Petroleum system modelling of the deep-water Otway Basin

Oliver Schenk
Schlumberger GmbH
Ritterstr. 23
52072 Aachen, Germany
OSchenk@slb.com

Emmanuelle Grosjean
Geoscience Australia
GPO Box 378
Canberra ACT 2601, Australia
Emmanuelle.Grosjean@ga.gov.au

Dianne S. Edwards
Geoscience Australia
GPO Box 378
Canberra ACT 2601, Australia
Dianne.Edwards@ga.gov.au

Christopher J. Boreham
Geoscience Australia
GPO Box 378
Canberra ACT 2601, Australia
Chris.Boreham@ga.gov.au

Tekena West
Schlumberger
Buckingham Gate, Horley
Gatwick RH6 0NZ, West Sussex, UK
TWest2@slb.com

Alexander Karvelas
Schlumberger
Level 5, 256 St Georges Terrace
Perth WA 6000, Australia
AKarvelas@slb.com

Duplo Kornpihl
Schlumberger GmbH
Ritterstr. 23
52072 Aachen, Germany
KKornpihl@slb.com

SUMMARY

The Otway Basin is a broadly northwest-southeast trending basin and forms part of a rift system that developed along Australia's southern margin. It is an established hydrocarbon province with onshore and shallow-water offshore discoveries. The outboard deep-water Otway Basin, with water depths ranging from 500 m to 6300 m, is comparatively underexplored and considered a frontier area. Following the completion of a basin-wide seismic program in 2020 and insights from revised regional seismic interpretation, we undertook a comprehensive petroleum system modelling (PSM) study, integrating these data and findings.

The modelling results indicate that hydrocarbon generation is mainly controlled by burial of Upper Cretaceous intervals (Shipwreck and Sherbrook supersequences), especially in the deep-water areas of the basin where generation is predicted to have ceased at the end of the Cretaceous. Towards the southeast, source rocks are generally shallower at present-day, and this part of the basin was also less affected by Late Cretaceous erosion, resulting in greater post-Cretaceous hydrocarbon potential. There are several areas across the basin where modelled generation from Upper Cretaceous source rocks occurred during the Cenozoic. These are located 1) in the far outboard areas of the study area where isolated Cenozoic depocenters exist, and 2) in tilted fault blocks closer to the current shelf edge where they are positively influenced by the late burial of the Heytesbury and Whalers Bluff supersequences. In the deep-water part of the basin, where postulated source rocks are overmature prior to seal effectiveness, model results still predict hydrocarbon potential due to the modelled slow migration of hydrocarbons through mud-dominated intervals, charging potential traps later when seals are effective.

The regional PSM study represents a framework for improved understanding of the dynamic evolution of the Otway Basin and its complex thermal and charge history. Model refinements and additional sensitivity analyses should enable play elements to be better defined.

Key words: Otway Basin, petroleum system modelling, thermal history, hydrocarbon prospectivity

INTRODUCTION

The Otway Basin is a northwest-southeast trending on- and offshore rift basin that extends from southeast South Australia to southwest Victoria and offshore northwest Tasmania (Figure 1). It is an established hydrocarbon-producing province with most discoveries made onshore and on the continental shelf. In contrast, the deep-water area, with water depths up to 6300 m, is relatively underexplored with no wells drilled at water depths greater than 1500 m and that includes the three most outboard wells Amrit 1, Somerset 1 and Morum 1, with water depths of 1425 m, 525 m, and 294 m, respectively.

The Otway Basin is part of the Southern Rift System between Australia and Antarctica, which developed during the fragmentation of Gondwana, forming the extensional basins of the southern margin. The largely N–S directed extension along the southern margin of Australia was diachronous, starting in the west during the mid-Jurassic and becoming progressively younger towards the east during the Early Cretaceous (Romine *et al.*, 2020). It was followed by a phase of predominantly thermal subsidence during the Aptian and Albian, before major plate tectonic reorganisation in the Cenomanian resulted in compression and reactivation of extensional faults along the southern margin (Blevin and Cathro, 2008). Commencing in the west during the Turonian, a second phase of extension affected Australia's southern margin, which ultimately led to continental break-up. The extension propagated from N-S in the west to NE-SW in the east. The diachronous nature of this phase of extension is evident by the ages of seafloor spreading, with oceanic crust forming in the Bight Basin in the west at ~83 Ma (Sayers *et al.*, 2001), off the Otway Basin at ~65 Ma, and off western Tasmania at ~55 Ma (Gibson *et al.*, 2012). Continuing N–S extension separated Antarctica from Australia at ~35 Ma, leading to the development of the circum-Antarctic current and open-marine conditions along the entire southern margin.

The key objective of this Otway Basin regional study was an improved understanding of the hydrocarbon prospectivity of the deep-water Otway Basin. The recent 2020 Otway Basin 2D seismic program allowed for new insights into the distribution of regional stratigraphic supersequences, both laterally across the basin and from the shelf towards the deep-water areas (Abbott *et al.*, 2023; Nicholson *et al.,* 2022). This refined mapping of the supersequences has been used in the development of an integrated petroleum system modelling (PSM) study that expands on our preliminary results (Schenk *et al.*, 2021a). A comprehensive report with detailed input parameters and modelling results is available on NOPIMS (Schenk *et al.*, 2021b)

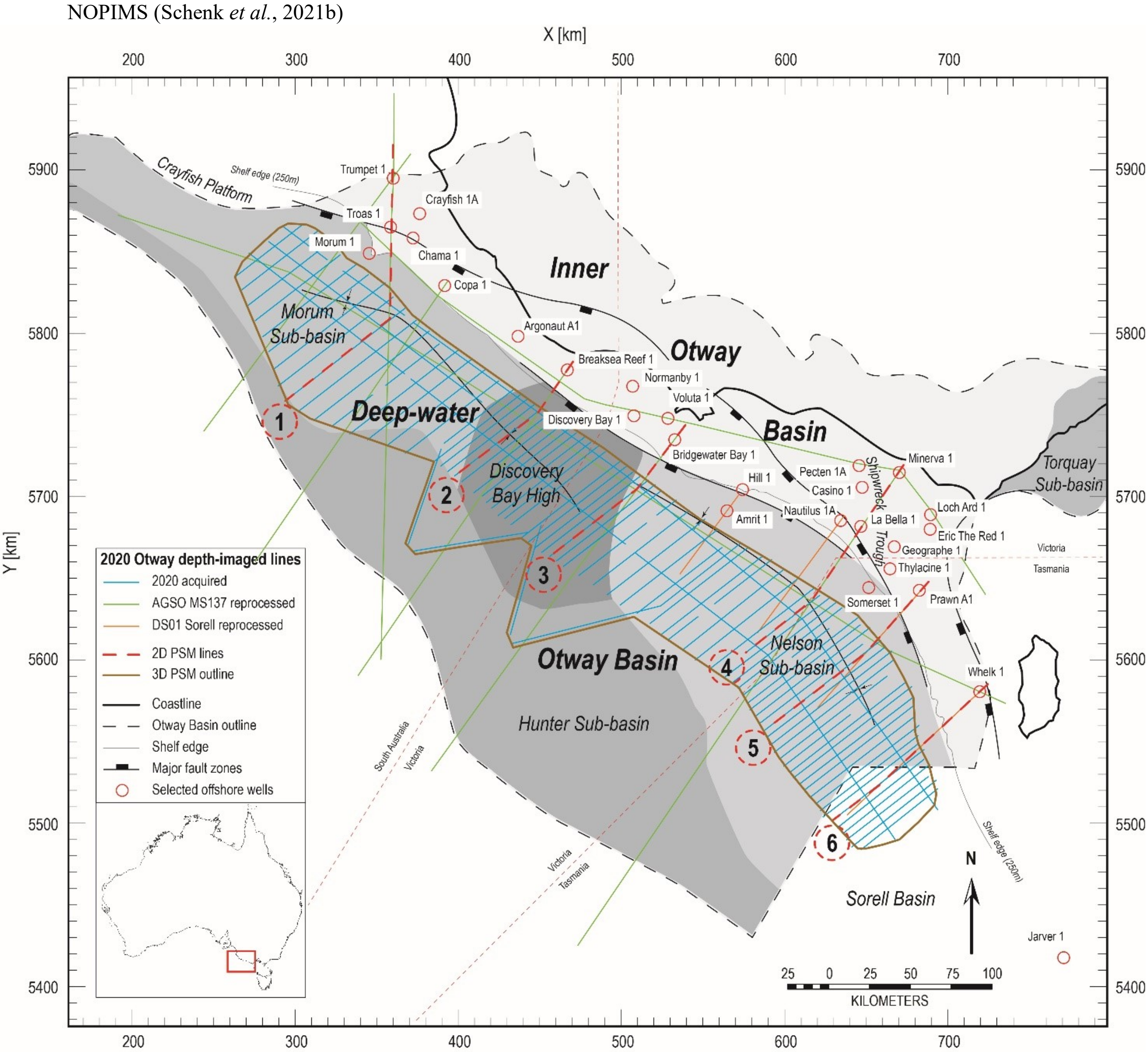

Figure 1. Map of the Otway Basin showing the 2020 acquired Otway seismic survey, AGSO and DSO1 lines (both reprocessed in 2020) and selected offshore wells. The map also shows the six composite lines used for 2D and the outline for the 3D petroleum system modelling (PSM), respectively. The location of sub-basins is adopted from Totterdell *et al.* (2014), and the major fault zones are plotted after Krassay *et al.* (2004).

PETROLEUM SYSTEM MODELLING

Model Input

The basis for our petroleum system modelling study is the interpretation of data from the 2020 Otway Basin 2D seismic program. This regional program acquired 2D reflection seismic data in the deep-water part of the Otway basin and was jointly processed together with selected lines from the AGSO MS137 and DS01 Sorell 2D seismic surveys that intersect wells on the continental slope and shelf. Extending the 2D PSM models towards the continental shelf to integrate well information was necessary to constrain interpretation of regional horizons, litho- and organo-facies assignment and their distribution, erosion reconstruction, and thermal calibration. Determined by data availability from wells, we selected six composite seismic sections for 2D petroleum system modelling with the aim to provide a representative regional spread across the offshore Otway Basin (Figures 1, 2). Eight interpreted supersequence boundaries after Krassay *et al.* (2004) and four additionally interpreted markers form the basis for the model framework (Figure 3).

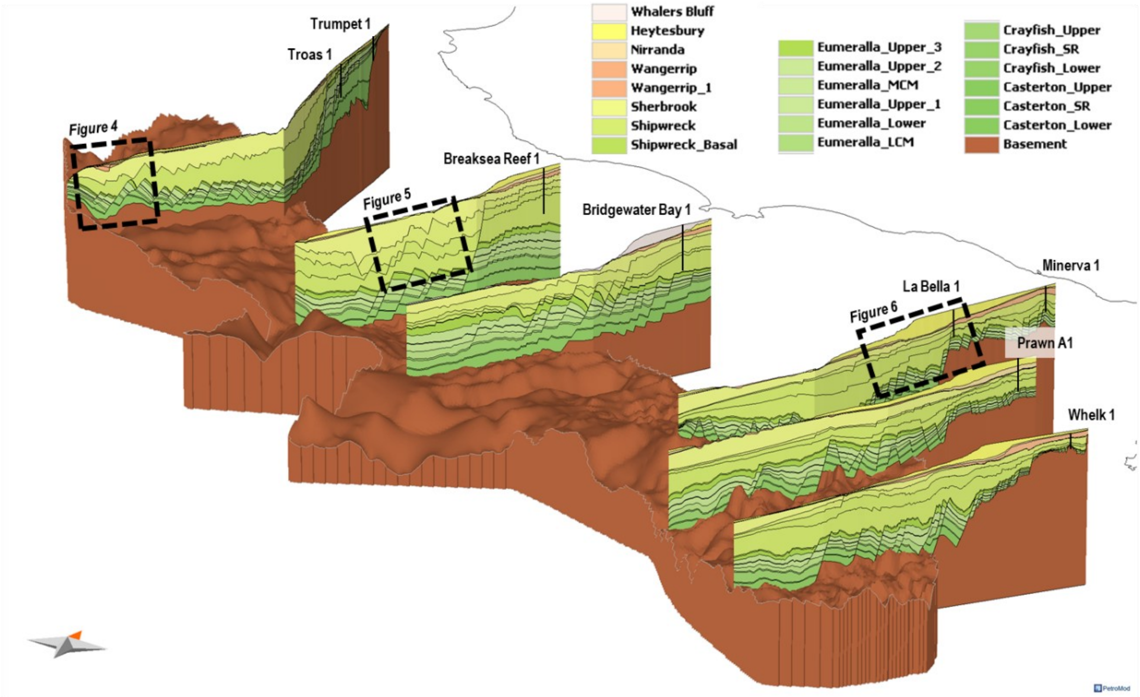

Figure 2. Three-dimensional view of the six 2D PSM lines extending from the shelf into the deep-water area of the Otway Basin. The 3D PSM covers the deep-water part of the Otway Basin and is highlighted by the interpreted structure of the top of the basement. Dashed boxes refer to charge history examples shown in Figures 4 to 6.

Key petroleum system elements are highlighted in Figure 3. In our modelling proven and postulated source rocks are assigned according to the 'Austral Supersystem' (A1, A2 and A3; e.g., Bradshaw, 1993) (Table 1). Source rock information from the continental shelf and onshore Otway Basin along with an analogue of organic-rich marine source rock from the Bight Basin were integrated conceptually for the deep-water area. In our models, emphasis was placed on postulated Turonian–Santonian Shipwreck Supersequence source rocks. Global anoxic conditions were present in the Turonian with good potential for high-quality source rocks to be developed in deeper, more distal marine depositional environments (Boreham *et al.*, 2004) as demonstrated in the adjacent Ceduna Sub-basin (Totterdell *et al.*, 2008). Customised multicomponent source rock kinetics acquired for Bight Basin dredge samples (Boreham, 2009) were assigned to postulated Turonian–Santonian organic-rich shales, as no such source rocks are intersected in the inboard Otway Basin for the Shipwreck Supersequence. Additional postulated Austral 1 and 2 and Belfast Mudstone-equivalent (Austral 3) source rocks have been integrated in the models conceptually, being included as part of stacked intervals with regular spacing between the mapped tops of the supersequences, where Pepper and Corvi (1995) kinetics were assigned (Table 1). The most important reservoir rocks in the deep-water Otway Basin included in the models occur within the Shipwreck Supersequence and are equivalent to the Turonian Waarre Formation and the Santonian Thylacine Sandstone Member. In addition, we considered reservoirs in the Lower Cretaceous rift-related Crayfish (Pretty Hill Formation) and Eumeralla (intra-Eumeralla sag-phase sandstones) supersequences. The regional seal is placed within the Shipwreck Supersequence being equivalent to the Coniacian–Santonian Belfast Mudstone. Additional intraformational shale-dominated seals within the Lower Cretaceous to Paleogene succession were modelled for their sealing efficiency in the individual sub-basins through geologic time.

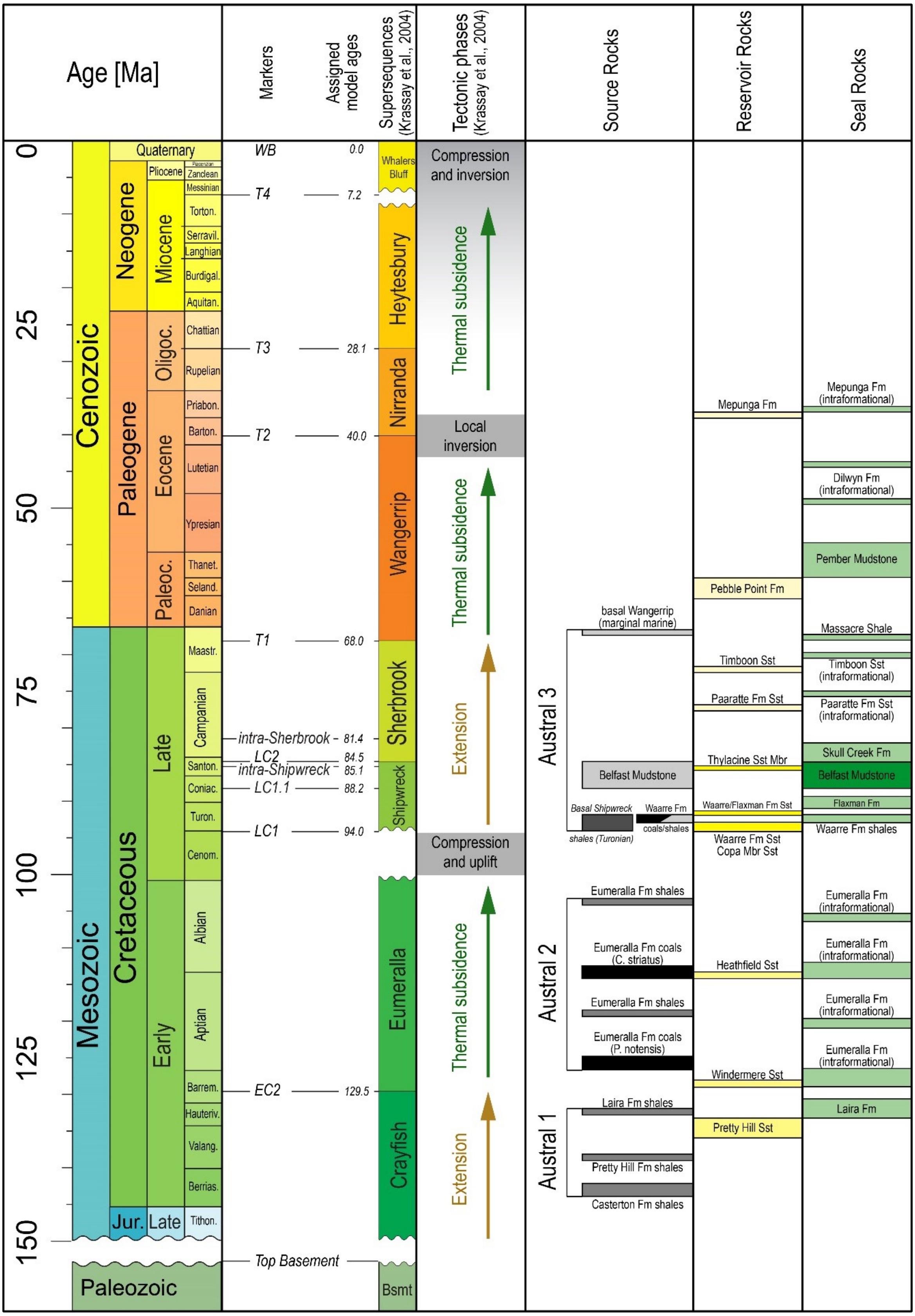

Figure 3. Simplified stratigraphic column of the Otway Basin including proven and postulated petroleum system elements. Stratigraphic ages are adopted from Charles et al. (2019), and supersequence nomenclature and tectonic events are from Krassay *et al.* (2004) with additional information from Boreham *et al.* (2004), Totterdell *et al.* (2008; 2014), Boreham (2009), and Santos (2015).

To constrain the basin's thermal history, we used results derived from gravity and magnetic data, i.e., the depth of the Mohorovičić discontinuity and the lithosphere-asthenosphere boundary. We calculated the regional present-day basal heat flow by integrating the lithospheric thicknesses into the crustal model, comparing the modelling results with the corrected temperature data, and by finally adjusting the lithospheric thickness where necessary. To estimate the paleo-basal heat flow we shifted the predicted present-day basal heat flow values for paleo-events by estimating trends according to the tectonostratigraphic evolution. Local adjustments were required to better match vitrinite reflectance data. Although this hybrid workflow of combining a crustal model for the present-day and adjusting the basal heat flow trends for paleo-events is based on many assumptions and simplifications, the models reflect lower heat flow values for the deep-water area as a result of thinned Upper and Lower Crust, which has significant implications on the timing of maturity of source rocks postulated for the deep-water areas of the Otway Basin.

Austral Supersystem	***Source rock (SR)* [Litho-facies (model) name]**	***TOC_o* [%]**	***HI_o* [mgHC/gTOC]**	***Thickness* [m]**	***Kerogen type***	***Source rock kinetic***
Austral 3	Shipwreck – Belfast SR proximal	1	150	~50-150	III/IV	F
	Shipwreck – Belfast SR distal	1	350	~50-150	II	B
	Shipwreck – Waarre B coal	1	250	~100	III	DE
	Shipwreck – Basal SR	2	550	100	II	Customized
Austral 2	Eumeralla – Mid Coal Measures	2	300	50	II/III	DE
	Eumeralla – Shaly SR	1	150	~50-150	III	DE
	Eumeralla – Lower Coal Measures	1	250	150	II/III	DE
Austral 1	Crayfish – Shaly SR	1	250	100	II/III	DE
	Casterton Formation SR	1	600	0-100	I	C

Table 1. Source rock properties assigned to the individual facies for the 2D and 3D petroleum system modelling. Estimated original HI (HI_o) and TOC (TOC_o) values are generalized and based on well information from Geoscience Australia's database, public reports, and conceptual ideas. Assigned source rock kinetics are based on Pepper and Corvi's (1995) organo-facies classification, except for the postulated Turonian–Santonian (basal Shipwreck Supersequence) organic-rich shales to which we assigned the customized multicomponent kinetic acquired from the Bight Basin dredge samples (Boreham, 2009).

Results

Thermal calibration data from 35 offshore wells were quality-controlled, sorted, and colour-coded by laboratories and analysts, and ranked by data reliability. Our thermal modelling setup allowed for a good calibration against corrected temperature and vitrinite reflectance data on the shelf. It also predicts the thermal regime in the deep-water areas of the basin with lower temperatures compared to the shelf resulting from a combination of both greater (paleo-) water depth and lower basal heat flow due to a comparably thinner crust.

Modelling results show that hydrocarbon generation is mainly driven by the burial of the Upper Cretaceous Shipwreck and Sherbrook supersequences, especially in the deep-water areas of the basin where hydrocarbon generation is predicted to have ceased over large areas at the end of the Cretaceous. Reconstruction of maximum burial is critical for modelling source-rock maturity and petroleum-charge timing. The areal extent and amount of erosion for the Sherbrook Supersequence have been reconstructed for the Late Cretaceous guided by the seismic sections flattened to the interpreted T1 unconformity event. In the Nelson Sub-basin, represented by PSM lines 4 to 6, the modelled source rocks are generally shallower at present-day. In addition, it appears that regionally, this southeastern part of the deep-water Otway Basin was less affected by Late Cretaceous erosion which results in greater post-Cretaceous hydrocarbon potential. There are several areas where Upper Cretaceous source rocks generate hydrocarbons during the Cenozoic. Some of them are located in the far outboard areas of the study area where isolated Cenozoic depocenters are present, whereas others occur closer to the current shelf edge being affected by the late burial of the Heytesbury and Whalers Bluff supersequences.

In the following, we show some charge history examples to evaluate the hydrocarbon prospectivity of the deep-water Otway Basin. PSM Line 1 in the Morum Sub-basin shows an example of modelled accumulations in the very outboard areas of the study area, where a Wangerrip Supersequence depocenter has been interpreted from seismic data (Figure 4). Here, the combination of deep-water setting and shallower Cretaceous intervals results in lower thermal maturity of the source rocks. The time extraction for the Basal Shipwreck distal source rock shows that hydrocarbon generation started during the Late Cretaceous but continues into the Cenozoic as result of Wangerrip Supersequence burial. The Belfast Mudstone is modelled to be able to seal some postulated distal reservoir sands. The time extraction shows that sealing efficiency is predicted to have improved significantly during the Campanian, in parallel with hydrocarbon generation from of the Basal Shipwreck distal source rock. The timing for such a play is promising. Source rock tracking indicates that the predicted accumulation is also charged from Austral 1 and Austral 2 source rocks.

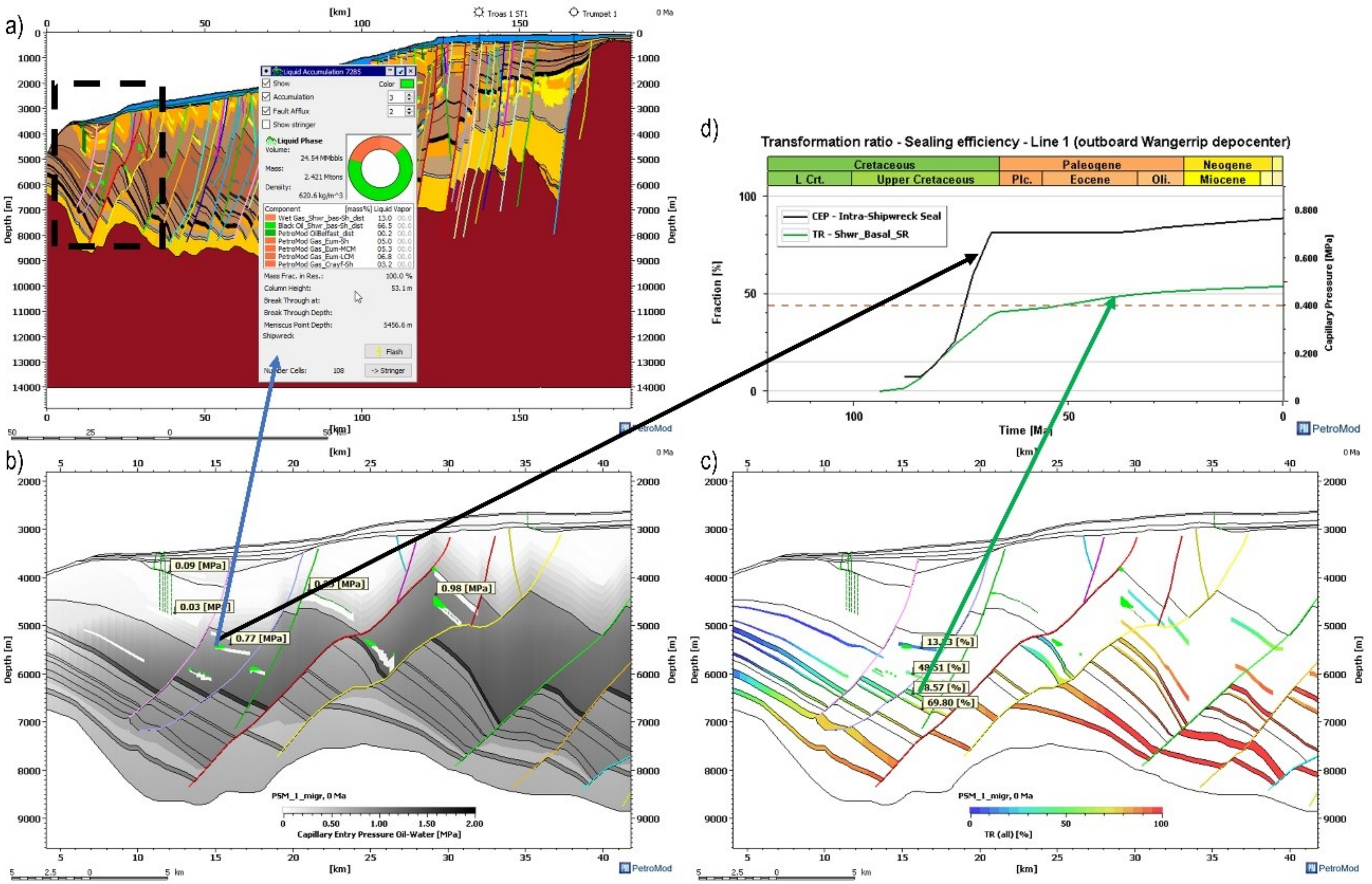

Figure 4. Charge timing of a predicted accumulation underlying a Wangerrip depocenter in the outboard part of PSM Line 1: a) modelled section highlighting detail; b) predicted sealing efficiency of the focus area; c) transformation ratio of source rocks for the focus area; d) timing relationship of transformation ratio and sealing efficiency.

Further southeast on the Discovery Bay High, several accumulations have been predicted in stacked reservoirs within the Shipwreck Supersequence along PSM Line 2 (Figure 5). Compared to other deep-water areas in the Otway Basin the predicted capillary entry pressures of the mud-dominated Upper Cretaceous intervals is higher due to the significant erosion of the Sherbrook Supersequence at the end of the Cretaceous. Time extractions indicate that the Basal Shipwreck Supersequence distal source rock reached almost a transformation ratio of 100% at ~ 80 Ma, when the capillary pressure of sealing Belfast Mudstone started to be efficient (~0.4 MPa), suggesting unfavourable timing for hydrocarbon charge from this Basal Shipwreck Supersequence distal source rock. However, the modelled accumulation predicts ~40% contribution from this source rock. We interpret this as the result of retarded hydrocarbons through this low permeable Belfast Mudstone, possibly preventing hydrocarbon losses.

Such retarded migration is also predicted for an accumulation in a tilted fault block close to the shelf edge near La Bella 1 along PSM Line 4 (Figure 6). The contribution from the Basal Shipwreck distal source rock is in excess of 80%; however, only limited hydrocarbon generation from this source rock has been predicted since the end of the Cretaceous. The Belfast Mudstone sealing the postulated basin floor fan is predicted to work efficiently from Miocene times onwards driven by the significant burial of the Heytesbury Supersequence. This is much later than the end of hydrocarbon generation from Basal Shipwreck distal source rock, which suggests that the Belfast Mudstone is capable of keeping hydrocarbons within the system. Modelling results point to favourable timing in other areas in the Nelson Sub-basin where the sealing efficiency of the Belfast Mudstone capping a Thylacine Sandstone equivalents has been modelled to predate the generation of hydrocarbons from the Basal Shipwreck Supersequence distal source rock. Such setting is especially promising close to the shelf edge where the impact of Cenozoic burial is most significant resulting in a late pulse of hydrocarbon generation and expulsion.

CONCLUSIONS

Hydrocarbon prospectivity of the deep-water Otway Basin depends largely on the presence, depth, and properties of postulated source rocks. Critical for source rock maturity and petroleum charge timing is the burial history, including the maximum depth of burial, and the timing and extent of any uplift and erosion. The revised seismic interpretation of the Otway Basin regional study provided new insights into the distribution of the regional stratigraphic supersequences and their thickness distribution. These are key elements for evaluating the timing of hydrocarbon generation from the various postulated Austral source rocks.

Petroleum systems in the deep-water areas are mainly influenced by the burial of thick Upper Cretaceous intervals (Shipwreck and Sherbrook supersequences), resulting in postulated Austral 1 and 2 source rocks being overmature by the Late Cretaceous. As such, hydrocarbon prospectivity in the deep-water Otway Basin depends largely on the deposition and depth of postulated Austral 3 source rocks, and on the timing of hydrocarbon generation in relation to trap formation and seal effectiveness.

PSM results indicate that hydrocarbon generation is mainly controlled by the burial of Upper Cretaceous intervals (Shipwreck and Sherbrook supersequences), especially over large areas of the deep-water basin where hydrocarbon generation is predicted to have almost ceased at the end of the Cretaceous. Towards the southeast, source rocks are generally shallower at present-day, and regionally it appears that the southeastern part of the basin was less affected by Late Cretaceous erosion, resulting in greater post-Cretaceous hydrocarbon potential. Areas exist where Upper Cretaceous source rocks are predicted to generate hydrocarbons during the Cenozoic. These are located in the far outboard areas of the study area where isolated Cenozoic depocenters are present. They also occur in tilted fault blocks closer to the current shelf edge and are positively influenced by the late burial of Heytesbury and Whalers Bluff supersequences. Even in the deep-water part of the basin where postulated source rocks are overmature prior to seal effectiveness, model results predict hydrocarbon potential due to slow hydrocarbon migration through mud-dominated intervals and retarded charge.

The regional PSM study represents a framework for improved understanding of the dynamic evolution of the Otway Basin and its complex thermal and charge history. It provides an ideal basis for model refinements and additional sensitivity analyses.

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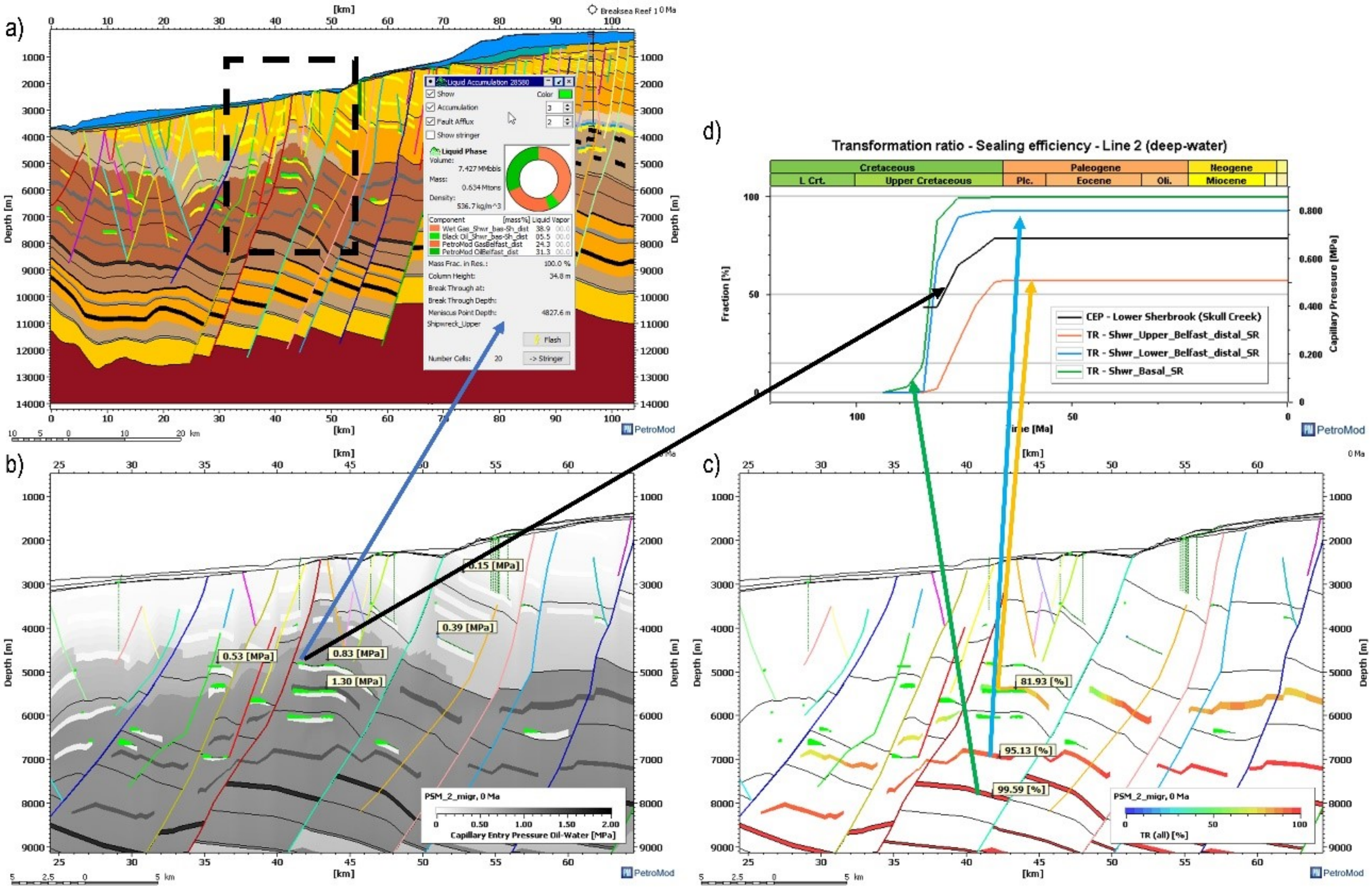

Figure 5. Charge timing of a predicted accumulation in the Late Cretaceous deep-water depocenter along PSM Line 2: a) modelled section highlighting detail; b) predicted sealing efficiency of the focus area; c) transformation ratio of source rocks for the focus area; d) timing relationship of transformation ratio and sealing efficiency.

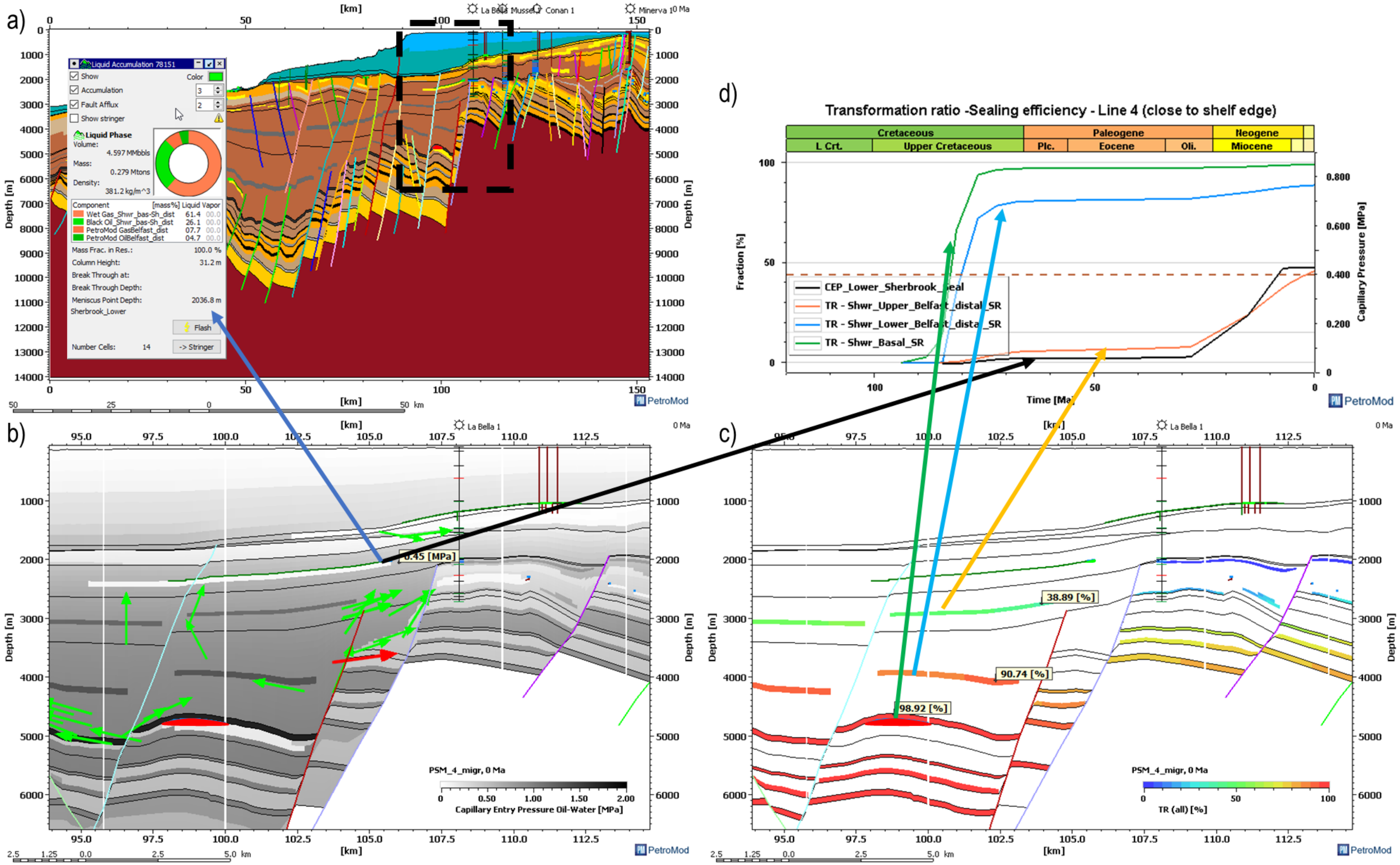

Figure 6. Charge timing of a predicted accumulation close to the shelf edge along PSM Line 4: a) modelled section highlighting detail; b) predicted sealing efficiency of the focus area; c) transformation ratio of source rocks for the focus area; d) timing relationship of transformation ratio and sealing efficiency.

REFERENCES

Abbott, S., Cubitt, C., Bernardel, G., Nicholson, C., and Nguyen, Duy., 2023, Towards a regional understanding of Sherbrook Supersequence Gross Depositional Environments, offshore Otway Basin: Extended Abstracts, 4th AEGC: Geoscience – Breaking New Ground, Brisbane, Australia.

Blevin, J., and Cathro, D., 2008, Australian southern margin synthesis: Project GA707, Client Report to Geoscience Australia by FrOG Tech Pty Ltd., Canberra.

Boreham, C.J., Hope, J.M., Jackson, P. Davenport, R., Earl, K. I., Edwards, D.S., Logan, G.A., and Krassay, A.A., 2004, Gas-oil-source rock correlations in the Otway Basin: In 'PESA Eastern Australasian Basins Symposium II, Adelaide, 19-22 September 2004' (Eds P.J. Boult, D.R. Johns, and S.C. Lang), 603-627.

Boreham, C.J., 2009, Organic geochemistry – source rock characterisation. In 'Bight Basin Geological Sampling and Seepage Survey, RV Southern Surveyor Survey SS01/2007: Geoscience Australia Record 2009/24, Canberra. (Eds J.M. Totterdell, and C.H. Mitchell), 36-60.

Bradshaw, M.T., 1993, Australian Petroleum Systems: PESA Journal 21, 43-53.

Charles, A., Hannaford, C. Korasidis, V., Lignum, J. Macphail, M., Mantle, D., Morgan, R., Schioler, P., and Young, M., 2019, New palynology results from legacy core and cuttings: Onshore Otway Basin, Victoria: Victorian Gas Program Technical Report 7, Melbourne.

Gibson, G.M., Totterdell, J.M., Morse, M.P., Goncharov, A., Mitchell, C.H., and Stacey, A.R., 2012, Basement structure and its influence on the pattern and geometry of continental rifting and breakup along Australia's southern rift margin: Geoscience Australia Record 2012/47, Canberra.

Krassay, A.A., Cathro, D.L., and Ryan, D.J., 2004, A regional tectonostratigraphic framework for the Otway Basin: In 'PESA Eastern Australasian Basins Symposium II, Adelaide, 19-22 September 2004' (Eds P.J. Boult, D. R. Johns, and S. C. Lang), 97-116.

Nicholson, C., Abbott, S., Bernardel, G., and Gunning, M.-E., 2022, Stratigraphic and structural architecture of the Upper Cretaceous in the deep-water Otway Basin—implications for frontier hydrocarbon prospectivity: The APPEA Journal, 62, S467-S473, https://doi.org/10.1071/AJ21072.

Pepper, A.S. and Corvi, P.J., 1995, Simple kinetic models of petroleum formation: Part I. Oil and gas generation from kerogen: Marine and Petroleum Geology, 12, 291-319.

Romine, K. Vizy, J., Nelson, G., Lee, J. D., Baird, J., and Boyd, M., 2020, Regional 3D geological framework model: Otway Basin, Victoria: Victorian Gas Program Technical Report 35, Melbourne.

Santos, 2015, Seismic interpretation report OTSAN13R1 PSDM Reprocessing, Exploration Permit VIC/P44.

Sayers, J. Symonds, P.A., Direen, N.G., and Bernandel, G., 2001, Nature of the continent-ocean transition on the non-volcanic rifted margin of the central Great Australian Bight: In 'Non-Volcanic Rifting of Continental Margin: A Comparison of Evidence from Land and Sea' (Eds R.C.L. Wilson, R.B. Whitmarsh, B. Taylor, and N. Froitzheim): Geological Society of London Special Publication, 187, 51-76.

Schenk, O., Grosjean, E., Edwards, D.S., Boreham, C.J., West, T., and Karvelas, A., 2021a, New insights into the deep-water Otway Basin - Part 3: Petroleum system modelling: APPEA Journal 61, doi:10.1071/AJ20078.

Schenk, O., Karvelas, A., West, T., and Kornpihl, D., 2021b, Otway Basin regional study report: Report for Geoscience Australia: Available at https://www.ga.gov.au/nopims/releases/otway-basin-regional-study-report.

Totterdell, J.M., Struckmeyer, H.I.M., Boreham, C.J., Mitchell, C.H., Monteil, E., and Bradshaw, B.E., 2008, Mid-Late Cretaceous organic-rich rocks from the eastern Bight Basin: implications for prospectivity: In 'PESA Eastern Australasian Basins Symposium III, Sydney, 14-17 September 2008' (Eds J.E. Blevin, B.E. Bradshaw, and C.I. Uruski), 137-158.

Totterdell, J., Hall, L., Hashimoto, R., Owen, K., and Bradshaw, M., 2014, Petroleum geology inventory of Australia's offshore frontier basins: Geoscience Australia Record 2014/09, Canberra https://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search#/metadata/79058