

# The Bight Basin, Evolution & Prospectivity I: gravity, deep seismic & basin morphology

**Jane Cunneen**<sup>1,2</sup>  
[Jane.Cunneen@curtin.edu.au](mailto:Jane.Cunneen@curtin.edu.au)

**Chanel DePledge**<sup>3</sup>  
[Chanel.DePledge@gmail.com](mailto:Chanel.DePledge@gmail.com)

**Sharon Lowe**<sup>4</sup>  
[Sharon@SGC.com.au](mailto:Sharon@SGC.com.au)

**Kevin Hill**<sup>5,2</sup>  
[Kevin.hill@unimelb.edu.au](mailto:Kevin.hill@unimelb.edu.au)

**Candice Godfrey**<sup>1</sup>

**Amanda Buckingham**<sup>6,7</sup>  
[amanda@fathomgeophysics.com](mailto:amanda@fathomgeophysics.com)

**Rebecca Farrington**<sup>5,2</sup>  
[rebecca.farrington@unimelb.edu.au](mailto:rebecca.farrington@unimelb.edu.au)

<sup>1</sup> School of Earth and Planetary Sciences, Curtin University

<sup>2</sup> Basin Genesis Hub, The University of Sydney, <https://www.earthbyte.org/category/basin-genesis-hub/>

<sup>3</sup> Department of Exploration Geophysics, Curtin University

<sup>4</sup> Southern Geoscience Consultants, 183 Great Eastern Highway, Belmont WA, Australia

<sup>5</sup> School of Earth Sciences, The University of Melbourne, Parkville, VIC, Australia

<sup>6</sup> Fathom Geophysics Pty Ltd, PO Box 1253, Dunsborough, WA Australia

<sup>7</sup> Centre for Exploration Targeting, The University of Western Australia, Crawley WA Australia

## SUMMARY

Definition of the basement architecture within the Ceduna Sub-basin is poorly understood due to the depth of the basin and limited deep crustal geophysical datasets.

This study uses seismic interpretation of BightSPAN™ deep crustal seismic lines combined with 2D forward models of the gravity to define the basement architecture in the Ceduna Sub-basin. Gravity forward models identify two depocentres with maximum depths of 25 km overlying thinned continental crust. Syn-rift sedimentary packages are several km thick and underlie up to 10 km of post-kinematic Cretaceous deltaic sequences. Regional Moho models contain only sparse data points offshore and isostatic residual gravity data suggests substantial local variation in the depth to Moho. This local variation in the Moho surface is interpreted as boudinage of a weak lower crust along crustal shear zones. A gradual increase in basement density towards the continent-ocean transition suggests a diffuse rather than distinct boundary between continental and oceanic crust.

The results of this work are used to constrain the tectonic evolution, particularly in terms of the subsidence history and uplift and erosional pulses recorded on the seismic data in the Ceduna Delta (Hill et al., this volume) and then used as input for finite element numerical models of rifting (Farrington et al., this volume).

**Key words:** Bight Basin, gravity, Tectonics, crustal thickness, depocentre.

## INTRODUCTION

Recent improvements in the quality and availability of deep crustal seismic data have been instrumental in the understanding of rift processes in heterogeneous lithosphere (Clerc et al., 2018). Numerical models suggest that the architecture of rifted margins is controlled by crustal rheology, particularly the strength of the lower crust (Brune et al., 2017, Clerc et al., 2018). In many cases, rifted margins exhibit a

complex pre-rift evolution characterized by orogenic processes and the resulting lithospheric heterogeneity has a strong influence on structures during rifting (Duretz et al., 2016).

Many aspects of the rifting between Australia and Antarctica are well documented but there is ongoing debate about the timing (Direen, 2011a), style (Direen et al., 2012; Ball et al., 2013; White et al., 2013) and direction of the rift (Williams et al., 2011; Whittaker et al., 2013; Williams et al., 2019) which highlights gaps in our understanding. Within the Ceduna Sub-basin, the nature of the basement is difficult to constrain due to the depth of the basin and the thickness of the overlying Ceduna delta systems (Totterdell and Bradshaw, 2004; Gibson et al., 2013).

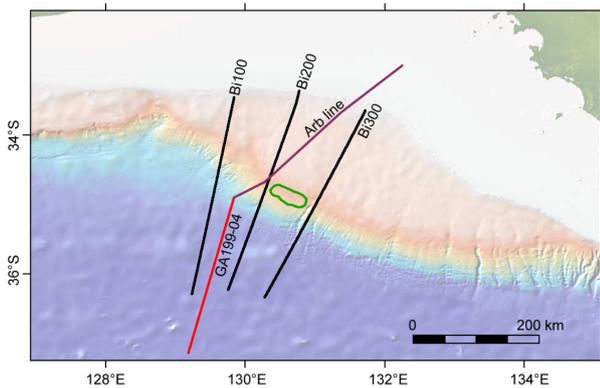
Here we analyse the tectonic evolution of Australia's southern margin in the Bight Basin, using BightSPAN™ deep crustal 2D seismic data and forward models of the gravity response along several seismic lines. The results of this work are used to constrain the tectonic evolution, particularly in terms of the subsidence history and uplift and erosional pulses recorded on the seismic data in the Ceduna Delta (Hill et al., this volume) and then used as input for finite element numerical models of rifting (Farrington et al., this volume).

## GEOLOGICAL BACKGROUND

The Ceduna Sub-basin is underlain by Proterozoic basement of the Gawler Craton and contains a thick series of syn and post-kinematic sedimentary packages. Due to the depth of the basin, the nature of the basement structure is poorly understood and the basement surface is not visible on conventional seismic data except along the northern basin boundary. Regional basement topography has been interpreted from aeromagnetic and gravity data (Blevin and Cathro, 2008), suggesting the basin is underlain by thinned Proterozoic crust.

Deposition of sediments began in the Middle Jurassic, during the break-up of eastern Gondwana (c. 165 Ma) and continued with the gradual separation of Australia and Antarctica in the Cretaceous-Palaeocene and rapid post-Eocene separation. The early rift sediments, intersected in the Jerboa-1 well in the adjacent Eyre Sub-basin, consist of fluvial-lacustrine sandstone, siltstone and claystone (Totterdell et al., 2014).

Post-kinematic Cretaceous packages comprise overlapping delta systems, which form deep-water fold-thrust belts (DDWFTB) towards the south-west basin margin (Struckmeyer et al., 2001; Espurt et al., 2009). The middle Albian-Santonian White Pointer and the late Santonian-Maastrichtian Hammerhead delta systems detach at the ductile shales of the Albian Blue Whale and Turonian-Santonian Tiger supersequences, respectively. A northwest to southeast trending anticline, the Stromlo High (Fig. 1), is present towards the south-western sub-basin boundary and is an area of interest for hydrocarbon exploration.



**Figure 1. Location map of the seismic sections used in this study, overlying the bathymetry image of the Ceduna Delta. Black lines are BightSPAN™ seismic lines, and red lines are the seismic section described in Hill et al. (this volume). Green ellipse shows the location of the Stromlo High.**

### SEISMIC INTERPRETATION

The BightSPAN™ deep crustal 2D seismic survey and associated potential fields datasets are used to examine the basement structure within the Ceduna Sub-basin. Seismic interpretation was integrated with gravity and magnetic datasets to define key features and provide constraints to understanding the deep structure.

Interpretations of the basement surface on three regional BightSPAN™ lines across the area of interest (Fig 1) show an east trending depocentre up to 25 km deep. Large-scale (10-20 km) tilted fault blocks are defined by low angle faults or shear zones, which also offset the Moho. In the outboard part of the basin, the basement surface shallows towards the continent-ocean transition zone and is defined by bright amplitude reflectors which are likely extrusive igneous rocks.

Basement thickness ranges from the thick continental root of approximately 35 km in the north, thinning offshore to a minimum thickness of <5 km under the main depocentre. A transition from continental to oceanic crust is obscured by a zone of likely serpentinised mantle and intruded igneous dykes and sills.

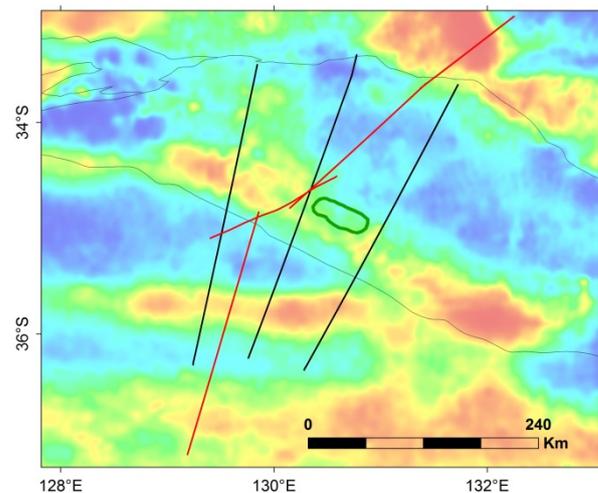
The Moho surface is challenging to resolve from seismic data, although in places the shear zones from basement faults are discernible. The interpretation of the Moho surface was therefore guided by the AusMoho grid (Kennet et al., 2011) and the MoGGIE model (Aitken et al., 2010) and refined where possible using seismic data.

### GRAVITY MODELS

Both gravity and magnetic data were acquired along the BightSPAN™ lines during seismic acquisition. 2D forward models of the gravity response were created using surfaces from the seismic interpretation imported into Geosoft's GM-SYS software. An iterative process of re-assigning densities (within geological and geophysical constraints) and basement structure was undertaken to achieve the closest fit between modelled and observed profiles.

Unit densities were formulated using a combination of well reports, density logs and current literature. Adjustments of basement density models were required to reduce error on the gravity curves. The basement in the southern part of the basin was assigned slightly increased density values, still within the ranges described by Direen et al. (2011b). Lower than expected densities towards the continent-ocean transition are partially compensated for with the introduction of serpentinised mantle layers.

A regional Isostatic Residual Gravity model (IR gravity) (Figure 2) was used to cross reference the models. Relatively short wavelength variation in the gravity response was difficult to replicate within the constraints of the seismic interpretation of the basin fill and top basement horizon, suggesting that there is local variation in the Moho surface which is not visible in the seismic and is not captured by regional Moho models. This variation, or 'steps' in the Moho on a 10-50 km scale, may be related to the basement shear zones interpreted in seismic data.



**Figure 2. Isostatic residual gravity image of the Ceduna Sub-basin (histogram equalised, 150 mGal range). Black lines are BightSPAN™ seismic lines, and red lines are the seismic section described in Hill et al. (this volume). Green ellipse shows the location of the Stromlo High.**

Gravity models identify two main depocentres in the Ceduna-Sub-basin; one trending eastwards in the northwest of the sub-basin and another trending south-easterly in the central part of the sub-basin. Both depocentres are up to 25 km deep, substantially deeper than previous estimates. Hyperextended continental crust underlies the depocentres and in places is less than 10 km thick. A thicker piece of crust on the outer part of the margin underlies the Stromlo High.

## DISCUSSION

Recent models of rifting suggest that the lower crust is often much weaker than suggested by traditional models, and may contain structures such as boudinage and shallow-dipping ductile shear zones (Clerc et al., 2018). Such structures are visible in places in the BightSPAN™ data, and interpretation of a locally variable Moho depth is supported by the gravity models.

The 2D forward models of the gravity response show very thin crust underlying the Ceduna depocentres overlain by a substantial thickness of syn-rift sediment that is not clearly visible on conventional seismic data. Thicker crust under the outboard part of the basin, including the Stromlo High area, suggests that extension in the mid-late Jurassic was focussed inboard under the present-day Ceduna depocentre, then jumped to the outer margin where breakup eventually occurred in the Late Cretaceous. This change in the location of extension was likely influenced by the overall crustal rheology including crustal heterogeneities and may also have been influenced by changes in the extension rate (Tetreault & Buijter, 2018).

The concept of a simple linear boundary between continental and oceanic crust at rift margins is now recognised as an oversimplification (Eagles et al., 2015). In this study, the transition from continental to oceanic crust is unclear in both the seismic data and the gravity models but there is a gradual increase in basement density to the south. This increase in density likely represents a greater input of intrusive and extrusive igneous rocks towards the south west margin of the basin, and the gradual transition from continental to oceanic crust.

Modelling is limited by the wide spacing of the deep crustal lines, but future work will involve modelling of more lines to produce a regional 3D model of crustal structure across the Ceduna Sub-basin.

## CONCLUSIONS

Gravity modelling of deep crustal seismic lines across the Ceduna Sub-basin shows very thin crust (<10 km) underlying the Ceduna depocentre, overlain by several km of syn-rift sediments which are not discernible on conventional seismic data. Local variations in the Moho surface are interpreted as crustal-scale shear zones offsetting the Moho and boudinage of a weak lower crust.

The transition from continental to oceanic crust is gradual and is represented by an increase in crustal density to the south, interpreted as increasing input of igneous material. Lower than expected density of the crust in the southern part of the sections is interpreted as serpentinised mantle.

The results of this work are used to constrain the tectonic evolution, particularly in terms of the subsidence history and uplift and erosional pulses recorded on the seismic data in the Ceduna Delta (Hill et al., this volume) and then used as input for finite element numerical models of rifting (Farrington et al., this volume). Future work will include modelling of other BightSPAN™ seismic lines including east-west cross lines, to produce a 3D forward model of the crust underlying the Ceduna Sub-basin.

## ACKNOWLEDGEMENTS

We would like to thank ION Geophysical for the BightSPAN™ seismic dataset. Geoscience Australia provided seismic line GA199-04. We thank Schlumberger for providing the Petrel licence and Geosoft for providing Oasis Montaj and GM-SYS licences.

## REFERENCES

- Aitken, A.R.A., 2010. Moho geometry gravity inversion experiment (MoGGIE): A refined model of the Australian Moho, and its tectonic and isostatic implications. *Earth and Planetary Science Letters* 297, 71-83.
- Ball, P., G. Eagles, C. Ebinger, K. McClay, and T. Totterdell, (2013), The spatial and temporal evolution of strain during the separation of Australia and Antarctica, *Geochem. Geophys. Geosyst.*, 14, (8) 2771–2799, doi:10.1002/ggge.20160
- Blevin and Cathro, 2008, Australian Southern Margin Synthesis, Project GA707, Client Report to Geoscience Australia by FrOG Tech Pty Ltd. <https://d28rz98at9flks.cloudfront.net/68892/68892.pdf>, retrieved 11/04/2019.
- Brune, S., Heine, C., Clift, P.D., Pérez-Gussinyé, M., 2017. Rifted margin architecture and crustal rheology: reviewing Iberia-Newfoundland, central South Atlantic, and South China Sea. *Marine and Petroleum Geology*, 79, 257-281.
- Clerc, C., Ringenbach, J.C., Jolivet, L., Ballard, J.-F., 2018. Rifted margins: Ductile deformation, boudinage, continentward-dipping normal faults and the role of the weak lower crust. *Gondwana Research*, 53, pp. 20-40
- Direen, N.G., 2011a. Comment on “Antarctica — before and after Gondwana” by S.D. Boger *Gondwana Research*, 19(2), March 2011, pp. 335–371. *Gondwana Research* 21 (1), 302–304. <http://dx.doi.org/10.1016/j.gr.2011.08.008>.
- Direen, N. G., Stagg, H. M. J., Symonds, P. A. & Colwell, J. B. 2011b. Dominant symmetry of a conjugate southern Australian and East Antarctic magmapoor rifted margin segment. *Geochemistry Geophysics Geosystems*, 12, Q02006, doi: 10.1029/2010gc.003306.
- Direen, N. J., H. M. J. Stagg, P. A. Symonds, and I. O. Norton (2012), Variations in rift symmetry: Cautionary examples from the Southern Rift System (Australia-Antarctica), in *Conjugate Divergent Margins*, vol. 369, edited by W. Mohriak, M. Nemcok, A. Danforth, and S. Sinha, pp. 1–20, *Geol. Soc. Spec. Publ.*, London, doi:10.1144/SP369.4
- Duret, T., Petri, B., Mohn, G., Schmalholz, S.M., Schenker, F.L., Müntener, O., 2016. The importance of structural softening for the evolution and architecture of passive margins. *Sci. Rep.* 6, 38704. <https://doi.org/10.1038/srep38704>
- Eagles, G., Perez-Diaz, L., Scarselli, N., 2015. Getting over continent ocean boundaries. *Earth Science Reviews*, 151, 244-265.

- Espurt, N., Callot, J.-P., Totterdell, J., Struckmeyer, H. and Vially, R., 2009. Interactions between continental breakup dynamics and large-scale delta system evolution: insights from the Cretaceous Ceduna delta system, Bight Basin, Southern Australian margin. *Tectonics*, 28, TC6002.
- Farrington R., Beucher R., Hill K.C. and Cunneen J., this volume. The Bight Basin, Evolution & Prospectivity III; Underworld Finite Element modelling, maturity & migration.
- Gibson, G.M., Totterdell, J.M., White, L.T., Mitchell, C.H., Stacey, A.R., Morse, M.P., Whitaker, A., 2013. Pre-existing basement structure and its influence on continental rifting and fracture zone development along Australia's southern rifted margin. *Journal of the Geological Society* 170, 365–377. <http://dx.doi.org/10.1144/jgs2012-040>.
- Hill, K.C., Cunneen, J.C., & Farrington, R., this volume. The Bight Basin, Evolution & Prospectivity II: Seismic, structure and balanced sections.
- Kennett, B.L.N., Salmon, M.L., Saygin, E., 2011. AusMoho: the variation of Moho depth in Australia. *Geophysical Journal International* 187, 946-958.
- Struckmeyer, H.I.M., Totterdell, J.M., Blevin, J.E., Logan, G.A., Boreham, C.J., Deighton, I., Krassay, A.A. & Bradshaw, M.T., 2001. Character, maturity and distribution of potential Cretaceous oil source rocks in the Ceduna Sub-basin, Bight Basin, Great Australian Bight. In: Hill, K.C. & Bernecker, T. (Editors), Eastern Australian Basin Symposium: a refocused energy perspective for the future. Petroleum Exploration Society of Australia, Special Publication, 543–552.
- Tetreault, J.L., & Buitter, S.J.H., 2018. The influence of extension rate and crustal rheology on the evolution of passive margins from rifting to break-up. *Tectonophysics*, 746, 155-172, doi:10.1016/j.tecto.2017.08.029
- Totterdell, J.M., Bradshaw, B.E., 2004. The structural framework and tectonic evolution of the Bight Basin. In: Boulton, P.J., Johns, D.R., Lang, S.C. (Eds.), Eastern Australasian Basins Symposium II. Petroleum Exploration Society of Australia, Adelaide, South Australia, pp. 41–61.
- Totterdell, J.M., Hall, L., Hashimoto, T., Owen, K. and Bradshaw, M.T., 2014. Petroleum geology inventory of Australia's offshore frontier basins. Record 2014/09. Geoscience Australia, Canberra. <http://dx.doi.org/10.11636/Record.2014.009>
- White, L., Gibson, G., and Lister, G., 2013, A reassessment of paleogeographic reconstructions of eastern Gondwana: Bringing geology back into the equation: *Gondwana Research*, 24, p. 984-998.
- Whittaker, J. M., S. E. Williams, and R. D. Muller (2013), Revised tectonic evolution of the eastern Indian Ocean, *Geochem.Geophys. Geosyst.*, doi:10.1002/ggge.20120
- Williams, S. E., Whittaker, J. M., and Muller, R. D. (2011), Full-fit, palinspastic reconstruction of the conjugate Australian–Antarctic margins, *Tectonics*, 30, TC6012, doi:10.1029/2011TC002912.
- Williams, S.E., Whittaker, J.M., Halpin, J.A., Müller, R.D., 2019. Australian-Antarctic breakup and seafloor spreading: balancing geological and geophysical constraints. *Earth-Sci. Rev.* 188, 41–58.