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Extended abstract

Integrated petroleum systems analysis to understand the source of fluids in the Browse Basin, Australia

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Abstract. The Browse Basin is located offshore on Australia's North West Shelf and is a proven hydrocarbon province, hosting gas with associated condensate in an area where oil reserves are typically small. The assessment of a basin's oil potential traditionally focuses on the presence or absence of oil-prone source rocks. However, light oil can be found in basins where source rocks are gas-prone and the primary hydrocarbon type is gas-condensate. Oil rims form whenever such fluids migrate into reservoirs at pressures less than their dew point (saturation) pressure. By combining petroleum systems analysis with geochemical studies of source rocks and fluids (gases and liquids), four Mesozoic petroleum systems have been identified in the basin.

This study applies petroleum systems analysis to understand the source of fluids and their phase behaviour in the Browse Basin. Source rock richness, thickness and quality are mapped from well control. Petroleum systems modelling that integrates source rock property maps, basin-specific kinetics, 1D burial history models and regional 3D surfaces, provides new insights into source rock maturity, generation and expelled fluid composition.

The principal source rocks are Early–Middle Jurassic fluvio-deltaic coaly shales and shales within the J10–J20 supersequences (Plover Formation), Middle–Late Jurassic to Early Cretaceous sub-oxic marine shales within the J30–K10 supersequences (Vulcan and Montara formations) and K20–K30 supersequences (Echuca Shoals Formation). These source rocks contain significant contributions of terrestrial organic matter, and within the Caswell Sub-basin, have reached sufficient maturities to have transformed most of the kerogen into hydrocarbons, with the majority of expulsion occurring from the Late Cretaceous until present.

Keywords: condensate, dew point, gas, geochemistry, oil, source rocks.

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Introduction

The Browse Basin located offshore on Australia's North West Shelf hosts considerable gas and condensate resources. It is poised to become Australia's next major conventional liquefied natural gas (LNG) province with the Ichthys, Prelude and Concerto fields currently under development and recent discoveries at Burnside, Lasseter and Crown/Proteus in the Caswell Sub-basin (Fig. 1*a*). Other significant gas accumulations are located along the Scott Reef Trend (Calliance, Brecknock, Torosa), as far north as Argus, and in the Heywood Graben (Crux). Oil discoveries are presently sub-economic and confined to the central Caswell Sub-basin (Caswell) and Yampi Shelf (Cornea, Gwydion).

This study combines a pseudo-3D basin model with a review of source rock data to gain an understanding of their distribution, quality and thermal maturity. Integration of this source rock assessment with fluid characteristics provides insights into the oil and gas prospectivity of the Browse Basin.

Burial and thermal history modelling set-up

A regional 3D geological model of the Browse Basin was developed from new seismic interpretations (Rollet *et al.* 2016*a*) and forms the basis of a pseudo-3D petroleum systems model (Fig. 1*a*). Information on the regional petroleum systems elements of the basin is limited below the Middle Triassic (Fig. 1*b*); hence, the basin model encompasses the

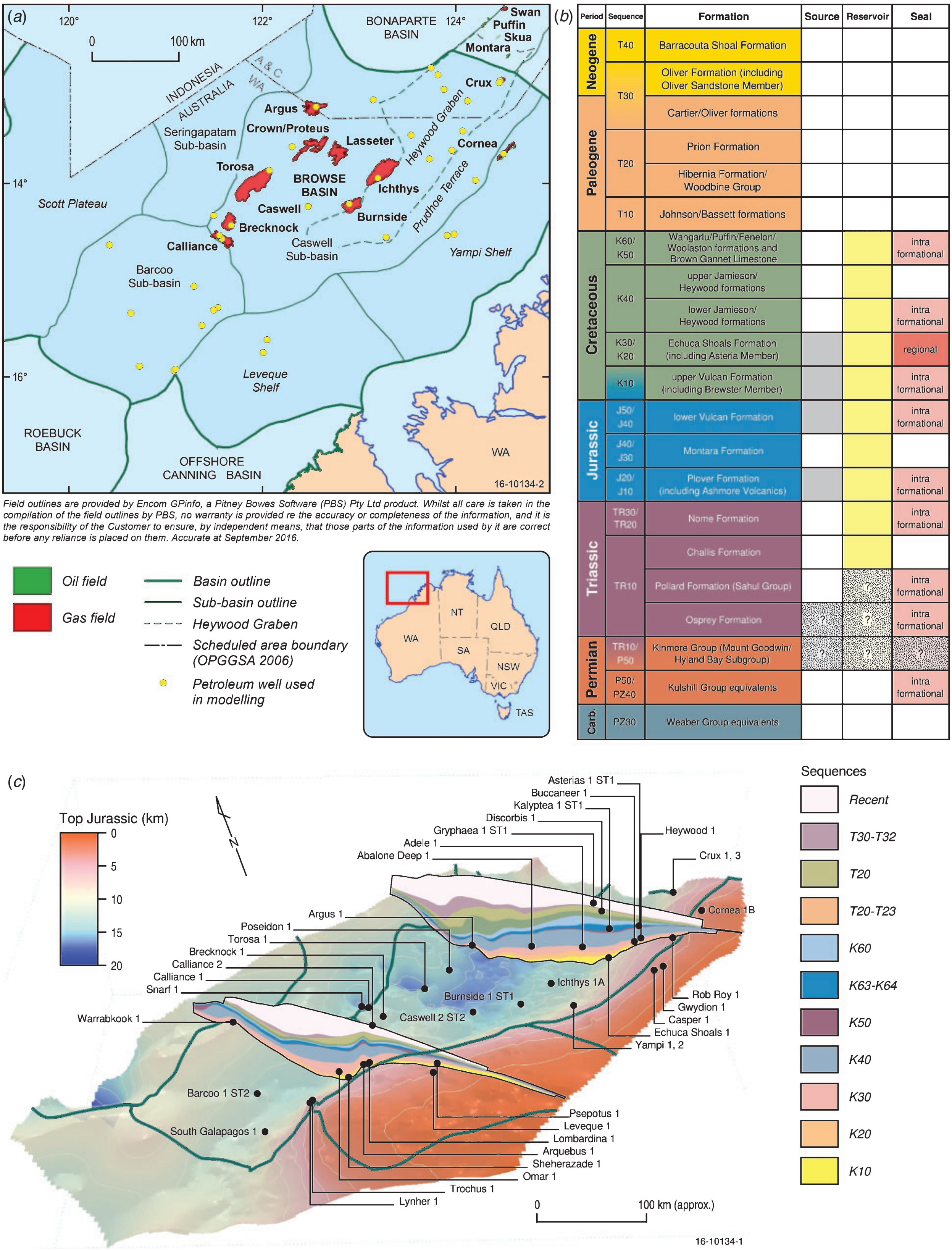

Fig. 1. (*a*) Location of the Browse Basin. (*b*) Petroleum systems elements of the Caswell and Barcoo Sub-basins. (*c*) 3D perspective of the pseudo-3D petroleum systems model, including location of calibration wells and cross-sections of constructed model.

Cretaceous–Jurassic petroleum systems, estimates the Triassic as the lower boundary, and assumes the top Permian as the basement for the thermal model boundary. The model was calibrated using corrected temperature and maturity data from 34 wells (Fig. 2).

Source rocks and charge history

Browse Basin source rocks are typically difficult to characterise because they are either sparsely drilled and/or sampled, or have only been penetrated on structural highs and basin margins where their quality may not be representative. Indicative source rock characteristics were assigned based on an updated compilation of quality-controlled total organic carbon (TOC), Rock-Eval pyrolysis and vitrinite reflectance data. The source rock property data were integrated with the pseudo-3D petroleum systems model to predict transformation ratio, maturity and charge history. Kerogen types were assigned by depositional environment and generalised expulsion parameters were applied (Pepper and Corvi 1995*a*, 1995*b*).

J10–J20 supersequences (Plover Formation)

Source rocks within the J10–J20 supersequences were deposited in extensive fluvio-deltaic systems that extended across most of the basin. They include pro-delta shales, coaly shales and thin coals containing abundant terrestrial organic matter with significant gas generation potential (kerogen type D/E, Pepper and Corvi 1995*a*, 1995*b*; equivalent to type III). Source rock distribution is difficult to constrain due to high sedimentation rates and the ephemeral nature of the fluvial and paralic environments (Blevin *et al.* 1998*b*). Transformation ratios reach up to 1 (>2% Ro) throughout the central Caswell Sub-basin (Fig. 2). Hydrocarbon expulsion began in localised areas in the Late Jurassic, followed by the main phase of expulsion in the Late Cretaceous. The Barcoo Sub-basin has not experienced the same amount of burial as the Caswell Sub-basin; hence, transformation of the kerogen is less extensive, but still reaches up to 0.95 in the deepest depocentre (~1.6% Ro). Onset of expulsion occurred in the Jurassic, with peak hydrocarbon expulsion occurring during the latest Cretaceous.

J30–K10 supersequences (Vulcan and Montara formations)

Source rocks within the J30–K10 supersequences are predominantly gas prone (kerogen type D/E); however, thin condensed mudstones—containing type B (equivalent to type II) kerogen—related to flooding events could be a source of liquid hydrocarbons where organic richness is sufficient (Blevin *et al.* 1998*b*). Transformation ratios reach 0.98 (~2% Ro) in the deepest part of the Caswell Sub-basin and the onset of hydrocarbon expulsion occurred in the latest Cretaceous. In the deepest section of the Barcoo Sub-basin, transformation

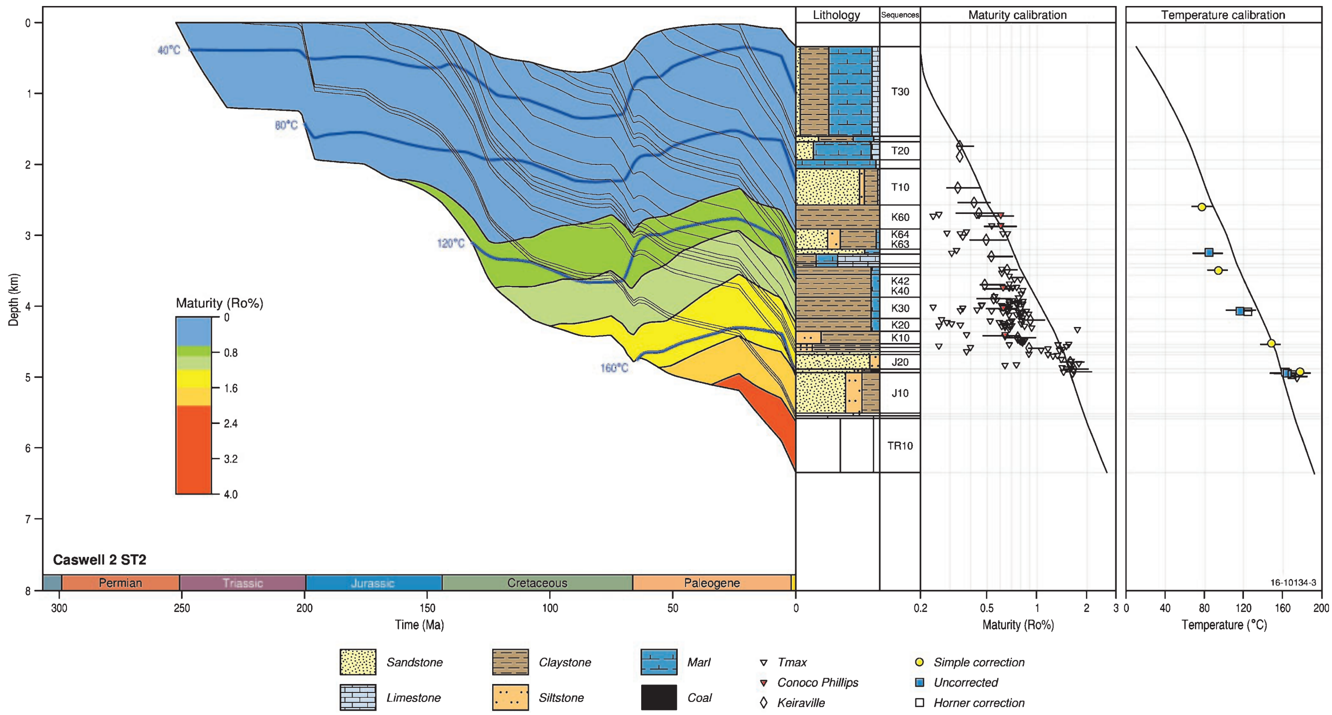

Fig. 2. Modelled burial history for Caswell 2 ST2 showing data calibration (palaeo-maturity and bottom hole temperature). Age, lithologies and palaeo-bathymetry were assigned by supersequence based on the regional tectonostratigraphic chart, lithology logs and well completion report (WCR) composite logs (Fig. 1*b*: Rollet *et al.* 2016). Uplift and erosion amounts were considered to be negligible (<100 m) throughout the basin and are therefore insignificant in the context of a basin model. The lower thermal boundary condition was set using a constant temperature at the base of the lithosphere. Crustal structure was estimated from AusMoho (Kennett *et al.* 2011) and subsidence analysis was used to model lithospheric extension through time. Modelling was conducted using the Trinity-Genesis-KinEx software suite (http://www.zetaware.com).

ratios reach 0.82 (~1.2% Ro), but only about one fifth of the sub-basin reaches transformation ratios >0.5. Charge histories show some limited expulsion in the Barcoo Sub-basin, beginning in the Early Cretaceous.

K20–K30 supersequences (Echuca Shoals Formation)

The K20–K30 supersequences comprise marine claystones containing mixed marine and terrestrial organic matter – containing mixed type B and type D/E kerogens – deposited during a period of high relative sea level (Blevin *et al.* 1998*a*). Most samples have only fair potential (TOC <2% and HI <200 mg hydrocarbons/g TOC), and therefore, are unlikely to be effective source rocks. Yields are too low to saturate the host shales sufficiently enough to allow continuous migration into and through carrier beds to a trap (Radlinski *et al.* 2004). However, the quality may improve into the undrilled parts of the depocentres. Transformation ratios reach ~0.9 (1.4% Ro) within the deepest part of the Caswell Sub-basin and hydrocarbon expulsion began during the Middle Eocene. Within the Barcoo Sub-basin, transformation ratios reach a maximum of 0.8 (1.1% Ro) in the thickest sections of these supersequences. Hydrocarbon expulsion is limited in the K20–K30 supersequences with some minor expulsion occurring in the Late Eocene.

Petroleum fluids

Bulk fluid properties

All publicly available hydrocarbon fluid compositional data were compiled. The characteristics of the fluids tested indicate that all samples belong to dew-point petroleum systems (Fig. 3*a*) with high (>10 000 scfs/bbl) gas–liquid ratios (GLR). Hence, most fluids in the basin are likely to be derived from gas-prone source rocks, consistent with the absence of substantial liquids-prone facies in the penetrated Jurassic and Cretaceous sections.

Figure 3*b* shows that most reservoired fluids are liquid-undersaturated gas-condensates. However, some accumulations appear to be close to their saturation pressure in the reservoir (e.g. Crux and Calliance) and slightly lower pressure would result in oil-rim formation (Fig. 3*b*). Palaeo-oil columns have been recognised at Crux 1 (Brincat *et al.* 2003) and Brecknock South 1 (CSIRO Petroleum, unpubl. data) – the discovery well of the Calliance accumulation. It is also noted that oil sampled from a thin shallow porous/fractured zone (~2150 mRT) in Torosa 4 is geochemically similar to the condensate recovered from the J10–J20 supersequences (Woodside Energy Ltd, unpubl. data), indicating a common (Plover Formation) source for these hydrocarbons. This oil may have formed by liquids dropping out of a Plover-derived gas-condensate as it migrated into a zone of reduced pressure with the associated gas not being retained.

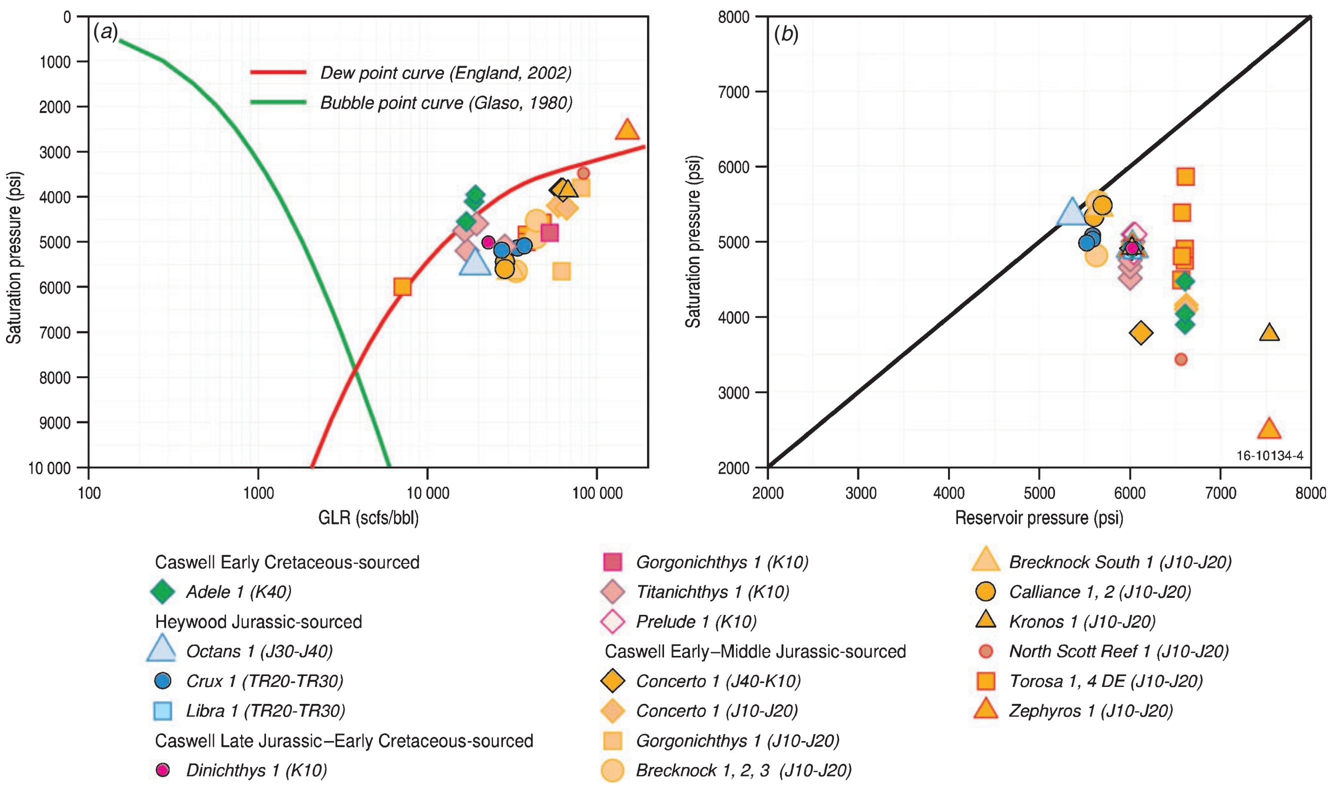

Fig. 3. Fluid analysis of Browse Basin samples showing: (*a*) gas–liquid ratio (GLR) vs saturation pressure; and (*b*) reservoir pressure vs saturation pressure. These data demonstrate that the tested accumulations are single-phase fluids, which are typically below their saturation pressure. The reservoir for the gas is denoted by the supersequence in brackets. The source of the gas is denoted by the colour symbology.

Geochemical typing

Edwards *et al*. (2016) and Grosjean *et al*. (2015, 2016) showed that the gas-prone source rocks of the J10–J20 supersequences have pervasively charged many gas accumulations across the basin, whereas gas charge from source rocks of the J30–K10 supersequences has been limited to the central Caswell Sub-basin at the Ichthys/Prelude and Burnside accumulations (Rollet *et al.* 2016*b*). The gases from Crux belong to a distinct family that has most likely been sourced by terrestrially derived organic matter within the thick Jurassic supersequences in the Heywood Graben. There is evidence that some gases (Adele 1, Kalyptea 1ST1) in the Caswell Sub-basin, north of the Ichthys field, may be derived from source rocks within the K20–K30 supersequences.

Oils recovered from wells on the Yampi Shelf (Cornea, Gwydion, Sparkle) have been correlated to source rocks within the Lower Cretaceous K20–K30 supersequences (Blevin *et al.* 1998*a*), whereas the co-occurring gas has been typed to the J10–J20 supersequences based on geochemical data (Grosjean *et al.* 2016). Given that only poor-quality Cretaceous source rocks have been penetrated, coupled with the volume expansion of gas as fluids migrate upwards, it seems likely that the Cretaceous-sourced oils on the Yampi Shelf were mobilised and transported to their traps by Plover-derived gas-condensate. The light oil at Caswell may also be the product of the co-mingling of fluids originating from several sources. Hence, prospectivity for oil derived from Cretaceous source rocks may depend on access to co-migrating Plover gas-condensate. This is most likely to occur along the shelf edge where seals pinch out against the basement, allowing fluids from multiple sources to mix.

Conclusions

Four Mesozoic petroleum systems have been identified in the Browse Basin from the geochemistry of the gases, condensates and oils recovered from accumulations and shows. Test data available from sampled accumulations demonstrate that they are primarily products of gas-prone source rocks with some liquids potential and are dew-point fluids. Source rock screening data available for the Jurassic and Cretaceous supersequences show that they predominantly comprise gas-prone kerogen, and that where penetrated, the marine shales within the J30–K10 and K20–K30 supersequences do not have sufficient organic richness and quality to expel significant amounts of oil.

Modelling shows that source rocks within the Caswell Sub-basin have reached sufficient maturities to have transformed most of the kerogen into hydrocarbons, with the majority of expulsion occurring from the Late Cretaceous until present. Within the Barcoo Sub-basin, only source rocks within the J10–J20 supersequences have reached sufficient maturity for generation, where the better-quality source rocks within this supersequence have expelled hydrocarbons.

In summary, petroleum systems analysis indicates that most hydrocarbon fluids found in the Browse Basin are single-phase dew point fluids (gas-condensates). However, these fluids are expected to drop out oil rims when migrating into shallower traps and this may result in light oil spilling up-dip or being present as a residual column after gas loss through leaking seals.

Conflicts of interest

No conflicts of interest exist between these authors and any other person or organisation.

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