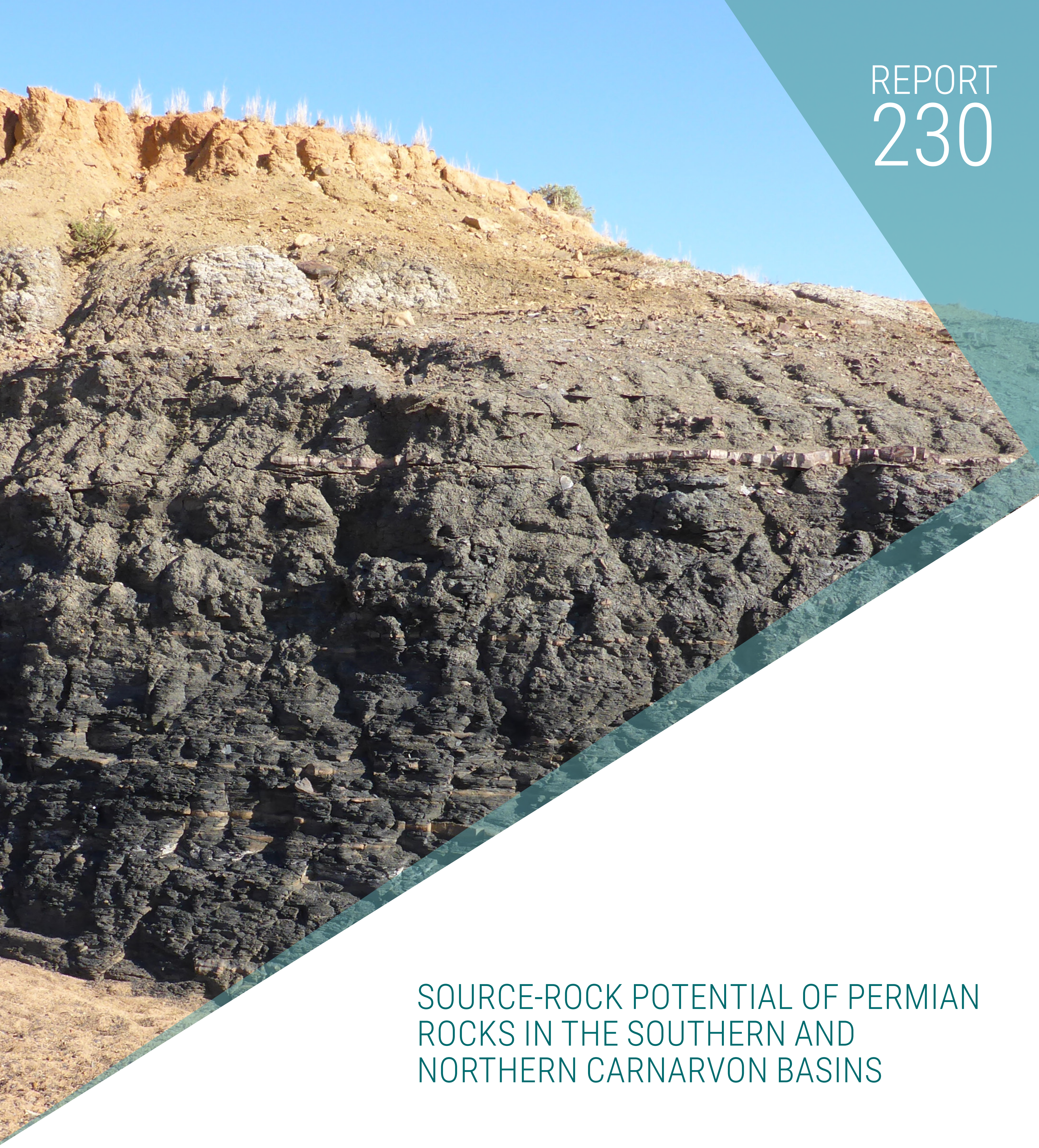

REPORT 230

SOURCE-ROCK POTENTIAL OF PERMIAN ROCKS IN THE SOUTHERN AND NORTHERN CARNARVON BASINS

CM Thomas

Government of **Western Australia**
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Cover photograph: A section of Bulgadoo Shale exposed along the Minilya River about 120 km north of Gascoyne Junction, Southern Carnarvon Basin

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Available with the PDF online as an accompanying digital resource

Source-rock potential of Permian rocks in the Southern and Northern Carnarvon Basins

CM Thomas

Abstract

The Permian is one of the thickest and most widely spread pre-breakup strata across the Southern and inboard Northern Carnarvon Basins, although is not yet confirmed to have sourced or currently host economic accumulations of hydrocarbons. The Permian section is highly prospective in the Perth Basin to the south, although the Southern Carnarvon Basin and the Permian level of the Northern Carnarvon Basin are under-explored. New pre-competitive Total Organic Carbon (TOC), Rock-Eval pyrolysis, organic petrography and palynostratigraphic data were collected from Permian rocks in the Southern and inboard Northern Carnarvon Basins. The objective of this study was to improve the spatial and depth coverage of Permian source-rock data, particularly in understudied parts of the basins. The results of this Report are consistent with previous studies finding the best Permian source intervals are thin mudstone interbeds within overall heterolithic or sandy packages, and has extended possible source areas farther west of the Peedamullah Shelf and within the Merlinleigh Sub-basin and possibly Byro Sub-basin. Further, a review of new and legacy organic petrography reports confirms the mixed kerogen assemblage in the Permian, and therefore the 'traditional' Rock-Eval plots used to determine kerogen type and expected hydrocarbon phase are misleading and likely underestimate the liquid potential.

KEYWORDS: Northern Carnarvon Basin, organic geochemistry, organic petrography, petroleum, Permian, source rocks, Southern Carnarvon Basin

Introduction

Previous studies and industry reports have confirmed the petroleum-generating potential of Permian source rocks in the Southern and inboard Northern Carnarvon Basins (Brooks, 1986; Dolan and Associates, 1991; Mitchell, 1992; Ghori, 1996, 1998); however, these were based on relatively few wells, and the areal extent and thickness of good quality source rocks remained uncertain (Ghori, 1996). These studies mainly reported total organic carbon (TOC) and Rock-Eval pyrolysis results, with few reporting Pyrolysis-GC or organic petrography results.

The aim of this study was to identify and sample wells and drillholes across the Southern and Northern Carnarvon Basins that contain Permian strata not yet analysed for their source-rock potential (Fig. 1). The primary analyses were Rock-Eval pyrolysis and organic petrography. Infill sampling in wells that had previously been sparsely sampled for source-rock analysis was also undertaken to identify possible thin potential source intervals. This study has provided greater spatial and depth coverage of geochemical and organic petrographic data needed to assess not only source potential and maturity, but also to better predict the original source-rock geochemistry for mature source rocks.

Methods

All existing Total Organic Carbon (TOC) and Rock-Eval pyrolysis data were collated from published Geological Survey of Western Australia (GSWA) reports, industry reports and well completion reports in WAPIMS. To improve on spatial coverage of data, holes not routinely analysed for organic geochemistry, such as water bores, mineral drillholes and legacy seismic shotholes, were also sampled at the DMIRS Perth Core Library. Waterbores were cross-referenced with the Department of Water and Environment's Water Information Reporting (WIR) database to confirm their geographical location. Only fine-grained lithologies were analysed in this study, and only those non-petroleum holes deep enough to have reached the Permian were sampled. Where the age of a sample was not previously reported or uncertain, samples were sent to MGPalaeo, Perth, Western Australia, for palynological analysis, with only confirmed Permian samples included for TOC and Rock Eval pyrolysis. Palynology also helped assess whether there was significant contamination from Mesozoic cavings (which often have high TOC and hydrocarbon generative potential) in samples that could bias Rock-Eval results. Samples were sent to Intertek (formerly Geotech), Perth, Western Australia, for Rock-Eval analysis, and analysed using the Rock-Eval 7 machine.

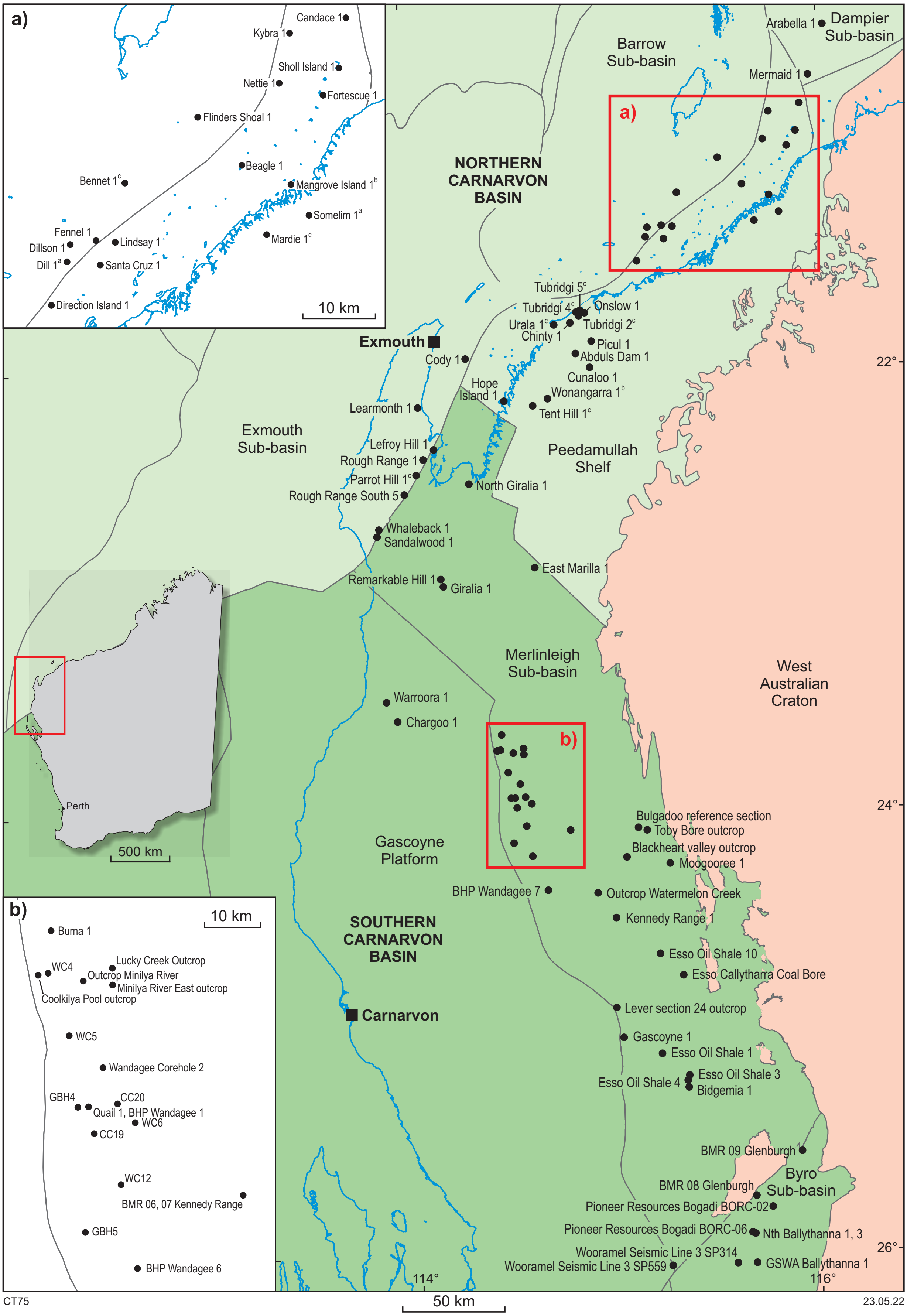

Figure 1. Wells and analysis sites of Permian strata in the Southern and Northern Carnarvon Basins – see subscripts as follows:
[a] wells with Permian intersections but no TOC or Rock-Eval analyses performed
[b] wells with Permian intersections but with low TOC only (<0.5%) and no further Rock-Eval analysis performed, thus does not appear on Rock-Eval interpretive crossplots
[c] wells mentioned in text but that did not intersect Permian strata

Samples were collected from core, cuttings and outcrop. Although not always possible, dark mudstone lithologies were hand-picked for analysis from cuttings of overall heterolithic sandstone-mudstone packages. A pitfall of using cuttings is that mudstone intervals within a sandstone-dominated package are often much thinner than the cuttings interval; therefore, a much larger sample of the cuttings volume is needed to extract enough mudstone. This presents an issue because the hand-picking of specific lithologies directly from the archived cuttings bag is not permitted at the DMIRS Perth Core Library because it can bias the lithology distribution of the remaining cuttings, thus cuttings were not collected if there was an insufficient remaining volume. Therefore, thin source intervals are under-represented in this study.

Total Organic Carbon (TOC) analysis and Rock-Eval pyrolysis

Analyses overview

Total Organic Carbon (TOC) analysis and Rock-Eval pyrolysis are two independent analyses that rapidly assess the petroleum source potential of organic rocks. A TOC of 0.5% is generally regarded to be the minimum requirement for an effective petroleum source rock (Peters, 1986). However, TOC on its own cannot distinguish all the different phases that contain organic carbon (i.e. extractable free hydrocarbons, bitumen, kerogens) and further analysis, such as Rock-Eval pyrolysis, is needed. In this study, only those samples with TOC >0.5% were submitted for Rock-Eval pyrolysis.

The Rock-Eval pyrolyser was developed as a basic screening tool to rapidly evaluate the amount of free hydrocarbons present within a rock sample and to indirectly measure the overall hydrogen and oxygen richness of organic matter (Espitalié et al., 1977, 1985). These parameters can help evaluate the type of organic matter (i.e. kerogens) present in the rock. Small rock samples (about 100 mg) are pulverised and initially heated to 300 °C, and then progressively heated to 550 °C to release and vaporise their volatile hydrocarbon components, which are continuously measured using a flame ionization detector (FID). Hydrocarbons are released in two broad phases. The first phase involves free hydrocarbons already present within the rock being vaporised, creating the first 'peak' — the S1 peak — in measured vapors, expressed as weight of hydrocarbons relative to original rock sample weight — usually mg/g. Free hydrocarbons include hydrocarbons that have already been generated naturally from kerogens in the rock but not yet expelled; migrated hydrocarbons generated elsewhere; bitumen; and possibly synthetic petroleum-based drilling fluids. The second phase occurs as temperatures are raised, with the second peak (S2) in measured hydrocarbons resulting from the transformation or 'cracking' of natural kerogens (including bitumen not burned during the S1 peak) into hydrocarbons until non-generating carbon components remain. Therefore, the S2 peak indicates the generative potential yield of hydrocarbons for a given rock sample. Some industry practice also includes the S1 measurement as part of the generative potential (i.e. S1+S2), which is followed in this Report. The ratio of S2 (mg hydrocarbons/g rock sample) to TOC gives the hydrogen index (HI) — an indirect measurement of a sample's hydrogen richness, calculated using: HI = S2/TOC x 100. Higher HI values generally correlate with increased oil-proneness of a rock. The temperature at which the S2 maximum occurs is the Tmax value, and generally the more thermally mature a sample is, the higher its Tmax measurement. The extremely rapid timescale of the heating from the Rock-Eval pyrolysis technique (20 minutes) means that the temperatures required to crack natural kerogens into hydrocarbons are significantly higher than that required from natural burial and thermal maturation in basins over geological time. The CO_2 generated throughout the pyrolysis is separated and measured at the end of the analysis, and produces the S3 peak, expressed in mg CO_2/g of rock sample. The ratio of S3 to TOC gives the oxygen index (OI), which indicates the level of oxidation of the organic matter, and is calculated using OI = S3/TOC x 100. The OI is related to the depositional environment of the organic matter, although is also affected by thermal maturation, post-depositional oxidation due to weathering, and drilling contaminants such as glycol.

Interpretation of data

The main value of TOC and Rock-Eval analyses is their rapid and relatively inexpensive acquisition of large volumes of data and assessment of petroleum source potential, although there are many documented shortcomings and pitfalls of Rock-Eval data and the technique (Peters, 1986; Collins and Lapierre, 2014). Therefore, the data is best used to highlight samples for further investigation, especially in studies such as this one that collate data from different sources, vintages and laboratories.

The TOC and Rock-Eval data are usually interpreted together in a series of crossplots (Peters, 1986). The TOC vs generative potential (S2 or S1+S2) crossplot provides visualisation of organic richness and quality in terms of potential yields of generated hydrocarbons. In this Report, the generative potential is taken to be the S1+S2 values, although this assumes that the free hydrocarbons that give the S1 value are unexpelled hydrocarbons derived in situ from organic matter originally within the rock, and not migrated hydrocarbons from elsewhere or drilling contamination. The guidelines developed for the REESA (Rock-Evaluation Expert System Advisor) software (Peters and Nelson, 1992) were used to assess whether Rock-Eval data were anomalous due to possibly migrated hydrocarbons or contamination. Samples suspected of having an artificially inflated S1 value were omitted, unless other data had demonstrated that the S1 peak was derived in situ (e.g. some samples for the Lyons Group in the Quail 1 well).

The HI vs OI crossplot (sometimes referred to as a pseudo-Van Krevelen plot) is used to evaluate the organic matter (i.e. kerogen) type, although the plot is strongly affected by thermal maturity. Kerogens are defined by petroleum geochemists as the insoluble macromolecular organic matter dispersed in rocks that may generate hydrocarbons as they thermally mature, and are classified into four different types based on their ratios of elemental H, O and C compositions (Tissot and Welte, 1978; Table 1). From Type I to Type IV kerogen, there is a decrease in hydrogen content and HI, an increase in oxygen content and OI, and an increase in carbon content.

Table 1. Comparison of organic matter types between the organic petrography and organic geochemistry disciplines, and the dominant hydrocarbons they generate. Consideration of vitrinite and inertinite maceral groups at the finer maceral level was not needed for this study, but are identified in organic petrography reports provided in the Appendix. Only those liptinitic macerals identified in this study are listed. Table collated from information presented in Hutton et al. (1994) and Walters (2006)

Geochemistry nomenclature	*Dominant hydrocarbon generated*	*Organic petrography nomenclature*		*Maceral origin*	
Kerogen		*Maceral group*	*Maceral (Submaceral)*		
Type I	waxy oil	Liptinite	Alginite (Telalginite)	Large colonial or unicellular algae found in freshwater and lakes, such as *Botryococchus*, *Tasmanites*	Aquatic
Type II (IIA)	oil and gas		Alginite (Lamalginite)	Small colonial or unicellular marine algae	
			Phytoplankton[a]	Marine microalgae including dinoflagellates	
			Bituminite	Altered algae or plant material	
Type II (IIB, 'exinite')	waxy oil and gas		Sporinite	Waxy and lipid-rich components of higher plants or fungi	Terrestrial
			Cutinite		
			Resinite[b]		
			Fluorinite		
			Liptodetrinite		
Type III	gas	Vitrinite	*(not listed)*	Cell walls of woody higher plants	
Type IV	none	Inertinite	*(not listed)*	Oxidized debris of higher plants or fungi	

NOTES: a Not a defined maceral but is frequently reported in organic petrography reports
b Considered a Type I kerogen

The HI vs TOC plot is used to visualise the organic richness against the expected hydrocarbon phase generated from the rock because the HI is a function of the type of kerogens present. These two plots can be misleading if there is a mixed kerogen assemblage within the rock, as demonstrated by Dembicki (2009). For example, a rock with a mixture of Type II (oil-prone) kerogens and Type IV (non-generating) kerogens will overall have an intermediate HI value, and may appear as gas-prone only on the TOC vs HI plot or as a Type III (gas-prone) kerogen on the HI vs OI plot. Therefore, the composition of the organic matter is best confirmed by microscopy such as that performed for organic petrographic studies originally developed for coal characterisation. There is a difference in how organic matter is typed between the organic geochemistry and organic petrography disciplines, which is summarised in Table 1. A maceral in coal/organic petrography nomenclature is analogous to a mineral — they are identified based on their optical and morphological properties in reflected light microscopy, which ultimately reflects their chemistry (Hutton et al., 1994), and which determines the types of hydrocarbons they would generate. In this study, kerogen typing using Rock-Eval crossplots was very misleading if not integrated with organic petrography from the same depths, because nearly all Permian rocks have mixed maceral and therefore kerogen assemblages.

Back-calculations

The S2 and TOC of thermally mature sediments are generally lower than the original immature sediment as a proportion of the kerogen would have already cracked to hydrocarbons and bitumen, which have either migrated away from the source rock or are still present, giving rise to the S1 peak. Several methods have been developed to “back” calculate to the original immature values that generally give comparable back-calculations of TOC; however, there can be large variations in the S2 and HI back-calculations (Bérdi, 2016). Some of these methods require prior knowledge of the organic matter type (via organic petrography), which may not be practicable on legacy data. The method of Jarvie et al. (2007) was used to back-calculate to immature values in this study, which requires knowledge of the kerogen type, which was assessed using organic petrography. Therefore back-calculations were performed only on the samples which had organic petrography at the same depth (new or legacy). The immature HI values for each kerogen type are taken from Jarvie et al. (2007).

The maturity profile down each hole/well or in outcrop samples was assessed using primarily vitrinite reflectance and, if unavailable, Tmax and TAI (Thermal Alteration Index) reported in palynological reports, or both. The back-calculated values here should only be taken as indicative because the equation is sensitive to the input percentage values for each kerogen type, which for most samples are only estimated visually from organic petrography, and not determined using point counting of components.

Organic petrography

Existing organic petrographic data were collated from reports in WAPIMS and reviewed to help understand trends in legacy Rock-Eval data, provide input to back-calculations, and to assess maturity. Samples for new organic petrography analysis were selected at the same depth as Rock-Eval results to compare the TOC and S2 values with the maceral/kerogen types and thus better predict expected hydrocarbon phase. Energy Resources Consultants in Brisbane, Queensland, provided visual estimates of maceral percentages, and these are provided in the Appendix. Definitions of reported abundances of maceral groups as a proportion of the whole rock sample are given in Table 2.

Where there was no material left to sample (e.g. sidewall core (SWC) or insufficient cuttings), any existing kerogen slides (a standard as part of most palynological preparations) from the same depth were sent to MGPalaeo in Perth to get an approximation of maceral abundances. Care was taken in the interpretation of maceral abundances from this method and it was only used for qualitative comparison, because the preparation of the rock material for palynology (which includes acid digest and sieving) could selectively degrade macerals, thereby skewing percentages.

Table 2. Reported abundance definitions of macerals or maceral groups as a proportion of the whole rock sample, as given in organic petrography reports used in this study (Appendix). Abbreviations: M, maceral/maceral group; OM, organic matter; where shaly coal or coal is reported, their maceral components and abundances are also given in the Appendix

Descriptor	*Percentage (%)*
Rare	<0.1
Sparse	0.1 <M <0.5
Common	0.5 = <M <2.0
Abundant	2 = <M <10
Major	10 = <M <30
Dominant	30 = <M <40
Shaly coal	40 = <OM <70
Coal	OM = >70

Stratigraphy and source-rock potential

Lyons Group (Upper Carboniferous – Lower Permian)

The Lyons Group (Fig. 2) is a mostly marine glacigene unit comprising tillites, diamictites, shales and poorly sorted conglomerates and breccias, with common Precambrian igneous and metasedimentary dropstones (Hocking et al., 1987). Localised thin beds of sandstone and limestone are also present. Fossiliferous beds are common in the unit, with the low diversity of marine macrofossils indicating it was deposited in restricted marine conditions (Mory and Haig, 2011). Locally, some intervals of the Lyons Group are interpreted as lacustrine (Hocking et al., 1987). The unit is widespread throughout the inboard Northern Carnarvon Basin and the Southern Carnarvon Basin, although together with the overlying Permian section, is mostly eroded over the Gascoyne Platform south of the Chargoo 1 and Waroorra 1 wells (Fig. 1). The Lyons Group is exposed in the Byro and southern Merlinleigh Sub-basins but outcrop is mostly poor. The thickness of this unit is highly variable and in places is exceptionally thick (up to 1500 m of intersected thickness), particularly in depositional lows adjacent to the major sub-basin bounding faults. Facies distribution within the Lyons Group is localised, making it difficult to divide into formations that can be regionally correlated, even within sub-basins.

Source-rock potential

Existing data indicate the Lyons Group is a poor hydrocarbon source rock, although very thin source horizons are present locally. For example, a sample from the formation in Quail 1 has relatively high S1 and S2 values (>2 mg/g), and a comparison between the pyrolysis-GC (chromatogram of hydrocarbons released during the S2 peak) and thermal extract (S1) traces suggests the lighter free hydrocarbons (up to C15) were generated in situ (Geotechnical Services Pty Ltd, 1994). GC traces show that the hydrocarbon products would be mainly gas with minor light oil.

Callytharra Formation (Lower Permian)

The Callytharra Formation conformably overlies the glacial Lyons Group (Figs 2, 3) and marks the onset of post-glacial warming and sea-level rise (Hocking et al., 1987). It contains predominantly marine mudstones and calcareous sandstones with common beds of fossiliferous limestones. The mudstones are commonly carbonaceous and pyritic, indicating deposition in quiescent marine conditions. The Callytharra Formation outcrops in the Merlinleigh and Byro Sub-basins and has been interpreted in wells in the Exmouth Sub-basin and Peedamullah Shelf. Although not interpreted as such in well completion reports, a review of palynology data from four deep wells on the Peedamullah Shelf by Mory and Backhouse (1997) suggests the presence of a Callytharra Formation-equivalent unit in this part of the basin (Fig. 4). In this Report, the interpretation of Mory and Backhouse (1997) for the designation of the Callytharra Formation in wells on the Peedamullah Shelf is followed.

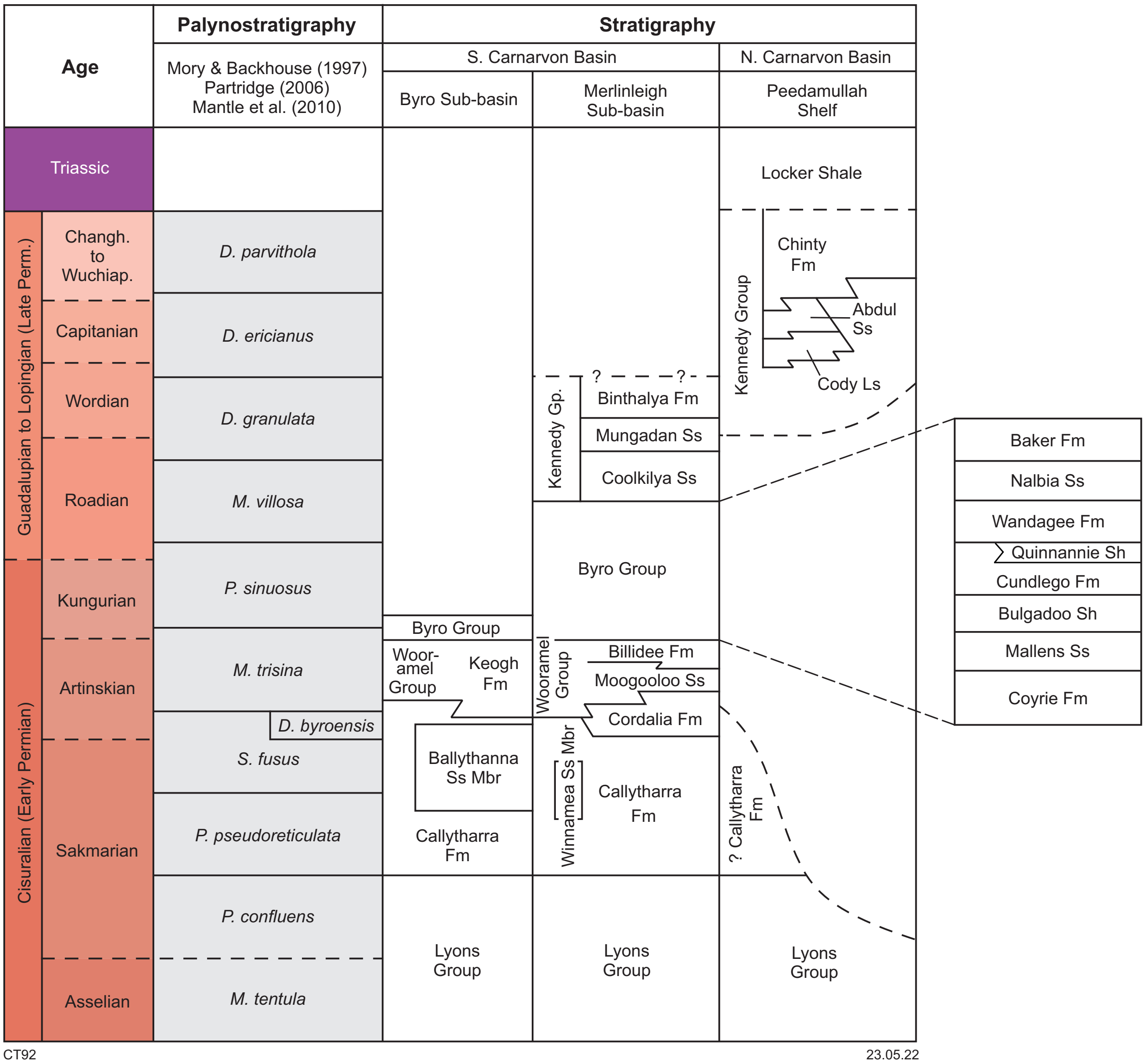

Figure 2. Stratigraphic column for the Permian of the Southern and Northern Carnarvon Basins (modified from Mory and Backhouse, 1997; Mory and Haig, 2011)

The Callytharra Formation is recognised in the onshore Exmouth Sub-basin, although detailed sedimentological interpretation has not been undertaken; however, the unit is a calcareous, fossiliferous mudstone similar to parts of the unit in the Merlinleigh Sub-basin. Two calcareous sandstone members are recognised in the Byro Sub-basin (the Jimba-Jimba Calcarenite and the Ballythanna Sandstone Member).

Source-rock potential

The Callytharra Formation is considered a poor source rock. The TOC/Rock-Eval sampling program for GSWA Ballythanna 1 stratigraphic drillcore in the Byro Sub-basin was designed to follow up on one sample in nearby BMR 09 Glenburgh with anomalously high TOC and S2 (Fig. 3); however, this drillcore did not reveal any good source rocks within the Callytharra Formation. More holes are required to determine whether the good source rock in BMR 09 Glenburgh is more widespread within the Byro Sub-basin.

Wooramel Group (Lower Permian)

The Wooramel Group marks the first progradation of delta plain sediments into the Carnarvon Basin. It is recognised in the Merlinleigh and Byro Sub-basins where it is interpreted to rest conformably on the Callytharra Formation (Crostella, 1996; Mory and Backhouse, 1997). It was first described in outcrop and is reliably correlated to well and drillhole data in the Merlinleigh Sub-basin (Hocking et al., 1987). In the Rough Range/Cape Range area, a thin Wooramel Group (~77 m) was recognised in the Learmonth 1 well based on lithology (Pudovskis, 1958) and palynology (Ingram, 1994). The Wooramel Group and younger Permian sections in this area are mostly eroded on the footwalls of the major faults, and are probably preserved in adjacent hanging walls at depth. Farther north, the Wooramel Group or equivalent aged rocks have been eroded from the Peedamullah Shelf, though it is possibly preserved deeper in the Barrow Sub-basin.

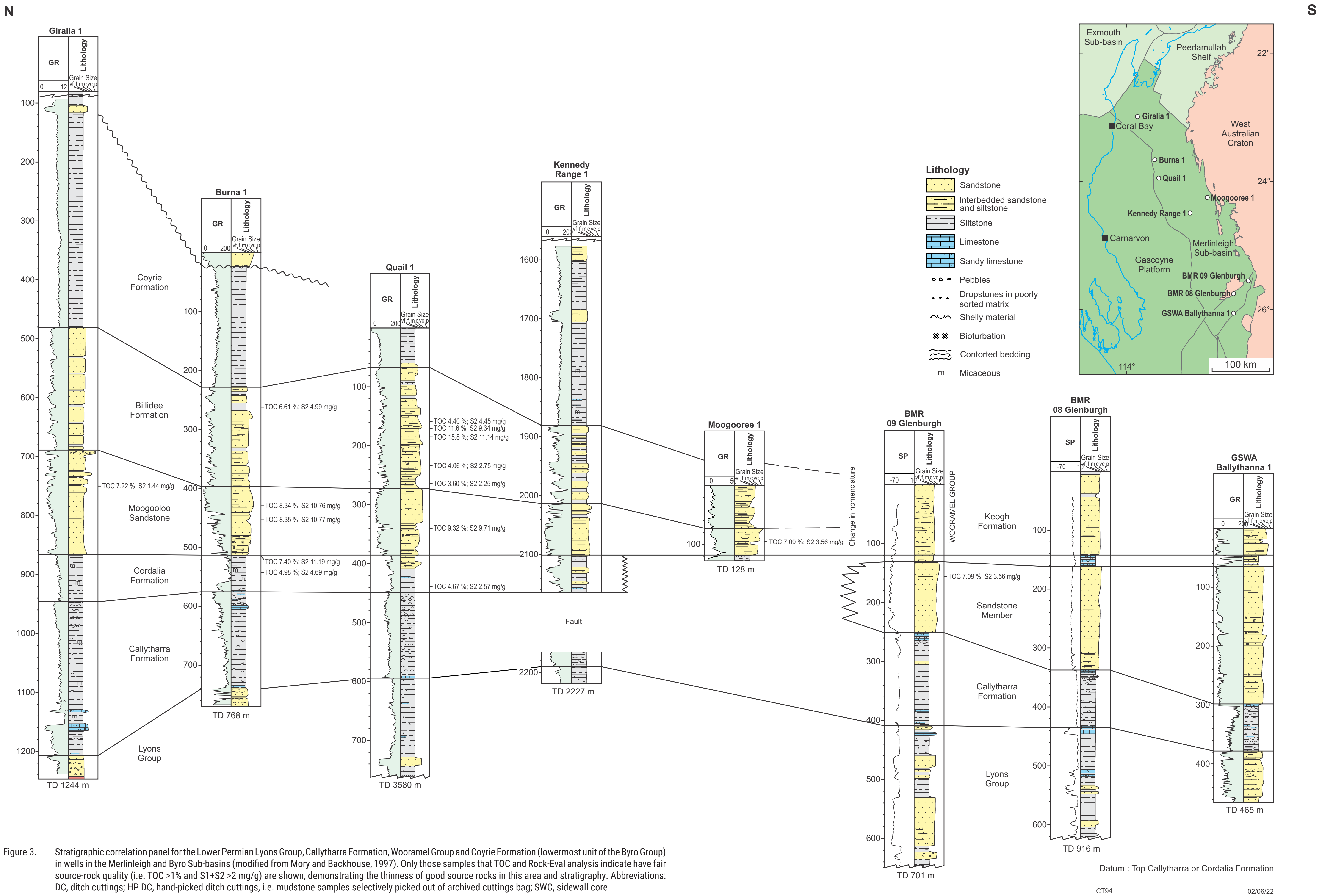

Figure 3. Stratigraphic correlation panel for the Lower Permian Lyons Group, Callytharra Formation, Wooramel Group and Coyrie Formation (lowermost unit of the Byro Group) in wells in the Merlinleigh and Byro Sub-basins (modified from Mory and Backhouse, 1997). Only those samples that TOC and Rock-Eval analysis indicate have fair source-rock quality (i.e. TOC >1% and S1+S2 >2 mg/g) are shown, demonstrating the thinness of good source rocks in this area and stratigraphy. Abbreviations: DC, ditch cuttings; HP DC, hand-picked ditch cuttings, i.e. mudstone samples selectively picked out of archived cuttings bag; SWC, sidewall core

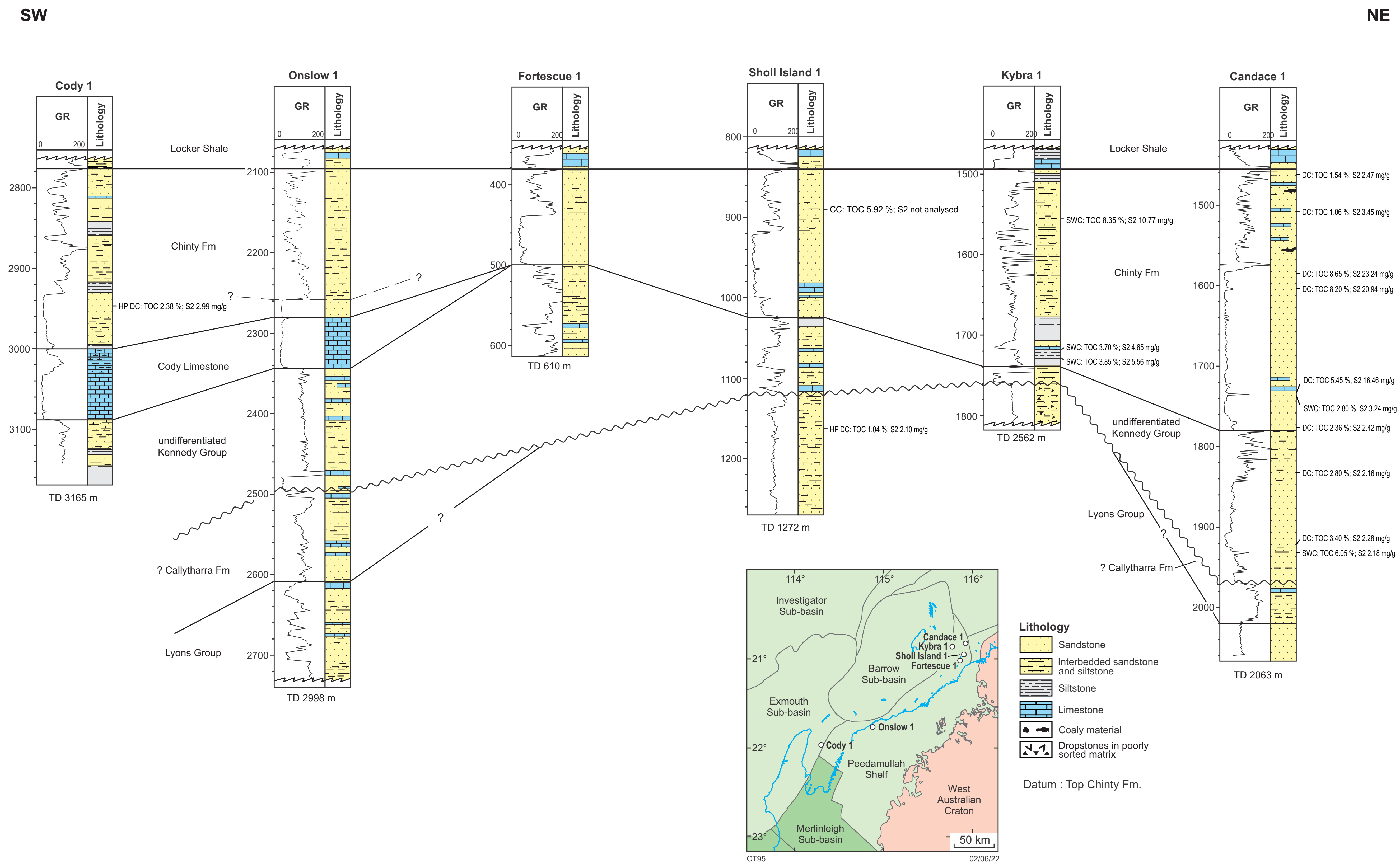

Figure 4. Stratigraphic correlation panel for the Lower Permian Lyons Group and ?Callytharra Formation, overlain unconformably by the Upper Permian Kennedy Group, in wells in the Peedamullah Shelf (modified from Mory and Backhouse, 1997). Only those samples that TOC and Rock-Eval analysis indicate have fair source-rock quality (i.e. TOC >1% and S1+S2 >2 mg/g) are shown, demonstrating the thinness of good source rocks in this area and stratigraphy. Abbreviations: DC, ditch cuttings; HP DC, hand-picked ditch cuttings, i.e. mudstone samples selectively picked out of archived cuttings bag; SWC, sidewall core; CC, conventional core

In the Merlinleigh Sub-basin, where thick sections are recognised in well data and in outcrop, the Wooramel Group is subdivided into three formations (Figs 2, 3). The basal Cordalia Formation is only recognised in wells and outcrop in the northern Merlinleigh Sub-basin (Hocking et al., 1987) and is partly equivalent in age to the uppermost Callytharra Formation. The Cordalia Formation is mostly thinly bedded, bioturbated fine-grained sandstones and siltstones deposited in a prodelta/lower delta-front environment (Hocking et al., 1987; Mory and Haig, 2011). The top of the Cordalia Formation is marked by a carbonaceous siltstone that coarsens upwards towards the overlying Moogooloo Sandstone. The Moogooloo Sandstone comprises mainly thickly bedded, well-sorted quartz sandstones deposited in a fluvial setting and becoming increasingly marine to the north (Mory and Haig, 2011). The sandstones have good reservoir quality (Baker et al., 2000), and are interbedded with thin mudstones that contain potential source intervals (Ghori, 1996). A transgressive surface in the upper part of the Moogooloo Sandstone marks the base of a retrogradational package that includes the overlying heterolithic mudstone-sandstone Billidee Formation, which is composed of carbonaceous shales, silty sandstones and fine-grained to coarse-grained sandstones and conglomerates. The depositional environment is interpreted as a tidally influenced marine shelf to delta plain.

The Keogh Formation is the sole member of the Wooramel Group in the Byro Sub-basin and is currently recognised as time-equivalent to the Cordalia Formation, Moogooloo Sandstone and Billidee Formation (Hocking et al., 1987). The Keogh Formation is lithologically similar to the Billidee Formation, containing carbonaceous shales, silty sandstones and conglomerates deposited in a tidally influenced delta plain or within inter-distributary bays (Hocking et al., 1987; Hocking, 1990).

Both the Billidee Formation in the Merlinleigh Sub-basin and the Keogh Formation in the Byro Sub-basin contain thin lenses of coal. Extensive coal exploration programs targeting the Wooramel Group were carried out in the 1970s and 1980s in both sub-basins (drillhole details collated in Simons, 2020) although no significant deposits were recorded. The Talisker coal deposit in the adjacent northern Coolcalalaya Sub-basin of the Perth Basin is within stratigraphy equivalent to the Keogh Formation. Coal exploration cores drilled by BHP and CRA Exploration in the Merlinleigh and Byro Sub-basins were sampled in this study.

Source-rock potential

The Wooramel Group in the Merlinleigh Sub-basin has excellent potential for generating gas and oil (Ghori, 1996), although source-quality rocks are only in the thin shale interbeds (Fig. 3). Although Rock-Eval data alone would suggest the Wooramel Group has the potential to generate gas only, pyrolysis gas chromatography confirms the unit can generate oil, gas and condensate (Ghori, 1996; Geotechnical Services Pty Ltd, 1994). A comparison of free hydrocarbons in the Wooramel Group in Quail 1 with the pyrolysis gas chromatogram of organic-rich mudstones in the same unit suggests the hydrocarbons were generated in situ in this well (Geotechnical Services Pty Ltd, 1994).

No geochemical or petrographic data for the Wooramel Group in the Byro Sub-basin were collected prior to this study. Historical exploration for coal and oil shale commonly encountered thin bands of 'oily dark shale', with some holes having reported oil appearing in the mud during drilling of black shales (Muggeridge, 1981). Subsequent Fischer analysis of some of these shales recovered oil but at the time were not considered sufficient for oil shale production (Karajas, 1983). 'Oil slicks' have also been reported in diamond and lithium exploration campaigns in the Byro Sub-basin (Samantha Exploration NL, 1980; Pioneer Resources Ltd, 2019) during the drilling of shales; however, it is unclear from these reports which shales produce oil slicks, and drillholes usually encountered different aged shales. Mineralogical examination of one of the shales showed the 'oil slick' to be a very fine black silt which had an oily appearance while in suspension in drilling-related fluids (Samantha Exploration NL, 1980); however, it's unclear from the report which stratigraphic interval was tested. Wooramel Group samples were collected for the first time from stratigraphic holes in the Byro Sub-basin for this study.

Byro Group (Lower Permian)

The Byro Group overlies the Wooramel Group and is recorded only in the Byro and Merlinleigh Sub-basins (Fig. 2). A Permian section broadly equivalent in age to the Byro Group and lowermost Kennedy Group (the uppermost Permian unit in the two Carnarvon Basins) was intersected in Sandalwood 1 in the onshore Exmouth Sub-basin (Crostella and Iasky, 1997), although it is unclear which formation it is equivalent to. Although the Byro Group was interpreted in well completion reports of several wells on the Peedamullah Shelf based on lithological similarities with the unit in the Merlinleigh Sub-basin, a review of the palynology by Mory and Backhouse (1997) shows all intersections designated as Byro Group are equivalent in age to the lower section of the Upper Permian Kennedy Group. Similar to the underlying Wooramel Group, the absence of the Byro Group on the Peedamullah Shelf is likely due to mid-Permian erosion, though both could be present at depth farther offshore.

The Byro Group contains thick successions of marine carbonaceous mudstone alternating with bioturbated quartz sandstones interpreted to represent slight changes in bathymetry during deposition in a stable shallow interior sea (Mory and Haig, 2011). The group is divided into several formations based on the predominance of either mudstone or sandstone, with the mudstone-dominated Coyrie Formation forming the basal unit. The Coyrie Formation is primarily a grey siltstone with minor black shale interbedded with thin fine-grained sandstones abundant in marine macro-fauna and micro-fauna. Towards the contacts with the underlying Billidee Formation and overlying Mallens Sandstone, the sandstone beds become thicker and coarser, thus constituting a greater proportion of the formation. The overlying Mallens Sandstone is a bioturbated, fine-grained to medium-grained sandstone with common hummocky cross-stratification (Hocking et al., 1987) and very minor mudstone interbeds. It is generally thick (up to 200 m) and has limited distribution due to pinch out. The Bulgadoo Shale overlies the Mallens Sandstone and represents the maximum flooding in the lower Byro Group (Mory and Haig, 2011). It is a black pyritic shale with minor finely interbedded sandstones and common horizons of large phosphatic and pyritic nodules, suggesting deposition in a reducing marine environment (Hocking et al, 1987). The Bulgadoo Shale is the youngest Permian unit preserved in the Byro Sub-basin.

The oldest three formations of the Byro Group (Coyrie Formation, Mallens Sandstone and Bulgadoo Shale) and the underlying Billidee Formation of the Wooramel Group are considered part of a transgressive sequence with the maximum flooding surface in the lower part of the Bulgadoo Shale (Mory and Haig, 2011). The upper part of the Bulgadoo Shale and most of the overlying Byro Group — the Cundlego Formation, Quinnanie Shale, Wandagee Formation and Nalbia Sandstone — form part of an overall progradational sequence (Mory and Haig, 2011).

The Cundlego Formation is a thick unit (up to 400 m) comprising parasequences of grey shale grading to fine to coarse-grained cross-stratified sandstones (Hocking et al., 1987; Mory and Haig, 2011). The overlying Quinnanie Shale is a predominantly black shale up to 135 m thick that coarsens upwards to a grey sandy siltstone towards the contact with the Wandagee Formation above, and was deposited in a mainly restricted marine environment. Several smaller scale shoaling upward cycles are recognised within the formation, with some mud units that may have been deposited during short periods of brackish conditions based on microfauna (Haig, 2003). This unit appears to be present only north of the Merlinleigh Homestead — south of this the unit grades into the Cundlego Formation (Hocking et al., 1987). The lower part of the overlying Wandagee Formation comprises short, coarsening upward cycles of black/dark grey siltstone to fine-grained sandstone and in the upper part of the unit it is dominated by shale and siltstone (Hocking et al., 1987). The overlying Nalbia Sandstone is a bioturbated and hummocky cross-stratified fine-grained sandstone unit deposited in lower to upper shoreface environments (Hocking et al., 1987). The Baker Formation is the youngest unit of the Byro Group, and is interpreted to form the base of a progradational sequence that includes part of the overlying Kennedy Group (Mory and Haig, 2011). It generally contains finer grained facies compared to the Nalbia Sandstone below (Hocking et al., 1987), and was deposited in an estuarine environment with fluctuating water depths and salinities (Haig and Mory, 2016).

Source-rock potential

The Bulgadoo and Quinnanie Shales contain fair to good source intervals; however, more data is needed (Ghori, 1996). Although the shales generally have high TOC, the generative potential yield is low due to their high inertinitic content (Ghori, 1996). Only Kennedy Range 1 intersected a complete section of the Bulgadoo and Quinnanie Shales, mostly as cuttings. Although these units were densely sampled for Rock-Eval in this well (every ~11 m or less), all but two of eight samples with S2 values >2.5 mg/g (a widely used threshold needed for a source rock; Peters, 1986) also have inflated S1 values, suggesting the presence of hydrocarbons. Whether these hydrocarbons are drilling contaminants, naturally migrated or generated in situ is unknown. Previously unanalysed coal exploration drillcores and outcrop were sampled for this study, and new infill samples were taken from coal drillcores sampled previously by Ghori (1996) to refine the quantity of good source intervals. Minor amounts of a 'black amorphous substance' with 'resinous lustre' were reported from the Bulgadoo Shale in the BMR 06 Kennedy Range stratigraphic hole (previously BMR Muderong bore 6), which was interpreted as ozokerite after chemical analysis (Perry, 1965).

Kennedy Group (Upper Permian)

The Kennedy Group is the youngest stratigraphic package of the Permian in the Southern and Northern Carnarvon Basins (Fig. 2) and was deposited in environments ranging from an open-marine sandy shelf to a marginal marine lagoonal or delta plain environment. The oldest section of the Kennedy Group is preserved only in the Merlinleigh Sub-basin, where three formations (in ascending stratigraphic order) — Coolkilya Sandstone, Mungadan Sandstone and Binthalya Formation — are recognised in outcrop and well intersections. These formations comprise shoaling upcycles ranging from 3 to 10 m thick, which represent changes in relative sea level with basin subsidence (Lever, 2002). The Coolkilya Sandstone is mostly a very fine to fine-grained sandstone deposited in offshore to upper shelf environments, and cross-stratification, bioturbation, ripple laminations and channel-form features are common (Hocking et al., 1987; Lever, 2002). The Coolkilya Sandstone today forms spectacular gorges and mesas in the Kennedy Range National Park. The conformably overlying Mungadan Sandstone comprises fine-grained to coarse-grained sandstones with minor interbedded siltstone deposited in upper shelf to shallow marine (shoreline, lagoonal, beach) environments with evidence of tidal influence (Hocking et al., 1987; Lever, 2002). The youngest unit of this group in the Merlingleigh Sub-basin is the fine-grained Binthalya Formation, which consists of cycles of dark grey-black siltstone to fine-grained sandstone (Lever, 2002). Specimens of dark siltstones from the Binthalya Formation were collected from outcrop for this study.

The youngest stratigraphic units of the Kennedy Group are intersected only on the Peedamullah Shelf, where they sit unconformably on the Callytharra Formation (Fig. 4), and were either eroded or not deposited farther south. Several wells on the Peedamullah Shelf (Arabella 1, Candace 1, Cody 1) were previously interpreted to have intersected the Byro Group based on lithology; however, these sections have since been reassigned to the Kennedy Group based on palynology (Mory and Backhouse, 1997). The youngest part of the Kennedy Group is formally divided into (in ascending stratigraphic order) the Cody Limestone, Abdul Sandstone and the Chinty Formation (Mory and Backhouse, 1997; Crostella et al., 2000). The basal part of the group, and overlying intervals where these lithofacies are not formally recognised, is designated as undifferentiated Kennedy Group. The Cody Limestone and Abdul Sandstone were only defined subsequent to most of the drilling on the Peedamullah Shelf and therefore these intervals have been called undifferentiated Kennedy Group in some well completion reports. The undifferentiated Kennedy Group comprises mainly sandstones with lesser amounts of carbonaceous shales, siltstones and limestones (Crostella et al., 2000). Its depositional environment includes marine shelf to marginal marine lagoon and delta plain (Hocking et al., 1987; Crostella et al., 2000).

The Cody Limestone ('Cody Formation' of Gorter and Davies, 1999) is predominantly a pale, dense to microcrystalline limestone consisting of fossiliferous calcarenite or calcilutite (Gorter and Davies, 1999; Crostella et al., 2000). Whereas Crostella et al. (2000) interpreted the basal contact of this unit as conformable, Gorter and Davies (1999) considered it as unconformable on the underlying Byro Group. Based on their interpretation of localised karst topography at the top of the Cody Limestone, Gorter and Davies (1999) also interpreted an unconformable upper contact between the Cody Limestone and the clastic section above. The definition of the Abdul Sandstone was introduced by Crostella et al. (2000) for the clean, fine-grained to medium-grained sandstone with minor interbedded limestone overlying the Cody Limestone in Abduls Dam 1 and nearby wells on the Peedamullah Shelf. The overlying Chinty Formation is the youngest formation of the Permian in the Northern Carnarvon Basin and was first defined in wells within a small onshore area of the Peedamullah Shelf where it consists of grey, silty fine sandstone with lesser amounts of organic-rich mudstone and limestone deposited on a sandy marine shelf (Hocking et al., 1987). The Chinty Formation was subsequently redefined to include the thick (>150 m), older, coarse sandstone-dominated package below, identified in wells along the eastern edge of the Peedamullah Shelf (Delfos and Dedman, 1988; Mory and Backhouse, 1997; Fig. 4), which was interpreted as delta plain sediments (Delfos and Dedman, 1988).

Source-rock potential

Ghori (1998) and Iasky et al. (2002) identified the Chinty Formation as containing source rocks with fair to excellent potential for generating oil and gas. Kybra 1 and Candace 1 in the offshore eastern Peedamullah Shelf have very good source intervals within the Chinty Formation; the aggressive sampling campaign in both these wells (all cuttings intervals were analysed) ensured that the very thin source intervals were detected. In Candace 1, the highest-yielding source intervals are <5 m thick coal-bearing mudstones within a sand-dominated package at the base of the Chinty Formation.

Previous geochemical investigations of hydrocarbons

There are no economic discoveries in the Permian section of the Carnarvon Basin, although hydrocarbon shows in the Permian have been reported in most sub-basins, though uncommon. In the Merlinleigh Sub-basin, only the Kennedy Range 1 well reported gas shows (in the Moogooloo Sandstone of the Wooramel Group), which marks the southernmost Permian show in the Carnarvon Basin. Trace fluorescence in the Moogooloo Sandstone in Quail 1 (Pearson, 1964) was later interpreted as possible oil staining in Kennedy Range 1 (Lehmann, 1967).

Oil and gas shows in Permian rocks are more common in the Upper Permian section of the Northern Carnarvon Basin. Hydrocarbon staining and dead oil were noted in Kybra 1 and Flinders Shoal 1 in the ‘Byro Group’ (now considered Kennedy Group) (Robertson Research Australia Pty Ltd, 1986; Bond Corporation Pty Ltd, 1988a). Analysis of organic extracts from oil inclusions in the Chinty Formation in Kybra 1, Sholl Island 1 and Arabella 1 was undertaken to determine if the oils could be sourced from Permian or Triassic rocks (Western Australia – Organic and Isotope Geochemistry Centre, 2014); however, the results were inconclusive. Grains with oil inclusions (GOI) analysis of oil shows in the Chinty Formation in Cody 1 suggest the oil was from a paleo-oil column, although whether these are generated from hydrocarbons locally or elsewhere is unknown. More samples were collected from Cody 1 to test whether the oil in the Chinty Formation was sourced locally. Minor gas shows were encountered in the Cody Limestone in Dillson 1 (Western Mining Corporation Limited, 1989) and Dill 1 (Hodge and Hillock, 1993) and in the Abdul Sandstone in Abdul 1 (Crostella et al., 2000). Within the study area, oil discoveries have only been made in the inboard Northern Carnarvon Basin, with hydrocarbons accumulated in Jurassic or Cretaceous rocks.

Although there is no definitive geochemical evidence for a Permian source for any of the oil discoveries in Jurassic or Cretaceous reservoirs, circumstantial evidence suggests it is possible. Oil from Bennet 1 shows a similar n-alkane profile to Permian-sourced oils in the Bonaparte Basin, although a definitive Permian source based on biomarkers could not be confirmed (Edwards and Zumberge, 2005). Much of the oil in the Barrow Sub-basin beyond the Peedamullah Shelf is mostly sourced from the *Wanaea spectabilis* interval within the Jurassic Dingo Claystone (van Aarssen et al., 1996), an open-marine claystone. Though heavily biodegraded, most recovered or extracted oil in wells on the Peedamullah Shelf show some geochemical similarities with Dingo Claystone-sourced oils in the Barrow Sub-basin, suggesting some lateral migration; however, they also show distinct differences that point to contribution from at least one other source rock with terrestrial affinities (Crostella et al., 2000), and in some cases suggest a source rock older than the Jurassic. Features of oil (high pristane-phytane ratios and the presence of higher plant biomarkers) from the Tubridgi 2, 4 and 5 wells in the now-depleted Tubridgi gasfield, onshore Peedamullah Shelf, suggest an additional charge from a terrestrial source (Geotechnical Services Pty Ltd, 1996). A very localised, post-Devonian, pre-Upper Jurassic terrestrial source was postulated for this additional source (Crostella et al., 2000). However, later work by Edwards and Zumberge (2005) also identified aromatic dinosteranes in oil from Tubridgi 2, suggesting some of the oil could be sourced from Late Triassic-aged or younger rocks (i.e. after evolution of dinoflagelates), but before Dingo Claystone deposition — raising the possibility of multiple sources, including a terrestrial source, for oil in the Peedamullah Shelf. A ‘very terrestrial’ source was also suggested for oils from Picul 1 (Pan Pacific Petroleum NL, 1993) and Sapphire 1 (Geotechnical Services Pty Ltd, 1996), which are not related to either typical Barrow Sub-basin oils or Tubridgi oil (Geotechnical Services Pty Ltd, 1996). Ratios of biomarkers of oil extracted from a core sample from Observation 1 (Fig. 1) were interpreted to be due to a pre-Jurassic source (Analabs, 1990a). Further interpretations of a terrestrial source were also made for oils from Fortescue 1 and Mardie 1 (Dolan and Associates, 1991). GC-MS of samples from the Cretaceous Birdrong Sandstone in Tent Hill 1, Hope Island 1 and Urala 1 also show higher plant biomarkers (odd-over-even predominance in C25+ range) and low pristane-phytane ratios, suggesting an anoxic, marine-to mixed marine/terrestrial source rock (Analabs, 1990b). Given that terrestrial kerogens dominate in Permian rocks even in those deposited in marine environments, a Permian terrestrial source contributing some oil in the Peedamullah Shelf is plausible. Based on the geochemistry of oil samples, another source of oil aside from the Dingo Claystone postulated for the Peedamullah Shelf is a distal marine carbonate source rock of unknown age (Edwards and Zumberge, 2005).

Farther west in the Exmouth Sub-basin, oil shows and dead oil were encountered in the Permian sections in Rough Range 1 and Sandalwood 1, respectively (Dolan and Associates, 1991; Mitchell, 1990). Oil shows in the Lyons Group in Rough Range 1 were interpreted to be sourced from the Paleozoic, as the gas chromatography traces are dissimilar to the Mesozoic gas chromatography traces in the same well (Dolan and Associates, 1991) and have pristine/phytane ratios more typical of hydrocarbons extracted from the Paleozoic (Alexander, 1991). Oil from Rough Range 1 and Whaleback 1 are interpreted to have had a dominant contribution from higher land plants from a pre-Jurassic source, based on the absence of Araucariaceae markers (Pott et al., 1990). Further analysis by Edwards and Zumberge (2005) found the presence of pre-Middle Triassic age markers and the absence of dinosterane in the oil from Rough Range 1, and they interpreted this as an early mature source rock with non-marine algae and land plants deposited in a delta-plain swamp/lacustrine setting. In their study of oil families in the North West Shelf, Edwards and Zumberge (2005) considered the oil from Parrot Hill 1 a vagrant oil sourced from lacustrine rocks of unknown age. Lacustrine facies are common throughout the Permian.

Results and Interpretation

Results of the TOC and Rock-Eval pyrolysis are discussed by group/formation (oldest to youngest) and then, where relevant, by sub-basin, and discussed in context with the existing TOC/Rock-Eval data and new and legacy organic petrography descriptions. For the TOC vs S1+S2 plot and the TOC vs HI plot, the data have been subdivided based on their maturities (immature/early mature and mid-mature to higher maturities) to highlight possible reduction in HI and generative potential yield in the more mature samples. Back-calculations were performed only on mid-mature and higher maturity samples and are presented as hollow shapes.

Lyons Group

The Lyons Group TOC/Rock-Eval plots and selected maceral abundances are presented in Figure 5. Despite the widespread intersection of this unit, relatively few wells (16) had existing Rock-Eval data for the Lyons Group prior to this study. New data collected from across all sub-basins were consistent with previous data in showing the Lyons Group has poor source-rock potential (Fig. 4). However, a review of legacy organic petrography reports undertaken in this study suggests there are thin horizons rich in oil-prone kerogens (liptinites) in the Lyons Groups that will not have been represented in the Rock-Eval of bulk cuttings. For example, bituminite is abundant in a thin-bedded limestone unit in BMR 08 Glenburgh in the Byro Sub-basin and other terrestrial and algal liptinites are collectively a common component (Keiraville Consultants, 1985). Unfortunately, no more material exists from this thin-bedded limestone interval of BMR 08 Glenburgh to further investigate this horizon and sample for Rock-Eval pyrolysis.

Callytharra Formation

The Callytharra Formation TOC/Rock-Eval plots and selected maceral abundances are presented in Figure 6.

Merlinleigh Sub-basin

No new samples of the Callytharra Formation were gathered from this sub-basin. Near complete sections of the Callytharra Formation are interpreted in Burna 1, Gascoyne 1 and Quail 1 (Mory and Backhouse, 1997), the legacy pyrolysis data of which all show that although the Callytharra Formation is mostly organically fair, it has poor generative potential yield.

Byro Sub-basin

New samples were collected from a mineral drillhole (Pioneer Resources Bogadi BORC-06) and a seismic shothole (Wooramel Seismic Line 3 SP314), which show high TOC (up to 6.75%), but poor to fair generative potential yield. The more promising results from the seismic shothole are from the uppermost Callytharra Formation (uppermost *S. fusus* to lowermost *M. trisina* zones; Hannaford, 2020), although it is possible that this section is the lowermost Wooramel Group. Organic petrography results from this hole show the presence of rare bitumen; however, where intersected, the unit is immature–early mature in this sub-basin.

Exmouth Sub-basin and northern Merlinleigh Sub-basin

Only eight data points across four wells previously existed for the Callytharra Formation in this area, which on average show fair to rich TOC but poor generative potential yield.

New samples for TOC and Rock-Eval were collected from cuttings from Whaleback 1 and North Giralia 1. Although the Permian section in North Giralia 1 was originally interpreted as the Byro Group, based on the facies and palynology, it is considered here to most likely be the Callytharra Formation. New palynological data from the top of the Callytharra Formation in Whaleback 1 confirm the presence of the *S. fusus* zone or older, but with frequent Cretaceous and Jurassic cavings (Mantle, 2021). Based on the presence of cavings, there is a possibility that the increased generative potential (S2) of the topmost sample (up to 2.62 mg/g) in Whaleback 1 is due to marine organic matter caved from the more prospective Mesozoic section or from organic matter in artificial composites noted in the organic petrography (Appendix).

Organic petrography results were previously available for only one sample in Sandalwood 1 (Mitchell, 1990). New organic petrography results were obtained for Whaleback 1. Both the new and legacy data show that the maceral assemblage is dominated by inertinite, and only rare to sparse liptinite and vitrinite, although rare *Botryococchus*-related telalginite was reported in Sandalwood 1 (Mitchell, 1990). Rare lamalginite was also noted in Whaleback 1 (Appendix), although this is possibly caved from the Mesozoic.

Until more reliable physical samples can be obtained (e.g. core or SWC), there is no strong evidence that the Callytharra Formation intersected to date has any source-rock potential in this area.

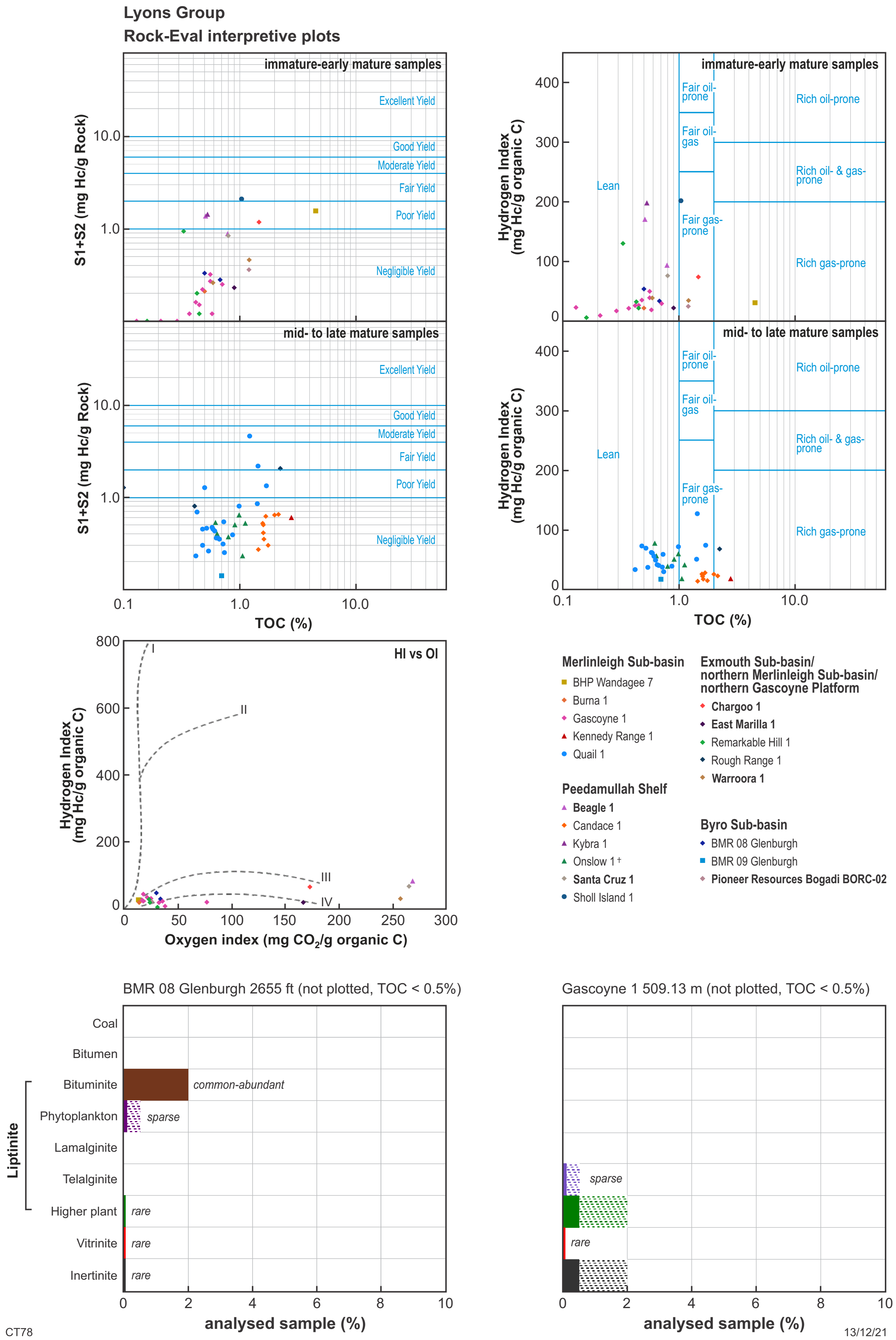

Figure 5. Interpretive Rock-Eval plots and maceral abundance ranges from organic petrography of selected new or legacy samples for the Lyons Group, where the solid and hatched bars show the minimum and maximum possible abundance. Well names in bold are new samples, and well names with a cross symbol are wells with new infill sampling

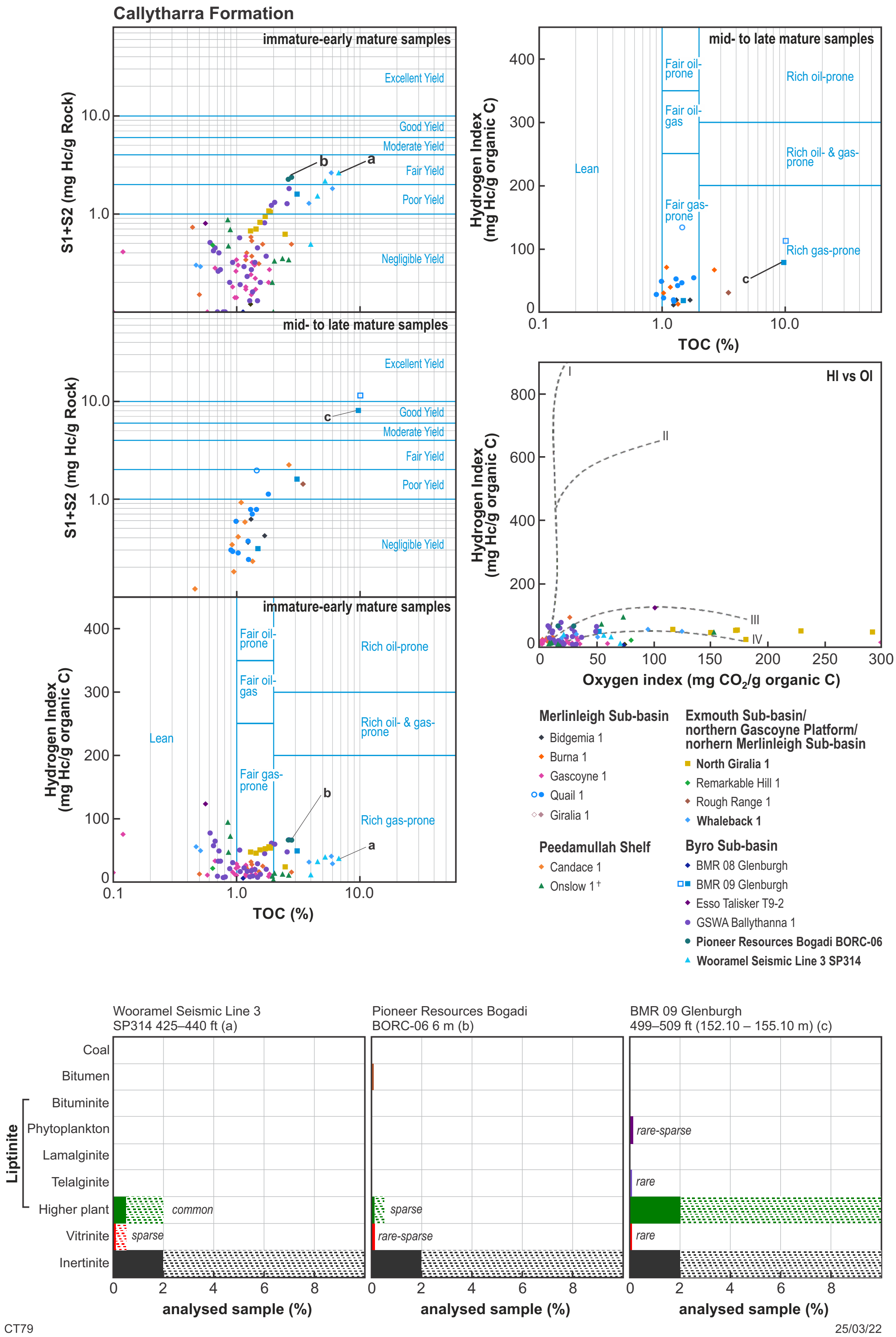

Figure 6. Interpretive Rock-Eval plots and maceral abundance ranges from organic petrography of selected new or legacy samples for the Callytharra Formation, where the solid and hatched bars show the minimum and maximum possible abundance. Well names in bold are new samples, and well names with a cross symbol are wells with new infill sampling

Peedamullah Shelf

Only three wells on the Peedamullah Shelf are interpreted to have intersected the Callytharra Formation: Candace 1, Onslow 1 and Sholl Island 1. Previously only Candace 1 and Onslow 1 had pyrolysis data for this formation, which shows that although the formation is organically rich, it has poor generative potential yield.

Wooramel Group (Lower Permian)

Merlinleigh Sub-basin and Exmouth Sub-basin

Legacy rock pyrolysis data exists from Kennedy Range 1, Quail 1, Burna 1, CRA coal exploration drillhole GBH4 and BHP coal exploration drillholes BHP Wandagee 1 and 6, and nearly all wells demonstrate that the mudstones within each of the three formations in this group can be good to very good gas-generating source rocks; however, these mud intervals are thin (Fig. 3). The new data from coal exploration drillholes CC19 and CC21 and stratigraphic hole Moogooree 1 in the far east of the Merlinleigh Sub-basin are all consistent with previous results of good source potential for gas interpreted within the mudstone intervals. In the onshore Exmouth Sub-basin, new pyrolysis data were collected from Learmonth 1 that show a similar trend to other Wooramel Group results; however, new palynological data from cuttings samples within the same unit suggest they are heavily contaminated with Jurassic and Cretaceous cavings (Mantle, 2021), and therefore the geochemical results possibly reflect the organic richness of the overlying Mesozoic section. It is unclear which formation/s within the Wooramel Group this section in Learmonth 1 represents.

Cordalia Formation

The Cordalia Formation TOC/Rock-Eval plots and selected maceral abundances are presented in Figure 7. No new sampling was undertaken from the Cordalia Formation. The existing measured pyrolysis data for interpreted early mature samples and for back-calculated interpreted mature samples show that the best source intervals are in the northern Merlinleigh Sub-basin in Burna 1 and Giralia 1.

Legacy organic petrography reports for Giralia 1, Burna 1 and Kennedy Range 1 reveal that the organic-rich claystones in Burna 1 are abundant in terrestrial liptinites with equal or lesser amounts of inertinite; therefore, there is some liquid potential despite the lower HI values given by the Rock-Eval dataset. The samples from Burna 1 are early mature (mean Rv max = 0.57 – 0.69%; Percival, 1985) and therefore may have generated some minor oil. Oil inclusions in the overlying Moogooloo Sandstone in Burna 1, Kennedy Range 1 and Quail 1 were generated at the onset of the oil window based on fluid inclusion studies (Eadington, 1997) with the organic mudstones in the Cordalia Formation or Moogooloo Sandstone the most likely source. In Giralia 1, the mudstones are also rich in terrestrial liptinites and show minor lacustrine influence due to the presence of rare *Botryococchus*-related telalginite. The maceral assemblage in Giralia 1 is dominated by inertinite, with liptinite commonly present with sparse to rare vitrinite (Ranasinghe and Crosdale, 2018; note the samples are incorrectly labelled as being from Bulgadoo Shale in the original report, which conflicts with the biostratigraphic data). The Wooramel Group in this well is early to mid-mature (mean Rv max = 0.67 – 0.73%; Ranasinghe and Crosdale, 2018), so hydrocarbons may have already been generated.

Moogooloo Sandstone

The Moogooloo Sandstone TOC/Rock-Eval plots and selected maceral abundances are presented in Figure 8. No new data was obtained from the Moogooloo Sandstone. Existing Rock-Eval data suggest the thin mudstones (Fig. 3) within this formation are rich source rocks with good to excellent generative potential in most wells except Giralia 1 and Kennedy Range 1, although the unit is more mature in the latter well (mature for gas). Legacy organic petrography results for one mudstone interbed in Giralia 1 show inertinite is the most abundant maceral with common liptinites (sporinite, liptodetrinite, cutinite) and rare *Botryococchus* telalginite, indicating some lacustrine influence (Ranasinghe and Crosdale, 2018).

Billidee Formation

The Billidee Formation TOC/Rock-Eval plots and selected maceral abundances are presented in Figure 9. Legacy pyrolysis data show the mudstone interbeds of the Billidee Formation are rich, gas-prone source rocks in most wells except Remarkable Hill 1. Kennedy Range 1 results are anomalously poor; however, it is clear that the Wooramel Group is overmature in this well (mean vitrinite reflectance ranging from 1.59 to 1.86%) and may have already generated hydrocarbons, as indicated by high S1 values and PI values up to 0.4 in some samples.

The new results from Rock-Eval analysis from Burna 1, Moogooree 1 and exploration coal drillcores CC19 and CC21 (note that the geographical coordinates for CC21 are uncertain and likely close to CC20) are consistent with legacy organic geochemistry and show that good source intervals persist farther north in Burna 1 and east in Moogooree 1.

Legacy organic petrography reports for Gascoyne 1 (Esso Australia Limited, 1985), Kennedy Range 1 (Keiraville Consultants, 1985), Burna 1 (Percival, 1985), Remarkable Hill 1 (Dolan and Associates, 1991) and Giralia 1 (Ranasinghe and Crosdale, 2018) state that inertinite is the dominant maceral with lower amounts or complete absence of liptinite and vitrinite. However, it is unclear if these samples were from the organic mudstone lithologies.

New organic petrography results were obtained from dark mudstone beds in Burna 1 and in GBH4, which pyrolysis data indicate are good source rocks (Appendix). These mudstones are abundant in both inertinite and liptinite macerals (mostly sporinite, and including *Botryococcus* telalginite), which suggests there is potential for minor liquids, despite the gas-prone classification given by the pyrolysis data. Aside from Kennedy Range 1, vitrinite reflectance data across all wells suggest the Billidee Formation is early mature for oil generation.

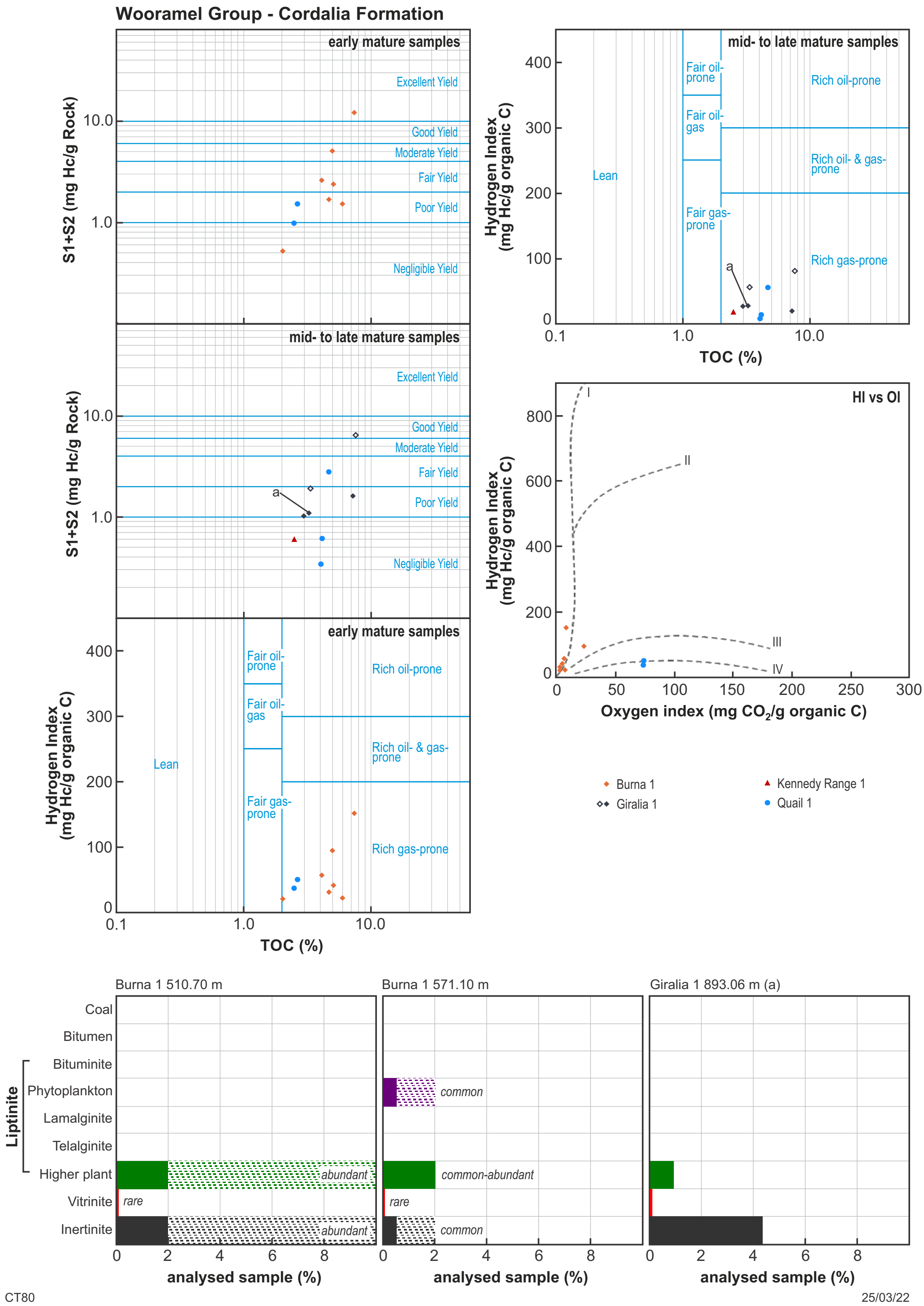

Figure 7. Interpretive Rock-Eval plots and maceral abundance ranges from organic petrography of selected new or legacy samples for the Cordalia Formation of the Wooramel Group, where the solid and hatched bars show the minimum and maximum possible abundance. Well names in bold are new samples, and well names with a cross symbol are wells with new infill sampling

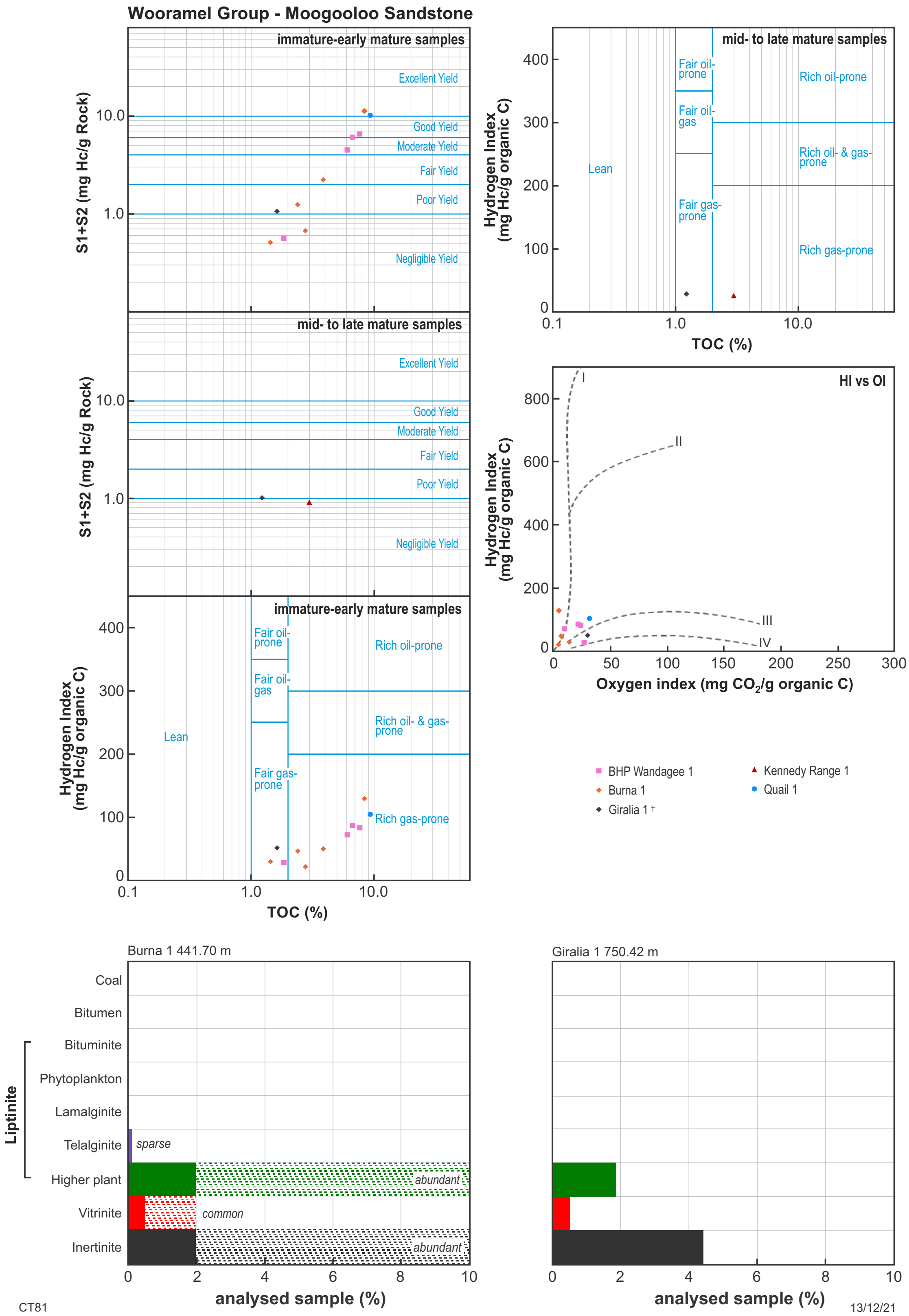

Figure 8. Interpretive Rock-Eval plots and maceral abundance ranges from organic petrography of selected new or legacy samples for the Moogooloo Sandstone of the Wooramel Group, where the solid and hatched bars show the minimum and maximum possible abundance. Well names in bold are new samples, and well names with a cross symbol are wells with new infill sampling

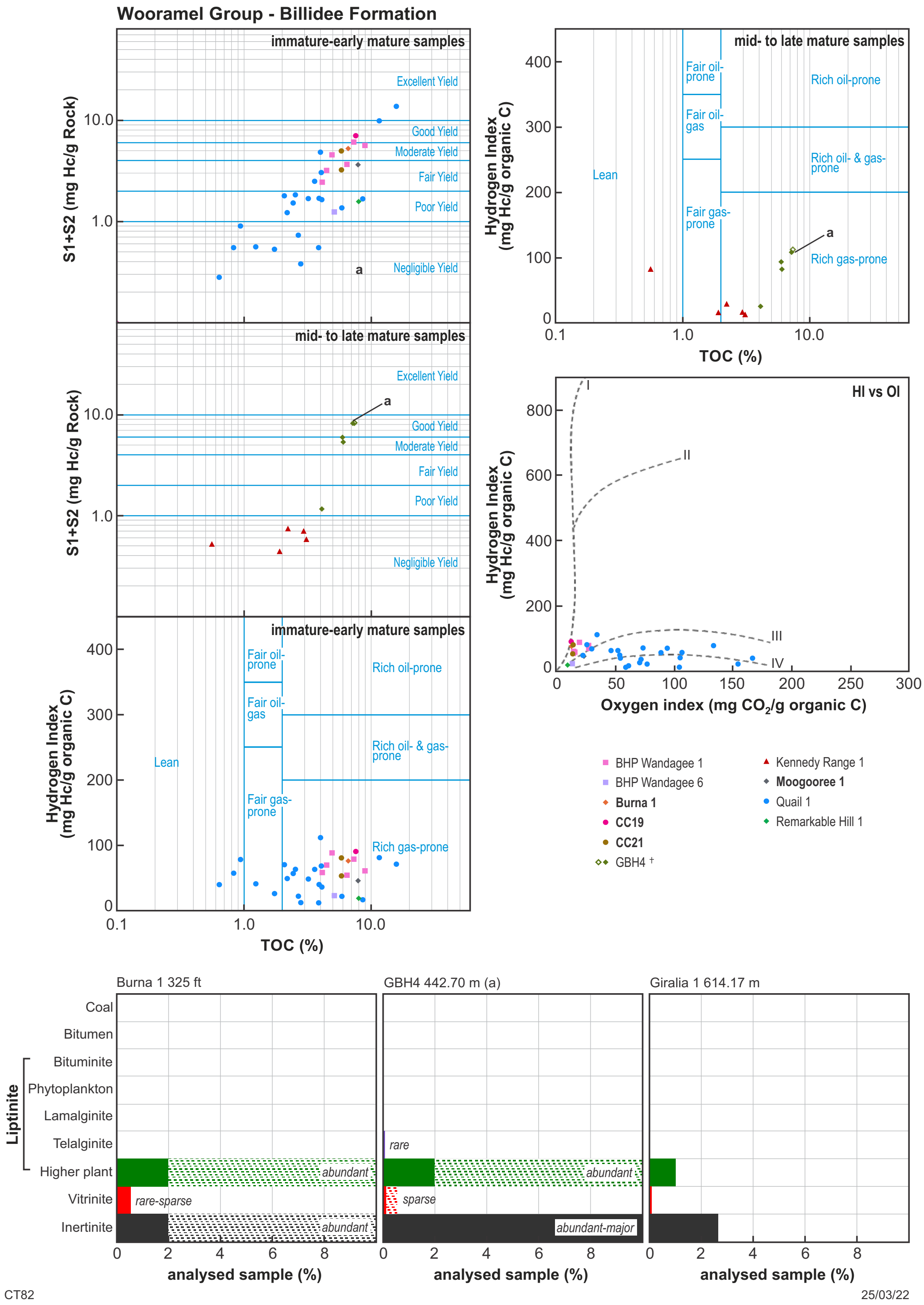

Figure 9. Interpretive Rock-Eval plots and maceral abundance ranges from organic petrography of selected new or legacy samples for the Billidee Formation of the Wooramel Group, where the solid and hatched bars show the minimum and maximum possible abundance. Well names in bold are new samples, and well names with a cross symbol are wells with new infill sampling

Byro Sub-basin – Keogh Formation

The Keogh Formation TOC/Rock-Eval plots and selected maceral abundances are presented in Figure 10. Previously, no pyrolysis data were gathered from the Wooramel Group (Keogh Formation) in the Byro Sub-basin. New cuttings samples from stratigraphic holes North Ballythanna 1 and 3 were collected for TOC and Rock-Eval pyrolysis. These had high TOCs (up to 3.4%) but negligible to poor generative potential (S2 <2 mg/g).

New organic petrography results from North Ballythanna 1 show that inertinite is abundant in mudstone lithofacies, with abundances of terrestrial liptinite (consisting of liptodetrinite and sporinite) equal or less than that of inertinite (Appendix). A comparison in Rock-Eval results between the two samples suggests that the modest increase in S2 and HI is driven by an increase in proportion of terrestrial liptinite.

Byro Group (Lower Permian)

Merlinleigh Sub-basin

Coyrie Formation

The Coyrie Formation TOC/Rock-Eval plots and selected maceral abundances are presented in Figure 11. New samples from the Coyrie Formation were collected for Rock-Eval pyrolysis from Burna 1, Giralia 1 and from outcrop. The results are consistent with previous data that show that mudstone lithofacies in the Coyrie Formation have high organic richness (up to 3.3% TOC, average 2.6%), but with low generative potential yield. The new outcrop samples are unreliable as they show high Tmax values and are probably weathered.

Legacy organic petrography reports were reviewed for Burna 1 (Percival, 1985; labelled as Mallens Sandstone in report), Giralia 1 (Ranasinghe and Crosdale, 2018; labelled as Bulgadoo Shale in report) and Kennedy Range 1 (Keiraville Consultants, 1985), and new data was obtained from higher up in the Coyrie Formation in Burna 1 (Appendix). In all three wells, inertinite is the major maceral component with vitrinite rare to absent, although in Burna 1 and Giralia 1, liptinite (sporinite, liptodetrinite) is common and a sample from the base of Burna 1 near the contact with the Billidee Formation is abundant in liptinite macerals, suggesting possible minor liquids potential. The abundance of inertinite has driven down the HI value. Samples in Burna 1 and Giralia 1 are early to mid-mature based on vitrinite reflectance (Rv max 0.67 – 0.73%; Ranasinghe and Crosdale, 2018). In Kennedy Range 1, two samples in the Coyrie Formation are late mature (Keiraville Consultants, 1985). Back-calculations were not performed as inertinite is practically the only maceral, and it is unknown what the original maceral abundances were.

Mallens Sandstone

All well intersections of the Mallens Sandstone had been previously sampled for Rock-Eval analysis; therefore, no new samples were gathered for this study. Existing samples from Kennedy Range 1 and BMR 07 Kennedy Range show the thin mudstone intervals to be a potentially good source for gas. Legacy organic petrography data exist for only two samples in the Kennedy Range 1 well, which show that inertinite ± vitrinite dominate the maceral assemblage.

Bulgadoo Shale

The Bulgadoo Shale TOC/Rock-Eval plots and maceral abundances are presented in Figure 12. Given the coarse sampling density of this unit in most wells, new infill sampling between existing samples was undertaken in coal exploration drillcores to see if thin intervals of good source-rock horizons existed. Like the legacy data, all new drillcore samples showed high organic richness but low generating potential, implying that if any good source-rock interval existed within the Bulgadoo Shale, it would be very thin (i.e. <5 m and below the resolution of the sampling interval). Although new samples from outcrop have improved the spatial coverage of Rock-Eval data, with the northernmost and easternmost samples of Bulgadoo Shale collected to date, only two samples from Lucky Creek at the western edge of the sub-basin indicated fair source generative potential yield (S1+S2 >2 mg/g).

Six legacy Rock-Eval data points from Kennedy Range 1 have been omitted from the interpretation as they show evidence of either migrated hydrocarbons or contamination based on the high S1 values between 0.5 and 20 mg/g. It is unclear if this is from in situ hydrocarbon generation. The anomalously high S2 sample from Kennedy Range 1 is inconsistent with other S2 results from the unit in this well and is considered suspicious because another legacy Rock-Eval result from the same cuttings interval (although also including a farther 10 ft below) reported in a different study is exactly an order of magnitude lower, therefore this data point could possibly be incorrect due to a transcription error.

The only published organic petrography results from the Bulgadoo Shale prior to this study are from Kennedy Range 1 (Keiraville Consultants, 1985), and all samples have inertinite as the dominant maceral. The upper section of the Bulgadoo Shale in this well contains liptinite as a common maceral including rare *Botryococchus*, and bitumen was also noted in the sample at a depth of 3922 m. New organic petrography analysis was undertaken from coal exploration drillhole GBH4 (Appendix) from samples with S1+S2 values ranging from 2.50 mg/g (the highest in the drillhole) to 1.18 mg/g. The maceral assemblage in all samples is dominated by inertinite, which accounts for most of the organic richness, although terrestrial liptinite was also a common component. The sample with the highest generative potential yield (S1+S2 = 2.5 mg/g) was the only sample in which *Botryococcus* algae was recorded.

Cundlego Formation

The Cundlego Formation TOC/Rock-Eval plots and selected maceral abundances are presented in Figure 13. New TOC and Rock-Eval results were obtained from coal exploration drillhole WC4, representing the northernmost samples of this formation. The new and legacy pyrolysis data (Fig. 13) show that the mudstone intervals within the Cundlego Formation are generally poor source rocks with high TOC but poor generative potential yield, and only rarer horizons with fair potential yield (Fig. 14). The new organic petrography results in WC4 and BMR 07 Kennedy Range show that the slight increases in generative potential yield and HI are due to increased percentage of terrestrial liptinite content.

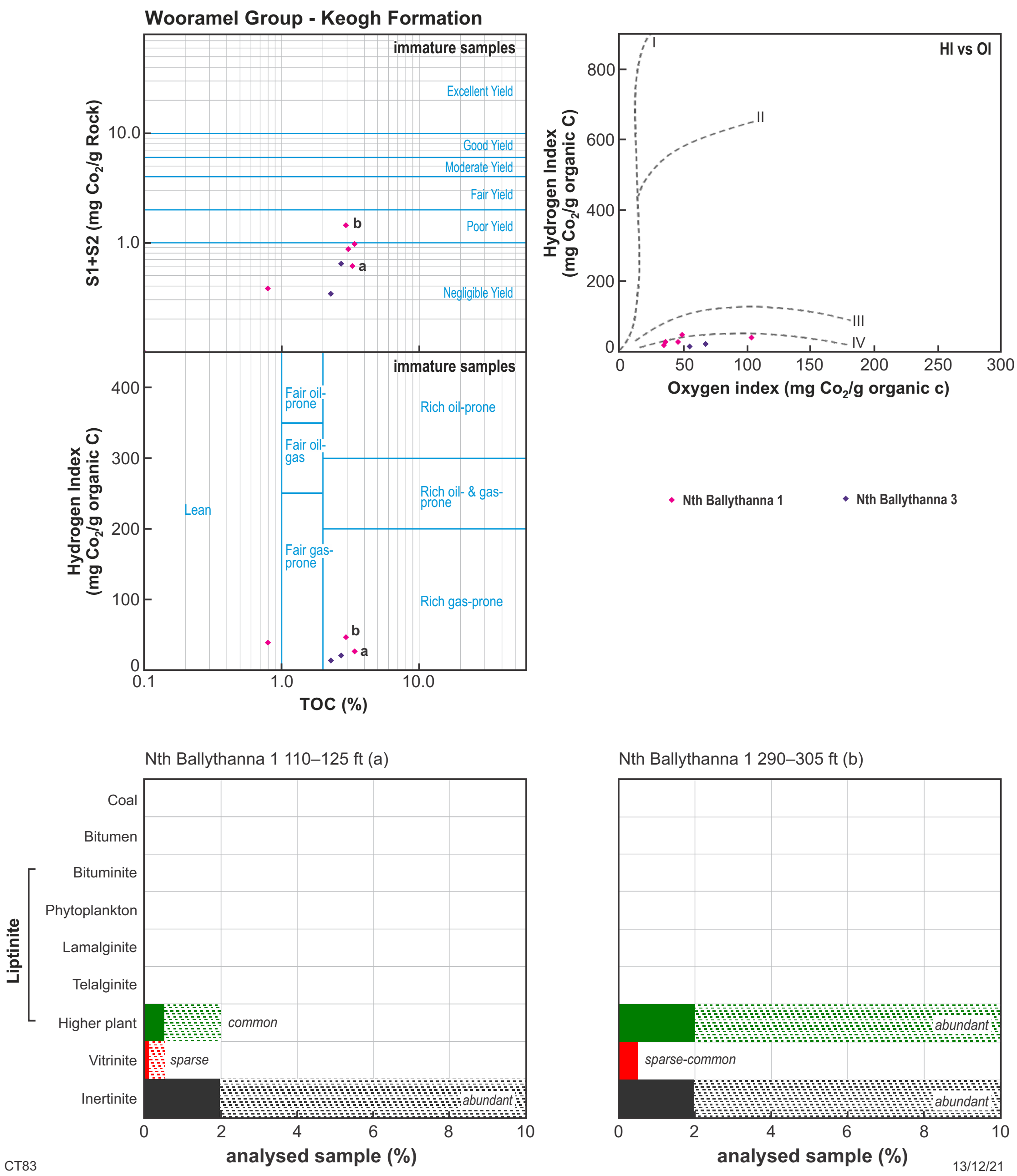

Figure 10. Interpretive Rock-Eval plots and maceral abundance ranges from organic petrography of selected new or legacy samples for the Keogh Formation of the Wooramel Group, where the solid and hatched bars show the minimum and maximum possible abundance. Well names in bold are new samples, and well names with a cross symbol are wells with new infill sampling

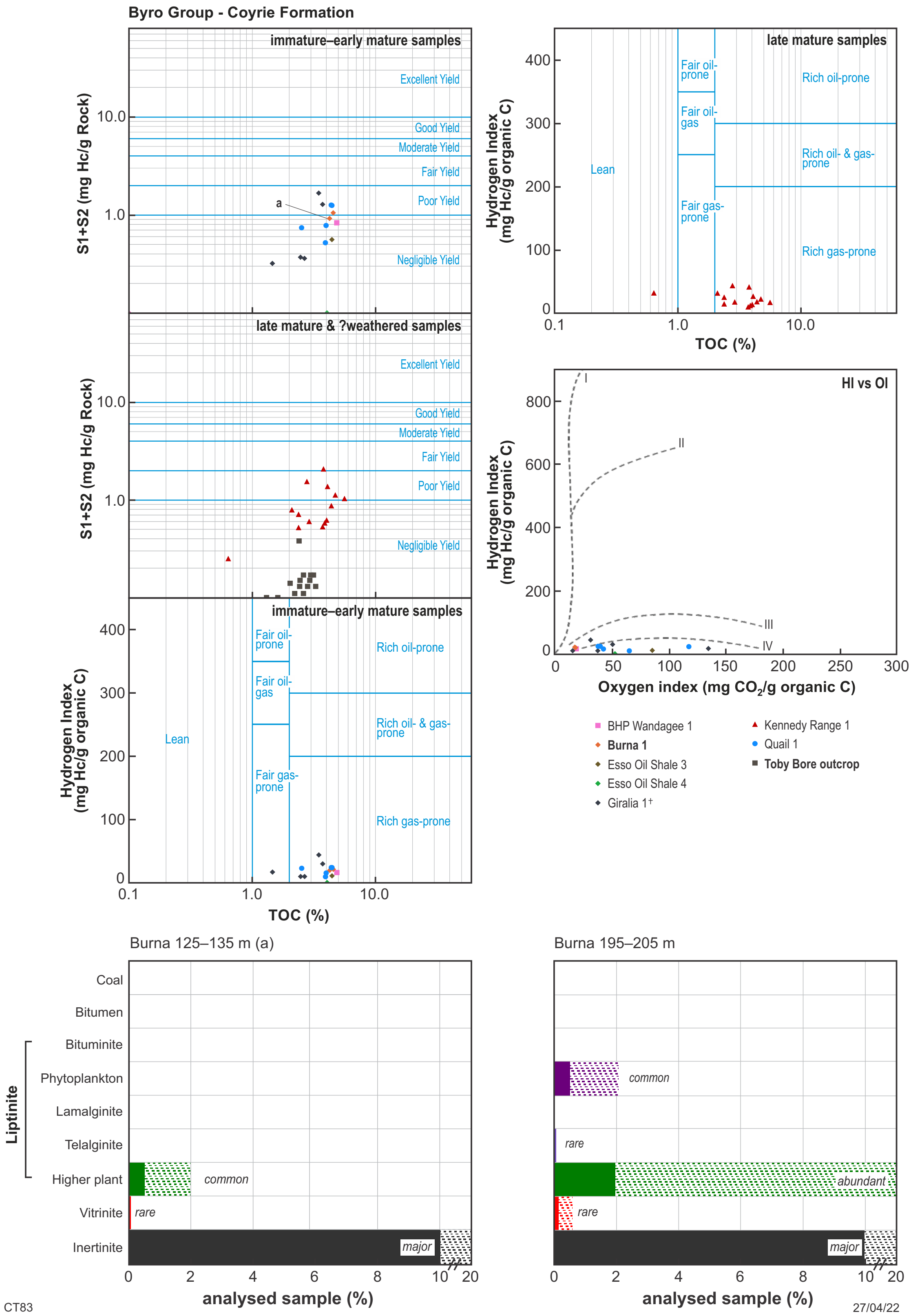

Figure 11. Interpretive Rock-Eval plots and maceral abundance ranges from organic petrography of selected new or legacy samples for the Coyrie Formation of the Byro Group, where the solid and hatched bars show the minimum and maximum possible abundance. Well names in bold are new samples, and well names with a cross symbol are wells with new infill sampling

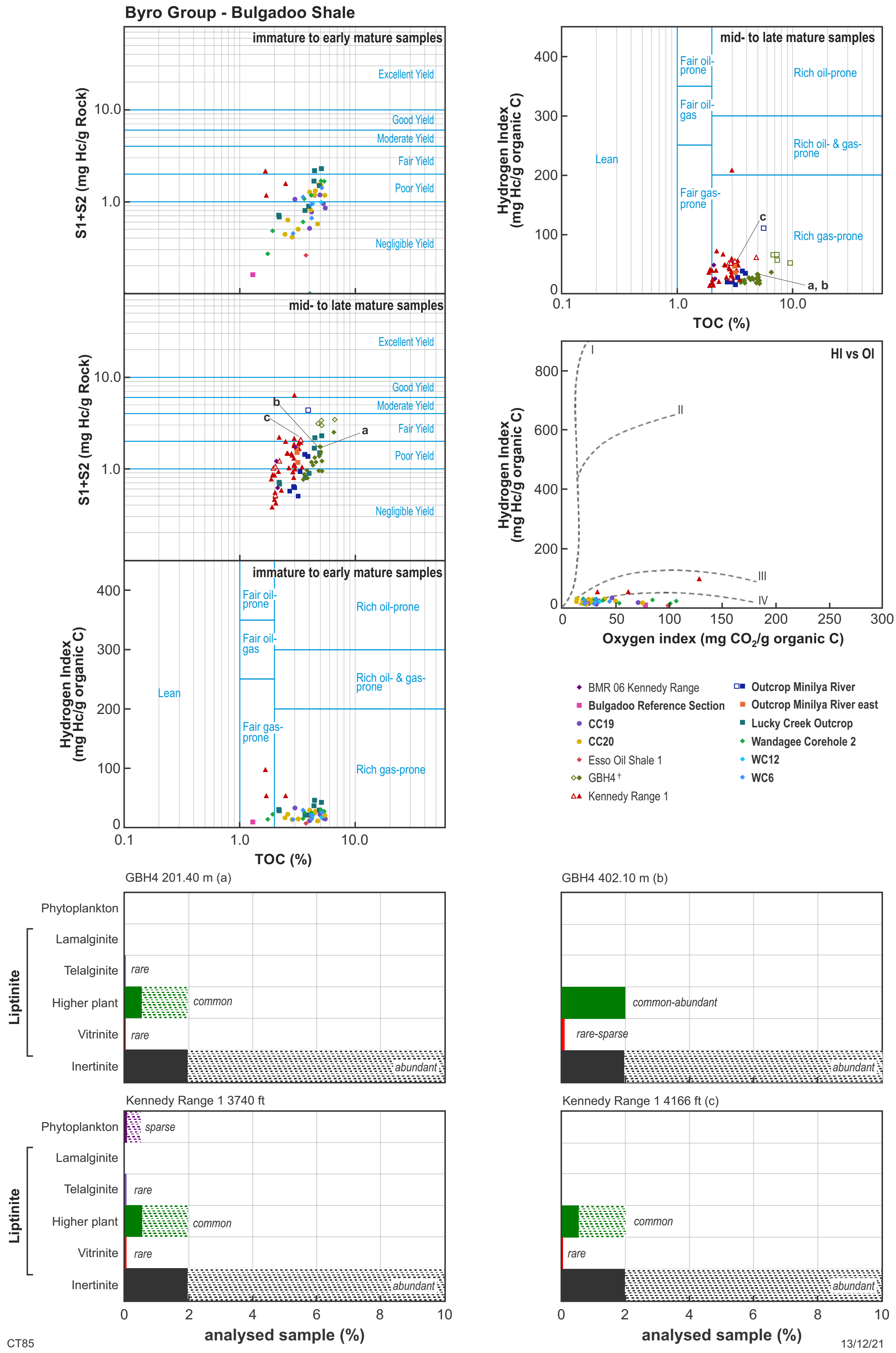

Figure 12. Interpretive Rock-Eval plots and maceral abundance ranges from organic petrography of selected new or legacy samples for the Bulgadoo Shale of the Byro Group, where the solid and hatched bars show the minimum and maximum possible abundance. Well names in bold are new samples, and well names with a cross symbol are wells with new infill sampling

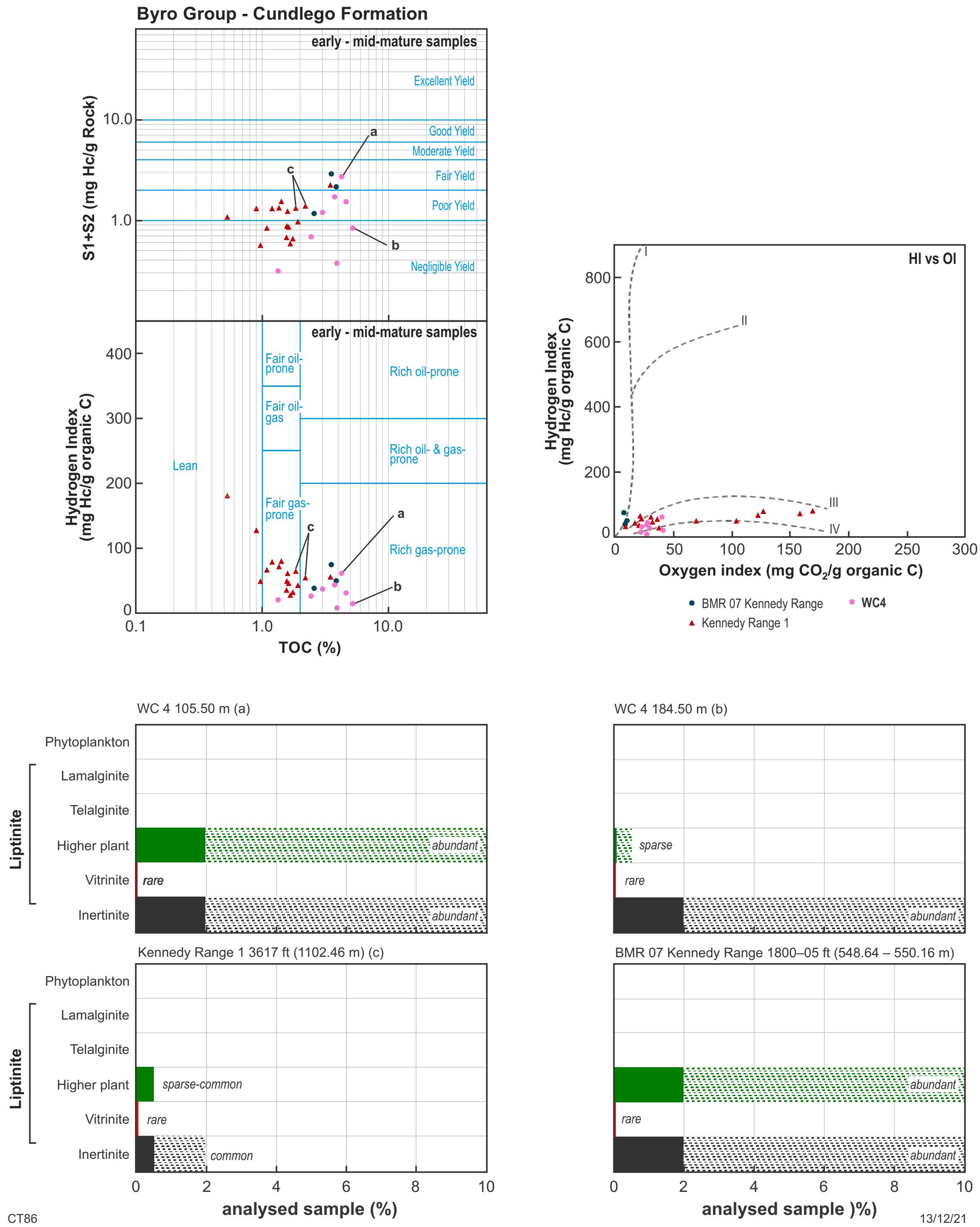

Figure 13. Interpretive Rock-Eval plots and maceral abundance ranges from organic petrography of selected new or legacy samples for the Cundlego Formation of the Byro Group, where the solid and hatched bars show the minimum and maximum possible abundance. Well names in bold are new samples, and well names with a cross symbol are wells with new infill sampling

Figure 14. Stratigraphic log of WC4 corehole in the Merlinleigh Sub-basin showing new sampling results

Quinnanie Shale

The Quinnanie Shale TOC/Rock-Eval plots and selected maceral abundances are presented in Figure 15. New Quinnanie Shale samples were collected from outcrop and drillholes, which demonstrate this formation has fair organic richness (1–2% TOC) but poor generative potential yield. This is in contrast to the only legacy data for the Quinnanie Shale in Kennedy Range 1, which indicated an average TOC of 3% and S1+S2 of 2–3 mg/g (excluding possible migrated values). The poor values from the outcrop samples could be due to weathering. The higher S2 values in Kennedy Range 1 show good source potential, although at the base of the Quinnanie Shale they are also associated with inflated S1 values, suggesting possible generation of hydrocarbons. New organic petrography results from BMR 07 Kennedy Range (Appendix) confirm that inertinite is the most abundant maceral, with common liptinite and rare vitrinite.

Wandagee Formation

The Wandagee Formation TOC/Rock-Eval plots and selected maceral abundances are presented in Figure 16. New samples were taken from the Wandagee Formation within the coal exploration drillhole WC5 (Fig. 1) and from outcrop at Coolkilya Pool, a well-exposed section along the Minilya River. All new samples are organically rich (TOC >1%), although only three samples taken from Coolkilya Pool show a generative potential yield (S1+S2) of >2 mg/g. The highest values are in the shale-dominated middle section of the formation, mainly from relatively fresh outcrop exposed in river bed outcrops, in contrast to the lower section which is exposed only along the more weathered banks of the river. The high S1+S2 values in Kennedy Range 1 are also associated with a shale in the middle of the Wandagee Formation.

Organic petrography results of a sample from Kennedy Range 1 (Keiraville Consultants, 1985; designated as Quinannie Shale in report) identified abundant inertinite and terrestrial liptinite, and is the only sample from Kennedy Range 1 that contains fluorinite (a type of liptinite that forms during the process of oil generation from plant liptinitic material; Stach et al., 1982). Unfortunately, no Rock-Eval data was obtained for this sample.

New organic petrography results were obtained from the Coolkilya Pool outcrop, which show that the high TOC can be partially explained by the abundance of inertinite (2-10%), although in samples with S2 values >2 mg/g, terrestrial liptinite was common (0.5-2%) and *Botryococchus* telalginite was a rare component, suggesting possible minor liquids potential in addition to gas.

Kennedy Group (Upper Permian)

Merlinleigh Sub-basin

The sandstone-dominated Kennedy Group succession in the Merlinleigh Sub-basin generally has very low source-rock potential. Only one well (Kennedy Range 1) has 19 Rock-Eval data points in the Coolkilya Sandstone, with all but one <1% TOC, and all with negligible generative potential yield. Data for the overlying Binthalya Formation were collected for the first time from outcrop, which identified no prospective source rocks; however, these samples are probably very weathered and therefore there is low confidence in the results.

Only one organic petrography sample previously existed for the Kennedy Group in the Merlinleigh Sub-basin, and it is from an approximately 9 m-sampled interval of cuttings from an interbedded sandstone-siltstone section within the Coolkilya Sandstone in Kennedy Range 1. The siltstone is abundant in inertinite and liptinite, indicating some limited liquids potential in the fine-grained lithologies of the formation (Keiraville Consultants, 1985). The Rock-Eval data covering the same interval indicates poor source potential, which could reflect the dilution of any fine-grained lithology (and potential source rock) by the sandstone that dominates the interval. The vitrinite reflectance suggests the Kennedy Group is immature to possibly early mature in Kennedy Range 1 (Keiraville Consultants, 1985).

Peedamullah Shelf and northernmost Merlinleigh Sub-basin

Kennedy Group undifferentiated

The undifferentiated Kennedy Group TOC/Rock-Eval plots and selected maceral abundances are presented in Figure 17. New samples were collected for the first time from four wells in the Peedamullah Shelf that partially penetrated this unit (Fortescue 1, Lindsay 1, Direction Island 1 and Nettie 1), and from Lefroy Hill 1 in the northern Merlinleigh Sub-basin. All new analysis of TOC and Rock-Eval from this unit plot within the range of most legacy data, showing that, apart from a few intervals of good source rock in Candace 1 and Flinders Shoal 1 in the eastern Peedamullah Shelf, this unit is generally a poor source rock. It is possible that good source-rock intervals away from the eastern Peedamullah Shelf are present although these are expected to be much thinner than cuttings intervals.

Although no organic petrographic analysis was undertaken in the Permian strata from Flinders Shoal 1, visual analysis of palynological kerogen strew slides suggests the section is dominated by inertinite (Lignum, 2015). Fortescue 1 and Sholl Island 1, which are also in the eastern part of the Peedamullah Shelf and originally had sparse organic geochemistry analysis in the Permian, were sampled as part of this study, although given these wells penetrated relative structural highs over which the formation is thinner, it was predicted source-rock potential was low. New organic petrography results obtained from Fortescue 1 revealed rare lamalginite (marine alginite), which could account for the higher HI in the topmost sample at 55–561 m; however, it is also possible these could be from cavings from the Locker Shale above. As is more typical of the Lower Triassic shales in Western Australian basins, the Locker Shale has been demonstrated to have intervals of higher HI and source-rock potential (Molyneux et al., 2016).

Cody Limestone

The Cody Limestone TOC/Rock-Eval plots and maceral abundances are presented in Figure 18. All existing data for the Cody Limestone suggest it is a poor source rock, although nearly all previous samples were from cuttings taken at 15 m intervals in Fennel 1 (Fig. 1a), so good source intervals within thin shales may have been heavily diluted. New Rock-Eval data from a marl and calcareous mudstones in cuttings from Cody 1 show similarly poor source-rock quality. New organic petrography results from Cody 1 confirm that inertinite is the dominant maceral. In one sample, lamalginite was a common maceral, although this is possibly caved from the Triassic Locker Shale based on reporting of caved Triassic spiny acritarchs in palynological descriptions at similar depths in the Permian formations in Cody 1 (Mobil Exploration and Producing Services Pty Ltd, 1992b).

Chinty Formation

The Chinty Formation TOC/Rock-Eval plots and selected maceral abundances are presented in Figure 19. Of the legacy TOC and Rock-Eval data from the Chinty Formation, only Candace 1 and Kybra 1 (Fig. 1a) contained analysis results with S2 values >3 mg/g and TOC >2%. All other legacy Rock-Eval measurements from wells farther southwest reveal poor generative potential yield. New samples were taken from Cody 1, the westernmost intersection of the Chinty Formation that previously had only sparse SWCs sampled for geochemistry.

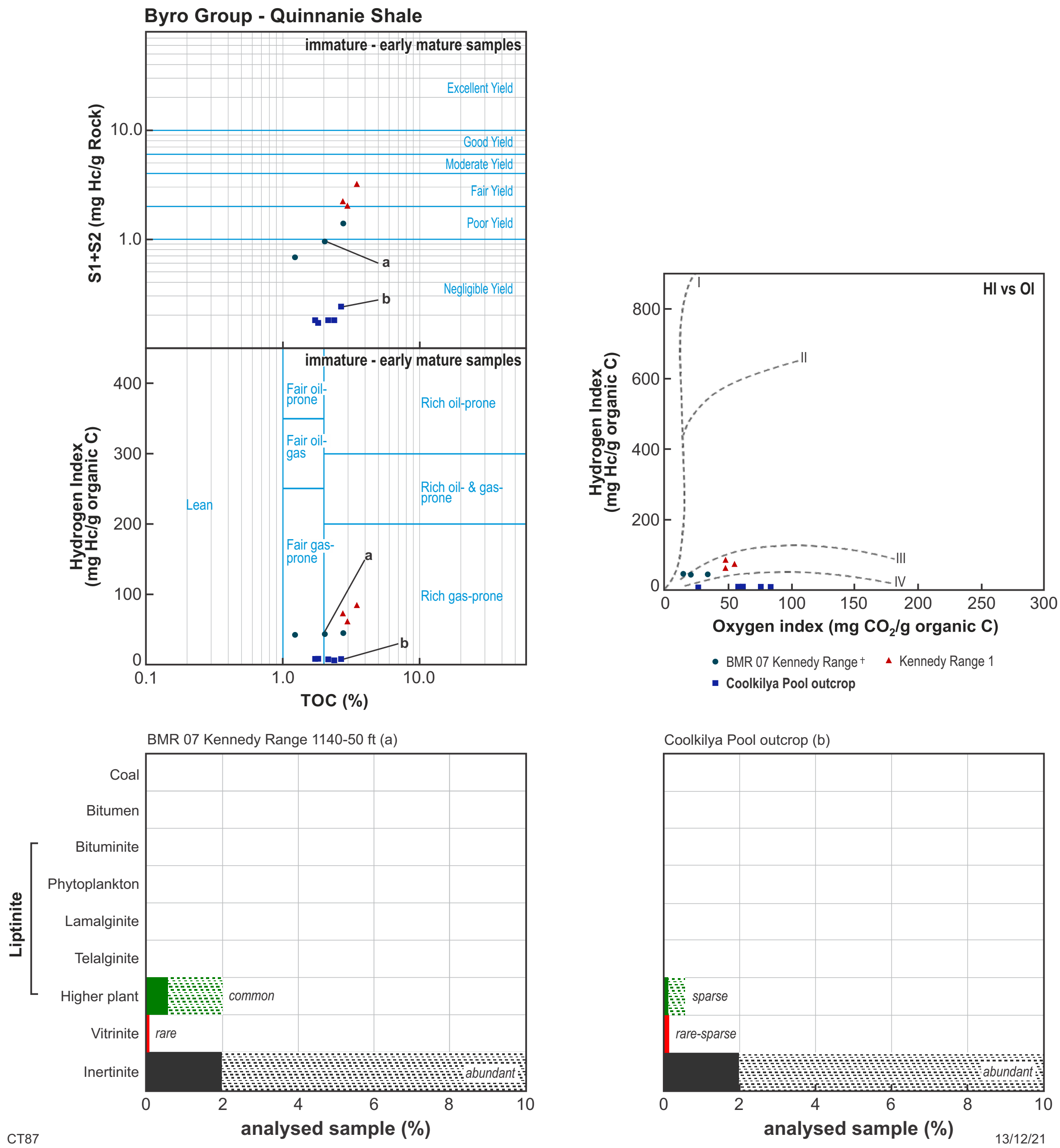

Figure 15. Interpretive Rock-Eval plots and maceral abundance ranges from organic petrography of selected new or legacy samples for the Quinnanie Shale of the Byro Group, where the solid and hatched bars show the minimum and maximum possible abundance. Well names in bold are new samples, and well names with a cross symbol are wells with new infill sampling

The Chinty Formation in Cody 1 has intervals with reported oil stains and gas shows (Mobil Exploration and Producing Services Pty Ltd, 1992a) and the only other data for this formation in Cody 1 was a fluid inclusion study (FIS) sample from shale/sandstone/carbonate cuttings at a depth of 2920 m, which showed only a low percentage of gas-prone kerogens (Fluid Inclusion Technologies, Inc., 2009). Although the new Rock-Eval data suggest the Chinty Formation here is a poor source rock, new organic petrography results demonstrate that it is late mature (Ro ~1.09%) and therefore may have already generated hydrocarbons.

The highest TOC (>8%) and S2 values (>20 mg/g) obtained from the Chinty Formation in Candace 1 correspond to thin coaly shales within a thick sandstone package at the base of the formation. Legacy visual maceral analysis of one of these shales shows it is abundant in terrestrial liptinites (sporinite, cutinite, resinite) and vitrinite, which contains resinous inclusions (Cook, 1983). Individual coal grains are rich in vitrinite and terrestrial liptinite (Cook, 1983). The presence of the open marine acritarch *Veryhachium* could suggest a marine influence. A FIS analysis of a similar thin shaly interval at 1593 m shows it is rich in gas-prone and oil-prone kerogens (Fluid Inclusion Technologies, Inc., 2009).

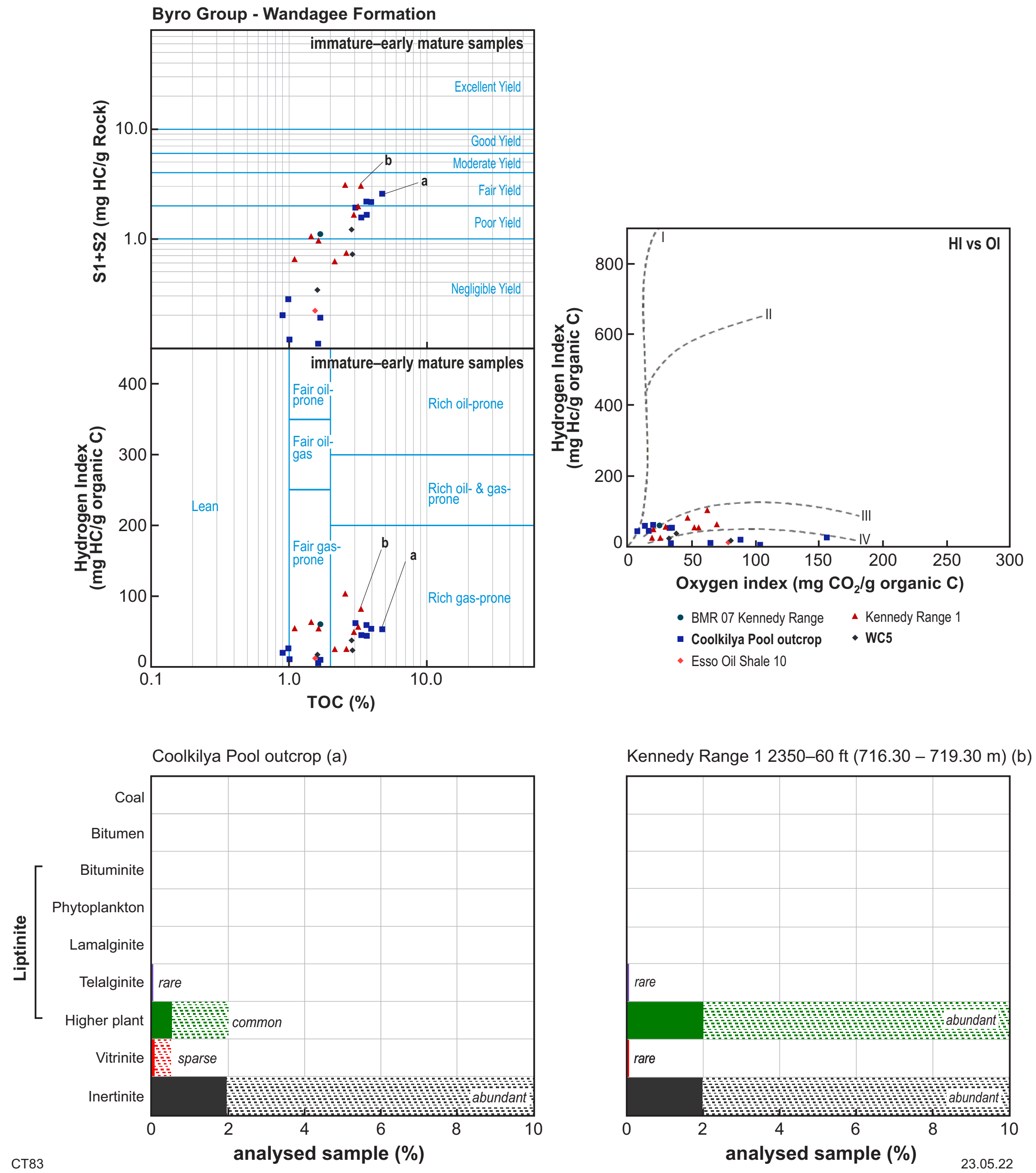

Figure 16. Interpretive Rock-Eval plots and maceral abundance ranges from organic petrography of selected new or legacy samples for the Wandagee Formation of the Byro Group, where the solid and hatched bars show the minimum and maximum possible abundance. Well names in bold are new samples, and well names with a cross symbol are wells with new infill sampling

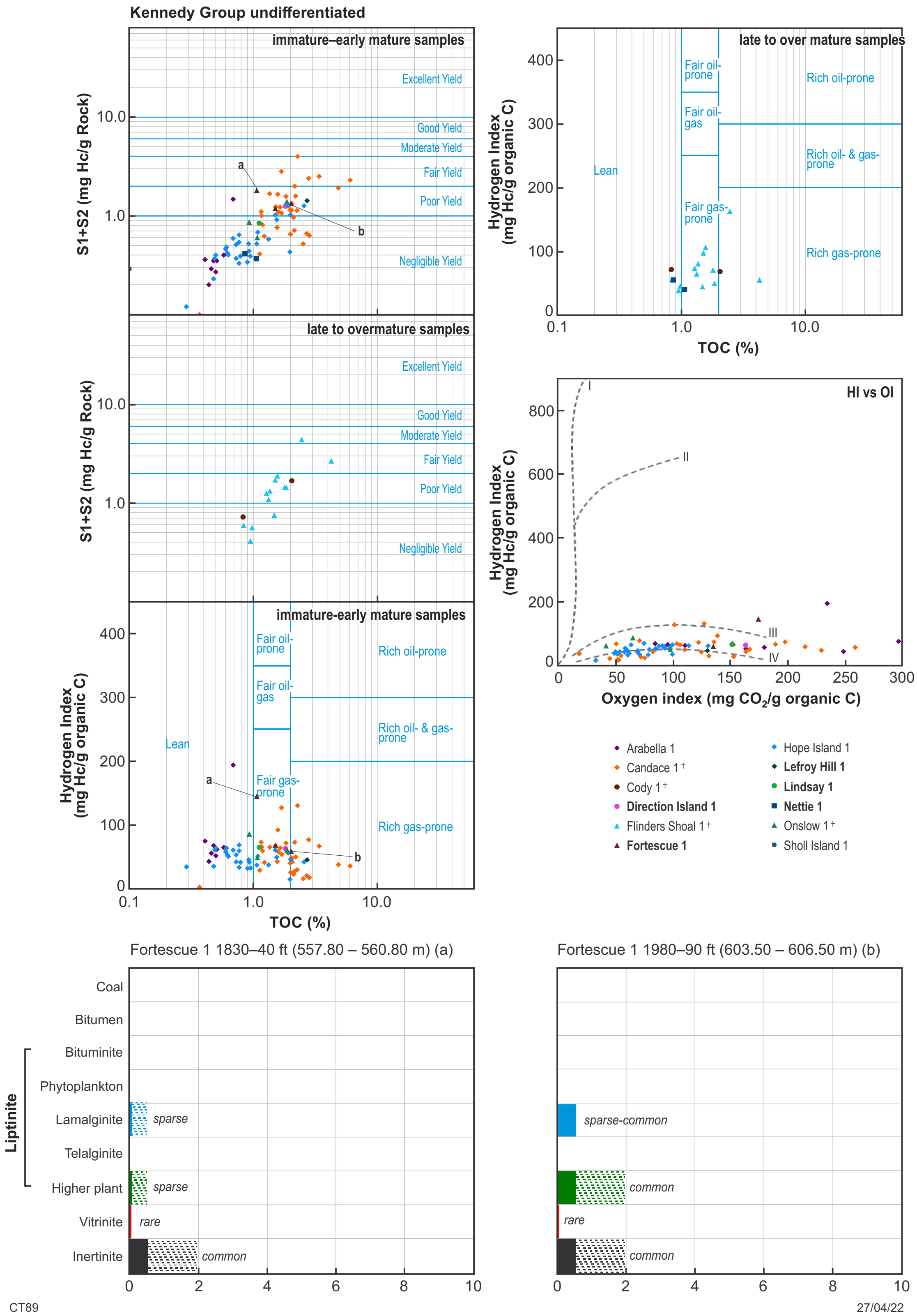

Figure 17. Interpretive Rock-Eval plots and maceral abundance ranges from organic petrography of selected new or legacy samples for the undifferentiated Kennedy Group, where the solid and hatched bars show the minimum and maximum possible abundance. Well names in bold are new samples, and well names with a cross symbol are wells with new infill sampling

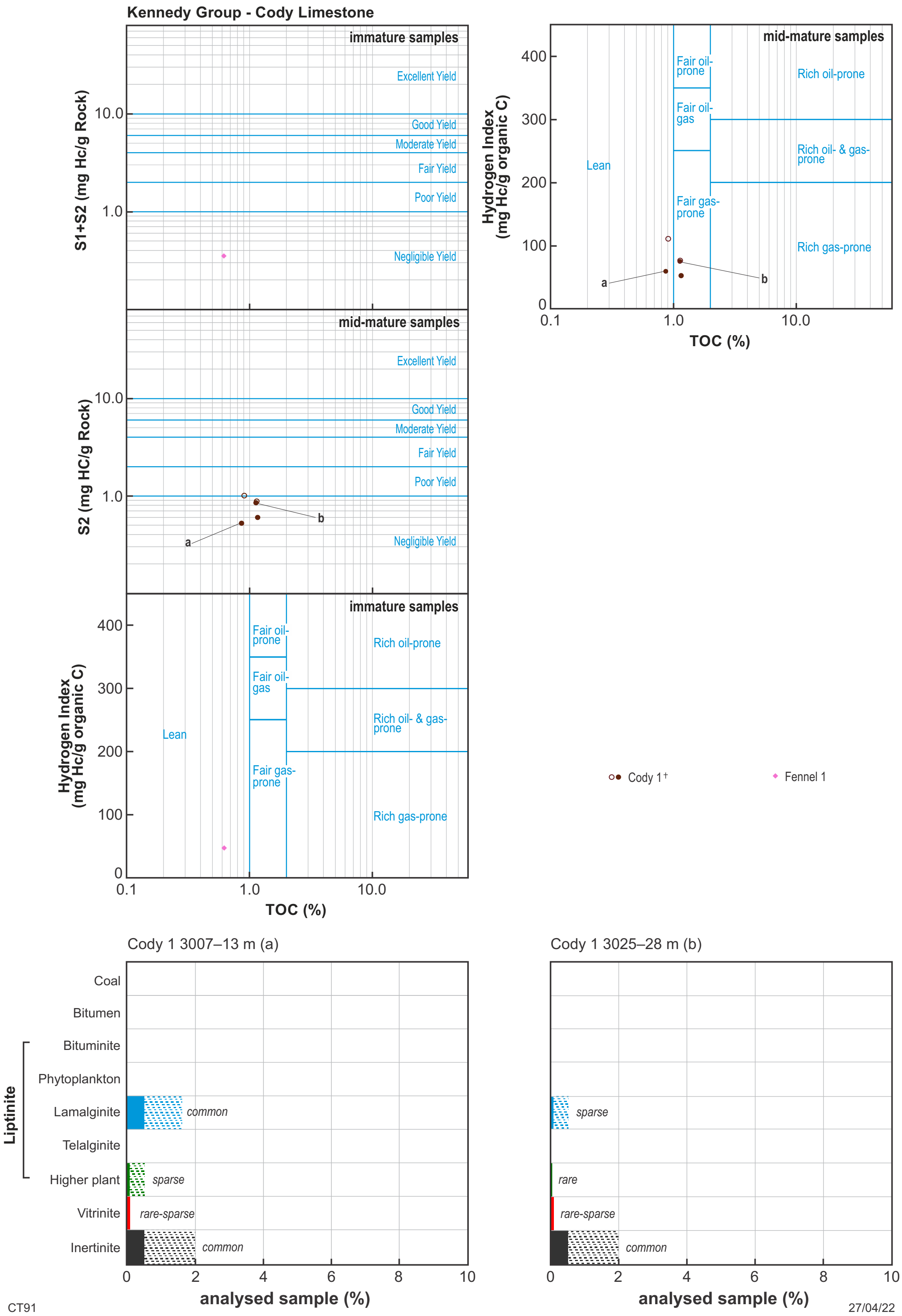

Figure 18. Interpretive Rock-Eval plots and maceral abundance ranges from organic petrography of selected new or legacy samples for the Cody Limestone of the Kennedy Group, where the solid and hatched bars show the minimum and maximum possible abundance. Well names in bold are new samples, and well names with a cross symbol are wells with new infill sampling

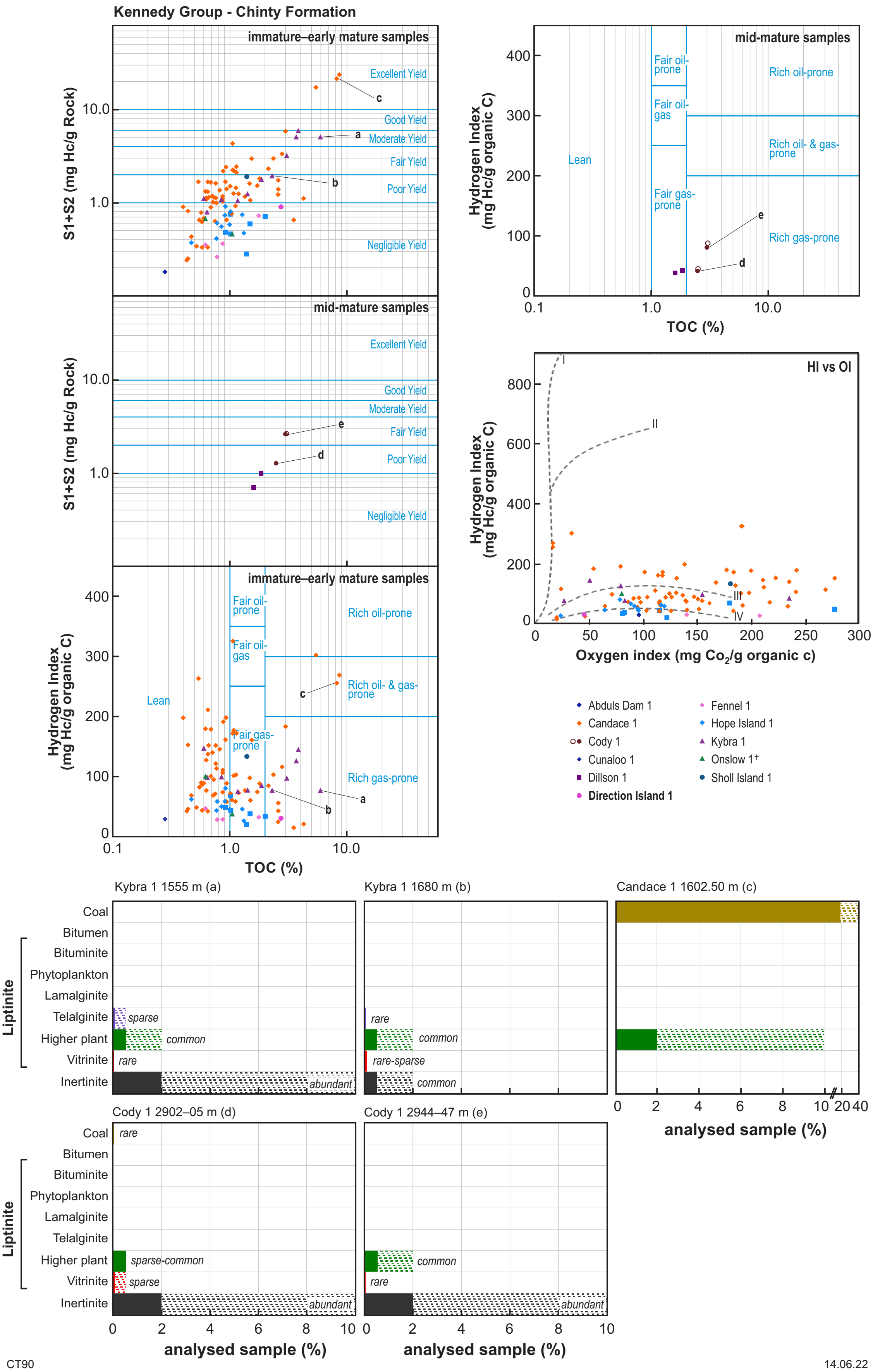

Figure 19. Interpretive Rock-Eval plots and maceral abundance ranges from organic petrography of selected new or legacy samples for the Chinty Formation of the Kennedy Group, where the solid and hatched bars show the minimum and maximum possible abundance. Well names in bold are new samples, and well names with a cross symbol are wells with new infill sampling

In Kybra 1, organic petrography analysis was performed on only two organic-rich cuttings intervals, the results of which show they are rich in terrestrial liptinite macerals (common sporinite and liptodetrinite) with equal or higher abundances of inertinite, and contain *Botryococcus*-related telalginite (Bond Corporation Pty Ltd, 1988b). The sample with the higher S2 value (4.53 mg/g) contains a higher abundance of terrestrial liptinites and *Botryococcus* telalginite, although the presence of abundant inertinite may have depressed the HI value. These intervals in Kybra 1 sampled for organic petrography are dominated by carbonates that also contain rare bitumen. A kerogen slide prepared by the operator from a SWC with good source-rock quality (TOC 3.85% and S2 5.56 mg/g) was submitted for analysis, which indicates 27% of the organic matter is vitrinite, 18% is inertinite and 50% is ‘amorphous organic matter’ (AOM) (Mantle, 2021). It is not possible to determine what constitutes this AOM using transmitted light microscopy, although AOM is typically in palynological preparations of good, oil-prone source rocks and is commonly assumed to be composed of degraded phytoplankton, bacterially-derived organic matter or plant resins (Tyson, 1995). AOM is an abundant constituent in kerogen slides prepared from the Hovea Member of the Kockatea Shale — an excellent source rock in the Perth Basin (Thomas et al., 2004). The AOM in Kybra 1 is atypical to the AOM in marine source rocks in that it does not fluoresce (Mantle, 2021) — a feature often attributed to increased oxidation during deposition (Pacton et al., 2011). The AOM in Kybra 1 is interpreted here to be mostly fine terrestrial liptinitic macerals such as sporinite and liptodetrinite, and possibly a smaller percentage of fine inertinite and vitrinite.

New organic petrography results of the Chinty Formation from Cody 1 show it is abundant in inertinite, with one sample containing rare coal, which is composed of all three maceral groups. Although terrestrial liptinites were sparse in both samples, it was noted that fluorescing liptinite (masked by mineral fluorescence) may be more abundant in the sample with the higher S2 value (2.38 mg/g). Although no bitumen was recorded, given the maturity of the sediment (late mature), it is possible the original kerogen content was higher.

Conclusions

New geochemical and organic petrographic data have helped fill gaps in knowledge about the distribution and quality of Permian source rocks within the Southern and Northern Carnarvon Basins. This study has highlighted the pitfalls of only using Rock-Eval pyrolysis data (e.g. HI vs TOC) to determine kerogen type and tendency to yield oil vs gas. The only useful Rock-Eval plot for these Permian samples is the TOC vs S1+S2 or S2 only plots for assessing generative potential. Instead, direct observation of organic matter via organic petrography is more useful in determining kerogen type and expected hydrocarbon phase. A review of all legacy and new organic petrography data suggests that thin shaley horizons with good source potential can be found throughout the Permian, although the averaging effect of Rock-Eval data from cuttings samples can mask these intervals. Permian organic-rich rocks are rich in terrestrial liptinites such as sporinite and cutinite, and commonly contain freshwater algae such as *Botryococchus*, although at much lower concentrations, indicating that some waxy oil and gas could be generated. These source rocks almost always have equal or higher concentrations of inertinite compared to liptinite, which, when consulting only the Rock-Eval data (HI), the indicated hydrocarbon product will be gas only.

New insights from the study include:

- the presence of thin intervals of fair to good source-rock potential within the Bulgadoo Shale, Cundlego Formation and Wandagee Formation of the Byro Group in the Merlinleigh Sub-basin northwards from Kennedy Range 1
- new areas where the Billidee Formation contains good source intervals in the far east (Moogooree 1) and in the north of the Merlinleigh Sub-basin
- the upper Callytharra Formation or lowermost Wooramel Group in the Byro Sub-basin contains a thin source interval with fair generative potential yield
- the Chinty Formation contains at least one thin source interval with fair generative potential yield in Cody 1 on the western Peedamullah Shelf.

Nearly all data in the onshore Exmouth Sub-basin are unreliable due to the contamination of cuttings. Due to the lack of reliable rock material, a Permian candidate could not be confirmed for the lacustrine/terrestrial source rock suggested by Edwards and Zumberge (2005) to have sourced some oil in Rough Range 1 and Parrot Hill 1. However, given the abundance of terrestrial liptinite macerals and the presence of lacustrine algae throughout the Permian elsewhere in the basin, the Permian is confirmed as a regionally distributed oil-source candidate.

Shale interbeds in heterolithic formations tend to be better source rocks than the thick shale formations, although they are thin (<5 m) and can be easily missed with cuttings. While hand-picking of shale cuttings helps to concentrate on these thin source intervals, this is not possible in some cases, and uncertainty will remain as to the abundance of these thin potential good source-quality shales without finer sampling.

Acknowledgements

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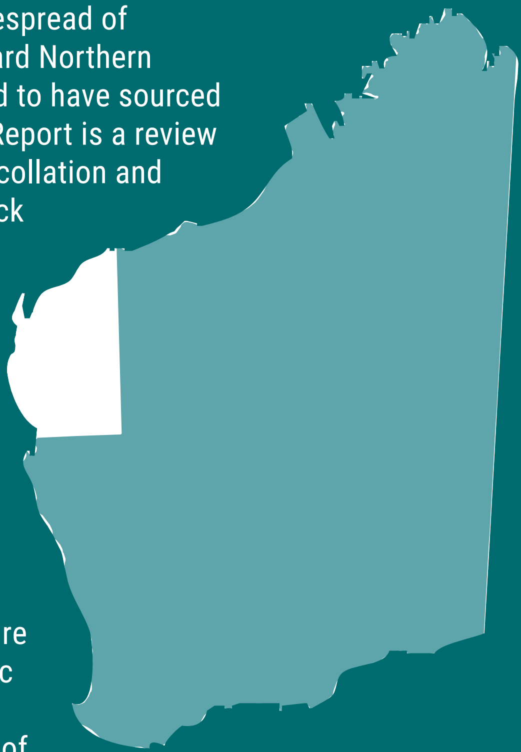
SOURCE-ROCK POTENTIAL OF PERMIAN ROCKS IN THE SOUTHERN AND NORTHERN CARNARVON BASINS

CM Thomas

The Permian is one of the thickest and most widespread of pre-breakup strata across the Southern and inboard Northern Carnarvon Basins, although it is not yet confirmed to have sourced economic accumulations of hydrocarbons. This Report is a review of Permian source-rock intervals, and includes a collation and interpretation of basic data needed for source-rock evaluation, including Total Organic Carbon (TOC), Rock-Eval data, organic petrography and palynological data. Additionally, new pre-competitive data were collected from previously unsampled Permian rocks in the Southern and inboard Northern Carnarvon Basins. The objective of this study was to improve the spatial and depth coverage of Permian source-rock data, particularly in understudied parts of the basins. This Report confirms that the best Permian source intervals are thin mudstone interbeds within overall heterolithic or sandy packages, and new areas with good source intervals have been identified. The review of new and legacy organic petrography also confirms the mixed kerogen assemblage in Permian source rocks, and found that the liquid potential of these rocks has likely been underestimated.



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