PS Source Rocks and Hydrocarbon Fluids of the Browse Basin*

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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. Oil reserves in the area are small with most in-place oil likely the result of hydrocarbon fluids experiencing pressures less than their saturation pressure resulting in dual phase fluids, coupled with secondary alteration processes and gas leakage. This study reviews the distribution, quality and maturity of source rocks and fluid characteristics in the Browse Basin. All publicly-available Total Organic Carbon (TOC) and Rock-Eval pyrolysis data were compiled and quality checked to determine multiple, viable source rock units. Jurassic and Cretaceous source rock distributions and net thickness were studied using integrated seismic and well log lithofacies mapping, combined with organic geochemistry data. Source rock transformation ratio and generation potential were investigated using a regional pseudo-3D petroleum systems model constructed from new seismic interpretations and calibrated using temperature and maturity data from 34 wells. Monte Carlo simulations were used to test uncertainties around key input parameters including thermal history, source thickness, TOC, Hydrogen Index (HI), and kerogen kinetic composition. Results show that the Jurassic Plover Formation (J10-J20 supersequences) coals and carbonaceous shales are effective, primarily gas-prone source rocks which may have some liquid potential when the generated gas migrates into shallow reservoirs at reduced pressures. Additional sources of hydrocarbons include shales in the Upper Jurassic lower Vulcan Formation (J40 supersequence), Lower Cretaceous upper Vulcan Formation (K10 supersequence) and Echuca Shoals Formation (K20-K30 supersequences). However, these are likely to have only expelled hydrocarbons locally in areas of optimal organic-richness and maturity. Key uncertainties include TOC and HI variability due to lack of well penetration in the depocentres. The molecular composition of the fluids was compiled and quality checked and used to investigate the relationship between the saturation pressure and condensate-gas ratio (CGR). By combining the bulk properties and molecular and isotopic compositions of the fluids with the geochemical compositions of the source rocks in a petroleum systems model, four Mesozoic petroleum systems have been identified and mapped to help understand the source rock potential and fluid characters for the Browse Basin.

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Introduction

Basin architecture

The Browse Basin is located offshore on Australia's North West Shelf (Figure 1) and is poised to become Australia's next major conventional liquefied natural gas (LNG) province. Although the basin hosts considerable gas and condensate resources, 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 when such fluids migrate into reservoirs at pressures less than their dew point (saturation) pressure.

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.

Three major source rocks are assessed, as shown in Figure 2:

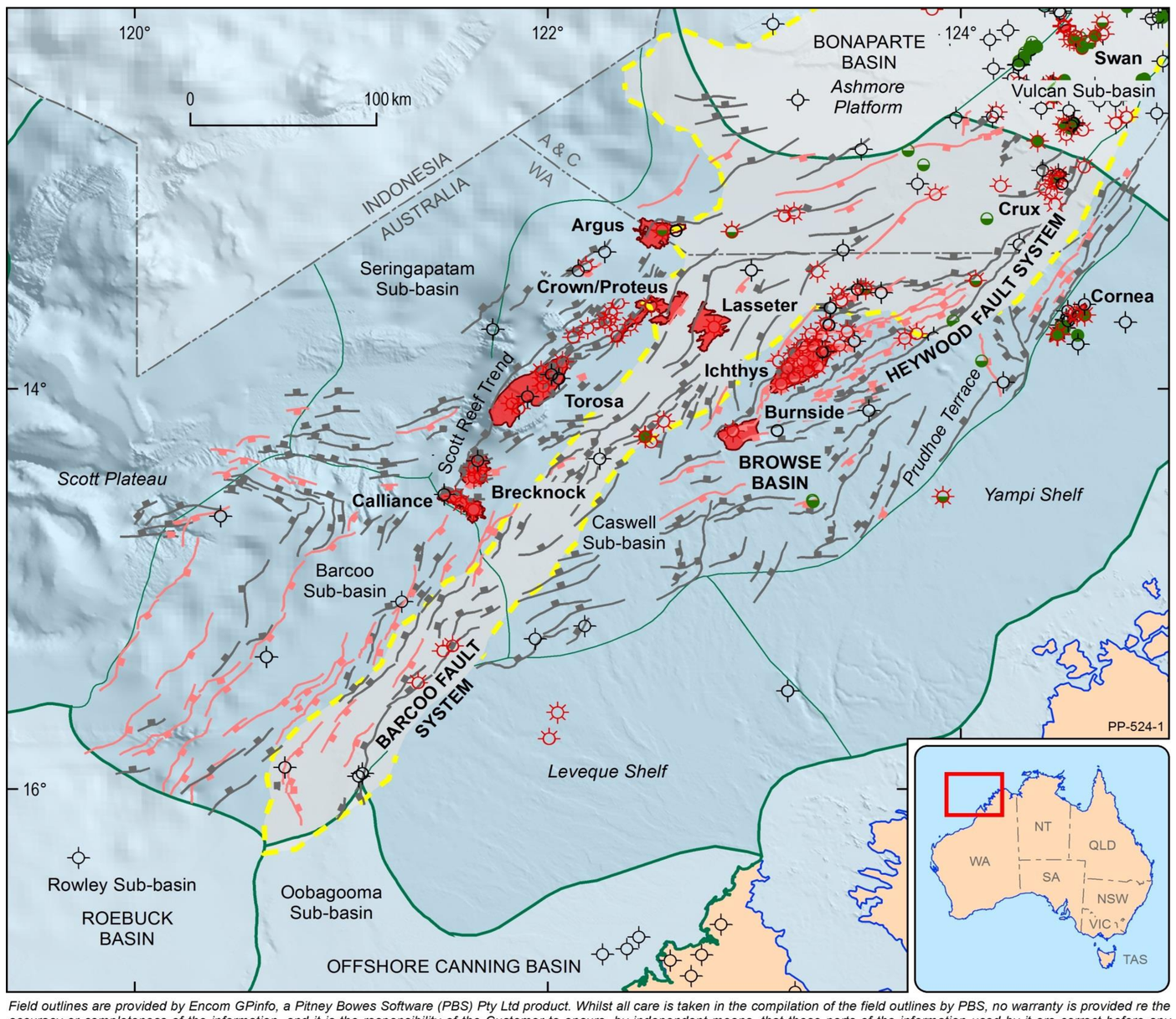
- K20-K30 supersequences (Echuca Shoals Formation),
- J30-K10 supersequences (Vulcan Formation) and;
- J10-J20 supersequences (Plover Formation).

Regional geology and stratigraphy

The Browse Basin is one of a series of extensional basins that form the Westralian Superbasin underlying the North West Shelf region. The basin formed through two main phases of extension in the Carboniferous to early Permian and the Early to Middle Jurassic.

The major depocentres are the Caswell and Barcoo sub-basins (Figure 1) which have maximum thicknesses of >15 km and ~12 km, respectively (Figure 3). Inboard lie the Yampi and Leveque shelves.

Regional seismic and well interpretations (Rollet et al., 2016a,b) were used to develop a 3D geological model of the Browse Basin (Figure 4).



Field outlines are provided by Encom GPinfo, a Pitney Bowes Software (PBS) Pty Ltd product. Whilst all care is taken in the compilation of the field outlines by PBS, no warranty is provided re the accuracy or completeness of the information, and it is the responsibility of the Customer to ensure, by independent means, that those parts of the information used by it are correct before any reliance is placed on them. Accurate at September 2016.

Figure 1. Structural elements of the Browse Basin and location of accumulations and shows.

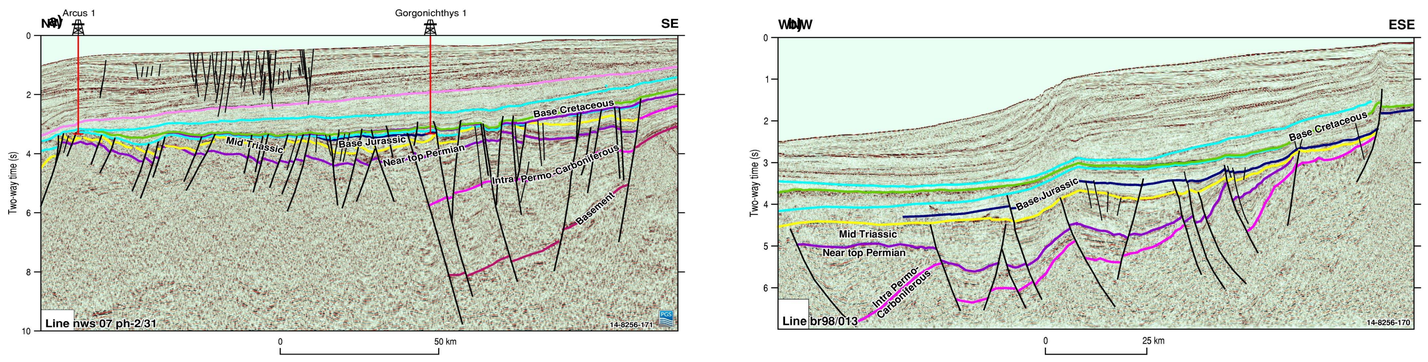


Figure 3. a) Seismic line nws07ph2/31 illustrating the structural style in the Caswell Sub-basin (seismic line courtesy of PGS), and b) Seismic line br98/013 illustrating the structural style in the Barcoo Sub-basin (Rollet et al., 2016a).

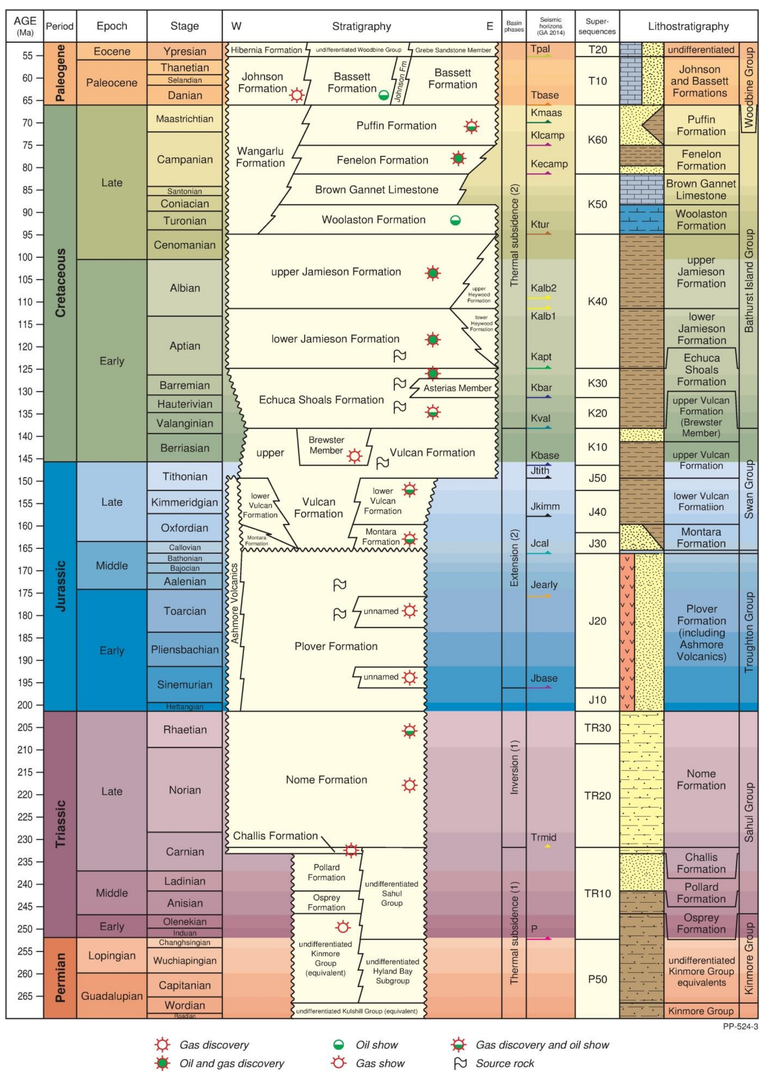


Figure 2. Sequence stratigraphy of the Browse Basin based on a revised tectonostratigraphic framework for the basin, standardised to the North West Shelf stratigraphic nomenclature (after Marshall and Lang, 2013) and the Geologic Timescale Scale 2016 (Gradstein et al., 2016) modified from Kelman et al. (2016). Hydrocarbon discoveries and source rocks are also shown.

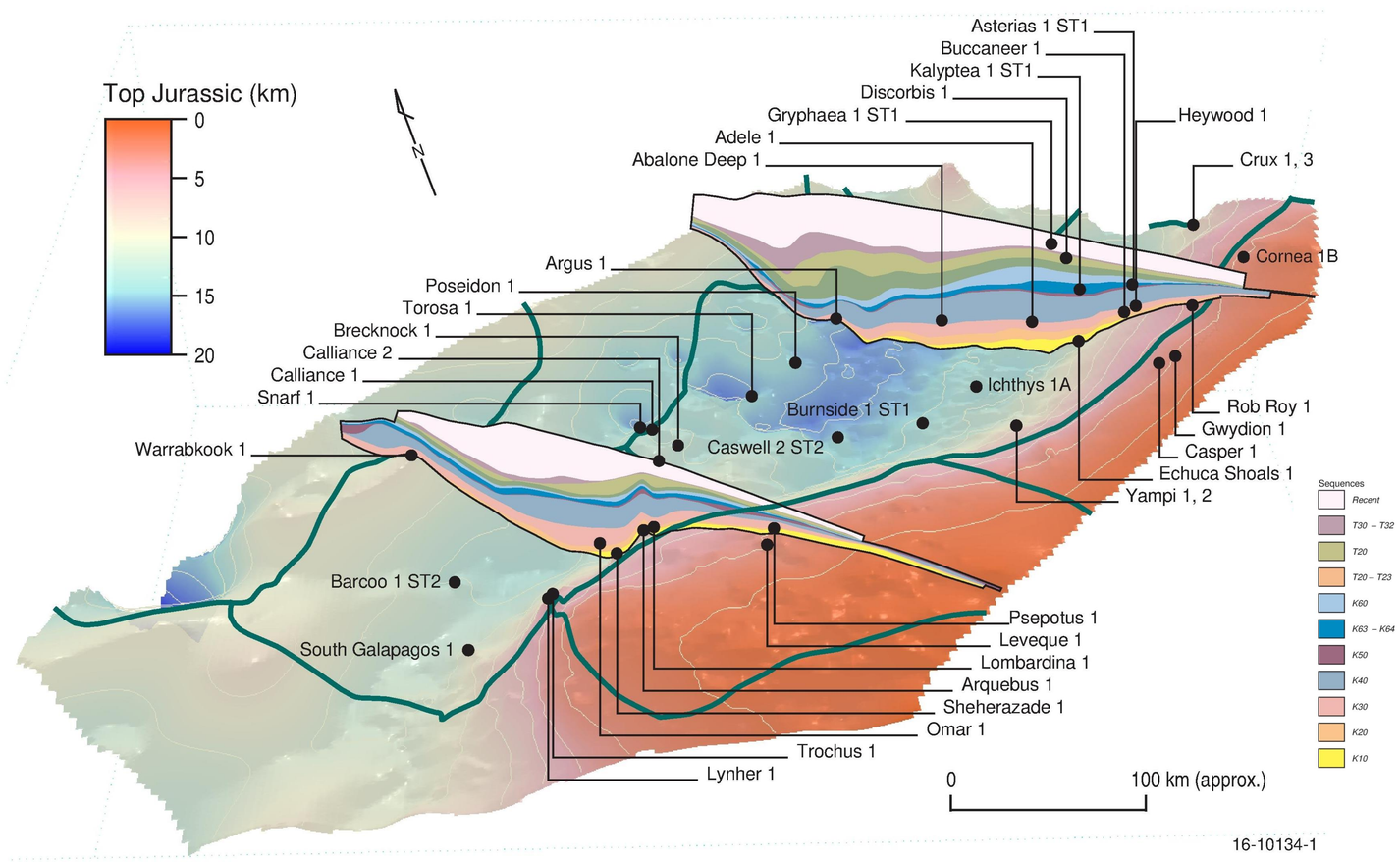


Figure 4. 3D perspective of the pseudo-3D petroleum systems model, including location of calibration wells and cross-sections of constructed model. The 3D geological model was developed from new seismic interpretation and tied well picks. Interpretation of the Cretaceous and younger sequences were derived from Rollet et al. (2016a), whereas initial Jurassic and older seismic horizons were provided by Bradshaw Geoscience Consultants.

Petroleum systems modelling

Basin architectural control on facies distribution

The regional 3D geological model was used to map the gross thickness of each set of supersequences containing source rocks (Figure 5). The fraction of shale and/or coaly shale facies within each supersequence was calculated for 60 wells using well log data and well completion report information. Multiplying the fraction of source rock facies present with the gross sequence thickness provided an estimate of total source rock facies thickness. The maximum extent of each source pod was estimated from palaeogeographic mapping (Rollet et al., 2017, 2018) tied to well geochemistry data.

Burial and thermal history modelling

The regional 3D geological model was also used to develop a pseudo-3D petroleum systems model, focusing on the Jurassic–Cretaceous petroleum systems. The model was calibrated using corrected bottom hole temperature and maturity data from 34 wells (Figures 6 and 7). The top Permian structure surface was used as the lower thermal boundary of the model. Model calibration revealed that both temperature and heatflow at top Permian "basement" strongly correlates with total sediment thickness (Figure 8).

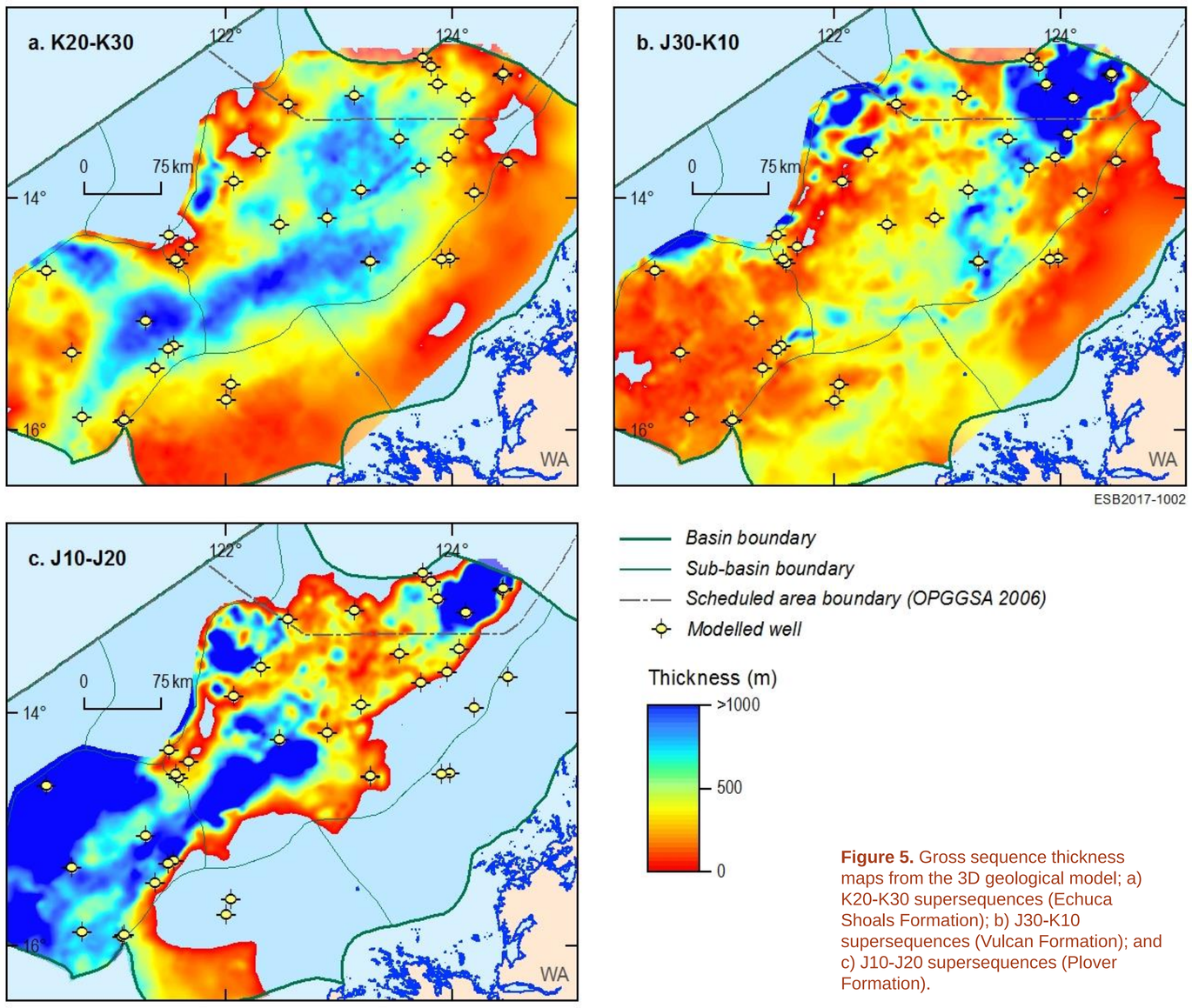


Figure 5. Gross sequence thickness maps from the 3D geological model; a) K20-K30 supersequences (Echuca Shoals Formation); b) J30-K10 supersequences (Vulcan Formation); and c) J10-J20 supersequences (Plover Formation).

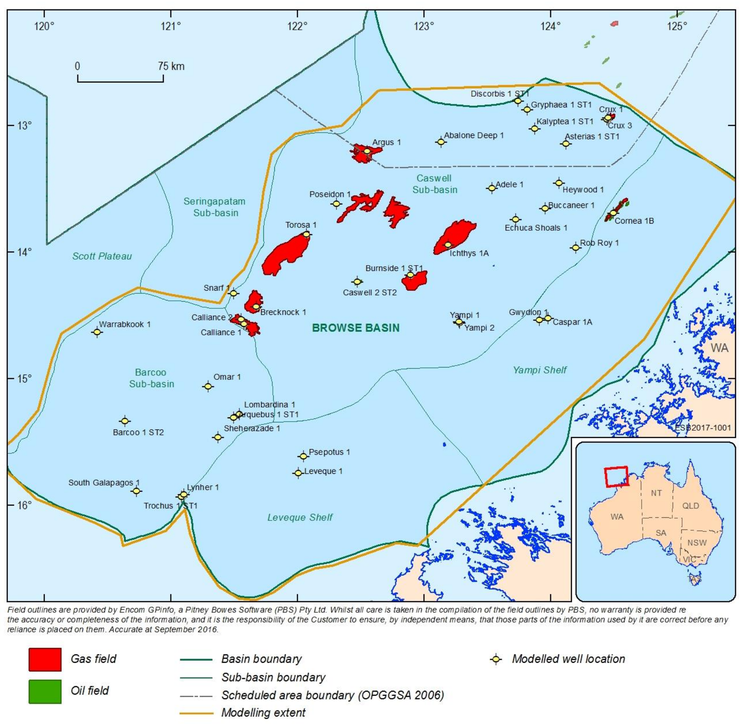


Figure 6. Browse Basin pseudo-3D petroleum systems model extent. Locations of calibration wells are also shown. Modelling was conducted using the Trinity-Genesis-KinEx software suite (http://www.zetaware.com).

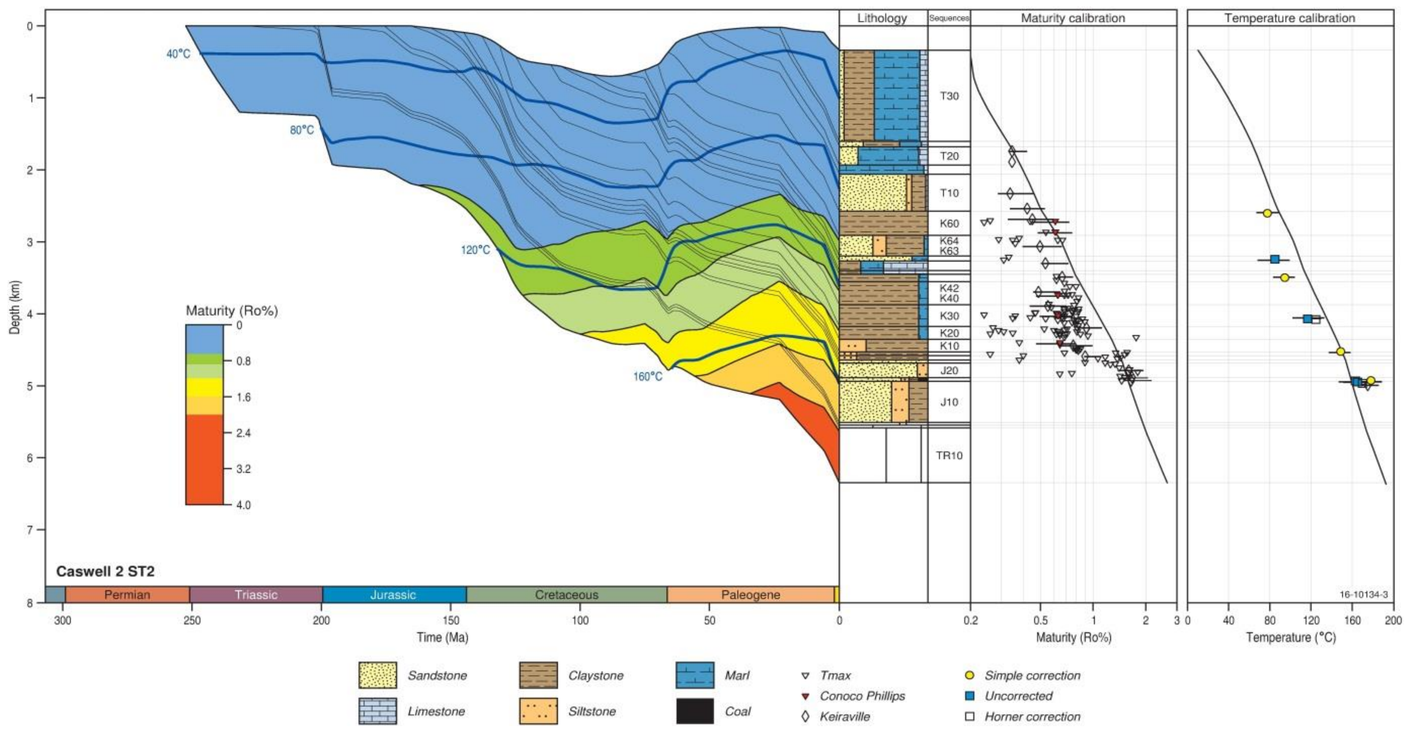


Figure 7. Modelled burial history for Caswell 2 ST2 showing data calibration (palaeo-maturity and bottom hole temperature). Age, lithologies and palaeo-bathymetry were assigned by supersequence based on the regional tectonostratigraphic chart, lithology logs and well completion report composite logs (Rollet et al., 2016a). Uplift and erosion amounts were considered to be negligible (<100m) throughout the basin and are therefore insignificant in the context of the 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.

Source rock geochemistry

Source rock characteristics were assigned based on an updated compilation of quality-controlled total organic carbon (TOC) and Rock-Eval pyrolysis data (Figure 9 and Table 1). To capture the total generative potential of each source rock, an estimate of the original hydrogen index (HI) prior to the onset of hydrocarbon generation was used. Kerogen types were assigned by depositional environment and generalised expulsion parameters were applied (Figure 10; Pepper and Corvi, 1995a,b).

The source rock property data were integrated with the pseudo-3D petroleum systems model to predict transformation ratio, maturity and charge history.

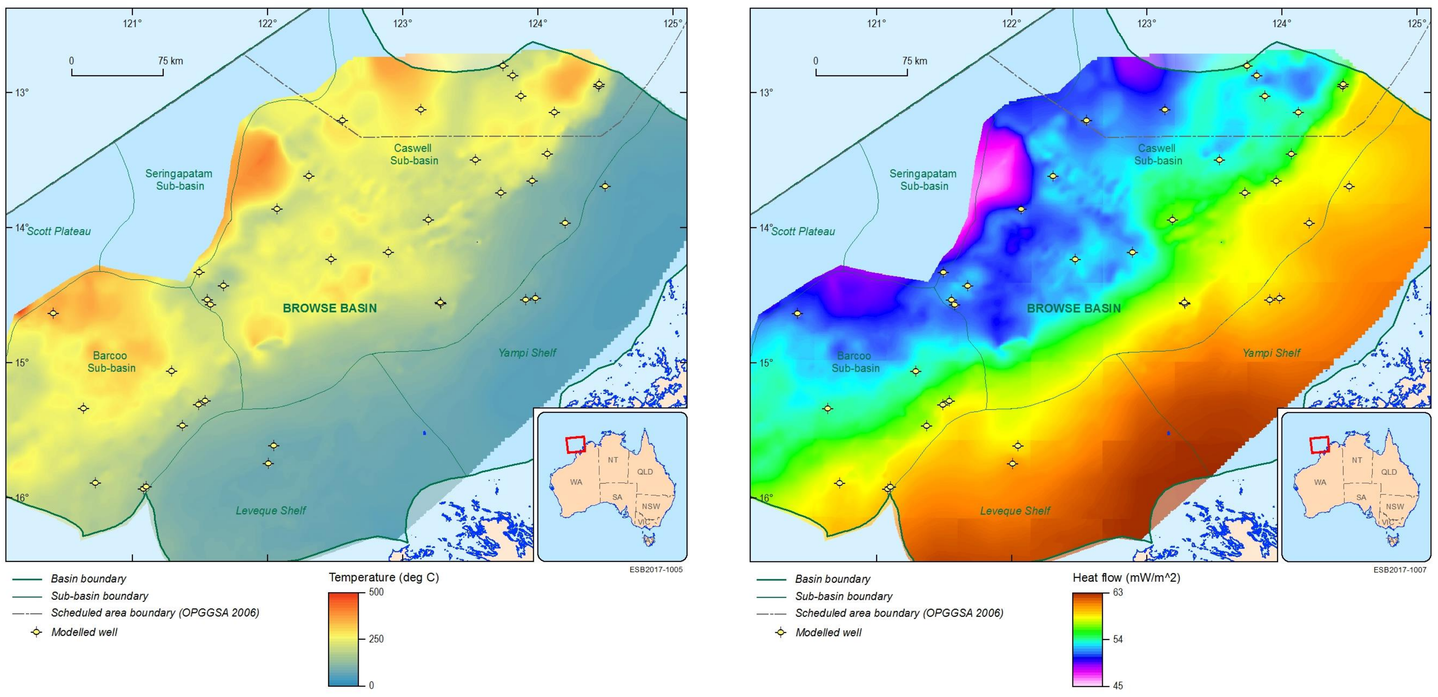


Figure 8. Present day a) temperature (ºC) and b) heatflow (mW/m^{-2}) at the top Permian horizon.

Integrated charge analysis

J10–J20 supersequences (Plover Formation)

Source rocks within the J10–J20 supersequences were deposited in extensive fluvial-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, 1995a; equivalent to type III). Source rock distribution is difficult to constrain due to the ephemeral nature of the fluvial and paralic environments and high sedimentation rates (Blevin et al., 1998b).

Transformation ratios reach up to 1 (>2% Ro) throughout the central Caswell Sub-basin (Figure 11). 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).

Using median source rock characteristics (TOC = 1.8%; original HI = 152 mg HC/g TOC; Table 1) only gas is generated (Figures 11 and 12). However the source rock geochemistry indicates the presence of higher quality source rock (HI >200 mg HC/g TOC) in localised areas, which would have the potential to generate some liquids (Figure 9 and Figure 12). Hydrocarbon expulsion began in the Late Jurassic, with peak expulsion occurring during the latest Cretaceous.

J30–K10 supersequences (Vulcan Formation)

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., 1998b).

Transformation ratios reach 0.98 (~2% Ro) in the deepest part of the Caswell Sub-basin (Figure 11). In the deepest section of the Barcoo Sub-basin, transformation ratios reach 0.82 (~1.2 % Ro), but only one fifth of the sub-basin reaches values >0.5.

Using median source rock characteristics (TOC = 1.2%; original HI = 232 mg HC/g TOC; Table 1), the modelling results suggest that source rocks within the J30–K10 supersequences have generated gas and liquids across the central Caswell Sub-basin (Figure 12). Charge histories show the onset of expulsion occurred in the 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., 1998a). The majority of samples have only fair potential (TOC <2% and HI <200 mg HC/g TOC). Yields are too low to saturate the host shales sufficiently to allow continuous migration into and through carrier beds to a trap (Radlinski et al., 2004). Hence, the K20-30 supersequence does not comprise a world class oil-prone source rock. Having said this, source quality may improve in the undrilled 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 (Figure 11).

Although hydrocarbon expulsion is likely to be limited in the K20-K30 supersequences, modelling results using median source rock characteristics (TOC = 1.5%; original HI = 201 mg HC/g TOC; Table 1) suggest that these Lower Cretaceous source rocks have the potential to generate some gas and minor liquids across the central Caswell Sub-basin (Figure 12), with minor expulsion occurring in the late Eocene.

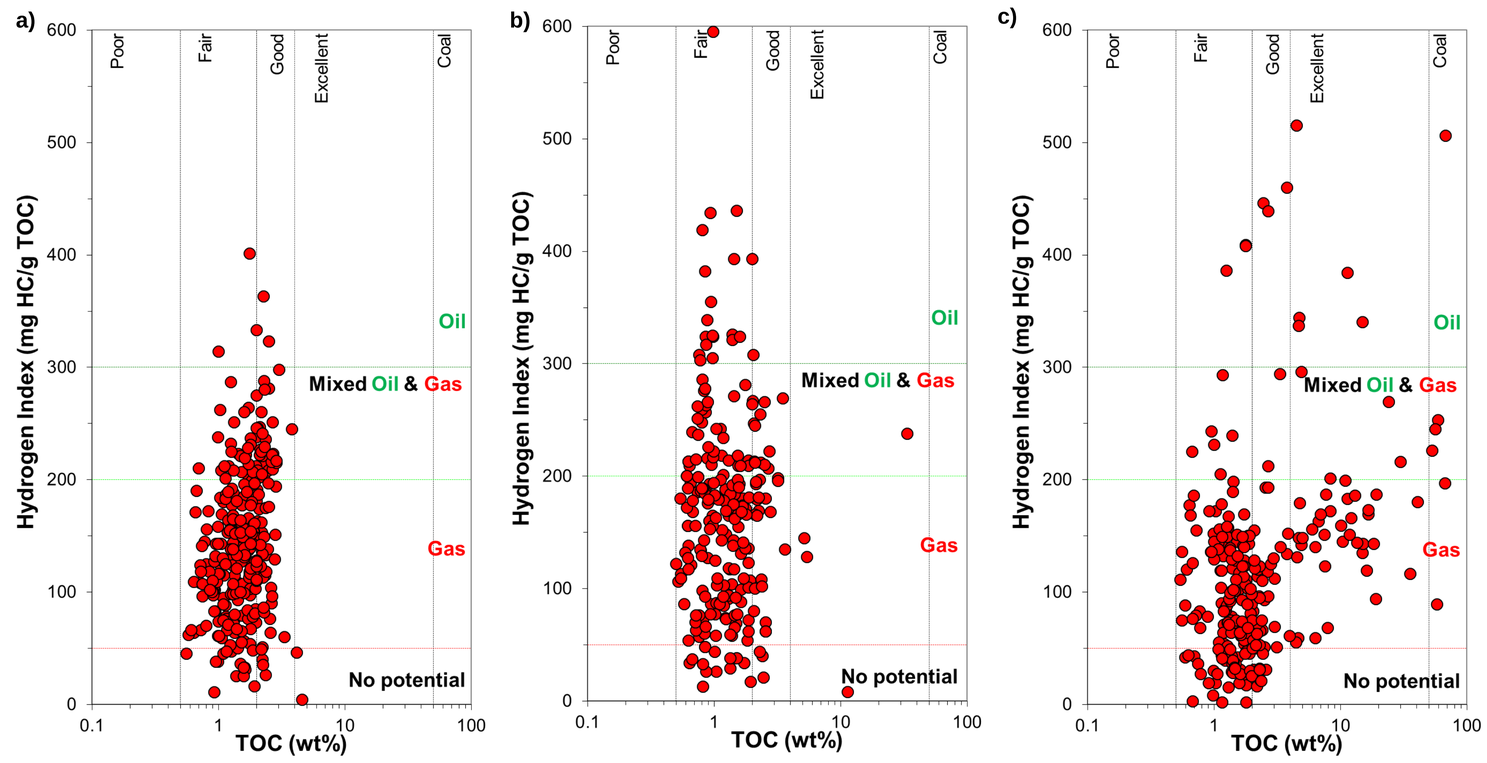


Figure 9. TOC versus HI for a) K20-K30 supersequences (Echuca Shoals Formation); b) J30-K10 supersequences (Vulcan Formation); and c) J10-J20 supersequences (Plover Formation). Browse Basin source rocks are typically difficult to characterise because they are either sparsely drilled and/or sampled, or have only been penetrated on structural highs and basin margins where their quality may not be representative.

Table 1. Browse Basin source rock characteristics, including TOC, measured HI, original HI and typical kerogen type. P10, P50 and P90 values are exceedance probabilities. Samples with TOC contents less than 0.5% are not considered to be a source rock and have been excluded from these analyses.

Source Rock	TOC (%)			HI (mg HC/g TOC)			Original HI (mg HC/g TOC)			Kerogen type
	P10	P50	P90	P10	P50	P90	P10	P50	P90	
K20-K30 Echuca Shoals Formation	2.4	1.5	0.9	227	137	61	336	201	71	D/E (with significant marine influence)
J30-K10 Vulcan Formation	2.3	1.2	0.7	268	166	59	379	232	89	D/E (with some marine influence)
J10-J20 Plover Formation	12.0	1.8	1.0	207	110	35	298	152	60	D/E (with some marine influence)

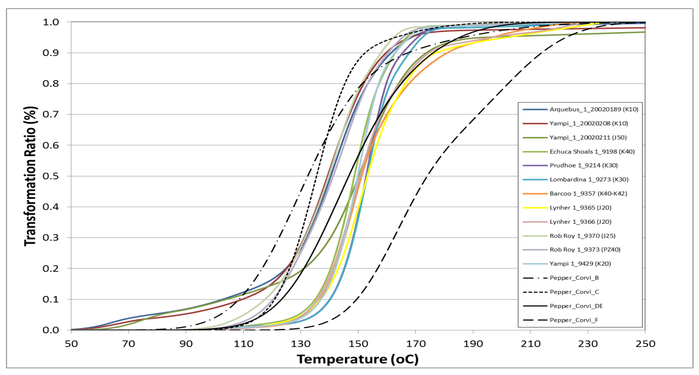


Figure 10. Transformation ratio (TR) versus temperature curves for Browse Basin bulk kinetics from Kennard et al. (2004), compared with relevant generic kinetics for organofacies from Pepper and Corvi (1995a). Geological heating rate: 3 K/My.

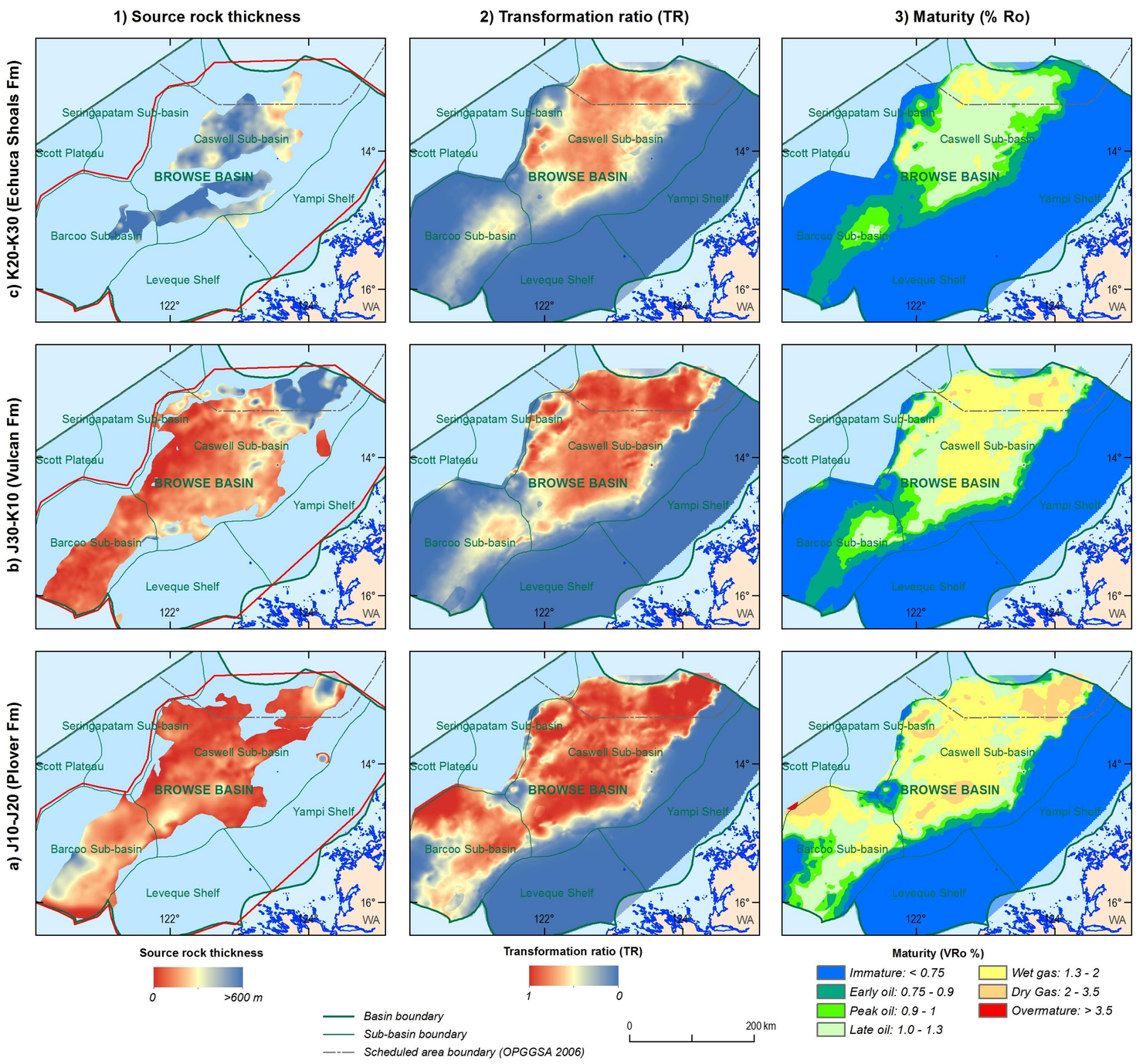


Figure 11. Petroleum systems modelling results for a) K20-K30 supersequences (Echuca Shoals Formation); b) J30-K10 supersequences (Vulcan Formation); and c) J10-J20 supersequences (Plover Formation). Columns definitions are; 1) net source rock thickness (m); 2) transformation ratio (TR; mass fraction); and 3) maturity (%Ro).

Petroleum fluids

Bulk fluid properties

The characteristics of compiled publicly available hydrocarbon fluid compositional data indicate that all samples belong to dew-point petroleum systems (Figure 13a), where gas-liquid ratios (GLR) are high (>10,000 scf/bbl). 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. 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 (Figure 13b). Palaeo-oil columns have been recognised at Crux 1 (Brincat et al., 2003) and Brecknock South 1 (CSIRO Petroleum, 2002). Oil sampled from a thin shallow porous/fractured zone (~2150 mRT) in Torosa 4 is geochemically similar to condensate recovered from the J10–J20 supersequences (Woodside Energy Ltd, 2008), indicating a common (Plover Formation) source. 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.

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 (Figure 14), 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. 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, Rondo 1 and 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 K20–K30 (and possibly K10) supersequence source rocks (Figure 14; Blevin et al., 1998a; Spry and Ward, 1997), whereas the co-occurring gas has been geochemically typed to the J10–J20 supersequences (Grosjean et al., 2016). As only poor-quality Lower Cretaceous source rocks have been penetrated, coupled with the volume expansion of gas as fluids migrate upwards, it is likely that the Cretaceous-sourced oils on the Yampi Shelf were mobilised and transported to their traps by Jurassic (Plover)-derived gas-condensate. The light oil at Caswell may also be the product of fluids mixing from several sources. Hence, prospectivity for Cretaceous- derived oil may depend on access to co-migrating gas-condensate. This is most likely to occur either along the shelf edge where seals pinch out against the basement or where fault reactivation has provided pathways for fluids to migrate into Upper Cretaceous reservoirs, and allowing fluids from multiple sources to mix.

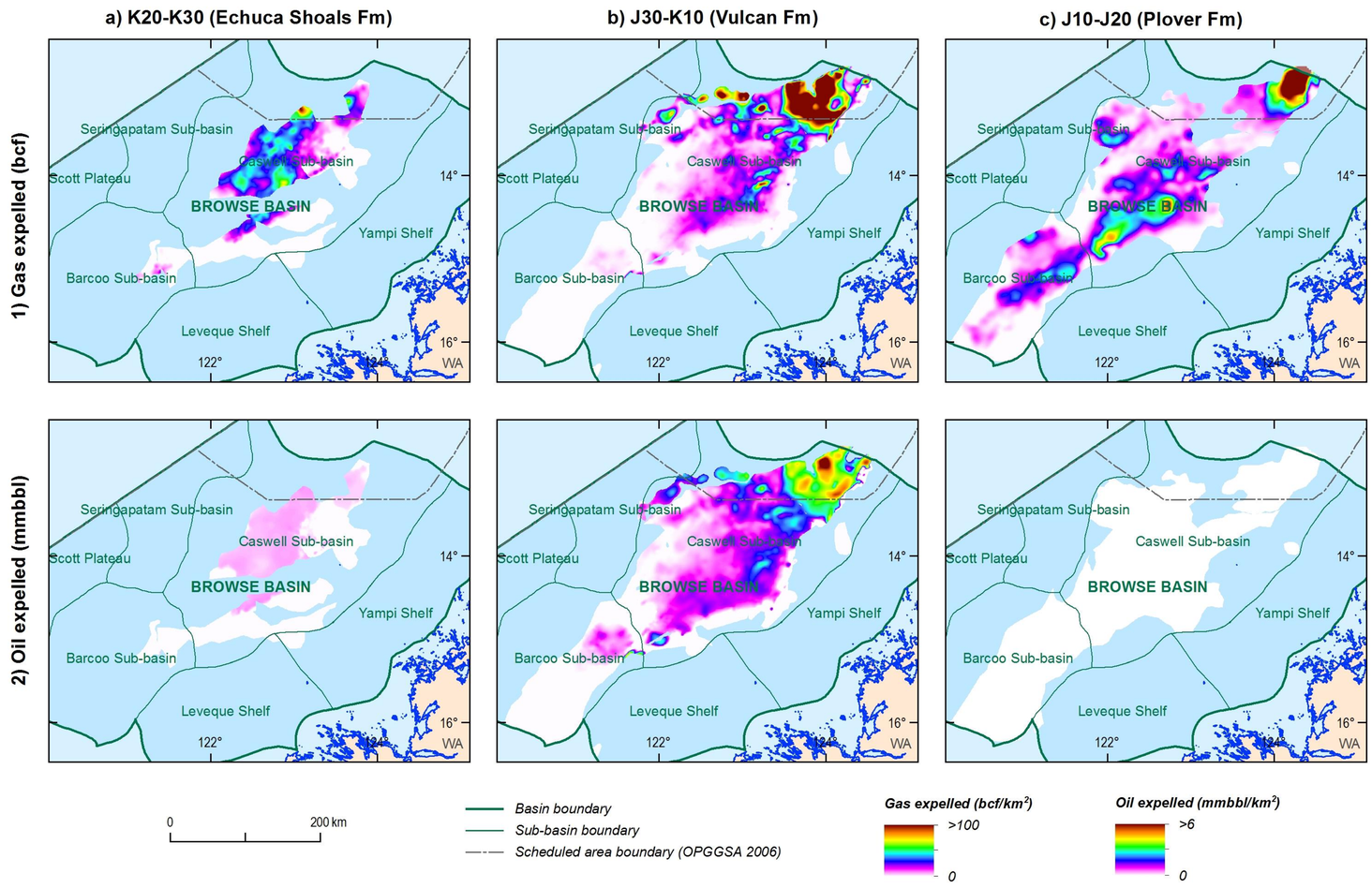


Figure 12. Petroleum systems modelling results for; a) K20-K30 supersequences (Echuca Shoals Formation); b) J30-K10 supersequences (Vulcan Formation); and c) J10-J20 supersequences (Plover Formation). Row definitions; 1) gas expelled (bcf/km^2); and 2) oil expelled (mmbbl/km^2). These analyses use the P50 TOC and original HI values shown in Table 1. Note no oil is expelled from the Plover Formation as the P50 HI is around 144 mg HC/g TOC. However some liquids may be expelled in localised areas where source rock quality is higher.

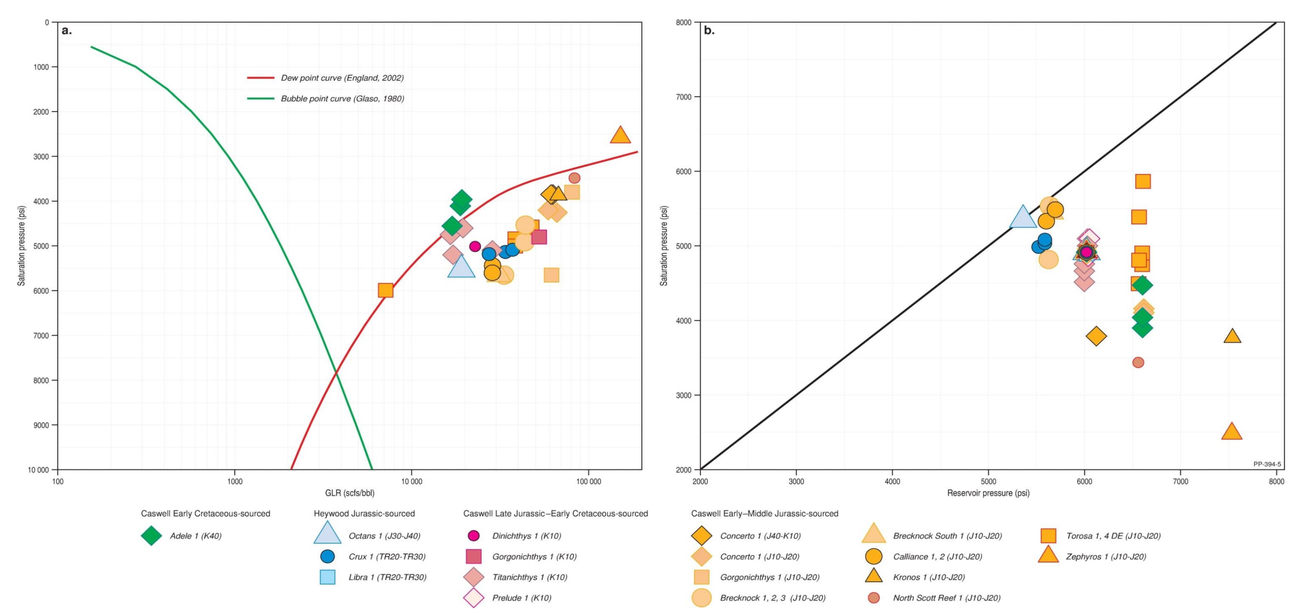


Figure 13. Fluid analysis of Browse Basin samples showing; a) gas-liquid ratio (GLR) vs saturation pressure with the solid lines representing global trends of dew point and bubble point thresholds; and b) reservoir pressure vs saturation pressure. These data demonstrate that the tested accumulations 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 of the symbol.

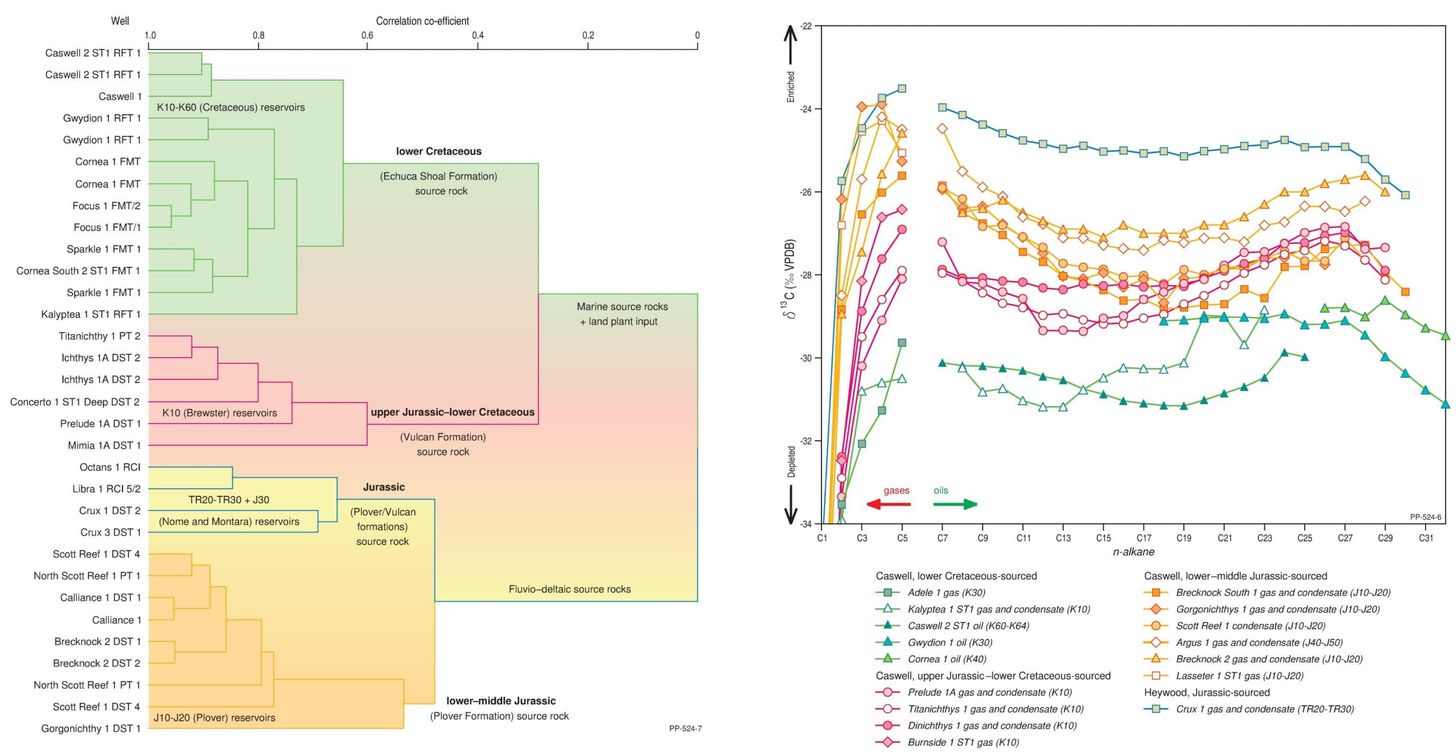


Figure 14. a) Hierarchical cluster analysis for oil and condensate families in the Browse Basin (Edwards et al., 2016) and b) carbon isotopic data for individual hydrocarbons in natural gases and oils from the Browse Basin (Grosjean et al., 2015, 2016). These data highlight the source differences between the Cretaceous-sourced (K20-K30 supersequences) fluids, from Adele-1 (gas) and Kalyptea-1 ST1 (gas and oils), which are depleted in ^{13}C (green), with those of Jurassic-sourced fluids (J10-J20 supersequences) from the Scott Reef Trend, which are enriched in ^{13}C (orange), and fluids with intermediate composition from the Ichthys and Burnside accumulations that are interpreted to be sourced and sealed by the K10 supersequence (pink). Fluid from Crux-1 in the Heywood Graben is isotopically enriched in ^{13}C (blue). The supersequence labelled after the well name in the key is the reservoir.

Conclusions

Regional petroleum systems

Four Mesozoic petroleum systems have been identified in the Caswell Sub-basin from the geochemistry of the gases, condensates and oils recovered from accumulations and shows, with one system being restricted to the region known as the Heywood Graben (Figures 14 and 15).

Most hydrocarbon fluids found in the 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 being present either in reservoirs higher up in the section or as residual columns after gas loss through leaking seals (Figure 16).

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 (Figure 15).

Screening of the source rock data for the Jurassic and Cretaceous supersequences show that they predominantly comprise gas-prone kerogen. Modelling results show that the marine shales within all supersequences do not have sufficient organic richness and quality to expel large volumes of oil, however oil generation is highly sensitive to the original HI.

Integration of the newly defined Browse Basin sequence stratigraphic framework, with a comprehensive petroleum system analysis, improves the understanding of the type, extent and charge history of a wide range of play types across the Browse Basin (Figure 16). The new precompetitive data produced from this study de-risks key outstanding exploration issues associated with the Browse Basin and aids the identification of new prospective areas in what has previously been perceived to be a relatively well explored sedimentary basin. Furthermore, the systematic workflow applied in this study demonstrates the importance of integrated sequence stratigraphic, geochemical and petroleum systems analysis studies as a predictive tool for understanding the petroleum resource potential of Australia's sedimentary basins.

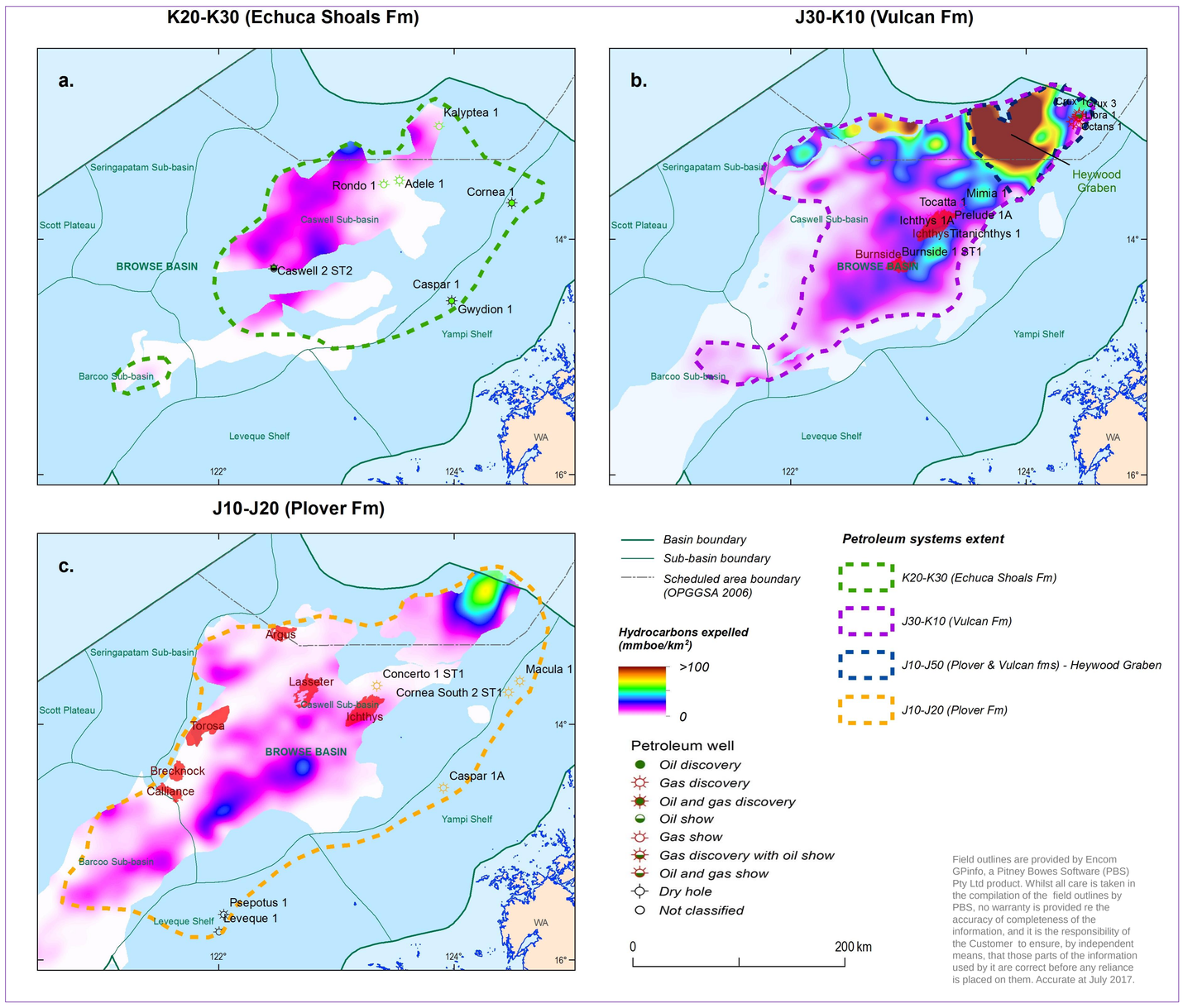


Figure 15. Hydrocarbon expulsion maps (oil + gas mmboe/km^2) for; a) K20-K30 supersequences (Echuca Shoals Formation); b) J30-K10 supersequences (Vulcan Formation); and c) J10-J20 supersequences (Plover Formation). The extent of the modelled expelled hydrocarbons and known hydrocarbon accumulations are used to define the potential extent of the associated petroleum systems. Locations of 1D burial history models used for calibration are shown on Figure 6.

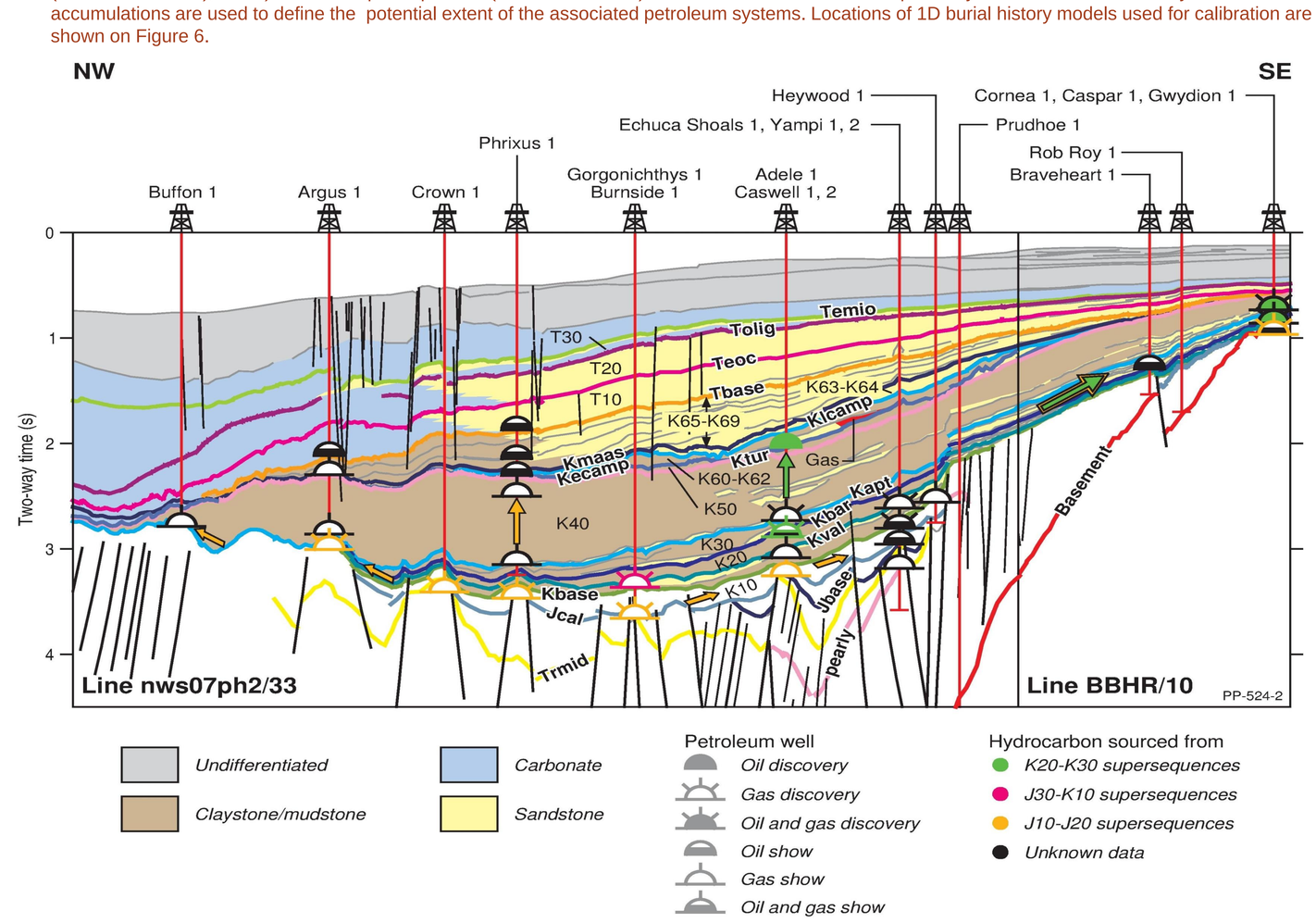


Figure 16. Schematic cross-section through the Caswell Sub-basin, showing sequences containing major source rocks and key petroleum wells.

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