The potential extent of Early Triassic Kockatea Shale equivalent source rocks in the Northern Carnarvon and Perth Basins (Western Australia)

Abbreviated title: Potential Early Triassic source rock extent

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Abstract

In the northern Perth Basin (Western Australia), the Early Triassic Kockatea Shale is the primary petroleum source rock. Possible source rocks in the Northern Carnarvon Basin are more varied and include the Upper Jurassic Dingo Claystone as well as the Early Triassic Locker Shale. Biomarker analyses were conducted on petroleum samples from these basins to understand the nature of the petroleum systems. Many of the analysed petroleum samples contain carotenoids (okenane, chlorobactane and isorenieratane) derived from photosynthetic sulfur bacteria, suggesting that their source rocks were deposited under conditions of photic zone euxinia (PZE) and/or derived from microbialites. In the northern Perth Basin, the major lithofacies contributing to the

source rock are dark coloured mudstones deposited under PZE conditions and/or derived from microbialites. In the southern Perth Basin, the potential source rock is either Permian, Jurassic or Cretaceous in age as indicated by the low concentrations or absence of carotenoids and the Triassic biomarker *n*-C_{33} alkylcyclohexane. There is also a possibility that the Lower Triassic Locker Shale is the source rock of petroleum in the Tubridgi field on the Peedamullah Shelf of the Northern Carnarvon Basin, based on the similarity of biomarkers to Perth Basin petroleum sourced from the Kockatea Shale. However, the possibility of charge from the Upper Jurassic Dingo Claystone cannot be entirely excluded.

Introduction

The Perth and Northern Carnarvon basins are located on the western and northwestern coasts of Australia, respectively. In the northern Perth Basin, the Early Triassic Kockatea Shale is considered to be the primary source rock for petroleum based on Rock-Eval, biomarker and stable carbon isotope analyses (Thomas 1979; Scott 1994; Boreham *et al.* 2000; Thomas *et al.* 2004; Dawson *et al.* 2005; Grice *et al.* 2005c, a, b, 2007; McIldowie and Alexander 2005; Langhi *et al.* 2014; Grosjean *et al.* 2017). The basal section of the Kockatea Shale, which is assigned to the Hovea Member, has high total organic carbon (TOC, up to 5 %) and hydrogen indices (HI, up to 800 mg/gTOC) indicating good potential for petroleum generation (Thomas and Barber 2004; Taniwaki *et al.* 2021). In large parts of the southern Perth Basin, the source rock is assumed to be Permian in age because younger source rocks in Jurassic and Cretaceous sequences are too immature for hydrocarbon generation and expulsion, while the Lower Triassic is dominated by sandy lithofacies (Crostella and Backhouse 2000). However, in the central part of the basin such as the Vlaming Sub-basin, the Upper Jurassic Yarragadee Formation is buried deeply enough to reach maturity and is a source rock for oils containing relatively high abundances of conifer-derived organic materials (Crostella and Backhouse 2000). In the Northern Carnarvon Basin, there are several potential source rocks. The Upper Jurassic Dingo Claystone is recognised as a source rock in the Barrow and Exmouth sub-basins (Volkman *et al.* 1983; van Aarssen *et al.* 1996; Tindale *et al.* 1998), Lower to Middle Jurassic marine and deltaic sequences are untested potential source rocks (Edwards and Zumberge 2005) and the Middle to Upper Triassic fluvial-deltaic to marine Mungaroo Formation is also considered a source rock (Edwards and Zumberge 2005). The Lower Triassic Locker Shale, which is an equivalent of the Lower Triassic Kockatea Shale, also has source rock potential with high TOC and HI (Molyneux *et al.* 2016). Triassic or older strata have been cited as possible source rocks for the Tubridgi field on the Peedamullah Shelf (Yasin and Iasky 1998; Edwards and Zumberge 2005).

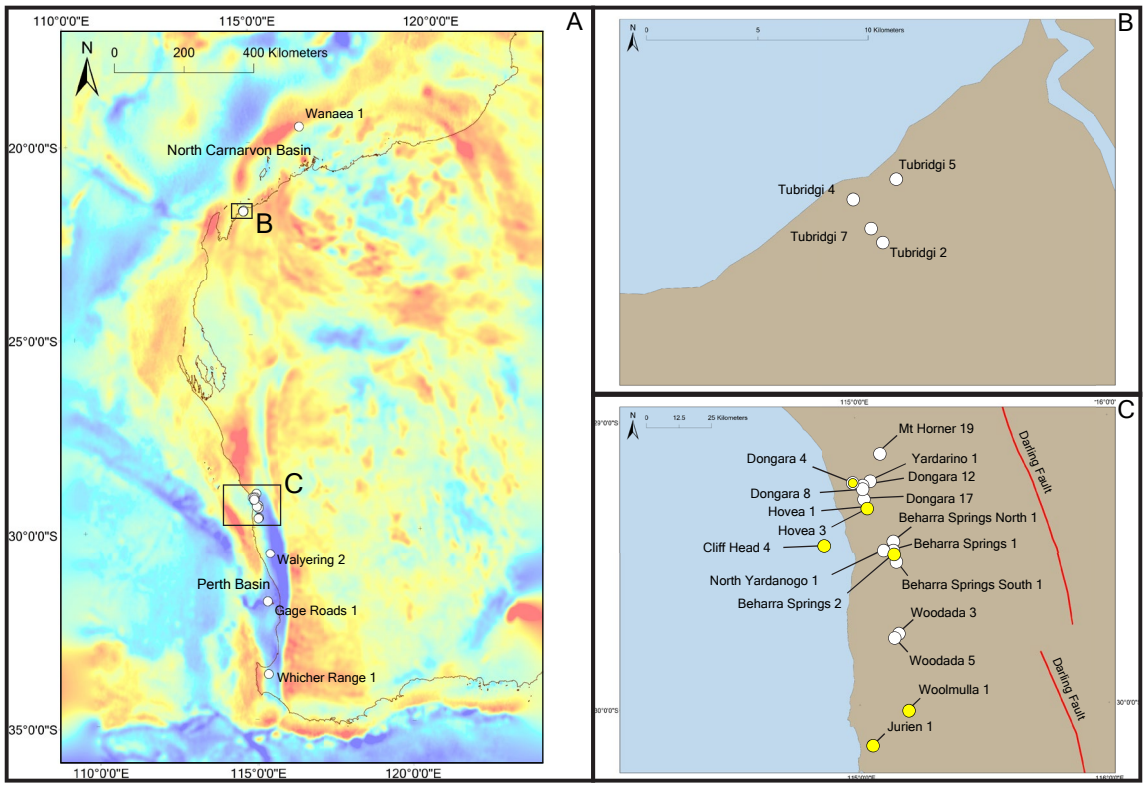
During the Late Permian/Early Triassic, massive volcanic activity from the Siberian Traps caused both global warming and anoxia (Erwin 1994; Knoll *et al.* 1996; Wignall and Twitchett 1996; Twitchett *et al.* 2004; Nabbefeld *et al.* 2010; Song *et al.* 2014; Whiteside

and Grice 2016). Development of PZE in the ancient water-column has been recognized in Permian/Triassic sections around the globe, including the northern Perth Basin (Grice *et al.* 2005c). Under PZE conditions, anoxygenic photosynthetic sulfur bacteria can thrive at the chemocline (the transition between oxic and anoxic conditions) (Pfenning 1978). These bacteria include purple, green-green and green-brown coloured sulfur bacteria. These organisms make specific carotenoid pigments (purple sulfur bacteria: okenone, green-green sulfur bacteria: chlorobactene: green-brown sulfur bacteria: isorenieratene) which yield biomarkers following diagenesis in the water column/sediments (okenane, chlorobactane and isorenieratane, respectively). Such biomarkers have been identified in both sediments and petroleum, suggesting PZE depositional conditions (Grice *et al.* 1996, 2005c; Clifford *et al.* 1998; Pedentchouk *et al.* 2004; Maslen *et al.* 2009; Sousa Júnior *et al.* 2013; Tulipani 2013). In addition, similar bacterial communities can develop in microbialites (Brocks and Schaeffer 2008; Pagès *et al.* 2014; Fox *et al.* 2020; Schaefer *et al.* 2020). In this study, biomarker analyses were conducted on petroleum samples (crude oils and condensates) from both the Perth and Northern Carnarvon basins to evaluate the nature of their petroleum systems.

Geological setting

The Perth Basin developed during several rifting, subsidence and uplift events from the Devonian to the Early Cretaceous (Fig. 1-Fig. 2) (Jablonski and Saitta 2004; Norvick 2004). The Late Permian to Early Triassic Kockatea Shale was deposited in a transgressive deeper water setting as part of a post-rift sequence following Late Permian rifting. Facies distribution in the Kockatea Shale was controlled by remnant topography created by the rift event (Taniwaki *et al.* 2021). The Middle Triassic Woodada Formation and younger strata were deposited during subsequent phases of extension.

The tectono-stratigraphy in the Northern Carnarvon Basin is similar to the Perth Basin (Ferdinando *et al.* 2007; l'Anson *et al.* 2019). Late Permian rifting is also evident in the Northern Carnarvon Basin. The Early Triassic Locker Shale, the equivalent of the Kockatea Shale, was deposited during a transgression that forms part of the post rift sequence. The Middle Triassic Mungaroo Formation and younger strata were deposited during subsequent phases of subsidence and rifting. The Upper Jurassic Dingo Claystone was mainly deposited in an open marine anoxic deeper water setting (Hocking 1992). Parts of the basin experienced significant uplift and erosion in the Early Cretaceous, as expressed by the Valanginian Unconformity.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C
Walyering 2
Perth Basin
Gage Roads 1
Whicher Range 1
20°0'0"S
25°0'0"S
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35°0'0"S
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Tubridgi 5
Tubridgi 4
Tubridgi 7
Tubridgi 2
C
Mt Horner 19
Dongara 4
Yardarino 1
Dongara 12
Dongara 8
Dongara 17
Hovea 1
Beharra Springs North 1
Hovea 3
Cliff Head 4
Beharra Springs 1
North Yardanogo 1
Beharra Springs South 1
Beharra Springs 2
Woodada 3
Woodada 5
Woolmulla 1
Jurien 1
Darling Fault
Darling Fault

Fig. 1.

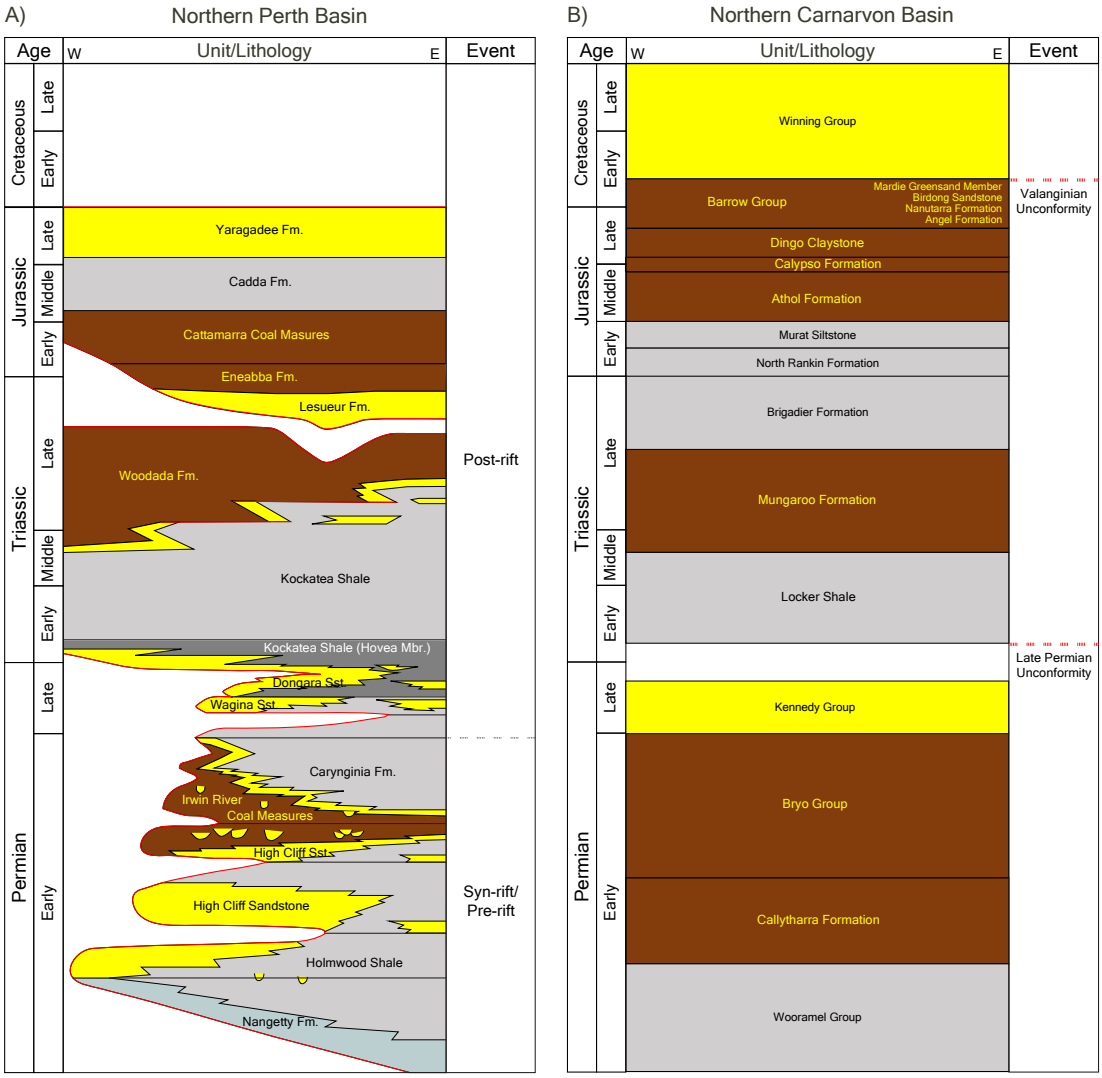


Fig. 2.

Data & Methodology

Samples

Twenty-one petroleum samples (crude oils and condensates) from both the Perth and Northern Carnarvon basins were used for this study (Fig. 1, Tab. 1). In the Northern Carnarvon Basin, one sample (Wanaea 1) comes from the Dampier Sub Basin and four other samples are derived from the Tubridgi field on the Peedamullah Shelf. The petroleum samples from the Northern Carnarvon Basin were recovered from the Cretaceous Birdrong Formation and Mardie Greensand Member (Tubridgi), and the Jurassic Angel Formation (Wanaea). In the Perth Basin, petroleum samples were derived

from the Early Permian Carynginia Formation, Late Permian Dongara and Wagina Sandstones, Late Permian to Early Triassic Kockatea Shale, and Jurassic Cattamarra Coal Measures and Cockleshell Gully Formation. In the southern Perth Basin, the Early Permian Irwin River Coal Measures and Jurassic Yaraggadee Formation and Cattamarra Coal Measures are the reservoir formations for the samples.

Tab. 1.

Well	Type	Basin	Formation	Age
Beharra Springs 1	Condensate	North Perth Basin	Carynginia Fm.	Permian
Beharra Springs North 1	Oil	North Perth Basin	Wagina Sandstone	Permian
Beharra Springs South 1	Oil	North Perth Basin	Kockatea Shale	Permian/Triassic
Dongara 04	Oil	North Perth Basin	Irwin River Coal Measures	Permian
Dongara 08	Oil	North Perth Basin	Dongara Sandstone	Permian
Dongara 12	Oil	North Perth Basin	Wagina Sandstone	Permian
Dongara 17	Oil	North Perth Basin	Dongara Sandstone	Permian
Hovea 1	Oil	North Perth Basin	Dongara Sandstone	Permian
Mt Horner 09	Oil	North Perth Basin	Cattamarra Coal Measures	Jurassic
North Yardanogo 1	Oil	North Perth Basin	Cockleshell Gully Fm.	Jurassic
Woodada 03	Oil	North Perth Basin	Carynginia Fm.	Permian
Woodada 05	Oil	North Perth Basin	Carynginia Fm.	Permian
Yardarino 1	Oil	North Perth Basin	Wagina Sandstone	Permian
Gage Roads 1	Oil	South Perth Basin	Yaraggadee Fm.	Jurassic
Walyering 2	Oil	South Perth Basin	Cattamarra Coal Measures	Jurassic

Whicher Range 1	Oil	South Perth Basin	Irwin River Coal Measures	Permian
Tubridgi 02	Oil	North Carnarvon Basin	Birdong Sandstone	Cretaceous
Tubridgi 04	Oil	North Carnarvon Basin	Mardie Greensand Mbr. & Birdong Sandstone	Cretaceous
Tubridgi 05	Oil	North Carnarvon Basin	Mardie Greensand Mbr.	Cretaceous
Tubridgi 07	Oil	North Carnarvon Basin	Mardie Greendand Mbr., Birdong Sandstone & Nanutarra Fm.	Cretaceous
Wanaea 1	Oil	North Carnarvon Basin	Angel Fm.	Jurassic

Fractionation of samples

The petroleum samples were fractionated into saturated, aromatic, and polar fractions using small scale silica gel column chromatography. Samples (~10 mg) were weighed and put onto a 5.5 cm column packed with activated silica gel (160 °C overnight). The saturated hydrocarbons were eluted with 4 mL of *n*-hexane. The aromatic hydrocarbons were separated using a mixture of 1.2 mL dichloromethane and 2.8 mL of *n*-hexane. The polar fraction was eluted with a 1:1 mixture of methanol (2 mL) and dichloromethane (2 mL). Each fraction was evaporated to dryness with a nitrogen purge and then weighed.

Analysis

Gas chromatography-mass spectrometry (GC-MS) analyses were conducted on both saturated and aromatic hydrocarbon fractions. Gas chromatography-metastable reaction monitoring-mass spectrometry (GC-MRM-MS) was also conducted on all samples.

Gas Chromatography-Mass Spectrometry (GC-MS)

For the saturated fractions, an Agilent 5973B MSD interfaced to an Agilent 7890B gas chromatograph was used for GC-MS analysis. A J&W Scientific DB-1MS column of 60 m length, 250 µm inner diameter and 0.25 µm film thickness was installed. The GC oven was programmed from 40 °C to 325 °C at a heating rate of 3 °C/min. The holding time at initial and final temperature was 1 and 30 minutes, respectively. The MS was set with an ionisation energy of 70 eV and measured a mass range from 50 to 550 Daltons.

For the aromatic fractions, an Agilent 5975B MSD interfaced to an Agilent 6890N gas chromatograph was used for GC-MS analysis. A J&W DB-5MS column of 60 m length, 250 µm inner diameter and 0.25 µm film thickness was used. The oven program and scanned range of the MS was the same as that used for the saturated fractions.

GC-MS, metastable reaction monitoring- (GC-MRM-MS)

Saturated and aromatic fractions were combined in equal amounts for GC-MRM-MS analysis. An Agilent 7890B GC interfaced to an Agilent 7010B Triple Quadruple MS operated in metastable reaction monitoring (MRM) mode was used for the analysis. A DB-5MS UI capillary column of 60 m length, 250 µm inner diameter, and 0.25 µm film thickness was installed. The temperature of the GC oven was set from 40 °C to 325 °C with a heating rate of 4 °C/min. The final holding time was 20.75 minutes. The MS was programmed at 50 eV ionisation energy. The QQQ temperature was set at 150 °C. D4-C_{27} ααα cholestane was added as an internal standard to the combined sample. Compounds were identified by comparing with reference standards, matching retention times and elution order.

Rock samples

Rock samples from the earliest Triassic part of the Kockatea Shale from the northern Perth Basin were used for comparison with petroleum samples. The rock samples were analyzed and described in detail by Taniwaki *et al*. (2022).

Results and discussion

Thermal maturity assessment

The thermal maturity of each sample was determined based on C_{32} 22*S*/(22*S*+22*R*) αβ-homohopane, 17β,21α C_{30} hopane/17α,21β C_{30} hopane (moretane/hopane), C_{29} 20*S*/(20*S*+20*R*) (ααα+αββ) sterane ratio, αββ/(αββ+ααα) C_{29} sterane, 18α22,29,30-*trisnor*hopane (Ts) to 17α22,29,30-*trisnor*hopane (Tm) ratio (Ts/(Ts+Tm)) and diasteranes/(diasteranes+regular steranes): $\Sigma C_{27\text{-}29}$ diasteranes/($\Sigma C_{27\text{-}29}$ diasteranes+$\Sigma C_{27\text{-}29}$ steranes) (abbreviated to Dia/(Dia+Reg)) (Tab. 3). C_{32} 22*S*/(22*S*+22*R*) αβ-homohopane, moretane/hopane and C_{29} 20*S*/(20*S*+20*R*) (ααα+αββ) sterane ratios reached their thermal equilibrium values, indicating that the thermal maturity is equivalent to at least 0.8 % vitrinite reflectance (Ro) (Peters *et al.* 2004). αββ/(αββ+ααα) C_{29} sterane, Ts/(Ts+Tm) and Dia/(Dia+Reg) are still lower than their thermal equilibrium values indicating that the thermal maturity for all samples is less than 0.9 % Ro equivalent. Therefore, the thermal maturity level of samples ranges between 0.8 and 0.9 % Ro equivalent (Peters *et al.* 2004).

Characteristics of major biomarkers (Pr/Ph, C_{35} homohopane index, gammacerane index, and $C_{27\text{-}29}$ regular sterane ratio)

Tubridgi petroleum appears to have experienced biodegradation (biodegradation rank: 3-4, (Trolio et al, 1999; Grice et al. 2000; Wenger *et al.* 2002; Peters *et al.* 2004)) based on the elevated unresolved complex mixture and the depletion of *n*-alkanes in total ion chromatograms, most significantly in Tubridgi 7. Samples from other fields do not show significant biodegradation.

Pr/Ph ratios show a significant difference between the basins: 1.7-4.1 for most of the Northern Carnarvon Basin petroleum, 0.4-1.3 for the northern Perth Basin and 1.4-1.8 for the southern Perth Basin. However, Pr/Ph in the Tubridgi petroleum appears to be influenced by biodegradation (Tab. 2 and S1). C_{35} homohopane and gammacerane indices (hopane index: C_{35} (22*S*+22*R*) αβ-homohopane/C_{34} (22*S*+22*R*) αβ-homohopane, gammacerane index: gammacerane/(gammacerane+C_{30}αβ-homohopane)) overlap between basins (Tab. 2 and S1). C_{27} to C_{29} regular sterane ratios also show similar

characteristics between basins, except petroleum from Gage Roads 1. C_{27} and C_{29} regular steranes generally range between 30-50%, and C_{28} regular steranes generally range between 20-30%. However, the sterane ratio in Gage Roads 1 shows a higher abundance of C_{29} regular sterane reaching 81% (Tab. 2 and S1).

Relative abundance of carotenoid biomarkers (okenane, chlorobactane and isorenieratane) in petroleum samples

Most of the petroleum samples contain biomarkers derived from anoxygenic photosynthetic sulfur bacteria (okenane: purple sulfur bacteria, chlorobactane: green-green sulfur bacteria, isorenieratane: green-brown sulfur bacteria) (Fig. 3). Beharra Springs North 1 does not contain either chlorobactane or okenane but does contain isorenieratane. Beharra Springs South 1, Whicher Range 1 and Tubridgi 7 contain both chlorobactane and isorenieratane but no okenane. Wanaea 1 and Walyering 2 do not contain chlorobactane, isorenieratane nor okenane (Fig. 4).

Tab. 2.

	Pr/Ph	**C_{35} homohopane index**	**Gammacerane index**	**C_{27-29} regular sterane ratio**	***n*-C_{33} ACH ratio**	**Okenane ratio**	**Carotenoids (ug/gTOC)**
Northern Carnarvon Basin	1.7-4.1	0.4-1.0	0.01-0.06	C_{27}: 30-50% C_{28}: 30-50% C_{29}: 20-30%	0-0.01	1.00-1.05	Ok: 0.00-0.32 Ch: 0.00-6.19 Is: 0.00-22.46
Northern Perth Basin	0.4-1.3	0.4-0.7	0.02-0.08	C_{27}: 30-50% C_{28}: 30-50% C_{29}: 20-30%	0.02-0.57	1.00-1.15	Ok: 0.00-1.26 Ch: 0.00-4.18 Is: 0.06-159.86
Southern Perth Basin	1.4-1.8	0.1-0.7	0.01-0.05	C_{27}: 30-50% C_{28}: 30-50% C_{29}: 20-30% *Gage Roads 1 C_{27}: 8% C_{28}: 11% C_{29}: 81%	0-0.02	1.00-1.06	Ok: 0.00-0.04 Ch: 0.00-0.21 Is: 0.00-0.37

Tab. 3.

Well	Basin	C_{32} 22*S*/(22*S*+22*R*) αβ-homohopane	Moretane/ Hopane	C_{29} 20*S*/(20*S*+20*R*) sterane ratio	αββ/(αββ+ααα) C_{29} Sterane	Ts/(Ts +Tm)	Dia/(Dia +Reg)
Beharra Springs 1	North Perth Basin	0.61	0.06	0.42	0.63	0.61	0.49
Beharra Springs North 1	North Perth Basin	0.61	N/I	0.29	0.72	N/I	0.35
Beharra Springs South 1	North Perth Basin	0.58	0.07	0.43	0.64	0.69	0.55
Dongara 04	North Perth Basin	0.61	0.06	0.47	0.59	0.49	0.35
Dongara 08	North Perth Basin	0.58	0.06	0.44	0.61	0.65	0.49
Dongara 12	North Perth Basin	0.58	0.07	0.44	0.54	0.56	0.54
Dongara 17	North Perth Basin	0.60	0.07	0.46	0.50	0.70	0.32
Hovea 1	North Perth Basin	0.60	0.07	0.46	0.46	0.54	0.27

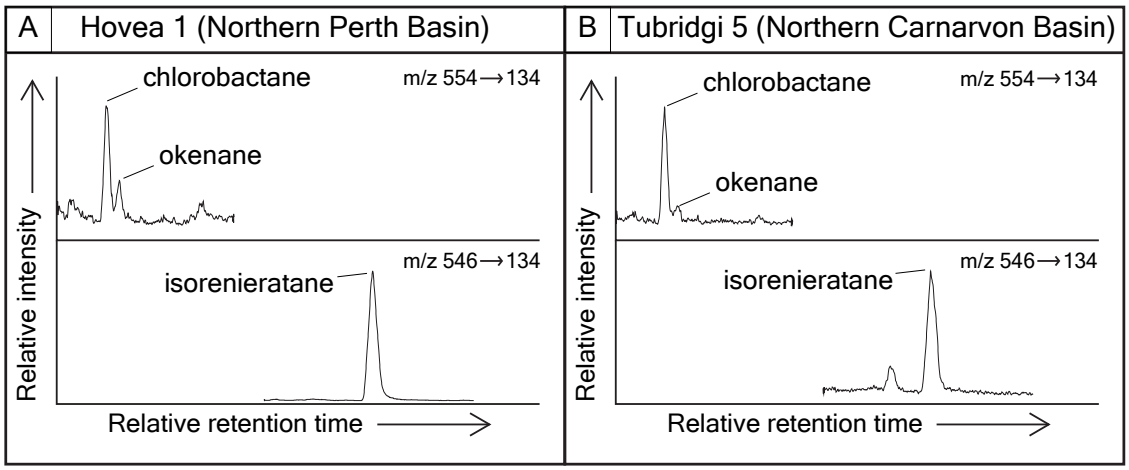
Mt Horner 09	North Perth Basin	0.55	0.05	0.47	0.58	0.76	0.42
North Yardanogo 1	North Perth Basin	0.59	0.05	0.46	0.58	0.71	0.34
Woodada 03	North Perth Basin	0.57	0.06	0.46	0.57	0.78	0.41
Woodada 05	North Perth Basin	0.55	0.06	0.47	0.60	0.84	0.60
Yardarino 1	North Perth Basin	0.58	0.04	0.45	0.64	0.77	0.57
Gage Roads 1	South Perth Basin	0.60	0.09	0.45	0.50	0.31	0.64
Walyering 2	South Perth Basin	0.56	0.04	0.41	0.59	0.74	0.54
Whicher Range 1	South Perth Basin	0.60	0.04	0.47	0.66	0.65	0.56
Tubridgi 02	North Carnarvon Basin	0.63	0.05	0.48	0.59	0.56	0.23
Tubridgi 04	North Carnarvon Basin	0.61	0.05	0.45	0.57	0.56	0.40

Tubridgi 05	North Carnarvon Basin	0.59	0.05	0.48	0.58	0.61	0.42
Tubridgi 07	North Carnarvon Basin	0.58	0.09	0.34	0.45	0.64	0.38
Wanaea 1	North Carnarvon Basin	0.58	0.06	0.48	0.65	0.80	0.70

The effect of thermal maturity on the concentrations of okenane, chlorobactane and isorenieratane is evaluated by comparing these biomarkers with αββ/(αββ+ααα) C_{29} sterane (Fig. 5). The concentrations of okenane, chlorobactane and isorenieratane generally decrease with increasing thermal maturity, suggesting that the compounds are likely affected by thermal maturity. The most significant change in concentrations occurs when αββ/(αββ+ααα) C_{29} sterane ratio reaches 0.6. The rate of decrease of each carotenoid concentration is similar. The okenane ratio, which is the relative abundance of okenane to chlorobactane and isorenieratane, distinguishes PZE dominated conditions (lower okenane ratio) and microbialite facies (higher okenane ratio) in less mature rock samples (Brocks and Schaeffer 2008; Pagès *et al.* 2014; Schaefer *et al.* 2020) but this ratio could be influenced by thermal maturity in the more mature petroleum samples and caution is therefore required if using it for comparison between samples from different wells.

The absence of some of these carotenoid biomarkers in Beharra Springs North 1, Beharra Springs South 1, Whicher Range 1 and Wanaea 1 could be the result of relatively higher thermal maturity, as αββ/(αββ+ααα) C_{29} sterane of these samples is higher than 0.64, which is nearly the thermal equilibrium value. However, αββ/(αββ+ααα) C_{29} sterane of Tubridgi 7 and Walyering 2 is lower (0.45 and 0.59, respectively), although Tubridgi 7 does not have okenane and Walyering 2 lacks all three carotenoid biomarkers. The absence of okenane in Tubridgi 7 may be the result of biodegradation. The absence of these biomarkers from Walyering 2 could indicate a difference in paleoenvironmental conditions during deposition of their source rocks. Gage Roads 1 and Whicher Range 1 in the southern Perth Basin contain carotenoids, but their concentrations are low compared to oils from the northern Perth and Northern Carnarvon basins.

Fig. 6 shows peaks for okenane, chlorobactane and isorenieratane from Tubridgi 2, 4, 5 and 7. These samples show a similar distribution of carotenoid biomarkers to rock (PZE and microbialite facies) and petroleum samples from the northern Perth Basin (Fig. 3).The similarity implies that the source of the Tubridgi petroleum samples shares similar paleoenvironmental conditions to the Kockatea Shale in the northern Perth Basin.


A
Hovea 1 (Northern Perth Basin)
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isorenieratane
Relative intensity
Relative retention time
B
Tubridgi 5 (Northern Carnarvon Basin)
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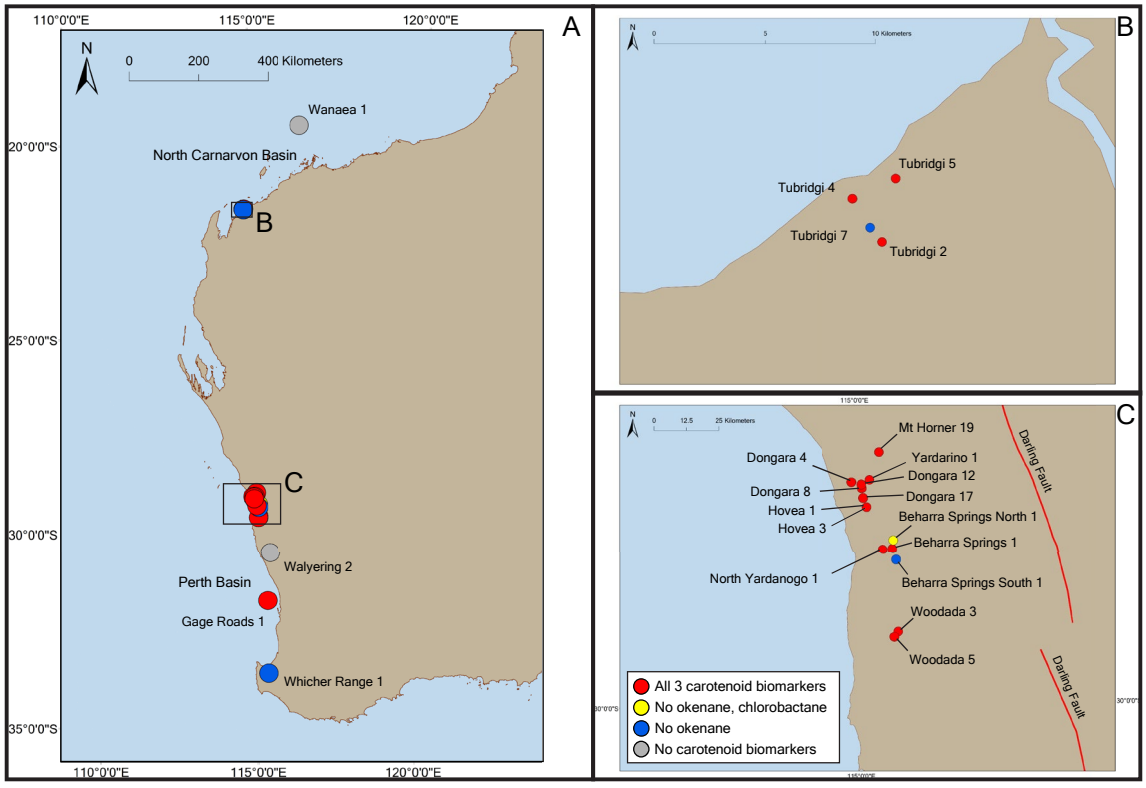
m/z 554⟶134
okenane
m/z 546⟶134
isorenieratane
Relative intensity
Relative retention time

Fig. 3.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Walyering 2
Perth Basin
Gage Roads 1
Whicher Range 1
35°0'0"S
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Tubridgi 5
Tubridgi 4
Tubridgi 7
Tubridgi 2
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Mt Horner 19
Dongara 4
Yardarino 1
Dongara 12
Dongara 8
Dongara 17
Hovea 1
Hovea 3
Beharra Springs North 1
Beharra Springs 1
North Yardanogo 1
Beharra Springs South 1
Woodada 3
Woodada 5
Darling Fault
All 3 carotenoid biomarkers
No okenane, chlorobactane
No okenane
No carotenoid biomarkers

Fig. 4.

Implications for source rocks

Perth Basin

In the northern Perth Basin, the Kockatea Shale is considered to be a primary source rock based on source-oil correlation, especially using the C_{33} *n*-alkylcyclohexane ratio (*n*-C_{33} ACH ratio, *n*-C_{33}ACH/*n*-C_{34}) (Dawson *et al.* 2005; Grice *et al.* 2005a; McIldowie and Alexander 2005; Jones *et al.* 2011; Owens *et al.* 2018). The samples analysed in this study also show variable abundances of *n*-C_{33} ACH (Fig. 7). In addition to *n*-C_{33} ACH, the presence of carotenoid biomarkers (okenane, chlorobactane and isorenieratane) provides further evidence that the Lower Triassic Kockatea Shale is the primary source rock for oils in the basin. In the Kockatea Shale rock samples, these carotenoid biomarkers and *n*-C_{33} ACH were only identified in the dark-coloured shale deposited under PZE conditions, and in microbialite samples (Taniwaki *et al.* 2022). Rock-Eval analysis shows that these lithofacies have higher source rock potential than other lithofacies that comprise the Kockatea Shale (TOC: up to 3.4 % and HI: up to 579 mg/gTOC), suggesting they are the main contributors to the petroleum systems (Taniwaki *et al.* 2021).

In the southern Perth Basin, oils from Gage Roads 1 and Whicher Range 1 contain some carotenoids, but their concentrations are low compared with the concentration in the northern Perth Basin. Walyering 2 does not contain these carotenoids. In addition, *n*-C_{33} ACH is absent from these petroleum samples. The low concentration of carotenoids in Whicher Range 1 and their absence from Walyering 2 could be because these samples have a higher level of thermal maturity (Figure 5). In addition, the high relative abundance of C_{29} steranes in Gage Roads 1 indicates significant input of terrigenous organic material. It is possible therefore that the low concentration of carotenoid biomarkers in this sample may result from dilution by terrestrial organic material. However, the low concentrations and/or absence of carotenoids and the lack of *n*-C_{33} ACH in these petroleum samples suggest that the Lower Triassic Kockatea Shale is not a source of oils in the southern Perth Basin. This is consistent with the observation that the Lower Triassic is dominated by sandy lithofacies in this part of the basin and favours the assumption that they are derived from potential Permian shaly coals (Summons *et al.* 1995; Crostella and Backhouse 2000 and references herein), and where sufficiently deeply buried, Jurassic (Summons *et al.* 1995; Crostella and Backhouse 2000 and references herein) or Cretaceous (Summons *et al.* 1995; Crostella and Backhouse 2000 and references herein) source rocks.

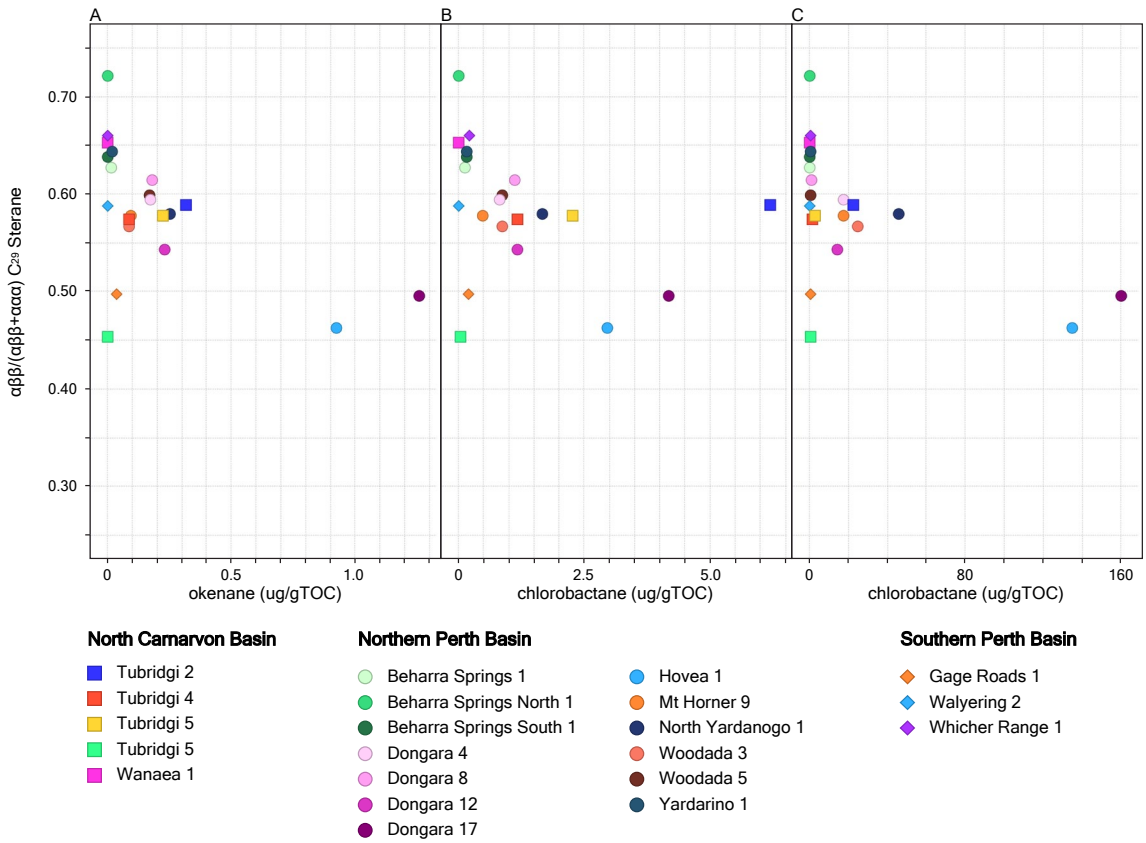
A
B
C
αββ/(αββ+ααα) C29 Sterane
0.70
0.60
0.50
0.40
0.30
0
0.5
1.0
okenane (ug/gTOC)
0
2.5
5.0
chlorobactane (ug/gTOC)
0
80
160
chlorobactane (ug/gTOC)
North Carnarvon Basin
Tubridgi 2
Tubridgi 4
Tubridgi 5
Tubridgi 5
Wanaea 1
Northern Perth Basin
Beharra Springs 1
Beharra Springs North 1
Beharra Springs South 1
Dongara 4
Dongara 8
Dongara 12
Dongara 17
Hovea 1
Mt Horner 9
North Yardanogo 1
Woodada 3
Woodada 5
Yardarino 1
Southern Perth Basin
Gage Roads 1
Walyering 2
Whicher Range 1

Fig. 5.

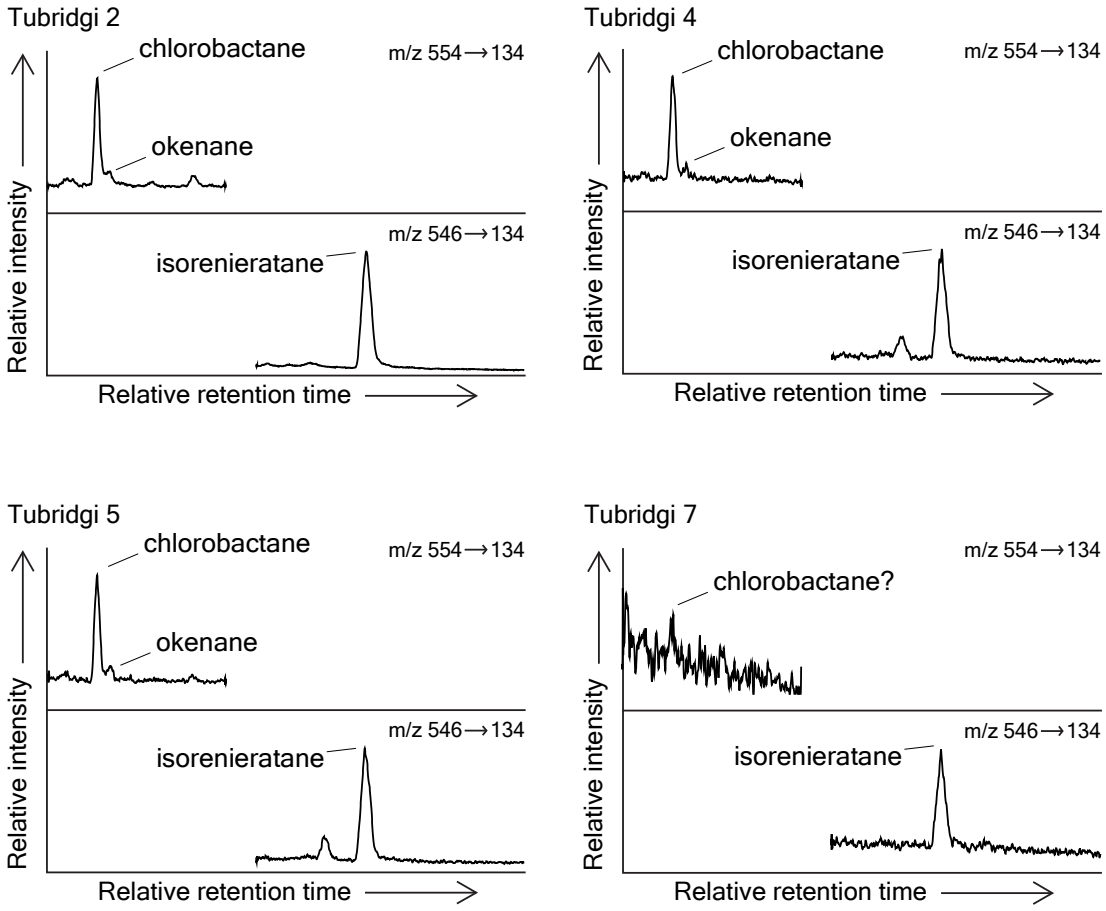
Tubridgi 2
chlorobactane
m/z 554→134
okenane
m/z 546→134
isorenieratane
Relative intensity
Relative retention time
Tubridgi 4
chlorobactane
m/z 554→134
okenane
m/z 546→134
isorenieratane
Relative intensity
Relative retention time
Tubridgi 5
chlorobactane
m/z 554→134
okenane
m/z 546→134
isorenieratane
Relative intensity
Relative retention time
Tubridgi 7
m/z 554→134
chlorobactane?
m/z 546→134
isorenieratane
Relative intensity
Relative retention time

Fig. 6.

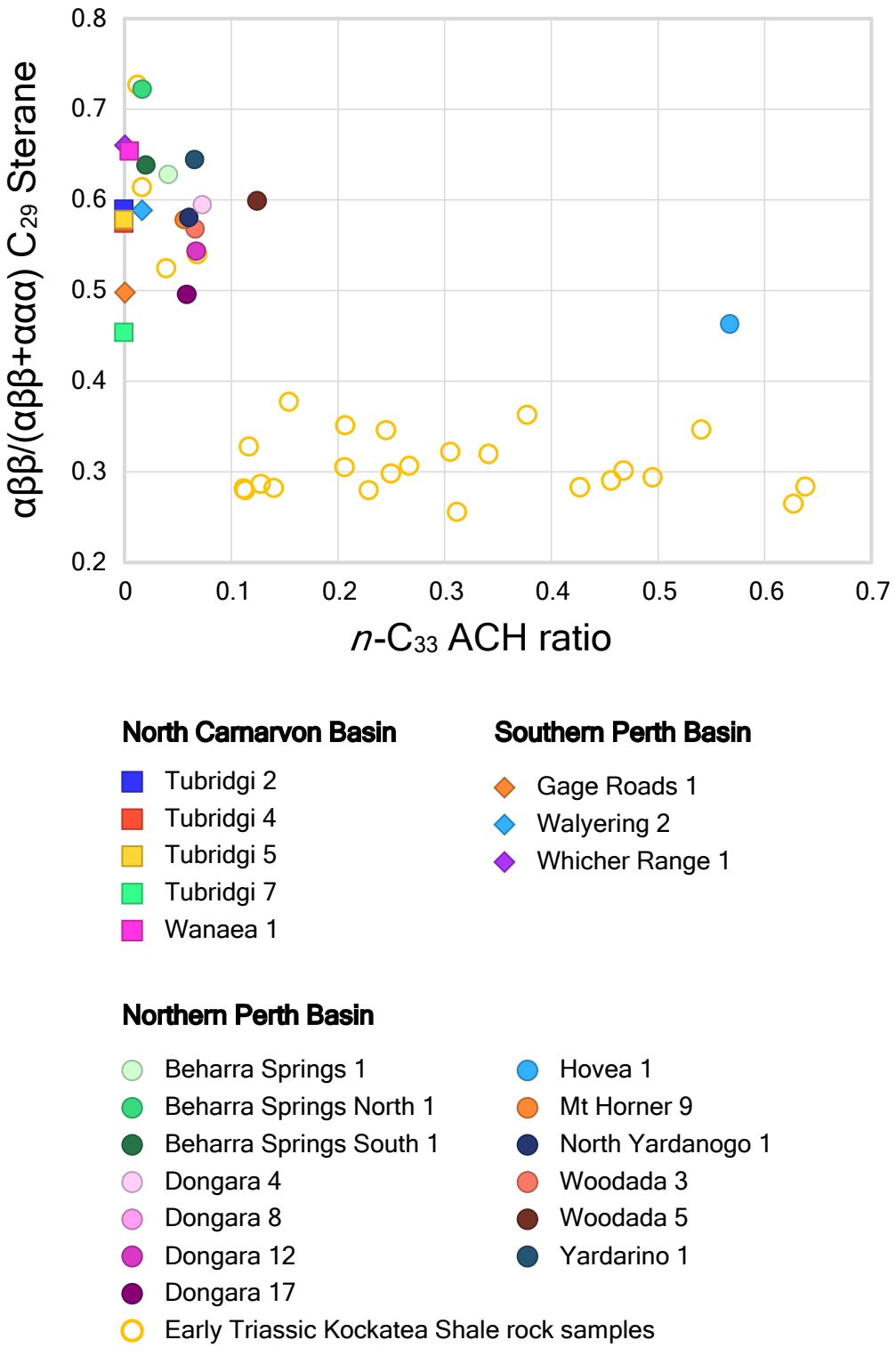
αββ/(αββ+ααα) C29 Sterane
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
n-C33 ACH ratio
North Carnarvon Basin
Tubridgi 2
Tubridgi 4
Tubridgi 5
Tubridgi 7
Wanaea 1
Southern Perth Basin
Gage Roads 1
Walyering 2
Whicher Range 1
Northern Perth Basin
Beharra Springs 1
Beharra Springs North 1
Beharra Springs South 1
Dongara 4
Dongara 8
Dongara 12
Dongara 17
Hovea 1
Mt Horner 9
North Yardanogo 1
Woodada 3
Woodada 5
Yardarino 1
Early Triassic Kockatea Shale rock samples

Fig. 7.

Northern Carnarvon Basin

Multiple source rocks from the Triassic to Cretaceous are recognised in the Northern Carnarvon Basin (and more generally on the entire the North West Shelf). The identification of source rocks is sometimes made difficult because of the mixing of liquids from different sources during migration and within reservoirs (Longley *et al.* 2002). However, the Upper Jurassic Dingo Claystone is traditionally considered to be one of the main petroleum source rocks (e.g. Volkman *et al.* 1983; Iasky *et al.* 2002; Longley *et al.* 2002; Edwards and Zumberge 2005; Boreham *et al.* 2008). This is based on source-oil correlation using steranes, hopanes and plant-derived aromatic biomarker evidence in the Barrow sub-basin (Volkman *et al.* 1983; van Aarssen *et al.* 1996). Basin modeling shows that the Dingo Claystone reached the oil window after the Late Cretaceous in the Exmouth sub-basin and generated large volumes of hydrocarbons (Tindale *et al.* 1998), confirming its potential importance in this basin. A range of other source rocks have been proposed from Cretaceous and Jurassic intervals (e.g. Longley *et al.* 2002; Edwards and Zumberge 2005). The source rock potential of the Triassic has also been identified (Molyneux *et al.* 2016).

The absence of carotenoid biomarkers and *n*-C_{33} ACH in the Wanaea petroleum sample favours derivation from a source rock deposited under more oxic conditions without PZE or the development of microbialites. However, the absence of these biomarkers may be due to thermal maturity effects because the sample shows higher thermal maturity than that of the Tubridgi petroleum samples, although the hopane index does show more oxic conditions than the Tubridgi samples. Although it is not possible to define precise sources, it is possible that Wanaea petroleum has migrated from source rocks deposited under more oxic conditions and is unlikely to be derived from any source rocks with characteristics similar to the Lower Triassic Kockatea Shale in the Perth Basin. This is consistent with the currently held view that Wanaea oil migrated from an Upper Jurassic source rock in the Lewis and Kendrew troughs (Longley *et al.* 2002). A characteristic of this source rock is that it contains terrigenous organic matter deposited under deltaic conditions. This distinguishes it from the Lower Triassic Kockatea Shale deposited under anoxic conditions under marine conditions, and explains the more oxic signature of oils derived from the Upper Jurassic source rock compared to those derived from a Lower Triassic Kockatea Shale-type source rock.

By contrast, the presence of carotenoid biomarkers derived from sulfur bacteria in the Tubridgi petroleum samples suggests that their source rock was developed under PZE conditions and/or was formed by microbialites. The biomarker characteristics of the Tubridgi petroleum samples are similar to the petroleum from the northern Perth Basin (Tab. 2 and S1), as well as to the mudstones deposited under PZE conditions and the microbialites from the Lower Triassic Kockatea Shale. Triassic and older strata subcrop the Valanginian unconformity on the Peedamullah Shelf and are present beneath the Tubridgi Field (Iasky *et al.* 2002). These have been suggested as potential sources for

Tubridgi oils based on the presence of aromatic dinosteranes and the absence of conifer-derived biomarkers such as retene, which are generally considered as proxies of Late Triassic-Middle Jurassic sources (Yasin and Iasky 1998; Iasky *et al.* 2002; Edwards and Zumberge 2005). The biomarker characteristics support the possibility that Tubridgi petroleum comes from the Lower Triassic Locker Shale which is an equivalent of the Lower Triassic Kockatea Shale. Further evidence that the Triassic acts as a source of oil in the Northern Carnarvon Basin comes from oil inclusions reported from the Upper Triassic Mungaroo Formation in the Pinhoe 1/ST1 well on the Exmouth Plateau, which indicate the presence of a paleo oil column (Bourdet 2016). It is difficult to envisage migration of petroleum from the Upper Jurassic Dingo Claystone because there is no large fault displacing the stratigraphically younger Dingo Claystone into a downdip position against the Middle Triassic Mungaroo Formation (Bernecker *et al.* 2018). The stratigraphic relationships suggest that the source of the oil is from within the Triassic – either local oil-prone sources within the Mungaroo Formation, or from the Lower Triassic Locker Shale.

The relative abundance of *n*-C_{33} ACH is a key biomarker used for correlation to the Lower Triassic Kockatea Shale in the northern Perth Basin, but it is absent from the Northern Carnarvon Basin samples including the Tubridgi wells. This absence could result either from thermal maturation, because this compound reduces in concentration as thermal maturity increases (Thomas and Barber 2004) (Fig. 7) or biodegaradation because alkylcyclohexanes are generally affected at biodegradation rank 3-4 (Wenger *et al.* 2002; Abdula 2019). Although the Tubridgi Field petroleum comes from a source rock deposited under PZE conditions, there are no published analyses to indicate whether or not the Dingo Claystone or other potential Jurasic source rocks were also deposited under these conditions. Furthermore, it cannot be determined if the petroleum in the Barrow and Exmouth sub-basins migrated from a source rock developed under PZE conditions and/or a microbialite source rock because published analyses are focused on steranes, hopanes and parameters related to terrestrial organic matter (Volkman *et al.* 1983; van Aarssen *et al.* 1996). This different analytical approach, and the limited nature of published analyses, precludes a direct comparison of the Tubdrigi petroleum samples analysed in this study with both the Dingo Claystone and the oils from the Barrow sub-basin. Therefore, despite the evidence to support a Lower Triassic source rock, a contribution from a Jurassic source rock to Tubridgi petroleum in the Peedamullah Shelf cannot be completely excluded. Further analysis of the Northern Carnarvon Basin petroleum and source rocks is clearly required. If the contribution from the Lower Triassic Locker Shale is substantiated, this opens up the potential for new plays on the southern margin of the Northern Carnarvon Basin and potentially more broadly in the basin.

Conclusions

Petroleum samples from the Perth Basin and the Tubridgi Field on the Peedamullah Shelf of the Northern Carnarvon Basin contain carotenoid biomarkers derived from photosynthetic sulfur bacteria, suggesting that the source rocks developed under PZE conditions and/or were formed by microbialites. In the northern Perth Basin, biomarkers proved that the microbialites and/or dark coloured mudstone deposited under PZE conditions in the Kockatea Shale are a major contributing lithofacies to the petroleum system. On the other hand, in the southern Perth Basin, it is possible that the source rock is Permian, Jurassic or Cretaceous in age based on the low concentrations or absence of carotenoids, the lack of *n*-C_{33} ACH and the overall geological setting. The presence of carotenoid biomarkers in the Tubridgi petroleum on the Peedamullah Shelf shows that petroleum also migrated from a source rock developed under PZE conditions and/or formed by microbialites. The similarity of biomarker characteristics to the Perth Basin petroleum suggests that this source rock could have been the Lower Triassic Locker Shale. However, the possibility of a contributuion from the Dingo Claystone or other Jurassic source rocks to the Tubridgi petroleum cannot be excluded due to the absence of *n*-C_{33} ACH and the lack of previous analyses targeting the carotenoids in the Dingo Claystone and oils derived from it. Further analysis of Northern Carnarvon Basin petroleum and source rocks has the potential to resolve this issue and to open up new plays on the southern margin of the Northern Carnarvon Basin and possibly more broadly in the basin.

Funding Sources

INPEX Corporation funds to Takashi Taniwaki for his PhD including this research.

WAIOGC funds for the lab expenditure.

Acknowledgements

We acknowledge Peter Hopper for technical support, and Roger Summons for arranging the GC-MRM-MS analysis. This is a part of the PhD project for the first author funded by INPEX Corporation. Alex Maftei is thanked for drawing our attention to the oil inclusions in the Pinhoe 1/ST1 well.

Author contributions

Takashi Taniwaki, Kliti Grice and Chris Elders designed the experiments. Petroleum samples used in this chapter were from those already available in the laboratory by Kliti Grice. Kliti Grice and Chris Elders supplied the technical advice for the interpretation of the results. The fractionation of petroleum samples and GC-MS analysis were performed by Takashi Taniwaki with help from Alex Holman and Peter Hopper. The manuscript was prepared during the PhD project by Takashi Taniwaki with detailed comments and discussion from Kliti Grice, Chris Elders and Alex I. Holman.

References

Abdula, R.A. 2019. *Advances in Petroleum Engineering and Petroleum Geochemistry*, https://doi.org/10.1007/978-3-030-01578-7.

Bernecker, T., Bernardel, G., Orlov, C. and Rollet, N. 2018. Petroleum geology of the 2018 offshore acreage release areas. *The APPEA Journal*, **58**, 437–461, https://doi.org/10.1071/aj17056.

Boreham, C.J., Hope, J.M., Hartung-Kagi, B. and van Aarssen, B.J.K. 2000. More sources for gas and oil in Perth Basin. *AGSO Research Newsletter*, 5–9.

Boreham, C.J., Edwards, D.S., Hope, J.M., Chen, J. and Hong, Z. 2008. Carbon and hydrogen isotopes of neo-pentane for biodegraded natural gas correlation. *Organic Geochemistry*, **39**, 1483–1486, https://doi.org/10.1016/j.orggeochem.2008.06.010.

Bourdet, J. 2016. Fluid charge history in the Upper Triassic Mungaroo Fm at Pinhoe 1 /

ST1 , Exmouth Plateau, Carnarvon Basin, Australia. *Confidential Report EP159238, CSIRO Energy, Perth Australia*.

Brocks, J.J. and Schaeffer, P. 2008. Okenane, a biomarker for purple sulfur bacteria (Chromatiaceae), and other new carotenoid derivatives from the 1640 Ma Barney Creek Formation. *Geochimica et Cosmochimica Acta*, **72**, 1396–1414, https://doi.org/10.1016/j.gca.2007.12.006.

Clifford, D.J., Clayton, J.L. and Sinninghe Damsté, J.S. 1998. 2,3,6-/3,4,5-Trimethyl substituted diaryl carotenoid derivatives (Chlorobiaceae) in petroleums of the Belarussian Pripyat River Basin. *Organic Geochemistry*, **29**, 1253–1267, https://doi.org/10.1016/S0146-6380(98)00086-2.

Crostella, A. and Backhouse, J. 2000. Geology and Petroleum Exploration of the Central and Southern Perth Basin. *Western Australia Geological Survey*, **Report 57**, 85p.

Dawson, D., Grice, K. and Alexander, R. 2005. Effect of maturation on the indigenous δD signatures of individual hydrocarbons in sediments and crude oils from the Perth Basin (Western Australia). *Organic Geochemistry*, **36**, 95–104, https://doi.org/10.1016/j.orggeochem.2004.06.020.

Edwards, D.S. and Zumberge, J.E. 2005. The oils of Western Australia II-regional petroleum geochemistry and correlation of crude oils and condensates from western Australia and Papua New Guinea. *Geoscience Australia Report*, **37512**.

Erwin, D.H. 1994. The Permo-Triassic extinction. *Nature*, **367**, 231–236.

Ferdinando, D., Baker, J.C., Gongora, A. and Pidgeon, B.A. 2007. Illite/smectite clays preserving porosity at depth in Lower Permian reservoirs, northern Perth Basin. *The APPEA Journal*, **47**, 69–88, https://doi.org/10.1071/aj06004.

Fox, C.P., Cui, X., Whiteside, J.H., Olsen, P.E., Summons, R.E. and Grice, K. 2020. Molecular and isotopic evidence reveals the end-Triassic carbon isotope excursion is not from massive exogenous light carbon. *Proceedings of the National Academy of Sciences*, **117**, 30171–30178, https://doi.org/10.1073/pnas.1917661117.

Grice, K., Schaeffer, P., Schwark, L. and Maxwell, J. 1996. Molecular indicators of palaeoenvironmental conditions in an immature Permian shale (Kupferschiefer, …. *Organic Geochemistry*, **25**, 131–147.

Grice, K., Alexander, R., Kagi, R.I. 2000. Diamondoid hydrocarbon ratios as indicators of biodegradation in Australian crude oils. *Organic Geochemistry*, **31**, 67-73.

Grice, K., Twitchett, R.J., Alexander, R., Foster, C.B. and Looy, C. 2005a. A potential biomarker for the Permian-Triassic ecological crisis. *Earth and Planetary Science*

Letters, **236**, 315–321, https://doi.org/10.1016/j.epsl.2005.05.008.

Grice, K., Summons, R.E., Grosjean, E., Twitchett, R.J., Dunning, W., Wang, S.X. and Böttcher, M.E. 2005b. Depositional conditions of the Northern Onshore Perth Basin (Basal Triassic). *The APPEA Journal*, **45**, 263–274.

Grice, K., Cao, C., et al. 2005c. Photic zone euxinia during the Permian-Triassic superanoxic event. *Science*, **307**, 706–709, https://doi.org/10.1126/science.1104323.

Grice, K., Nabbefeld, B. and Maslen, E. 2007. Source and significance of selected polycyclic aromatic hydrocarbons in sediments (Hovea-3 well, Perth Basin, Western Australia) spanning the Permian-Triassic boundary. *Organic Geochemistry*, **38**, 1795–1803, https://doi.org/10.1016/j.orggeochem.2007.07.001.

Grosjean, E., Hall, L., Boreham, C. and Buckler, T. 2017. Source rock geochemistry of the offshore northern Perth Basin: regional hydrocarbon prospectivity of the offshore northern Perth Basin. *Record 2017/18. Geoscience Australia, Canberra*, https://doi.org/10.11636/Record.2017.018.

Hocking, R.M. 1992. Jurassic deposition in the central and southern North West Shelf, Western Australia. *Geological Survey of Western Australia, Record 1992/7*, 101p.

I'Anson, A., Elders, C. and McHarg, S. 2019. Marginal fault systems of the Northern Carnarvon Basin: Evidence for multiple Palaeozoic extension events, North-West Shelf, Australia. *Marine and Petroleum Geology*, **101**, 211–229, https://doi.org/10.1016/j.marpetgeo.2018.11.040.

Iasky, R.P., Mory, A.J., Blundell, K.A. and Ghori, K.A.R. 2002. Prospectivity of the Peedamullah Shelf and Onslow Terrace revisited. *In*: *The Sedimentary Basins of Western Australia 3: Proceedings of the Petroleum Exploration Society of Australia Symposium*. 741–759.

Jablonski, D. and Saitta, A.J. 2004. Permian To Lower Cretaceous Plate Tectono-Stratigraphic Development of the Western Australian Margin. *The APPEA Journal*, **44**, 287–328, https://doi.org/10.1071/AJ03011.

Jones, A., Kennard, J.M., et al. 2011. New exploration opportunities in the offshore northern Perth Basin. *The APPEA Journal*, **51**, 45–78, https://doi.org/10.1071/aj10003.

Knoll, A.H., Bambach, R.K., Canfield, D.E. and Grotzinger, J.P. 1996. Comparative earth history and late Permian mass extinction. *Science*, **273**, 452–457, https://doi.org/10.1126/science.273.5274.452.

Langhi, L., Ross, A., Crooke, E., Jones, A., Nicholson, C. and Stalvies, C. 2014. Integrated hydroacoustic flares and geomechanical characterization reveal potential hydrocarbon leakage pathways in the Perth Basin, Australia. *Marine and Petroleum Geology*, **51**, 63–69, https://doi.org/10.1016/j.marpetgeo.2013.11.016.

Longley, I.M., Buessenschuett, C., et al. 2002. The North West Shelf of Australia - A Woodside Perspective. *In*: *The Sedimentary Basins of Western Australia 3: Proceedings of the Petroleum Exploration Society of Australia Symposium*. 1–86.

Maslen, E., Grice, K., Gale, J.D., Hallmann, C. and Horsfield, B. 2009. Crocetane: A potential marker of photic zone euxinia in thermally mature sediments and crude oils of Devonian age. *Organic Geochemistry*, **40**, 1–11, https://doi.org/10.1016/j.orggeochem.2008.10.005.

McIldowie, M. and Alexander, R. 2005. Identification of a novel C33 n-alkylcyclohexane biomarker in Permian-Triassic sediments. *Organic Geochemistry*, **36**, 1454–1458, https://doi.org/10.1016/j.orggeochem.2005.06.009.

Molyneux, S., Goodall, J., McGee, R., Mills, G. and Hartung-Kagi, B. 2016. Observations on the Lower Triassic petroleum prospectivity of the offshore Carnarvon and Roebuck basins Lead author. *The APPEA Journal*, **56**, 173–202.

Nabbefeld, B., Grice, K., Summons, R.E., Hays, L.E. and Cao, C. 2010. Significance of polycyclic aromatic hydrocarbons (PAHs) in Permian/Triassic boundary sections. *Applied Geochemistry*, **25**, 1374–1382, https://doi.org/10.1016/j.apgeochem.2010.06.008.

Norvick, M.S. 2004. Tectonic and Stratigraphic History of the Perth Basin. *Geoscience Australia*, **2004/16**, 18p.

Owens, R.J., Borissova, I., Hall, L.S., Bernardel, G., Southby, C., Grosjean, E. and Mitchell, C. 2018. Geology and prospectivity of the northern Houtman Sub-basin. *Geoscience Australia*, **2018/25**, 101 pp.

Pagès, A., Grice, K., Vacher, M., Welsh, D.T., Teasdale, P.R., Bennett, W.W. and Greenwood, P. 2014. Characterizing microbial communities and processes in a modern stromatolite (Shark Bay) using lipid biomarkers and two-dimensional distributions of porewater solutes. *Environmental Microbiology*, **16**, 2458–2474, https://doi.org/10.1111/1462-2920.12378.

Pedentchouk, N., Freeman, K.H., Harris, N.B., Clifford, D.J. and Grice, K. 2004. Sources of alkylbenzenes in Lower Cretaceous lacustrine source rocks, West African rift basins. *Organic Geochemistry*, **35**, 33–45, https://doi.org/10.1016/j.orggeochem.2003.04.001.

Peters, K., Walters, C. and Moldowan, J. 2004. *The Biomarker Guide*, 2nd ed.

Pfenning, N. 1978. Gemeral physiology and ecxology of photosynthetic bacteria. *In*: Clayton, R. K. and Sistrom, W. R. (eds) *The Photosynthetic Bacteria*. 3–18.

Sandwell, D., Garcia, E., Soofi, K., Wessel, P., Chandler, M. and Smith, W.H.F. 2013. Toward 1-mGal accuracy in global marine gravity from CryoSat-2, Envisat, and Jason-1. *The Leading Edge*, **32**, 892–899.

Sandwell, D.T. and Smith, W.H.F. 2009. Global marine gravity from retracked Geosat and ERS-1 altimetry: Ridge segmentation versus spreading rate. *Journal of Geophysical Research: Solid Earth*, **114**, B01411, https://doi.org/10.1029/2008JB006008.

Sandwell, D.T., Müller, R.D., Smith, W.H.F., Garcia, E. and Francis, R. 2014. New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure. *Science*, **346**, 65–67, https://doi.org/10.1126/science.1258213.

Schaefer, B., Grice, K., et al. 2020. Microbial mayhem in the nascent chicxulub crater. *Geology*, **48**, 328–332, https://doi.org/10.1130/G46799.1.

Scott, J. 1994. Source rocks of Western Australia - distribution, character and models. *In*: *The Sedimentary Basins of Western Australia: Proceedings of the Petroleum Exploration Society of Australia Symposium*. 141–155.

Song, H.H.H.H., Wignall, P.B., et al. 2014. Anoxia/high temperature double whammy during the Permian-Triassic marine crisis and its aftermath. *Scientific Reports*, **4**, 4132, https://doi.org/10.1038/srep04132.

Sousa Júnior, G.R., Santos, A.Ô.L.S.S., De Lima, S.G., Lopes, J.A.D.D., Reis, F.A.M.M., Santos Neto, E. V. and Chang, H.K. 2013. Evidence for euphotic zone anoxia during the deposition of Aptian source rocks based on aryl isoprenoids in petroleum, Sergipe-Alagoas Basin, northeastern Brazil. *Organic Geochemistry*, **63**, 94–104, https://doi.org/10.1016/j.orggeochem.2013.07.009.

Summons, R.E., Boreham, C.J., Foster, C.B., Murray, A.P. and Gorter, J.D. 1995. Chemostratigraphy and the Composition of Oils in the Perth Basin, Western Australia. *The APPEA Journal*, **35**, 613, https://doi.org/10.1071/aj94037.

Taniwaki, T., Elders, C. and Grice, K. 2021. Early Triassic paleogeography of the northern Perth Basin, and controls on the distribution of source rock facies. *Marine and Petroleum Geology*, **133**, 105314, https://doi.org/10.1016/j.marpetgeo.2021.105314.

Taniwaki, T., Elders, C., Böttcher, M.E., and Holman, A.I. 2022. Photic zone redox oscillations and microbialite development recorded by Early Triassic sediments of

the Perth Basin: A geochemical approach. *Geochimica et Cosmochimica Acta*, **336**, 188-207, https://doi.org/10.1016/j.gca.2022.09.011.

Thomas, B.M. 1979. Geochemical analysis of hydrocarbon occurrences in northern Perth Basin, Australia. *AAPG Bulletin*, **63**, 1092–1107, https://doi.org/10.1306/2F9184BE-16CE-11D7-8645000102C1865D.

Thomas, B.M. and Barber, C.J. 2004. A re-evaluation of the hydrocarbon habitat of the northern perth basin. *The APPEA Journal*, **44**, 59–92.

Thomas, B.M., Willink, R.J., et al. 2004. Unique marine Permian-Triassic boundary section from Western Australia. *Australian Journal of Earth Sciences*, **51**, 423–430.

Tindale, K., Newell, N., Keall, J. and Smith, N. 1998. Structural Evolution and Charge History of the Exmouth Sub-basin, Northern Carnarvon Basin, Western Australia. *In*: *The Sedimentary Basins of Western Australia 2: Proceedings of the Petroleum Exploration Society of Australia Symposium*. 447–472.

Trolio, R., Grice, K., Fisher, S.J., Alexander, R., Kagi, R.I. 1999. Alkylbiphenyls and alkyldiphenylmethanes as indicators of petroleum biodegradation. *Organic Geochemistry*. *30*, 1241-1253.

Tulipani, S. 2013. *Novel Biomarker and Stable Isotopic Approaches for Palaeoenvironmental Reconstruction of Saline and Stratified Ecosystems: The Modern Coorong Lagoon and Devonian Reefs of the Canning Basin*. Curtin University.

Twitchett, R.J., Krystyn, L., Baud, A., Wheeley, J.R. and Richoz, S. 2004. Rapid marine recovery after the end-Permian mass-extinction event in the absence of marine anoxia. *Geology*, **32**, 805–808, https://doi.org/10.1130/G20585.1.

van Aarssen, B.G.K., Alexander, R. and Kagi, R.I. 1996. The origin of Barrow Sub-basin crude oils: A geochemical correlation using land-plant biomarkers. *The APPEA Journal*, **36**, 465–476.

Volkman, K., Alexandert, R., Kagi, R.I., Noble, R.A. and Woodhouse, G.W. 1983. A geochemical reconstruction of oil generation in the Barrow Sub-basin of Western Australia. *Geochimica et Cosmochimica Acta*, **47**, 2091–2105.

Wenger, L.M., Davis, C.L. and Isaksen, G.H. 2002. Multiple controls on petroleum biodegradation and impact on oil quality. *SPE Reservoir Evaluation & Engineering*, 375–383, https://doi.org/10.2523/71450-ms.

Whiteside, J.H. and Grice, K. 2016. Biomarker Records Associated with Mass Extinction Events. *Annual Review of Earth and Planetary Sciences*, **44**, 581–612,

https://doi.org/10.1146/annurev-earth-060115-012501.

Wignall, P.B. and Twitchett, R.J. 1996. Oceanic anoxia and the end Permian mass extinction. *Science*, **272**, 1155–1158, https://doi.org/10.1126/science.272.5265.1155.

Yasin, A.R. and Iasky, R.P. 1998. Petroleum Geology of the Peedamullah Shelf , Northern Carnarvon Basin . *In*: *The Sedimentary Basins of Western Australia 2: Proceedings of the Petroleum Exploration Society of Australia Symposium*. 473–491.

Figure caption

Fig. 1. Location of both Perth and Northern Carnarvon basins and petroleum samples. A represents the location of both basins and samples with gravity anomaly map as background showing basin geometry. The public domain data used for the gravity map is published by the Scripps Institution of Oceanography (Sandwell and Smith 2009; Sandwell *et al.* 2013, 2014). B shows the detailed sample location around the Tubridgi Field in the Northern Carnarvon Basin. C indicates the detailed sample location around the northern Perth Basin. Yellow points represent the location of wells where rock sample analysis was conducted (Taniwaki *et al.* 2021).

Fig. 2. Stratigraphy in both (A) northern Perth and (B) Northern Carnarvon basins (Ferdinando *et al.* 2007; I'Anson *et al.* 2019). Light and dark grey: deeper water mudstone, yellow: shallow marine sandstone: brown: fluvial to deltaic/marine sediments, blue- green: open marine glacial sediments.

Fig. 3. GC-MRM-MS peaks of okenane, isorenieratane and chlorobactane from petroleum samples (A: Hovea 1, B: Tubridgi 5). Hovea 1 is located on the northern Perth Basin and Tubridgi 5 is located on the Peedamullah Shelf in the Northern Carnarvon Basin.

Fig. 4. Distribution of carotenoid biomarkers (okenane, chlorobactane and isorenieratane). A shows the entire region covering samples from the Northern Carnarvon Basin to the southern Perth Basin. B represents the detailed distribution around the Tubridgi Field in the Northern Carnarvon Basin. C indicates the distribution around the northern Perth Basin.

Fig. 5. The influence of thermal maturity on carotenoid biomarkers (A: okenane, B: chlorobactane, C: isorenieratane).

Fig. 6. GC-MRM-MS peaks of okenane, isorenieratane and chlorobactane from petroleum samples of Tubridgi 2, 4, 5 and 7.

Fig. 7. The thermal maturity influence on *n*-C_{33} ACH ratio. *n*-C_{33} ACH ratio = *n*-C_{33} ACH /C_{34} *n*-alkane.

Table caption

Tab. 1. Type of fluids, basin location, reservoir age and Formation and for each petroleum sample.

Tab. 2. Characteristics of biomarkers (Pr/Ph, C_{35} homohopane index, gammacerane index, and C_{27-29} regular sterane ratio, *n*-C_{33} ACH ratio, okenane ratio and carotenoids). Ok = okenane. Ch = chlorobactane. Is = Isorenieratane.

Tab. 3. C_{32} 22*S*/(22*S*+22*R*) αβ-homohopane, Moretane/Hopane, C_{29} 20*S*/(20*S*+20*R*) sterane ratio, αββ/(αββ+ααα) C_{29} Sterane, Ts/(Ts+Tm) and Dia/(Dia+Reg) of each sample for thermal maturity evaluation. N/I indicates not identified.