Understanding potential resource prospectivity: 1-D burial and thermal history modelling of the Adavale Basin

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SUMMARY

Lateral variation in maturity of potential Devonian source rocks in the Adavale Basin have been investigated using nine 1D burial thermal and petroleum generation history models, constructed using existing open file data. These models provide an estimate of the hydrocarbon generation potential of the basin. Total organic carbon (TOC) content and pyrolysis data indicate that the Log Creek Formation, Bury Limestone and shale units of the Buckabie Formation have the most potential as source rocks. The Log Creek Formation and the Bury Limestone are the most likely targets for unconventional gas exploration.

The models were constructed using geological information from well completion reports to assign formation tops and stratigraphic ages to then forward-model the evolution of geophysical parameters. The rock parameters, including facies, temperature, organic geochemistry/petrology, were used to investigate source rock quality, maturity and kerogen type. Suitable boundary conditions were assigned for paleo-heat flow, paleo-surface temperature and paleo-water depth. The resulting models were calibrated using bottom hole temperature and measured vitrinite reflectance data.

The results correspond relatively well with published heat flow predictions, however a few wells show possible localised heat effects that differ from the overall basin average. The models indicate full maturation of the Devonian source rocks with generation occurring during the Carboniferous and again during the Late Cretaceous. Any potential accumulations may be trapped in Devonian sandstone, limestone and mudstone units, as well as overlying younger sediments of the Mesozoic Eromanga Basin. Accumulations could be trapped by localised deposits of the Cooladdi Dolomite and other marine, terrestrial clastic and evaporite units around the basin. Migration of the expelled hydrocarbons may be restricted by overlying regional seals, such as the Wallumbilla Formation of the Eromanga Basin. Unconventional hydrocarbons are a likely target for the Adavale Basin with potential either for tight or shale gas in favourable areas from the Log Creek Formation and Bury Limestone.

Key words: Adavale Basin, petroleum systems modelling, Devonian, burial history, thermal history, Geoscience Australia.

INTRODUCTION

This work, conducted as part of Geoscience Australia's Exploring for the Future (EFTF) initiative, contributes to the 'Onshore Basin Inventories' study, which aims to promote exploration and investment in selected underexplored onshore basins. Basin Inventory reports and petroleum systems modelling are being undertaken in select basins to understand the energy potential in underexplored regions, and to increase the impact of existing datasets.

The Adavale Basin System consists of three Devonian remnants; the Adavale Basin to the east, the Warrabin Trough to the west, and the smaller Barrolka Trough to the southwest (Frogtech Geoscience, 2018; Korsch, in prep), which are located approximately 850 km west-northwest of Brisbane and southwest of Longreach in south-central Queensland. The basin system covers approximately 100,000 km^2 and represents an Early to Late Devonian (Pragian to Famennian) depositional episode, which was terminated in the Famennian by widespread contractional deformation, regional uplift and erosion (Draper et al., 2004). The Adavale Basin (Figure 1) is the primary focus for this modelling study.

Burial and thermal history models were constructed for 9 wells (Figure 1) using existing open file data to assess the lateral variation in maturity from potential source rocks in the Adavale Basin, and to provide an estimate of the hydrocarbon generation potential in the region.

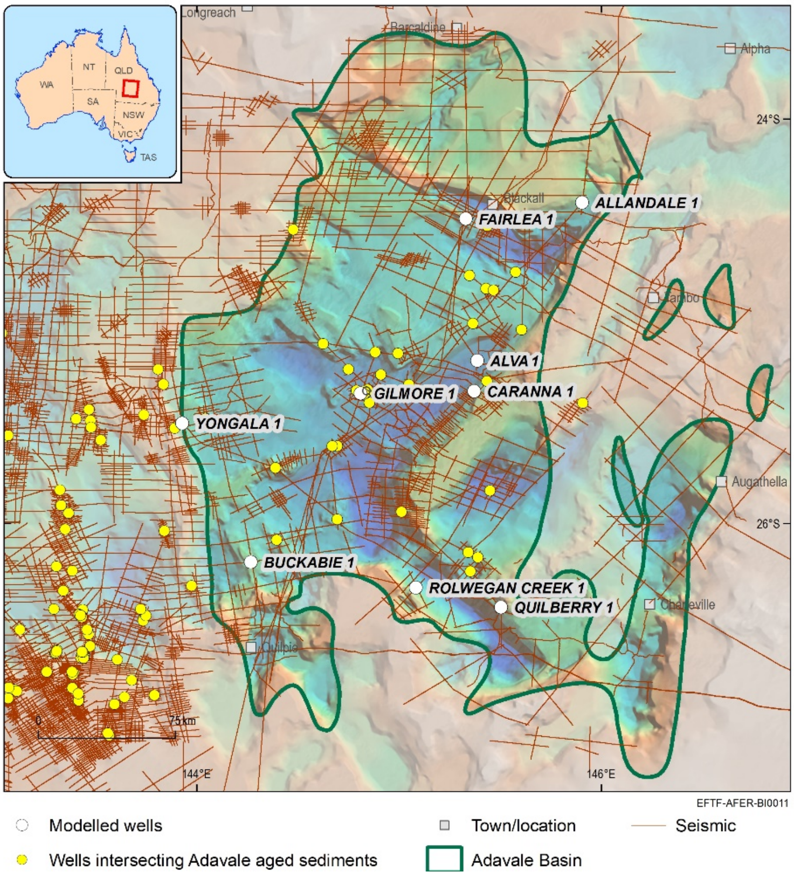


Figure 1. Location of the Adavale Basin, showing wells which intersect sedimentary rocks of the Adavale Basin, wells modelled for this study (labelled), and seismic data coverage. The base map is the SEEBASE map for the Adavale Basin modelled by Frogtech Geoscience (2018).

GEOLOGICAL SUMMARY

The Adavale Basin System consists of siliciclastic sedimentary rocks, carbonates, evaporites and minor volcanic rocks, which initiated in a back-arc extensional setting in eastern Australia, far to the west of an active convergent plate margin. The basin system overlies early Paleozoic metamorphic and igneous rocks of the Thomson Orogen (Asmussen et al., 2018; Cross et al., 2018; Murray & Kirkegaard, 1978; Purdy et al., 2016), with the Warrabin and Barrolka troughs overlying Cambrian and Ordovician sedimentary and volcanic rocks of the Warburton Basin. The basin system contains three stratigraphic sequences (Figure 2), and is overlain by 1000 to 3000 m of younger sedimentary rocks of the late Carboniferous to Middle Triassic Galilee Basin to the east of the Canaway Ridge, and the late Carboniferous to Middle Triassic Cooper Basin to the west of the ridge. The entire basin system is overlain by the Early Jurassic to early Late Cretaceous Eromanga Basin and the Cenozoic Lake Eyre Basin (McKillop et al., 2007). See Korsch (in prep) for a detailed description of the current knowledge of the Adavale Basin system, including its structural geology, basin evolution and depositional history.

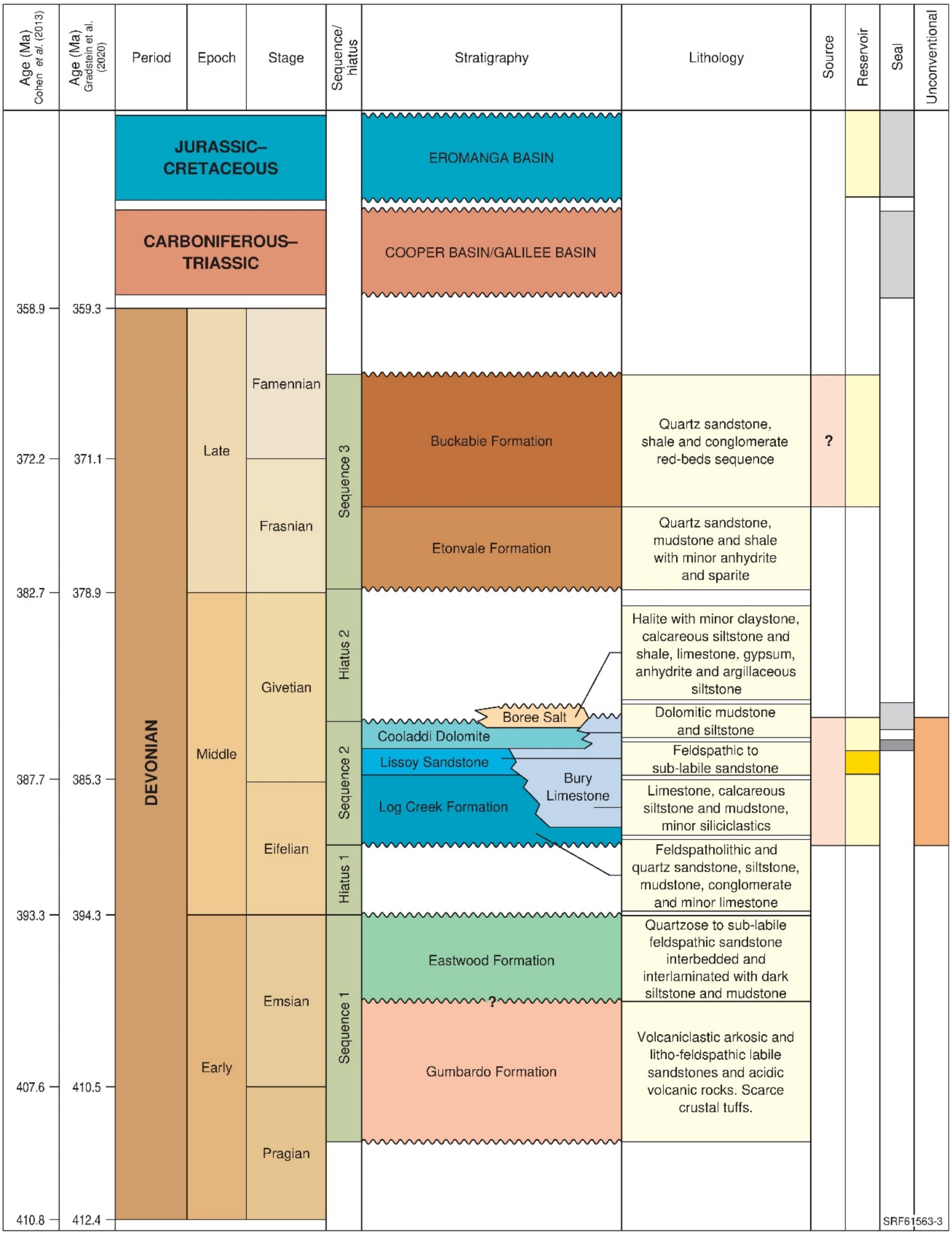


Figure 2.Stratigraphy of the Adavale Basin after Troup and Talebi (2019); formation descriptions follow McKillop et al. (2007). Timescales on the left side are from Cohen et al. (2013) and Gradstein et al. (2020).

BURIAL AND THERMAL MODELLING

The models were constructed using open file geological information from well completion reports, quality check by Khider and Kelman (in prep), to assign formation tops and stratigraphic ages to forward-model the evolution of geophysical parameters and rock properties, such as temperature and maturation of source rocks. Suitable boundary conditions were assigned for heat flow and either surface or sediment-water interface temperature (SWIT), using the PetroMod SWIT tool. The resulting models were then calibrated using bottom-hole temperature (BHT) data and measured vitrinite reflectance data. For the modelling workflows used, see Hall et al. (2016) and Palu et al. (2020).

Boundary conditions

Using the Zetaware Genesis™ 1D modelling software, the transient, fixed temperature at the base of the lithosphere of 1330°C is used as the thermal model. Heat production from the lower crust is set to 0.5 mW/m^3 and the upper crust varied to calibrate each well to the paleo-maturity and bottom hole temperature data. The upper and lower crust varies in thickness between 18–20 km, while the mantle thickness is adjusted to ensure the lithosphere is equal to 120 km. By combining these model parameters with the burial history of the region, an estimated paleo-heat flow curve is generated for each modelled well.

Paleo-water depth is estimated from modelling by Boreham & de Boer (1998) and adjusted to present-day elevation while SWIT is calculated using the global mean temperature at sea level using the auto transformation of Wygrala (1989) (Southern Hemisphere, Australia, latitude 25°), with an elevation and present day temperature correction applied.

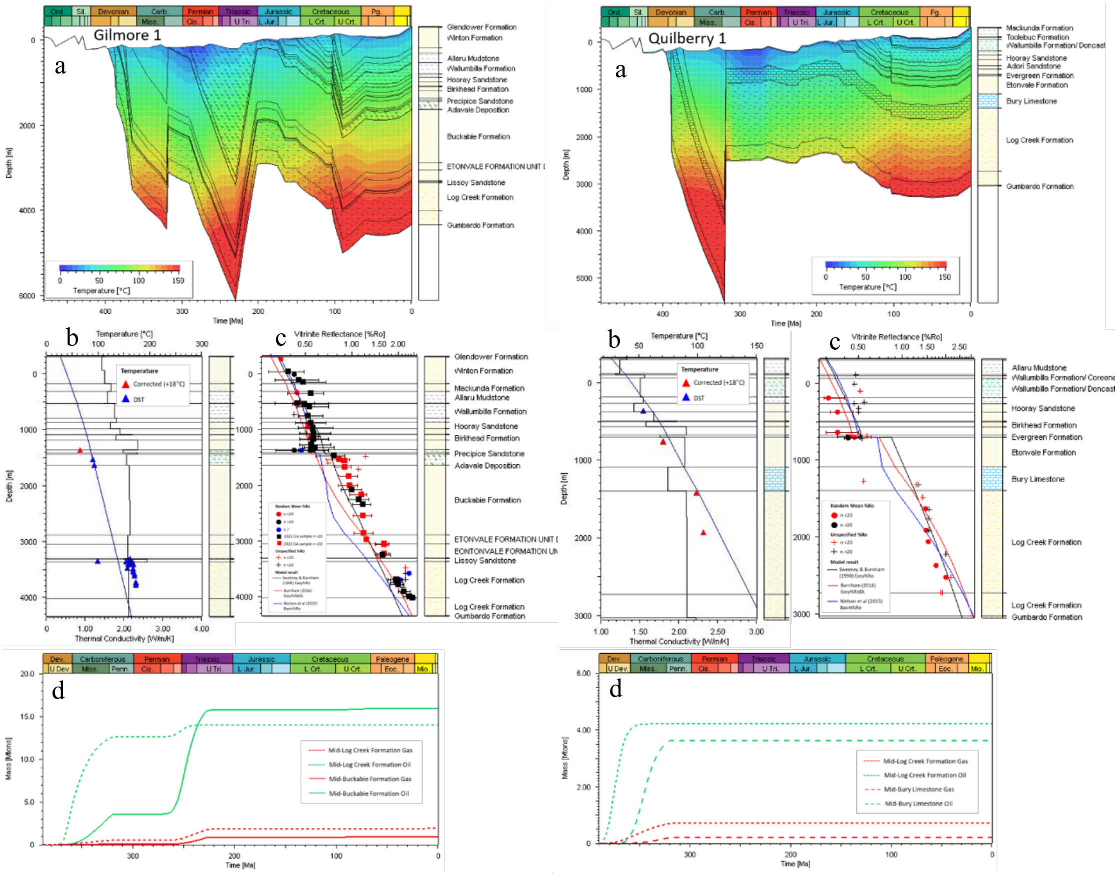
1D model construction

Models are constructed using the Schlumberger PetroMod© software, with some input data calculated using the Zetaware Genesis™ software (described above), and then imported to PetroMod as the boundary conditions for the more detailed 1D burial history modelling, with selected results presented in Figure 3 (see Palu et al. (in prep) for all modelling results):

- Formation tops reported in the well completion reports are quality checked (Khider & Kelman, in prep) and the updated information used in this study. The software uses sea level as the datum to reference all depths, hence, well depths and model results are either converted or displayed to referenced sea level. That is, negative numbers are above present day sea level, and positive numbers are below present day sea level.
- Lithologies are generalised from formation descriptions in published reports (ASUD, 2022; McKillop et al., 2007) and checked against core descriptions in the well completion reports. Standard thermal conductivities were assigned to sediments because published studies were not available to provide this information.
- Numerical ages for the stratigraphic formations are assigned from either Khider & Kelman (in prep), published reports (Hall et al., 2016) or estimated from the Australian stratigraphic units database (ASUD, 2022).
- Where wells did not penetrate basement, the depth of basement is derived from a basin model recently commissioned by Geoscience Australia (Paterson et al., 2022).
- Heat flow and amounts of uplift and erosion across the basin are poorly understood. Models are adjusted to fit the calibration data, which leads to some speculation and over-simplification of geological events. Present-day heat flow is derived through calibration to BHT data. Paleo-heat flow is estimated using Genesis software (Zetaware™) which calculates a paleo-heat flow using the burial history, crustal thickness, crustal heat flow and radiogenic heat from user-defined input parameters.
- Temperature and the upper model boundary is defined by the automatic SWIT tool (Hantschel & Kauerauf, 2009), using the southern hemisphere, Australia and latitude 25° for the area of interest.

Source rocks

Source rocks considered for modelling were the Middle Devonian (the Log Creek Formation and Bury Limestone), and shales from the Late Devonian Buckabie Formation. There is contention over whether or not the Buckabie Formation may host organic rich-rocks due to the lack of, or incomplete datasets from sparsely sampled wells. Nevertheless, Draper et al. (2004) summarised the known source rock information, and although the data were limited, they considered that the results were encouraging for future exploration (Korsch, in prep). In a combined assessment of source rock richness, thermal maturity and kerogen type, Miyazaki & Ozimic (1987) rated the basin as fair to good for gas and poor for oil. The Adavale Basin would benefit from an extensive source rock study. No basin-specific kinetic study has been undertaken, hence standard kinetics have been used that correspond to deep marine and algal type II(B) source rocks. Secondary cracking was not modelled for this study. Poor data coverage of source rock richness, and few geochemical analyses on immature samples prevents these components being mapped across the basin to determine their spatial variability. The source rock parameters used were Total Organic Carbon (TOC) of 5% and Hydrogen Index (HI) of 400 mg HC/gTOC for the Middle Devonian (Log Creek Formation and Bury Limestone) section, and TOC content of 5% and HI of 500 mg HC/gTOC for the Buckabie Formation, independent of the assumed thickness of the source rock. These TOC and HI values were estimated from available well data. This initial approach allows comparison of results between wells within the basin, with the option of modifying source rock properties in the 1D models when new data becomes available.



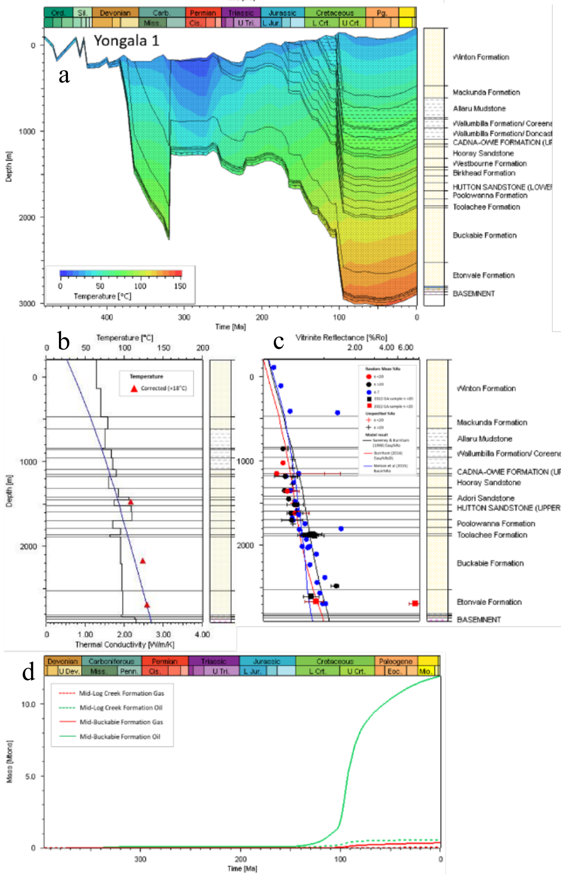


Figure 3. Modelling results for Gilmore 1, Quilberry 1 and Yongala 1 wells showing; a) predicted burial and temperature history; b) measured BHT data and predicted temperature (blue line); c) measured vitrinite reflectance data and predicted vitrinite reflectance using kinetic models of Sweeney and Burnham (1990) (black line), Burnham (2016) (red line) and Nielsen et al. (2017) (blue line); and d) predicted petroleum generation history for two Devonian source rocks (if present in the modelled well. Note, depths are converted to mean sea level for modelling purposes.

MODEL RESULTS AND DISCUSSION

Present-day heat flow

Radiogenic heat production from the lithosphere, derived through the calibration of the 1-D models (using bottom hole temperature and related data) is somewhat variable across the Adavale Basin (Figure 4) ranging from 31.53 mW/m^2 to 49.71 mW/m^2 for the wells modelled (Table 1), however a spatial trend is not apparent. These results are significantly lower than the inferred basement heat flow in the SEEBASE database (Frogtech Geoscience, 2018), but are analogous to the inferred radiogenic heat flow from the upper crust (Figure 4, Table 1), that is; mantle heat flow + radiogenic heat flow = total basement heat flow. Sensitivity analysis shows that using the total basement heat flow as estimated from the Frogtech Geoscience (2018) dataset, leads to a pronounced over-prediction of BHT values.

Paleo-heat flow model results shown in Table 1 and are compared with the SEEBASE radiogenic heat flow (Figure 4). Present-day heat flow values range between 52.41 and 73.13 mW/m^2 (Palu et al., in prep). Surface heat flow predicted at the well Fairlea 1 (Palu et al., in prep) is much higher than most other wells in the area, but was calibrated using poor quality data. The reason for the larger surface heat flow is most likely due to the significant erosion event that has been modelled at the Adavale/Eromanga contact, and is also the possible reason for the higher surface heat flow prediction in the well Quilberry 1. See Palu et al. (in prep) of full model results and discussion.

Table 1. Amount of erosion estimated for the modelling, calibrated to paleo-maturity data. Erosion 1 corresponds to the Devonian-Permian erosional event (except for Gilmore 1 which also includes a Late Triassic erosional event). Erosion 2 corresponds to erosion of the uppermost Eromanga Basin in the Late Cretaceous (see next section about erosion for further discussion). RHP modelled is the radiogenic heat production from lithosphere estimated from this modelling study, while RHP Frogtech (2018) is the radiogenic heat production from Frogtech Geoscience (2018); these are compared in Figure 4.

Well	*Erosion 1 m*	*Erosion 2 m*	*RHP modelled mW/m²*	*RHP Frogtech (2018) mW/m²*
Allandale 1	1000	none	27.62	30.91
Alva 1	1000	none	27.62	37.91
Buckabie 1	1000	none	27.62	45.68
Caranna 1	1000	none	36.69	40.7
Fairlea 1	4000	none	49.71	37.41
Gilmore 1	3500+1000	500	30.93	38.58
Quilberry 1	3000	none	45.29	37.55
Rolwegan Creek 1	2500	none	40.87	26.68
Yongala 1	1000	none	33.14	46.41

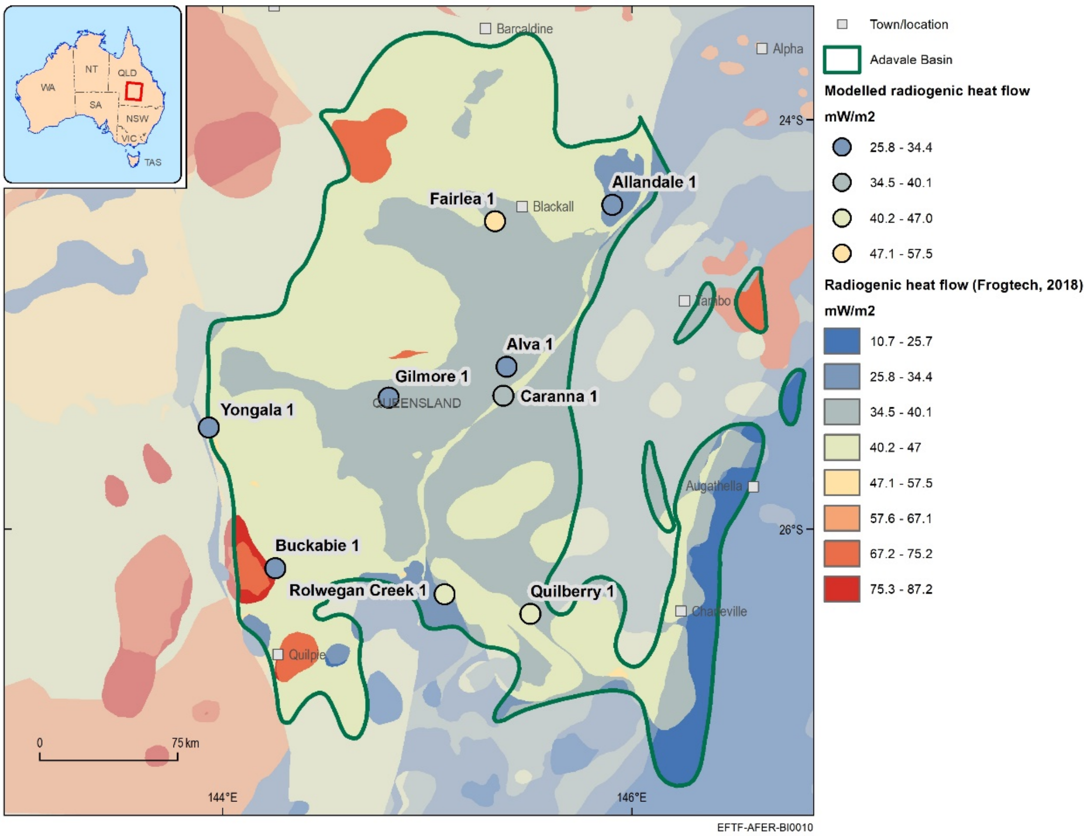


Figure 4. Basement heat flow after Frogtech Geoscience (2018), with circles at well locations showing present-day basement heat flow from the 1D models.

Uplift and erosion

A significant erosional event at the unconformity between the Adavale Basin and the overlying younger sediments is estimated to account for some of the large time gap. This event may actually represent at two unconformities in many locations in the basin; 1) the unconformity between the Adavale Basin and Galilee Basin and, 2) the unconformity between the Galilee Basin and the Eromanga Basin. In places where the Galilee Basin sediments have been fully eroded, these two unconformities become one in the stratigraphic column. For example, this is seen in the well Gilmore 1 (Figure 3). It is difficult to constrain this across the basin for the burial history models, however using paleo-maturity data, we predict that the top Galilee Basin erosional event is in fact much larger than the top Adavale Basin event. A second, smaller, but still significant, erosional event is evident in the Gilmore area at the top of the Eromanga Basin.

Given significant uncertainties in the modelling process, this study aims to be as consistent as possible with the modelling inputs, and then refine the amounts of erosion and boundary conditions, by adjusting crustal thickness and crustal heat production, to calibrate each model to the measured data. The final modelled erosion inputs (Table 1) show that erosion at the top Adavale Basin package could potentially vary between 1000 m and 4000 m, and the top Eromanga Basin erosional event varies in the models from no erosion up to 500 m.

Predicted petroleum generation potential

The results of this modelling for 3 of the wells in the Adavale Basin are documented in Figure 3 (see Palu et al. (in prep) for all model results). Burial history modelling by Boreham & de Boer (1998), using the WinBury software, inferred that, for the potential source rocks in the Cooladdi Dolomite and Log Creek Formation, onset of petroleum generation is reached during the final deposition of the (soon to be eroded) uppermost Buckabie Formation and concur with the results from this study. At the time of maximum burial in the Late Devonian, source rocks in the Log Creek Formation are actively expelling oil and gas and are at peak oil generation, compared to the organic matter in the Cooladdi Dolomite, which has not quite reached the stage of initial expulsion. Petroleum generation subsequently ceases after uplift and erosion of the thick Buckabie Formation succession. In most areas, sufficient sediment cover and elevated temperatures did not occur again until the Early Cretaceous, so that Devonian source rocks could once again begin to actively expel oil and gas (Figure 3; Palu et al., (in prep)). Primary oil and gas generation was almost complete between the Early and Late Cretaceous. By the end of deposition of the Eromanga Basin in the early Late Cretaceous, the Log Creek Formation was in the dry gas window (de Boer, 1996). Gilmore 1 is the exception to this, which hosts Galilee Basin sediments. Paleo-maturity data indicate that the erosional event between the Galilee Basin and Eromanga Basin is in fact much larger than the top Adavale Basin erosional event, and hence, experienced maximum burial during the Late Triassic before being uplifted, and then buried once again throughout the Cretaceous. This may be an area to investigate in future studies.

Modelling results show that all Devonian source rocks are mostly oil-prone, which is a function of the type II(B) organofacies (Pepper & Corvi, 1995) used for modelling in PetroMod. It is predicted that, due to the age and depth of these units, much of this oil has undergone secondary cracking, resulting in gas as the most likely phase state of hydrocarbons for this region. For those areas that have not undergone full transformation as per the modelling (i.e. Alva 1, Buckabie 1, Caranna 1, Gilmore 1, Rolwegan Creek 1 and Yongala 1), there may still be some possibility of both oil and wet and dry gas, if all other preservation conditions are favourable. For example, recent fluid inclusion stratigraphy analysis of the complete intervals in Gilmore 1 (Cowan et al., 2022a) and Yongala 1 (Cowan et al., 2022b) showed;

1) Gilmore 1; wet gas FIS responses occur at 3486.1–3491 m (Etonvale Formation) and together with a positive acetic acid response is indicative of the presence of hydrocarbons in the vicinity. Below 3980.7 m (Log Creek Formation) wet gas FIS responses are consistently measured.
2) Yongala 1; the Buckabie Formation shows the highest concentration of liquid-range alkanes occurring at 2197–2255.5 m, 2499.4 m, 2572.5 m and 2660.9 m, corresponding to local generation from mature organic matter. The underlying Etonvale Formation displays mostly dry gas FIS responses.

CONCLUSIONS

The results of the study show that the source rocks of the Devonian have been buried deep enough in their paleo-history across the Adavale Basin to have generated hydrocarbons. Some source rocks may still have the potential to be generating at the present day, if all other conditions of generation (organic matter type, TOC, HI) and trapping mechanisms (either conventional or unconventional) are favourable. With exhumation data and paleo-heat flow still largely uncertain for this region, the prediction of petroleum generation potential is still speculative. More detailed play-based assessments in localised regions should be further considered, while many questions remain unanswered in this under-explored basin. This is in-part driving some of the current work being undertaken by Geoscience Australia (Geoscience Australia, 2021) to contribute to reassessing the risks in this potential hydrocarbon province.

ACKNOWLEDGMENTS

The authors would like to thank Bianca Reece for figure production for the Adavale Basin project. Thank you also to L. Carr and J. Anderson for their valued peer-review comments. This work is published with the permission of the CEO Geoscience Australia.

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