic extension along the pre-existing fault plane. Location as per Figure 3.