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PETROLEUM GEOCHEMISTRY AND PETROLEUM SYSTEMS MODELLING OF THE PERTH BASIN, WESTERN AUSTRALIA

by **KAR Ghorl**



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PERTH 2018



**Geological Survey of
Western Australia**

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Contents

Abstract	1
Introduction	1
Geological setting	2
Petroleum geology	2
Petroleum geochemistry	2
Petroleum systems	2
Source-rock parameters	2
Source rocks	3
Pyrolysis gas chromatography	3
Gas chromatography	3
Source-to-oil correlation	4
Petroleum system modelling	6
Erregulla Area: northern Perth Basin	7
Whicher Range 1: southern Perth Basin	7
Potential self-contained petroleum systems	8
Discussion and conclusions	8
References	9

Figures

1. Major tectonic units, exploration wells, and petroleum discoveries in the Perth Basin	13
2. Stratigraphy, petroleum sources, reservoirs, systems, and discoveries in the Perth Basin	14
3. Histogram showing petroleum drilling in the Perth Basin	15
4. History of petroleum discoveries in the Perth Basin	15
5. Western Australian petroleum production in 2015	16
6. Estimated conventional and tight reservoir petroleum resources of the Perth Basin	17
7. Gas composition and geographic distribution within the Perth Basin	18
8. Oil and condensate gravity vs depth plot of the Perth Basin	19
9. Oil and condensate composition of the Perth Basin	19
10. Map of Perth Basin showing distribution of data used in this study	20
11. Discrimination between non-source- and source-rock samples based on TOC and Rock-Eval data	21
12. Summary of Rock-Eval data of Permian source rocks	22
13. TOC and Rock-Eval composite log of Permian source rocks	23
14. Summary of Rock-Eval data of Triassic source rocks	24
15. TOC and Rock-Eval composite log of Triassic source rocks	25
16. Summary of Rock-Eval data of Jurassic source rocks	26
17. TOC and Rock-Eval composite log of Jurassic source rocks	27
18. Summary of Rock-Eval data of Cretaceous source rocks	28
19. TOC and Rock-Eval composite log of Cretaceous source rocks	29
20. Pyrolysis-gas chromatography typing of the Permian, Triassic, Jurassic, and Cretaceous samples	30
21. Gas chromatography typing of the Permian, Triassic, Jurassic, and Cretaceous samples	31
22. Chemometric characterization of crude oil of the Perth Basin	31
23. Estimated subsurface temperatures of the Perth Basin	32
24. Measured thermal conductivity of the rock units in the Perth Basin	33
25. Estimated present-day heat flow in the Perth Basin	34
26. Perth Basin map, showing 1D-modelled, present-day heat flow	35
27. AFTA regional cooling events in the Perth Basin	36
28. Perth Basin maps, showing the generating potential S_2 distribution within the Jurassic Cattamarra Coal Measures, Triassic Kockatea Shale, Permian Carynginia Formation, and Permian Irwin River Coal Measures	37
29. Perth Basin map, showing the age of source rock distribution	38
30. Perth Basin map, showing structural elements and wells within the northern onshore part and a cross-section A–A ¹ shown in Figure 31	39
31. North to south cross-section, showing stratigraphy for model wells used in BasinView and 2D BasinMod modelling	40
32. Northern Perth Basin maps, summarizing the distribution of organic richness and temperature within the Kockatea Shale	41
33. Perth Basin maps, showing the location of the data wells and the thickness and elevation of the Kockatea Shale	42
34. Perth Basin maps, showing the location of the data wells and the generating potential and hydrogen index of the Kockatea Shale	43
35. Perth Basin maps, showing the location of the data wells and the oil and gas retained in the Kockatea Shale	44

36.	North to south cross-section, showing vitrinite reflectance maturity and hydrocarbon volume for the Jurassic Cattamarra Coal Measures, Triassic Kockatea Shale, Permian Carynginia Formation, and Permian Irwin River Coal Measures source beds	45
37.	North to south cross-section, showing the gas saturation within the Triassic Kockatea Shale, based on 2D basin modelling	46
38.	North to south cross-section, showing the oil saturation within the Triassic Kockatea Shale, based on 2D basin modelling	46
39.	Petroleum system modelling of the Erregulla area, northern Perth Basin, showing burial history, maturity calibration, kerogen transformation ratio, and oil generation rate	47
40.	Petroleum system modelling of the Erregulla area, northern Perth Basin, showing burial history, petroleum system elements and timing, and hydrocarbon expulsion timing from the Kockatea Shale source beds	48
41.	Petroleum system modelling of Whicher Range area, southern Perth Basin, showing burial history, maturity calibration, kerogen transformation ratio, and gas generation	49
42.	Petroleum system modelling of Whicher Range area, southern Perth Basin, showing burial history, petroleum system elements and timing, and hydrocarbon expulsion timing from the Permian source beds	50
43.	Summary of the minerals, clays, and kerogen composition of the Permian Carynginia Formation and Triassic Kockatea Shale	51
44.	Summary of the shale petroleum systems of Arrowsmith 2 showing burial history, petroleum system elements, gas, and oil retained in the Permian Carynginia Formation and Triassic Hovea Member Shale	52

Tables

1.	Selected parameters of the Perth Basin petroleum liquids	4
2.	Selected gas chromatography parameters for petroleum samples from the Perth Basin	5

Appendices

1.	Rock-Eval Expert System Analysis rules to filter out unreliable TOC, Rock-Eval, and vitrinite reflectance data.....	55
2.	Geochemical log of TOC and Rock-Eval data for 60 wells	57
3.	Maps of distribution of geochemical attributes for each potential source rock	117
4.	Plots of AFTA data for 14 samples from Arranoo South 1, Cataby 1, and West Erregulla 1.....	133

Petroleum geochemistry and petroleum systems modelling of the Perth Basin, Western Australia

by

KAR Ghorl

Abstract

Petroleum geochemistry, organic petrology, apatite fission track analysis (AFTA), heat flow, subsurface temperatures, and other exploration data from the onshore Perth Basin indicate that the Permian and Jurassic coal and shale source rocks are predominantly gas prone, whereas Triassic and Cretaceous source rocks are oil prone. Correlations between oil and source rocks show that the condensate from Whicher Range 1 has a Permian source. Oil and gas/condensate recovered from the Cliff Head, Dongara, Eremia, Hovea, Jingemina, Mondarra, Mount Horner, North Erregulla, Woodada, and Yardarino fields are derived from Triassic source rocks. Oil and gas/condensate from Gingin 1 and Walyering 1 and 2 are from a Jurassic source, and the oil from Gage Roads 1 is from a Jurassic–Cretaceous source.

These source rocks have also been studied for self-contained petroleum systems. Initial estimates by the US Energy Information Administration (EIA) indicate tight sand/shale oil and gas resources in Permian shales of up to 25 trillion cubic feet (Tcf) gas, and in Triassic shales up to 8 Tcf gas and 500 million barrels oil/condensate. Shale oil and gas exploration is at a very early stage, and more work is needed to verify these estimates and to include estimates for the Jurassic. By comparison, the Cretaceous is relatively thin onshore and is therefore unlikely to contain significant quantities of hydrocarbons.

Petroleum system modelling of over 60 wells with total organic carbon (TOC) and Rock-Eval data indicates major Permian–Jurassic subsidence and burial in the onshore Perth Basin. Models were constrained by AFTA data, indicating regional paleothermal events during the Cretaceous (135–56 Ma) and Tertiary (30–0 Ma), which vary locally and affect time and depth of burial. Consequently, there are variations in the timing of petroleum generation across the basin.

The recent large conventional oil and gas discoveries at Xanadu Oil Field (2017) within the Irwin River Coal Measures and the Waitsia Gas Field (2014) within the Kingia Formation verify the presence of new high potential Permian oil and gas plays sourced from proven petroleum source rocks.

In addition, emerging shale plays with encouraging results at Woodada Deep 1 and Arrowsmith 2 have revived exploration interest in the Perth Basin.

Locally significant petroleum production (194 790 L of oil, 19 087 980 L of condensate, and 260 855 806 m³ of gas) took place before 2016.

KEYWORDS: petroleum geochemistry, petroleum systems, Rock-Eval, source-rock quality, thermal maturity

Introduction

The Perth Basin covers an area of about 100 000 km² in the southwest of Western Australia (Fig. 1), containing mainly Permian–Cretaceous sedimentary rocks (Fig. 2). Petroleum exploration drilling in the Perth Basin started in the early 1950s and since then over 368 onshore and 61 offshore wells have been drilled (Figs 3, 4). As a result, several commercial oil and gas fields have been discovered and numerous other significant discoveries within tight sandstone have been made, such as Corybas 1, which is producing from the tight sandstones within the Irwin River Coal Measures. Since the 1970s, the Perth Basin has produced a cumulative total of 2 665 928 050 L oil, 167 047 550 L condensate, and 19 837 593 000 m³ gas. In 2015, the basin produced 194 790 L of oil, 19 087 980 L of condensate and 260 855 806 m³ of gas from conventional reservoirs. The Perth Basin is the second largest petroleum producer after the Northern Carnarvon Basin within Western Australian jurisdiction (Fig. 5).

Besides conventional petroleum resources (Fig. 6), resource estimates indicate tight sand/shale gas and oil within the Permian Carynginia Formation of up to 25 trillion cubic

feet (Tcf) gas, and within the latest Permian–Triassic Kockatea shales, up to 8 Tcf gas with 500 million barrels oil/condensate (Kuuskraa et al., 2011, 2013).

This has triggered exploration for petroleum shale plays in the Perth Basin with encouraging results at Woodada Deep 1 and Arrowsmith 2, and a new conventional Permian gas play as demonstrated by the Waitsia discoveries in the Carynginia Formation and Irwin River Coal Measures. The oil recovery from the Kockatea Shale in Arrowsmith 2 was the first proven shale oil play in the Perth Basin. Shale oil and gas exploration is at a very early stage, and more work is needed to assess the commercial potential. The Perth Basin has developed relatively few shale play wells in the last few years, compared with thousands of wells in the US.

To evaluate the Perth Basin conventional and tight petroleum resources, the focus of exploration and research is currently on the Permian Carynginia Formation and the latest Permian–Triassic Kockatea Shale-sourced petroleum systems. For these shaly formations, Middleton (2015) discussed maturity within the northern Perth Basin. Cooper et al. (2015) used a mass balance approach through basin modelling to estimate tight petroleum resources.

Rasouli and Rezaee (2014) provided results on mechanical properties of these shales, and CoreLab (2013) evaluated shale source–reservoir systems based on core analyses from six wells in the northern Perth Basin. Ghori (2013, 2015, 2016, 2017) discussed emerging shale and tight gas plays in Western Australia, petroleum systems, emerging shale and tight sand plays, and petroleum systems modelling of the Perth Basin.

This study focuses on petroleum systems of the onshore Perth Basin, based on petroleum geochemistry data currently available at the Department of Mines, Industry Regulation and Safety (DMIRS) via the Western Australian petroleum and geothermal information management system (WAPIMS).

Geological setting

The Perth Basin is a southerly trending, elongate rift trough along the west coast of Australia. There are two main depocentres in the onshore portion, the northern Dandaragan Trough and the southern Bunbury Trough, which are separated by the Mandurah Terrace (Fig. 1). The Dandaragan Trough is a major depocentre up to 12 km thick. The basin contains for the most part Lower Permian to Lower Cretaceous continental clastic rocks (Fig. 2), deposited in a rift system that culminated in the breakup of Gondwana in the Early Cretaceous. Two major tectonic phases are recognized: Permian extension in a southwesterly direction and Early Cretaceous transtension to the northwest during breakup. The current understanding of the Perth Basin tectonic framework is discussed by Thomas (2014).

Petroleum geology

All producing fields are located within the northern Perth Basin (Fig. 1), where oil and gas has been produced from numerous onshore fields and oil from one offshore field. Many of the fields are now either depleted, such as Apium, Eremia, Gingin West, Jingemina, Mondarra, Mount Horner, Xyris, Xyris South, and Yardarino, or not yet developed, such as the oil accumulation at North Yandanogo and the gas at Warro and Whicher Range. In 2015, seven fields were producing gas condensate (Fig. 5), and minor oil was produced from the Dongara field. Of these fields, Beharra Springs, Dongara, Hovea, Redback, and Tarantula are producing from Upper Permian reservoirs (Wagina Formation and Dongara Sandstone), Waitsia from Lower Permian reservoirs (Kingia and High Cliff Sandstones), Corybas from tight sandstone reservoirs within the Lower Permian Irwin River Coal Measures, and Red Gully from the Jurassic reservoirs within the Catta-marra Coal Measures (Fig. 2). The gas across the basin is mainly dry, contains over 94% methane (Fig. 7) with minimal condensate production, and the oil is light and constitutes a highly paraffinic crude, which frequently has a high wax content, high pour point, and is rich in saturate hydrocarbons (Figs 8, 9).

The oil and gas condensate reservoirs are within the Permian High Cliff Sandstone, Irwin River Coal Measures, Carynginia Formation, Beekeeper Formation, Dongara and Wagina Sandstones (northern Perth Basin), and the

Willespie Formation (southern Perth Basin), Triassic Arranoo and Woodada Sandstones, Jurassic Catta-marra Coal Measures, Cadda and Yarragadee Formations, and the Cretaceous Parmelia Group (Fig. 2).

Source rocks with predominantly gas condensate generating potential have been identified within the Permian, Triassic, and Jurassic intervals (Thomas, 1979; Thomas and Barber, 2004). Since then many publications have documented the oil and gas potential from different source rocks. These include marine source facies within the Permian Carynginia Formation and Triassic Kockatea Shale, and coaly and lacustrine source facies within the Permian Irwin River Coal Measures and Jurassic Catta-marra Coal Measures, which impact the geochemical characteristics of oil, condensate, and gas accumulations of the Perth Basin.

The majority of oil and gas condensate that has been commercially produced is correlated with the source rocks within the Hovea Member of the basal Kockatea Shale as documented from the Hovea 3 well (Thomas and Barber, 2004). This source interval is widely distributed within the northern Perth Basin. Other key publications on petroleum geochemistry of the Perth Basin include Thomas (1984), Thomas and Barber (2004), Summons et al. (1995), GeoMark and AGSO (1996), Edwards and Zumberge (2005). Publication on the offshore northern Perth Basin includes Jones and Hall (2002).

Petroleum geochemistry

Petroleum systems

Petroleum geochemistry (source rock and hydrocarbon analytical data), organic petrology, apatite fission track analysis (AFTA), heat flow, subsurface temperature data (Fig. 10), and other exploration data from the onshore Perth Basin are used to evaluate conventional and tight reservoir petroleum source potential. In tight reservoir systems, the timing of charge vs trap formation is not a critical element as it is in conventional reservoir systems.

Source rocks form the richest petroleum shale plays, because they retain a vast quantity of petroleum even after expelling significant petroleum to conventional reservoirs (Fig. 6). Shale reservoirs are texturally and mineralogically heterogeneous. Many similar looking types of shale often have different source-rock characteristics (Durham, 2010; Aplin and Macquaker, 2011).

The geochemical properties that help to form a good-quality shale gas and oil play are adequate source-rock thicknesses of net pay (>100 m) and high organic richness (>2% total organic carbon [TOC]), and adequate thermal maturity (>1.5% R_o) for shale gas plays (Parker, 2009).

Source-rock parameters

The source-rock characterization generally used by the petroleum industry (Baskin, 1997; Dembicki Jr, 2009) was used in this study, albeit with some modifications as discussed below.

The petroleum-generating capacity of a source rock depends on four factors: organic richness (amount of kerogen), organic facies (type of kerogen), organic maturity (kerogen-to-petroleum transformation ratio), and expulsion efficiency. Organic richness is measured by TOC content. In this Report, source-rock samples with TOC content >0.5% are classified as being of fair organic richness, between 1 and 2% as good, between 2 and 4% as very good, and over 4% as excellent.

Thermal and pyrolysate yield of organic compounds from Rock-Eval is expressed as $S_1 + S_2$ or potential yield, which quantifies the hydrocarbon-generating capacity of rocks. S_1 represents existing indigenous or migrated hydrocarbons in a rock and is approximately equivalent to the extractable organic matter (bitumen). S_2 represents the organic compounds generated from kerogens during heating within the Rock-Eval instrument. S_1 and S_2 are both measured as milligrams per gram of rock (mg/g rock). Samples with potential pyrolysate yield (S_2) of 2–5 mg/g rock are classified as fair, those with 5–10 mg/g rock as good, those with 10–20 mg/g rock as very good, and those over 20 mg/g rock as excellent.

Source-rock facies classification of the kerogen type was derived using a cross plot of TOC vs the hydrogen index (HI). Using this method, HI is calculated from Rock-Eval data and corresponds to the quantity of hydrocarbon compounds (HC) that can be pyrolyzed relative to the TOC (mg HC/g TOC). The equation is $HI = (S_2/TOC \times 100)$. Source rocks with HI values of less than 150 are classified as gas generating, while those with HI values over 150 are classified as oil and gas generating.

Source-rock maturity has been determined using a cross plot of the analysis temperature at maximum hydrocarbon generation (T_{max}) and the production index (PI). T_{max} provides an indication of source-rock maturity, but can be affected by organic facies type. T_{max} less than 435°C is classified as immature, between 435°C and 460°C as oil generating, between 460°C and 470°C as wet-gas generating, and over 470°C as dry-gas generating. The equation is $PI = S_1/(S_1 + S_2)$.

Vitrinite reflectance (VR) data and T_{max} from Rock-Eval indicate thermal maturity. AFTA indicates maximum paleotemperatures and their timing, whereas present-day temperatures are estimated from recorded temperatures in petroleum wells. Finally, organic maturity and timing of oil and gas generation from source rocks can be estimated using basin and thermal history modelling.

No direct method is available to measure expulsion efficiency, although a mass balance approach can be used to estimate petroleum expulsion efficiency (PEE) using Rock-Eval parameters (Cooles et al., 1986; Powell and Boreham, 1991).

Source rocks

Source rocks of the Perth Basin have been identified from analytical data available for about 4000 samples (Fig. 11). TOC and Rock-Eval data (Fig. 11a) are used to discriminate between source- and non-source-rock samples (Espitalié et al., 1985; Peters, 1986; Bordenave et al., 1993). Those samples with <0.5% TOC and <2 mg HC/g rock pyrolysate yield (S_2) are defined as non-source-

rock samples (Fig. 11b,c), and are excluded from further interpretation. For source-rock samples, a cross plot of T_{max} versus PI is used to discount contaminated samples (Fig. 11d). T_{max} represents the analysis temperature (°C) at maximum hydrocarbon generation during the S_2 cycle. PI represents kerogen conversion indices ($S_1/(S_1 + S_2)$). Its value increases with hydrocarbon generation as a function of increasing maturity. PI values higher than normal (0.4) are observed in migrated or accumulated hydrocarbons, non-source rock, or contaminated samples, whereas lower than normal (0.1) values are interpreted to be the result of the expulsion of hydrocarbons from the source rock. Parameters for source-rock richness, organic facies, and thermal maturity, as discussed above, are used to characterize petroleum source rocks (Espitalié, 1985; Peters, 1986; Peters and Moldowan, 1993; Peters and Cassa, 1994; Peters et al., 2005). The petroleum-generating potential of the Permian, Triassic, Jurassic, and Cretaceous source rocks are summarized in Figures 12–19. Of these, Figures 12, 14, 16, and 18 summarize organic richness, facies, and maturity for the Permian, Triassic, Jurassic, and Cretaceous source-rock samples, respectively. Composite logs of these samples are shown in Figures 13, 15, 17, and 19. Characterization of kerogen by pyrolysis gas chromatography (Py-GC) and gas chromatography mass spectrometry (GC-MS) for the Permian, Triassic, Jurassic, and Cretaceous are summarized in Figures 20 and 21, respectively, whereas Figure 22 shows the characterization of crude oil.

Pyrolysis gas chromatography

Beside TOC and Rock-Eval, Py-GC was used to determine the detailed molecular configuration of kerogen and its oil- vs gas-generating potential (Larter and Douglas, 1980; Larter, 1985; Larter and Senftle, 1985). The most important parameters derived from these analyses include: the gas/oil generation index: $GOGI = (C1 - C5)/C6+$ abundance), the oil yield = $C5 - C31$ (alkenes + alkanes), and the aromatics content or type index: $R = (m + (p\text{-xylene}/n\text{-octene}))$.

Figure 20 summarizes results of the available Py-GC data and indicates that most of the samples are oil prone. The Jurassic and Triassic Py-GC data reported by Dolan and Associates (1993) also indicate that most of the analysed samples are oil prone. These samples are mostly from the Triassic Kockatea Shale and Jurassic Cattamarra Coal Measures from offshore wells. The Permian Irwin River Coal Measures, Carynginia Formation, and Triassic Hovea Member Py-GC data (Thomas, 1979; Thomas and Barber, 2004; Thomas et al., 2004) indicate that the source rocks within the Hovea Member are predominantly oil prone, the Irwin River Coal Measures are predominantly gas prone, and Carynginia Formation are predominantly oil and gas prone.

Gas chromatography

Crude oil and condensate samples from reservoirs and hydrocarbons extracted from rock have been analysed by gas chromatography (GC) to confirm the source rocks. Tables 1 and 2 list the selected GC biomarkers for 29 samples used in this study. These ratios are sensitive to secondary processes and need support from other geochemical and geological data (Peters and Moldowan, 1993; Peters et al., 2005) in order to confirm the source rocks.

Isoprenoid/n-paraffin ratios (Fig. 21; Tables 1 and 2) show that the Permian and Triassic oils have high pristane/phytane ratios as compared to Jurassic and Cretaceous oils (Fig. 21a). The pristane/n C_{17} ratios and Phytane/n C_{18} ratios indicate oil-prone marine source rocks (Fig. 21b).

Source-to-oil correlation

Gas-prone source beds within the Permian Carynginia Formation, with an organic richness of up to 11% TOC, and latest Permian–Triassic Kockatea Shale, with TOC values over 2%, are part of the Gondwanan Petroleum Supersystem (Bradshaw et al., 1994). The Carynginia Formation is a marine deposit containing shelf to distal deltaic mudstone and siltstone, whereas the Kockatea Shale is composed of restricted marine mudstone and siltstone. The Hovea Member of the Kockatea Shale forms the main source rock of the northern Perth Basin. The oil- and gas-prone source beds within the fluvial–lacustrine shale facies of the Jurassic Cattamarra Coal Measures (TOC up to 27%) and Yarragadee Formation (TOC up to 2%) are part of the Austral Petroleum Supersystem (Bradshaw et al., 1994).

These source rocks have been correlated with oil accumulations in sandstone reservoirs (Fig. 22) by GeoMark Research and the Australian Geological Survey Organisation (now Geoscience Australia). First, 20 oil samples from the Perth Basin were analysed for their physical, chemical, biomarker, and isotopic characteristics (GeoMark and AGSO, 1996), followed by additional analyses of five samples from Bootline 1, East Lake Logue 1, Gingin 2, Mondarra 5, and Whicher Range 4 by Geoscience Australia (Edwards and Zumberge, 2005). These oil characteristics were used to describe the organic matter type, depositional environment, and mineralogy of the source rocks. Chemometric analyses were used to identify different oil families by removing noise from the large, regional database. This was followed by the statistical analysis of a multivariate dataset using the method described by Peters et al. (2005). This enabled recognition of four genetically related oil families based on principal component analysis (PCA) techniques (Fig. 22). These oil families can be correlated to the Permian, Triassic, Jurassic, and Cretaceous source rocks identified in the Perth Basin (GeoMark and AGSO, 1996).

Table 1. Selected sample parameters of the Perth Basin petroleum liquids (GeoMark and AGSO, 1996)

Well	Sample	Sat (%)	Aro (%)	NSO (%)	Pr/Ph	Pr/nC ₁₇	Ph/nC ₁₈	nC ₂₇ /nC ₁₇	CPI	API	S (%)
Bootline 1	DST 5	62.90	20.20	16.70	3.24	0.22	0.07	0.31	1.13	37.90	0.29
Dongara 1	PROD TEST 1	95.65	3.14	1.21	2.98	0.34	0.29	0.02	1.10	53.90	0.01
Dongara 4	DST 1	72.90	2.40	24.70	2.91	0.34	0.31	0.01	1.48	58.28	0.00
Dongara 14		77.67	18.10	3.85	1.31	0.31	0.26	0.67	1.08	35.10	0.06
Dongara 14	DST 1	76.70	17.70	5.60	1.23	0.30	0.28	0.58	1.07	39.15	0.05
East Lake Logue 1	DST 1	59.00	3.70	37.30	1.74	0.26	0.20	0.05	–	52.00	0.07
Erregulla 1	Swab test	74.87	18.75	5.27	1.12	0.55	0.50	0.84	1.05	34.80	0.03
Erregulla 1	Swab test	67.80	14.30	17.90	1.12	0.27	0.32	0.15	1.06	48.43	0.04
Gage Roads 1	DST 1A/2A	75.55	19.87	3.27	2.86	0.18	0.06	1.23	1.24	38.10	0.03
Gingin 1	DST 13	59.36	38.73	1.91	2.64	0.25	0.10	0.25	1.29	37.80	0.02
Gingin 2	DST 3A	59.00	25.30	15.70	3.11	0.27	0.10	0.17	1.15	41.20	–
Mondarra 1	DST 2	92.53	6.79	0.68	1.45	0.21	0.17	0.08	1.03	47.30	0.01
Mondarra 2	PROD TEST	89.31	10.30	0.40	1.73	0.26	0.19	0.01	5.03	50.80	0.00
Mondarra 3	DST 1	89.52	5.89	3.36	1.18	0.22	0.17	2.71	1.05	35.70	0.02
Mondarra 5		87.90	6.90	4.50	1.10	0.21	0.17	2.36	1.03	–	–
Mount Horner 1	DST 4	69.96	23.26	6.42	1.43	0.44	0.36	0.65	1.07	–	0.07
North Erregulla 1	DST 1	74.75	19.76	4.69	1.14	0.59	0.54	0.78	1.04	34.70	0.07
Walyering 1	PROD TEST 3	73.07	23.88	3.05	1.75	0.20	0.07	0.72	1.18	43.90	0.02
Walyering 2	PROD TEST 4	75.77	23.30	0.94	2.95	0.13	0.05	0.27	1.14	45.80	0.01
Whicher Range 1	DST 7	62.61	36.24	1.15	3.33	0.45	0.14	0.05	2.35	46.00	0.02
Whicher Range 2		45.30	33.90	20.80	5.03	0.49	0.11	0.09	–	39.70	0.03
Woodada 3	DST 2	78.67	18.21	2.59	2.48	0.53	0.23	0.55	1.07	34.60	0.17
Yardarino 1	DST 3	90.90	6.72	1.85	1.15	0.22	0.17	0.91	1.08	38.40	0.03
Yardarino 1	DST 3	86.36	10.61	2.87	1.05	0.22	0.19	0.76	1.06	38.40	0.02
Yardarino 1	DST 3	82.92	15.37	1.61	1.15	0.23	0.17	0.90	1.07	37.20	0.02

NOTE: Abbreviations: Sat, saturate hydrocarbons; Aro, aromatic hydrocarbons; NSO, nitrogen, sulfur, and oxygen compounds; Pr, pristane; Py, phytane; nC₁₈, number of carbon in compound; CPI, carbon preference index; API, American Petroleum Institute; S, sulfur

Table 2. Selected gas chromatography parameters for samples from the Perth Basin

Well	Sample	Pristane/ phytane	Phytane/ n-C ₁₇	Phytane/ n-C ₁₈	Formation	Age
Charlotte 1	1527.05	1.48	0.51	0.44	Gage Sandstone	Cretaceous
Gage Roads 1	DST 1A/2A	2.86	0.18	0.06	Perth Formation/Gage Sandstone Member	Cretaceous
Cataby 1	1692.50	2.15	0.21	0.11	Cattamara Coal Measures	Jurassic
Cataby 1	1750.00	4.77	0.87	0.21	Cattamara Coal Measures	Jurassic
Cataby 1	1789.00	3.26	0.37	0.12	Cattamara Coal Measures	Jurassic
Cataby 1	1801.00	2.83	0.47	0.18	Cattamara Coal Measures	Jurassic
Cockburn 1	1133.86	0.77	0.39	0.43	Yarragadee Formation	Jurassic
Warnbro 1	2879.08	1.63	0.53	0.37	Yarragadee Formation	Jurassic
Warnbro 1	3579.88	5.52	0.61	0.10	Yarragadee Formation	Jurassic
Warnbro 1	3580.49	5.16	0.63	0.11	Yarragadee Formation	Jurassic
Sugar Loaf 1	2298.19	1.64	0.56	0.32	Cadda Formation	Jurassic
Sugar Loaf 1	3493.01	3.26	1.08	0.28	Cadda Formation	Jurassic
Houtman 1	2950.00	1.95	1.23	0.72	Yarragadee Formation	Jurassic
Gage Roads 1	1782.00	4.80	0.15	0.03	Yarragadee Formation	Jurassic
Erregulla 1	Swab test	1.12	0.55	0.50	Cattamara Coal Measures	Jurassic
Gingin 1	DST 13	2.64	0.25	0.10	Cattamara Coal Measures	Jurassic
Walyering 1	PROD TEST 3	1.75	0.20	0.07	Cattamara Coal Measures	Jurassic
Walyering 2	PROD TEST 4	2.95	0.13	0.05	Cattamara Coal Measures	Jurassic
Erregulla 1	Swab test	1.12	0.27	0.32	Cattamara Coal Measures	Jurassic
Gingin 2	DST 3A	3.11	0.27	0.10	Cattamara Coal Measures	Jurassic
Bootine 1	DST 5	3.24	0.22	0.07	Cattamara Coal Measures	Jurassic
Wittecarra 1	2331.00	2.34	0.46	0.18	Woodada Formation	Triassic
East Heaton 1	2039.00	1.34	1.06	0.86	Kockatea Shale	Triassic
Dongara 14		1.31	0.31	0.26	Kockatea Shale	Triassic
Mondarra 1	DST 2	1.45	0.21	0.17	Basal sand	Triassic
Mondarra 3	DST 1	1.18	0.22	0.17	Basal sand	Triassic
Mount Horner 1	DST 4	1.43	0.44	0.36	Kockatea Shale	Triassic
North Erregulla 1	DST 1	1.14	0.59	0.54	Kockatea Shale	Triassic
Dongara 14	DST 1	1.23	0.30	0.28	Basal sandstone	Triassic
Dongara 4	DST 1	2.91	0.34	0.31	Basal sandstone	Triassic
East Heaton 1	2115.00	1.88	0.61	0.34	Wagina Sandstone	Permian
East Heaton 1	2513.00	2.54	0.91	0.36	Irwin River Coal Measures	Permian
Mondarra 2	PROD TEST	1.73	0.26	0.19	Wagina Formation/ Basal sand	Permian
Whicher Range 1	DST 7	3.33	0.45	0.14	Nangetty Formation/ Sue Coal Measures	Permian
Woodada 3	DST 2	2.48	0.53	0.23	Carynginia Formation	Permian
Yardarino 1	DST 3	1.15	0.22	0.17	Wagina Formation	Permian
Yardarino 1	DST 3	1.05	0.22	0.19	Wagina Formation	Permian
Yardarino 1	DST 3	1.15	0.23	0.17	Wagina Formation	Permian
Dongara 4	PROD TEST 1	2.98	0.34	0.29	Irwin River Coal Measures	Permian
Whicher Range 4		5.03	0.49	0.11	Upper Sue Coal Measures	Permian
Mondarra 5		1.10	0.21	0.17		Permian
East Lake Logue 1	DST 1	1.74	0.26	0.20	Carynginia Formation	Permian
Hovea 1	DST 1	1.43	0.70	0.64	Dongara Sandstone	Permian

These source rocks could also form potential petroleum shale plays within the onshore Perth Basin. Source beds within the Permian, Triassic, and Jurassic have a wide areal distribution and extend out to the offshore Perth Basin (Crostell, 1995; Grosjean et al., 2011; Thomas, 1984; Thomas and Barber, 2004).

Petroleum system modelling

Source-rock analysis data from 60 wells in the Perth Basin were used as input into petroleum system models using Platte River Associates' latest release of the Petroleum Systems Suite software 2017. The modules 1D BasinMod, BasinMod, BasinView, and 2D BasinMod were all used in order to create an integrated model of the basin. The TOC and Rock-Eval input data were filtered with the Rock-Eval Expert System Analysis (REESA) rules (Appendix 1). Appendix 2 shows geochemical logs for 60 wells (Appendices 2.1 – 2.60). The modelled Rock-Eval data were used to generate regional maps to show the broad geographic trends of measured TOC and measured and calculated Rock-Eval parameters S_2 , HI, PI, and T_{max} for the Carynginia Formation, Kockatea Shale, and Cattamarra Coal Measures (Appendices 3.1 – 3.28). These maps are computer generated from point data (wells) without any manual editing. They may extend into areas with missing data and the lack of structural information between wells, which is usually provided from seismic interpretation.

Model reconstructions were constrained using present-day temperatures (Fig. 23) and heat flows based on measured thermal conductivities (Figs 24–26), and AFTA paleothermal events (Fig. 27). These figures are based on subsurface well temperature information available from Geological Survey of Western Australia (GSWA) studies undertaken by Chopra and Holgate (2007) and Hot Dry Rocks Pty Ltd (2008), and AFTA data from GEOTRACK (Gibson, et al., 1997).

AFTA assists in constraining paleotemperatures and the cooling time since peak temperatures were reached. Fission track ages are a function of track annealing in response to an increase in temperature of between about 50 and 120°C and track length reflects the style of cooling. VR data are also used to constrain the range of paleotemperatures, since apatite fission tracks are totally annealed above approximately 110°C. This temperature corresponds to a VR range of 0.7 – 0.9%.

AFTA data are available for 15 samples, five each from Arranoo South 1, Cataby 1, and West Erregulla 1 (Gibson et al., 1997). These samples are from the Permian Carynginia Formation, latest Permian–Triassic Kockatea Shale, Jurassic Eneabba Formation, Cattamarra Coal Measures, and Yarragadee Formation. Measurements of 26 AFTA time constraints indicate two major regional episodes of heating and cooling (burial and erosion). The first took place between 135 and 65 Ma (Cretaceous), and the second between 30 and 0 Ma (Paleogene/Neogene/Quaternary) (Fig. 27, Appendices 4.1 – 4.14).

Green and Duddy (2013) provide detailed AFTA information and its influence on basin exhumation and petroleum prospectivity of the sedimentary basins of Western Australia, including six wells from the Perth

Basin. Of these, North Erregulla 1 and West Erregulla 1 are close to present-day temperatures. Hence, no significant post-Jurassic deposition has taken place in these areas, whereas Arranoo South 1, Dongara 1, and Mondarra 1 show post-Jurassic heating and indicate exhumation between 110 and 65 Ma. However, exhumation of about 700 m at Jurien 1 took place between 190 and 140 Ma.

In the modelling process, transient heat flow was applied in order to link the thermal history with tectonically induced heat changes. This provides a direct interpretation in terms of the physical processes involved in basin formation. This is because temperature gradients will vary with depth due to differences in lithology and compaction and thus thermal conductivities. Therefore, they do not provide a correct assessment of tectonically induced heat changes (Gallagher and Morrow, 1998). Default BasinMod fluid flow parameters were used as input for estimating compaction, pressure, and reduction in porosity and permeability. Predicted hydrocarbon thermal maturity windows are based on the Lawrence Livermore National Laboratory vitrinite and kerogen kinetics used by BasinMod.

The burial history was reconstructed from the rock unit thicknesses and lithologies interpreted in each of the modelled wells, and events that took place during times represented by unconformities. The thermal history was then reconstructed by adjusting thermal conductivities and heat flow to constrain the maturity model against measured corrected bottom hole temperatures (BHT), $\%R_o$, T_{max} , and AFTA data to constrain present and paleotemperatures. Finally, kinetic modelling and reconstruction of petroleum generation, as a function of geothermal history and the type and amount of kerogen, was used to estimate the time of petroleum generation. The depth of the oil and gas window is assumed to be equivalent to the burial depths necessary to convert 10–90% of the available kerogen to petroleum. On the basis of the geochemical data, the Permian and Jurassic source rocks are assumed to contain mostly type III kerogen. The Triassic and Cretaceous source rocks are assumed to contain mostly type II kerogen.

This study includes one-dimensional (1D) and two-dimensional (2D) modelling, 1D modelling is generally referred to as maturity modelling, whereas multi-dimensional modelling is generally referred to as fluid flow modelling. Most of the geological framework used in 1D maturity modelling is also used in 2D fluid flow modelling, with the kinetics of hydrocarbon generation and expulsion modelling. The thermal regimes used in 1D and 2D models are the same except for the inclusion of lateral heat transfer by convection or diffusion in the latter (Waples, 1998).

From a total of 60 developed well models using the 1D BasinMod module, 49 selected well models were imported in the BasinMod module to generate regional distribution maps of Rock-Eval parameters and a cross-section. TOC and Rock-Eval data were filtered using REESA rules (Appendix 1). REESA provided rapid and reliable interpretation of TOC and VR data. These BasinMod models were then exported to the BasinView and 2D BasinMod modules to generate surface maps and a cross-section. These output maps were created using the point data only. The resulting contour maps are not smoothed or linked to regional structural trends. The maps show the distribution of calculated source-rock potential, type, and

maturity within the onshore Perth Basin. They are used to evaluate and map the petroleum-generating potential (S_2 /mg) distribution within the onshore Perth Basin (Fig. 28). The Jurassic Cattamarra Coal Measures was intersected in most wells (Fig. 28a), whereas the uppermost Permian–Triassic Kockatea Shale was intersected in the least number of wells (Fig. 28b). The Permian Carynginia Formation and Irwin Coal Measures were intersected in wells drilled in the western part of the study area (Fig. 28c,d). Their lateral equivalents comprise the major source beds in the southern Perth Basin. The Kockatea Shale constitutes the main source beds in the northern Perth Basin, and the Cattamarra Coal Measures the main source beds in the central Perth Basin (Fig. 29). Hence, these areas are considered to be the main oil and gas provinces of the Perth Basin. These source rocks have been correlated with conventional reservoir oil accumulations, and could also be potential targets for petroleum shale plays within the onshore Perth Basin.

The location of the modelled wells, the basin's main structural elements, and the subsurface stratigraphy are summarized in Figures 30 and 31. In this study, measured TOC of the Kockatea Shale averages around 5% within the far northwest, but is low in the rest of the study area (Fig. 32a). The map of the calculated maximum temperature (Fig. 32b) indicates areas of high temperature, resulting in the maturation and generation of oil and gas. All of the producing fields are within the mature area. BasinView models were used to evaluate and map elevation, thickness, potential yield (S_2 /mg), HI, and oil and gas retained within the Kockatea Shale (Figs 33–35). All of these maps are based on wells with Rock-Eval data. Well elevations are measured from the ground level and formation thicknesses were determined in each well.

The well correlation A–A¹ from Mungarra 1 in the north to Woodada 5 in the south (Figs 30 and 31) summarizes the subsurface stratigraphy used in the basin modelling. The maturity and hydrocarbon expulsion volumes from the Cattamarra Coal Measures, Kockatea Shale, Carynginia Formation, and Irwin River Coal Measures are calculated from BasinView models (Fig. 36) and 2D BasinMod models (Figs 37, 38). The highest calculated expelled hydrocarbon volumes ranging from 700 000 to 800 000 barrels per acre are in the Arrowsmith and Woodada areas, followed by areas around Drakea and Jingemia, which were calculated to expel between about 200 000 and 400 000 barrels per acre (Fig. 36b). The oil and gas saturations from 2D modelling indicate very low values of present-day oil and gas saturation (Figs 37, 38).

Although petroleum geochemistry data are available for over 4000 rock and oil samples, reliable data remains limited (487 data points) after interpretation and filtering by REESA rules for the Jurassic, Triassic, and Permian source rocks modelled in this study.

Finally, the Erregulla area and Whicher Range 1 are used as examples to show the petroleum system models for the northern and southern Perth Basin, respectively. These wells were selected because AFTA data are available for the Erregulla area and the Whicher Range area has been extensively studied. However, these areas should not be considered as representative for the whole onshore Perth Basin.

Erregulla Area: northern Perth Basin

The West Erregulla 1 exploration well was drilled by Barrack Energy Ltd to a total depth of 4065.5 m in 1990. It is located within the Allanooka Terrace of the northern Perth Basin, and was drilled to test the structure within Early Jurassic and Late Permian rocks. North Erregulla 1 is located structurally updip and is 16 km north-northwest of Erregulla 1 and 2, which were drilled in 1966 and 1980, respectively. In Erregulla 1, oil was recovered from the Eneabba Formation, and in North Erregulla 1, Drill Stem Test (DST) 1 and 2 recovered 20 gallons (91 L) of 38° American Petroleum Institute (API) oil from the upper part of the latest Permian to Early Triassic Kockatea Shale, and 8 gallons (36 L) at the top of the Permian section (Crostella, 1995; Thornton, 1990).

Source-rock analyses are available from Erregulla 1 (Appendix 2.26) and North Erregulla 1 (Appendix 2.39), whereas AFTA data (Gibson et al., 1997) are available from West Erregulla 1 (Appendices 4.11 – 4.14). Petroleum-generation modelling for the Erregulla area is based on preserved stratigraphic thicknesses, geochemistry, organic petrography, and AFTA data available from the Erregulla area wells. Modelling results indicate that petroleum generation–migration–accumulation took place during the Cretaceous paleothermal event from the Triassic Kockatea Shale (Figs 39, 40).

Whicher Range 1: southern Perth Basin

The Whicher Range 1 exploration well was drilled by Union Oil Development Corporation (Union Oil Development Corporation, 1968) to a total depth of 4653 m in 1968. It is located in the Bunbury Trough of the southern Perth Basin. The well was drilled on a well-defined four-way dip anticline with approximately 274 m of closure height near the top of the Permian in order to test the Jurassic–Permian section. DSTs were run for the interval 3949.6 – 4027.4 m and recovered up to 1.93 million cubic feet per day (MMcfd) of gas, and a gas discovery was declared (Union Oil Development Corporation, 1968). Four more wells were drilled to appraise the Whicher Range tight sand gas field and detailed research is reported by the Western Australian Energy Research Alliance (2012).

Source-rock analyses are available from the Willespie Formation, Cattamarra Coal Measures, and Yarragadee Formation (Appendix 2.56). They indicate high-quality, gas-prone source rocks which are not mature for gas generation or expulsion at the Whicher Range 1 location. AFTA data are not available for this well. Thus, the petroleum-generation modelling for the Whicher Range area (Whicher Range 1) is based on preserved stratigraphic thicknesses, geochemistry, and organic petrography data. Modelling indicates that petroleum generation–migration–accumulation took place during the Jurassic (Figs 41, 42). This petroleum-generation modelling provides an update on the previous Whicher Range 1 modelling reported in Crostella and Backhouse (2000).

Potential self-contained petroleum systems

Shale reservoir systems form the richest petroleum plays and the geochemical, geomechanical, and petrophysical properties of source rocks determine the potential difficulty of producing the petroleum. Shale petroleum is usually produced through a combination of horizontal wells and hydraulic fracturing (Jacobi et al., 2008, 2009).

Good-quality shale gas resources depend on adequate source-rock thickness of net pay (>100 m), adequate porosity (>2%), high reservoir pressure (ideally overpressured), high thermal maturity (>1.5% R_o), high organic richness (>2% TOC), low clay content (<50%), high content of brittle minerals (quartz, carbonates, feldspars), and favourable in situ stresses. This Report has shown that the right thermal maturity and organic richness exists in shales within the Perth Basin, and the work of CoreLab (2013) demonstrates favourable fracturing properties of the Permian Carynginia Formation and Triassic Kockatea Shale (Fig. 43).

Exploration of shale petroleum in the Perth Basin has been encouraged by the rapid increase of shale gas production in the US since 2005. Production from these shale reservoirs has changed the US from being a net importer to a net exporter of petroleum products.

In the Perth Basin, the search for shale petroleum started with the deepening of the Woodada 4 well as Woodada Deep 1 (Australian Worldwide Exploration, 2011) in 2010, from 2269 to 2552 m to evaluate the Permian Irwin Coal Measures and Carynginia Formation. Three lithofacies were identified within the lower Carynginia Formation for assessing shale gas potential supported by four conventional cores between 2272 and 2542 m, totalling 69.25 m (Australian Worldwide Exploration, 2011). Arrowsmith 2 was the first dedicated shale play vertical well drilled in 2011. Five zones were stimulated to evaluate the Permian High Cliff Sandstone, Irwin River Coal Measures, Carynginia Formation, and Triassic Kockatea Shale (Norwest Energy Pty Ltd, 2011). These wells provided pioneering information and material for assessing northern Perth Basin shale petroleum reservoirs. The oil recovery from the Kockatea Shale in Arrowsmith 2 was the first proven shale oil play in the Perth Basin. Petroleum system modelling of Arrowsmith 2 was used to evaluate the shale self-sourcing petroleum systems of the Carynginia Formation and Kockatea Shale (Fig. 44). Petroleum geochemistry and organic petrology data from Arrowsmith 1 were used as an input into the basin modelling of Arrowsmith 2. Arrowsmith 1 flowed 4 MMcf/d from the Carynginia Formation and is located approximately 450 m northwest of Arrowsmith 2.

Evaluation of the regional shale petroleum characteristics of the Perth Basin is at an early stage as only a few vertical wells have been drilled. These wells indicate favourable geology and viable shale petroleum potential. However, to date, no shale plays have been placed in production (Fig. 6).

Discussion and conclusions

The onshore northern Perth Basin is the second highest petroleum-producing region in the Western Australian state jurisdiction. The basin is currently producing from conventional reservoirs in the Beharra Spring, Dongara, Hovea, Red Gully, Redback, Senecio, Tarantula, and Waitsia fields, and from the tight sandstone reservoir in the Corybas field. There is no production from shale reservoirs. The production in 2015 was 194 790 L of oil, 19 087 980 L of condensate, and 260 855 806 m³ of gas. The production of gas condensate is only locally significant as it is only sufficient for the local market. The volume of oil and gas produced from the Perth Basin is decreasing rapidly, as many fields are becoming depleted and many remain undeveloped.

The uppermost Permian–Triassic Kockatea Shale, specifically its basal Hovea Member, is the source of hydrocarbons in the Dongara, Erregulla, Mount Horner, and Yardarino fields in the northern Perth Basin. Gas within the Walyering and Red Gully fields in the central Perth Basin is sourced from the Cattamarra Coal Measures. The hydrocarbon accumulation in the Whicher Range area of the southern Perth Basin is sourced from the Permian Willespie Formation (GeoMark and AGOSO, 1996; Thomas et al., 2004). These source rocks are also potential shale plays and may contain significant petroleum resources.

Sixty wells across the Perth Basin have petroleum geochemistry data, representing a range of different rock units, data type, and quality (Appendices 2.1 – 2.60). Of these, 49 wells were selected for petroleum system modelling of the onshore Perth Basin. REESA rules were applied to eliminate unreliable geochemical data. The Cretaceous (135–56 Ma) and Tertiary (30–0 Ma) paleothermal events (AFTA data; Appendices 4.1 – 4.14) were used to estimate time and extent of burial and erosion. Most of the modelled wells were from the northern and central Perth Basin. These wells were used to generate maps showing the regional distribution of source-rock parameters and to highlight areas with hydrocarbon-generating potential (Appendices 3.1 – 3.28). The modelling results, the geochemistry data, the generated maps (Figs 32–35), and the well correlations (Figs 36–38) provide useful petroleum source information that can assist in understanding the risks associated with petroleum exploration.

The Triassic Kockatea Shale source rocks are restricted to the northwest corner of the study area (Fig. 28b), between Diamond Soak 1 in the north, Rakrani 1 in the west, Cadda 1 in the south, and CRA PER 10 in the east (Fig. 30). Organic richness is up to 13% TOC, but most of the measured values to date are in the range 2–3% TOC. The areas mature for hydrocarbon generation are represented by the areas of highest calculated present-day temperatures, which are up to 122°C around the Erregulla, Redback, and Arrowsmith gas condensate producing fields (Fig. 32b). The Kockatea Shale source rocks across the northern Perth Basin are mature based on the calculated VR, which is up to 1.65% R_o (Fig. 36a). The highest calculated volume of expelled hydrocarbons is around the Arrowsmith area, which is calculated to be up to 800 000 barrels per acre (Fig. 36a).

The Jurassic Cattamarra Coal Measures is penetrated in most wells (Fig. 29), but the best petroleum source rocks are interpreted to be around the Walyering field area where the organic richness is up to 10% TOC. However, these source rocks are not mature in the study area (Fig. 36a,b).

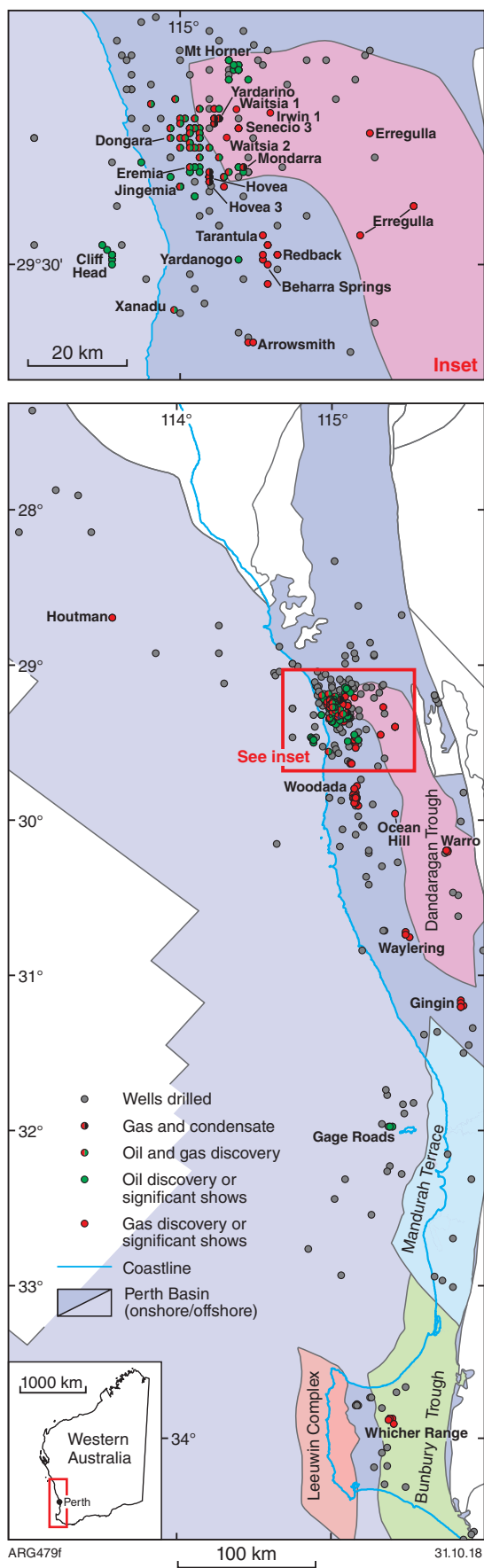
This study concludes that the onshore northern Perth Basin, which is rich in conventional and tight gas condensate, is the prime petroleum province of the Perth Basin. The new conventional Lower Permian gas play discovered at the Waitsia gasfield and the oil recovery from Triassic shale play at Arrowsmith 2 have renewed interest in exploration of the Perth Basin. The conventional petroleum-producing reservoirs are depleting rapidly. Its tight petroleum resources have the potential to compensate, but are presently at initial stages of exploration. The Perth Basin has only two horizontal shale play tests, viz. the Woodada Deep 1 (2010) and Arrowsmith 2 (2011). However, these wells provided pioneering geological information on shale reservoirs within the Permian Carynginia Formation and the Triassic Kockatea Shale. Emerging tight sand petroleum plays of the Perth Basin are already shown to be commercially viable with favourable geology.

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REPORT FIGURES



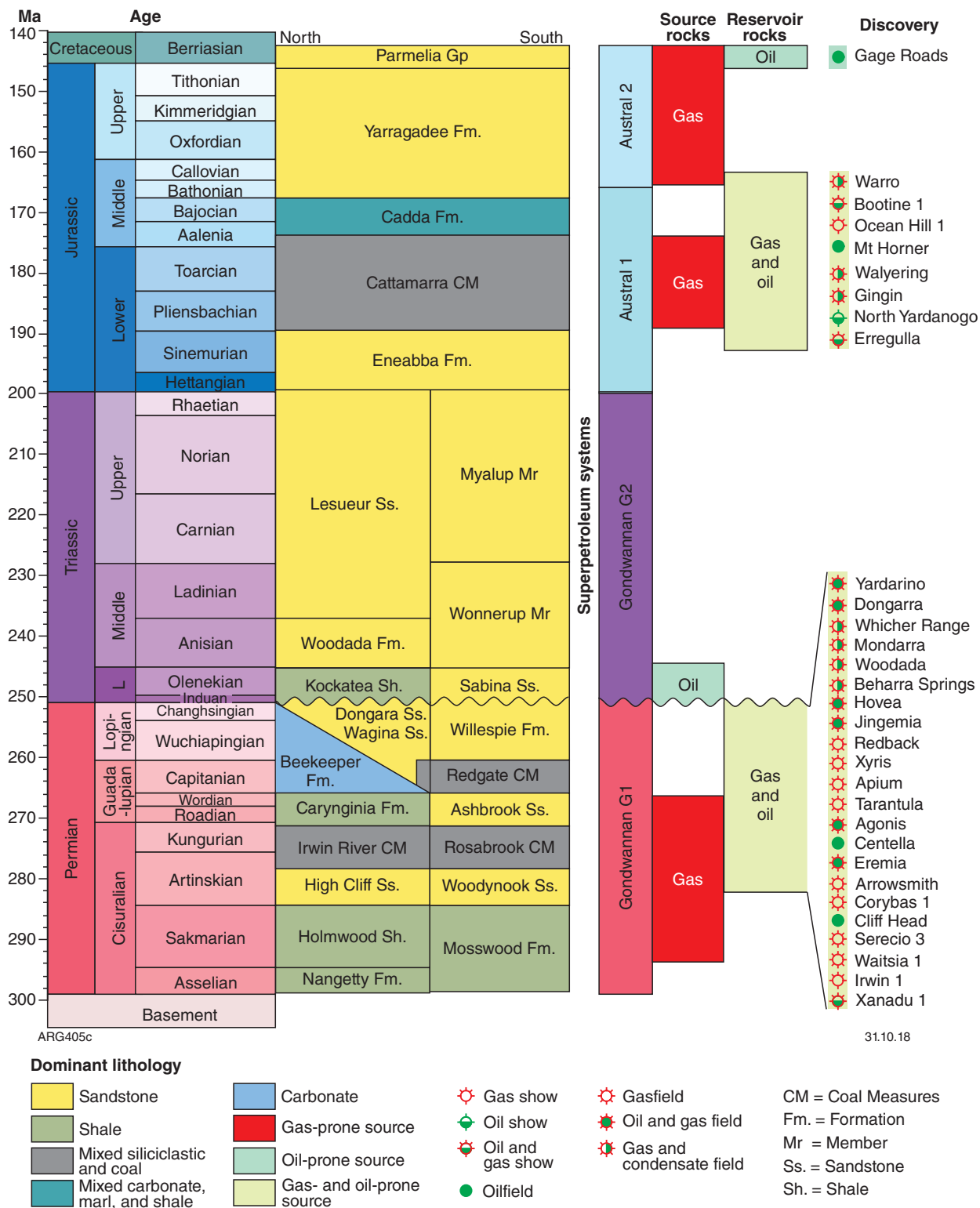


Figure 2. Stratigraphy and petroleum sources, reservoirs, systems, and discoveries in the Perth Basin

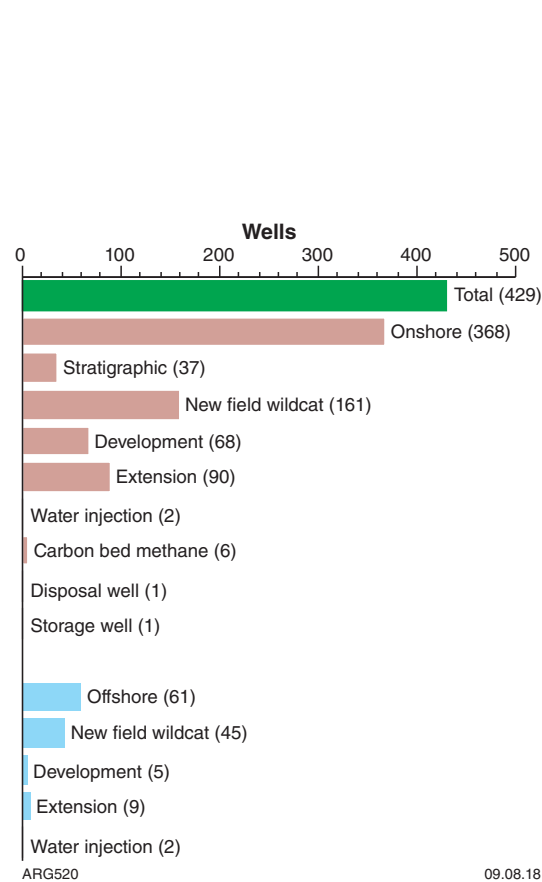


Figure 3 Histogram showing petroleum drilling in the Perth Basin. Site names in red indicate fields that were producing in 2015

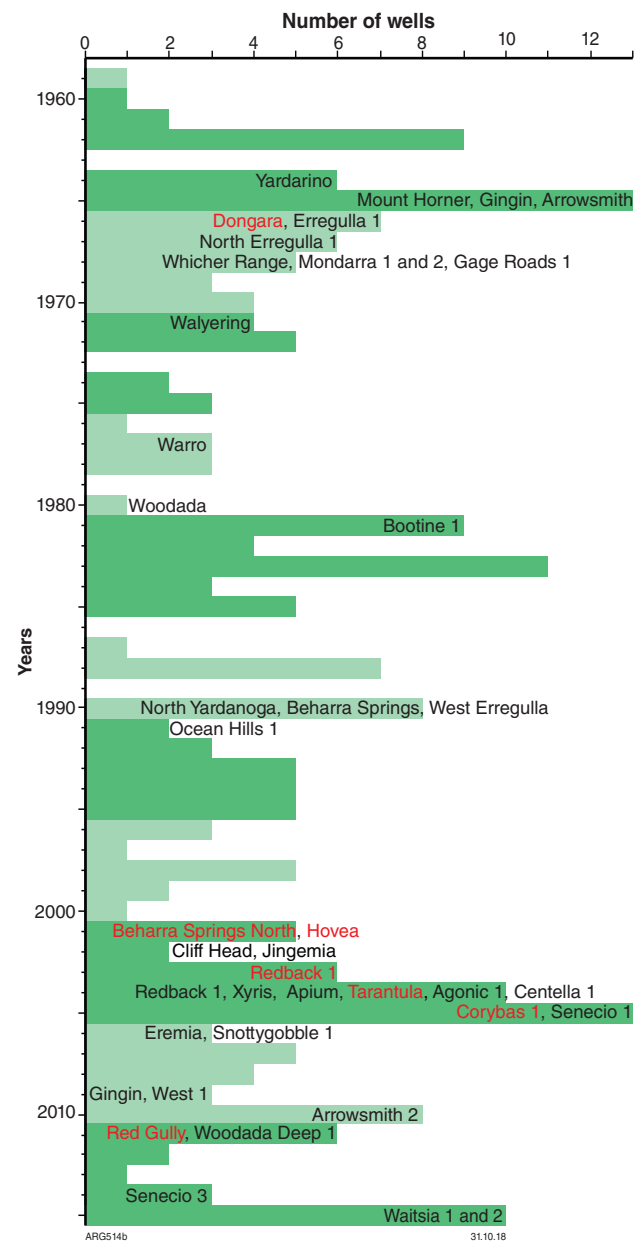


Figure 4. History of petroleum discoveries in the Perth Basin. Red text represents fields that were producing in 2015

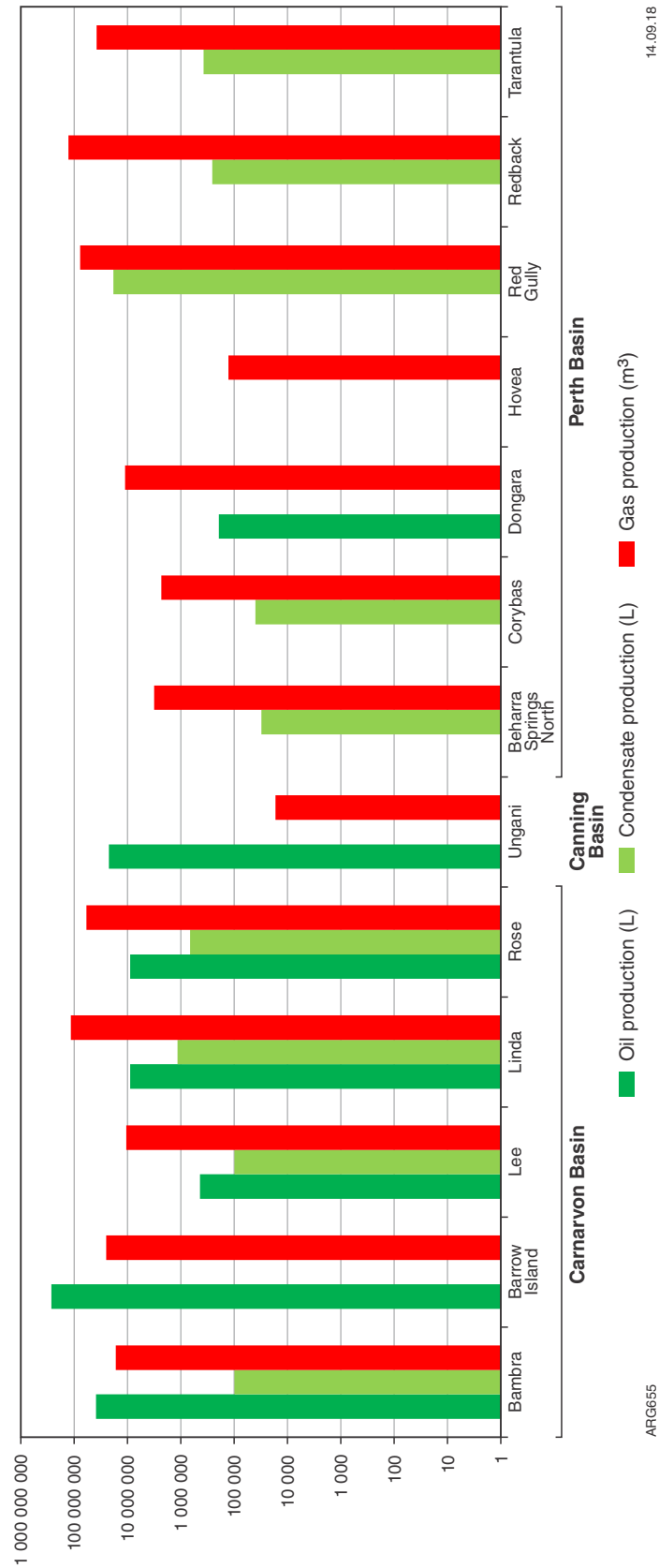


Figure 5. Western Australian petroleum production in 2015

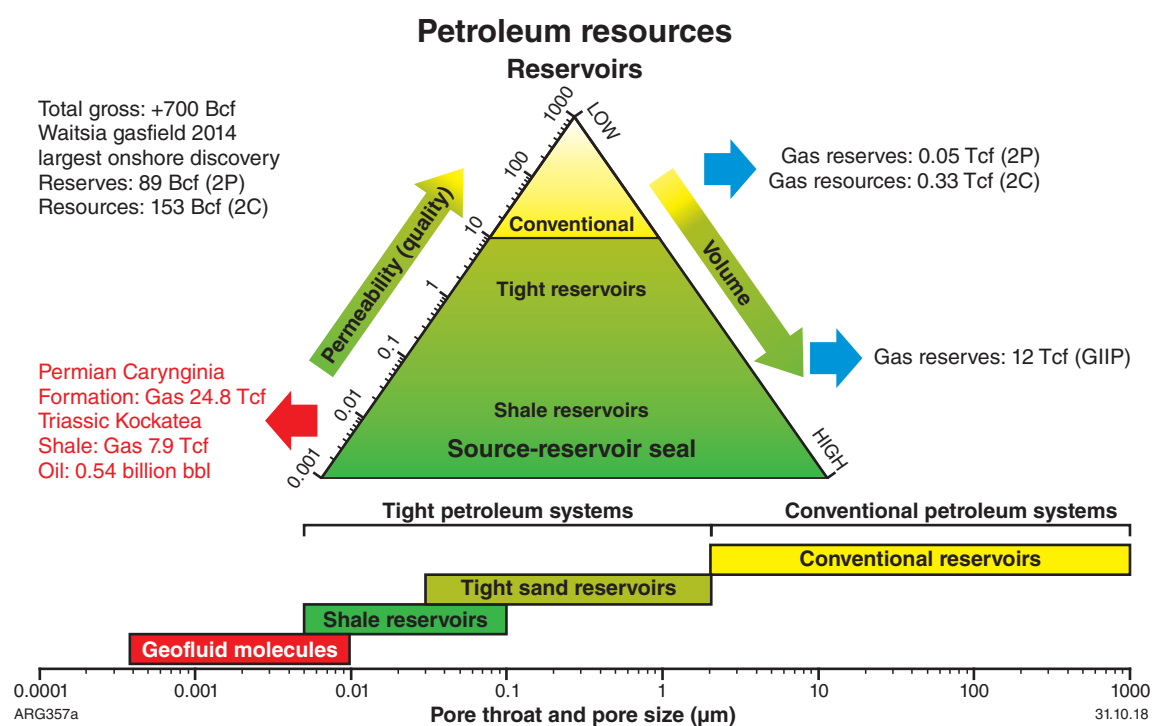


Figure 6. Estimated conventional and tight reservoir petroleum resources of the Perth Basin

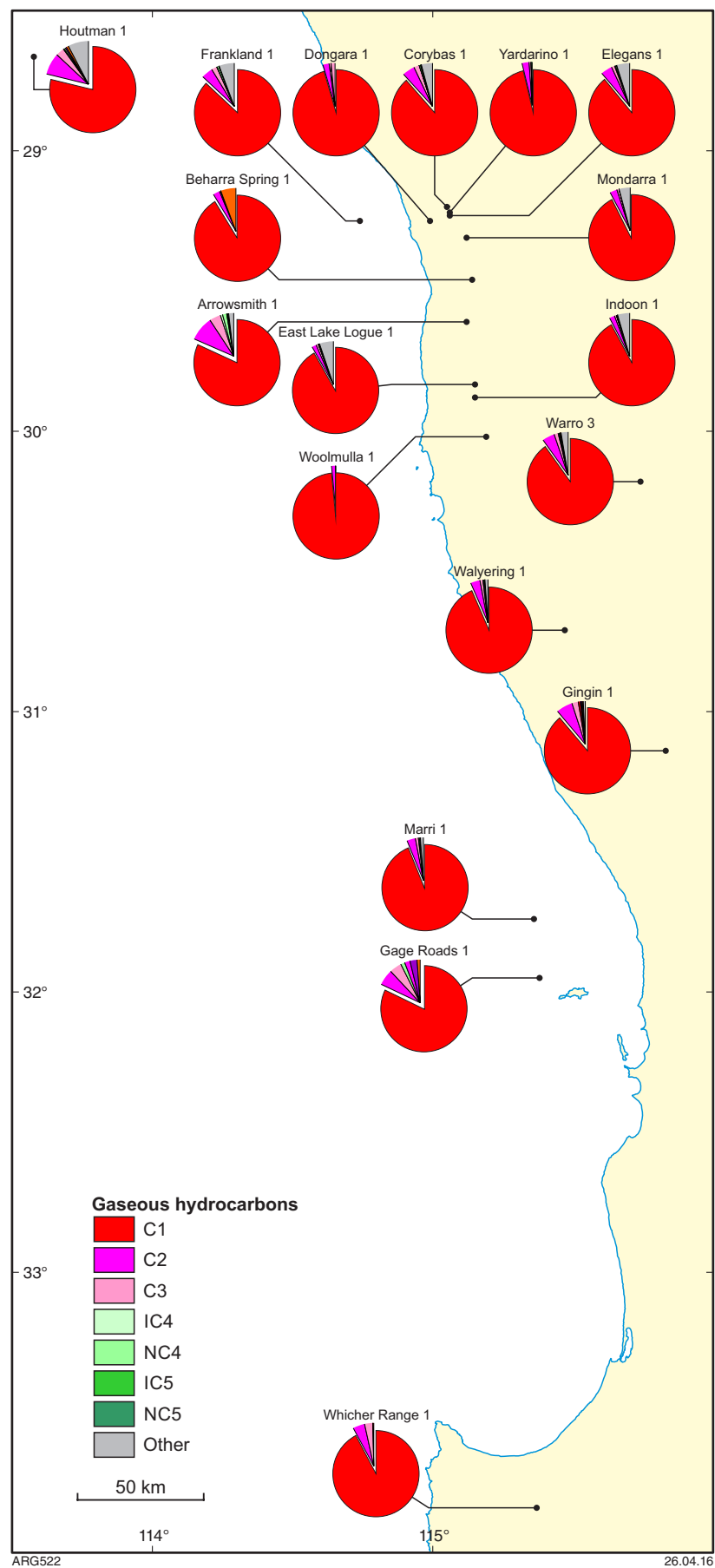


Figure 7. Gas composition and geographic distribution within the Perth Basin. Abbreviations: C1, methane; C2, ethane; C3, propane; IC4, isobutene; NCA, normal butane; IC5, isopentane; NC5, normal pentane; Other, compound containing over five numbers

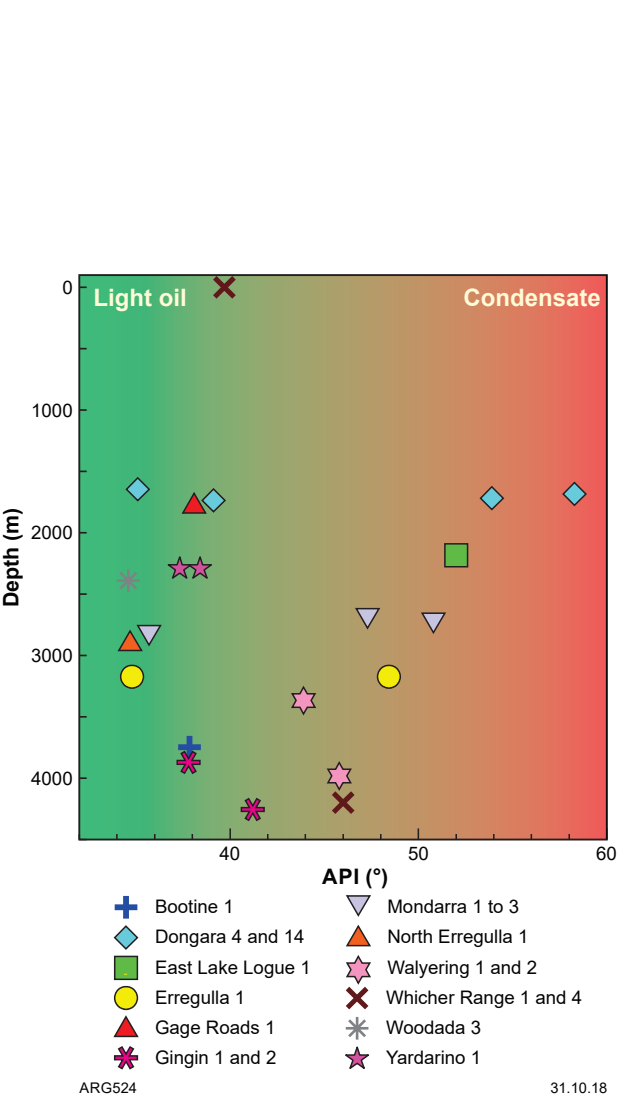


Figure 8. Oil and condensate gravity according to American Petroleum Institutes (API) vs depth plot in the Perth Basin

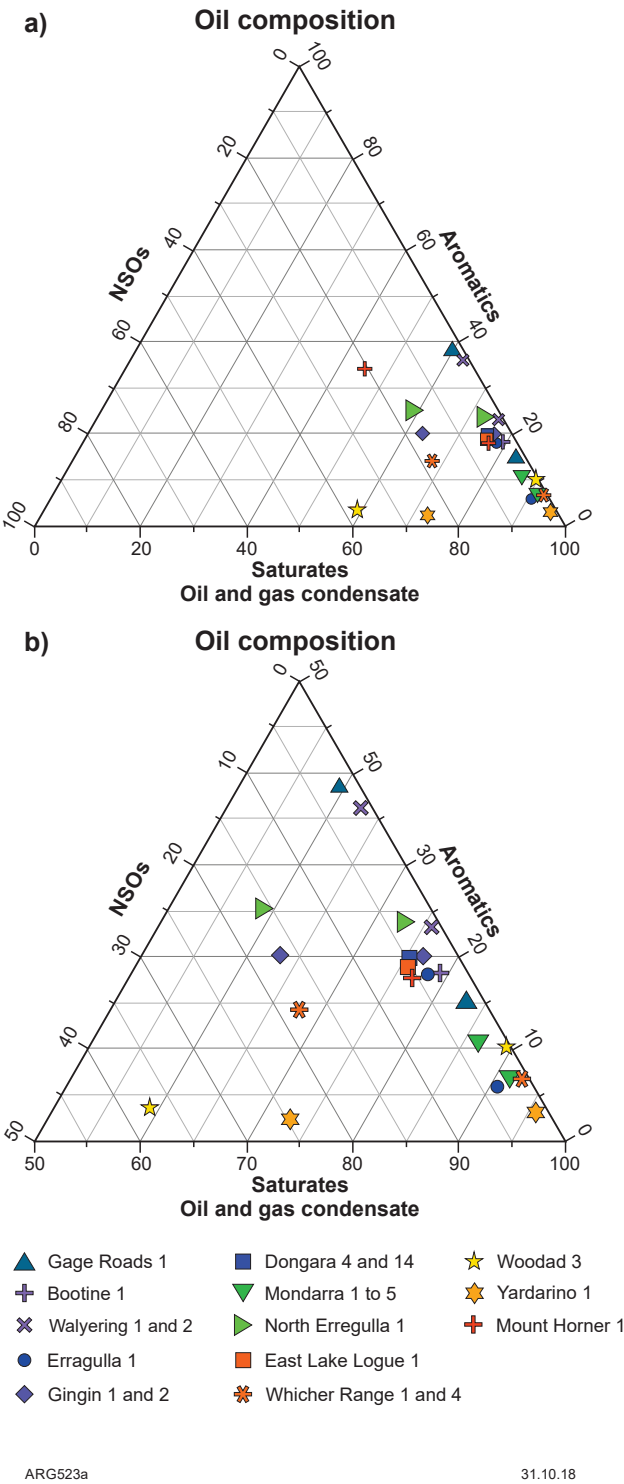


Figure 9. Composition of oils and condensates in the Perth Basin

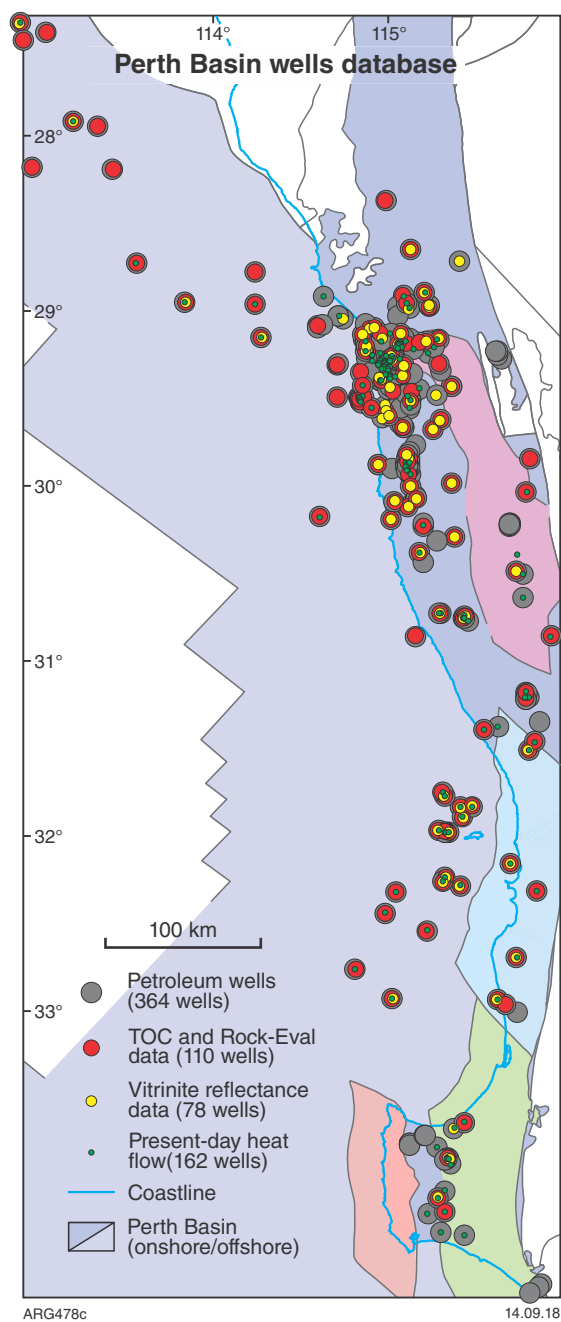


Figure 10. Map of the Perth Basin, showing the distribution of data used in this study

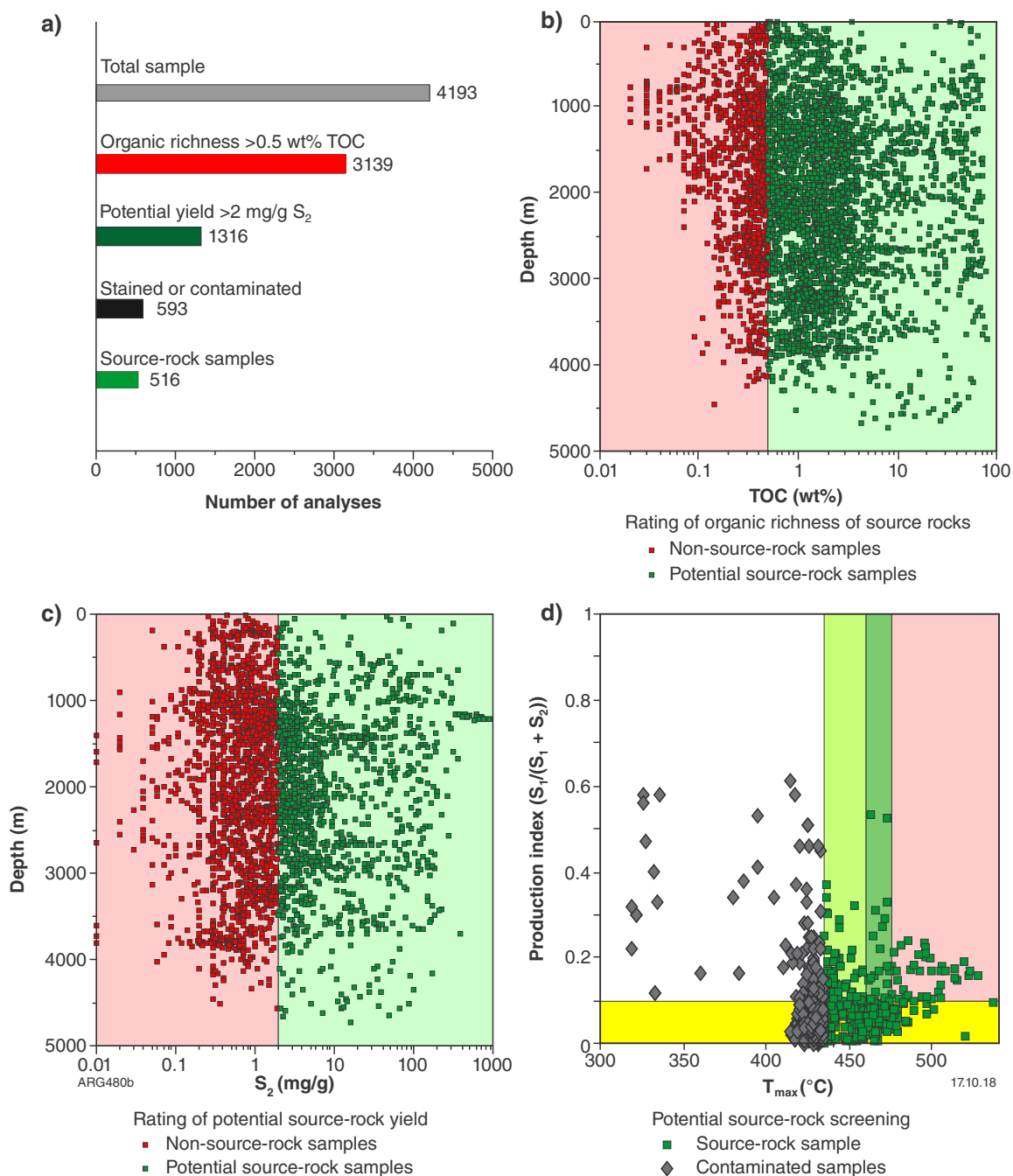


Figure 11. Discrimination between non-source- and source-rock samples based on TOC and Rock-Eval pyrolysis: a) histogram summarizing numbers of source rock analysis; b) potential source rocks based on organic richness; c) potential source rocks based on generating potential; d) discrimination between interpreted source-rock samples and petroleum-stained or contaminated samples

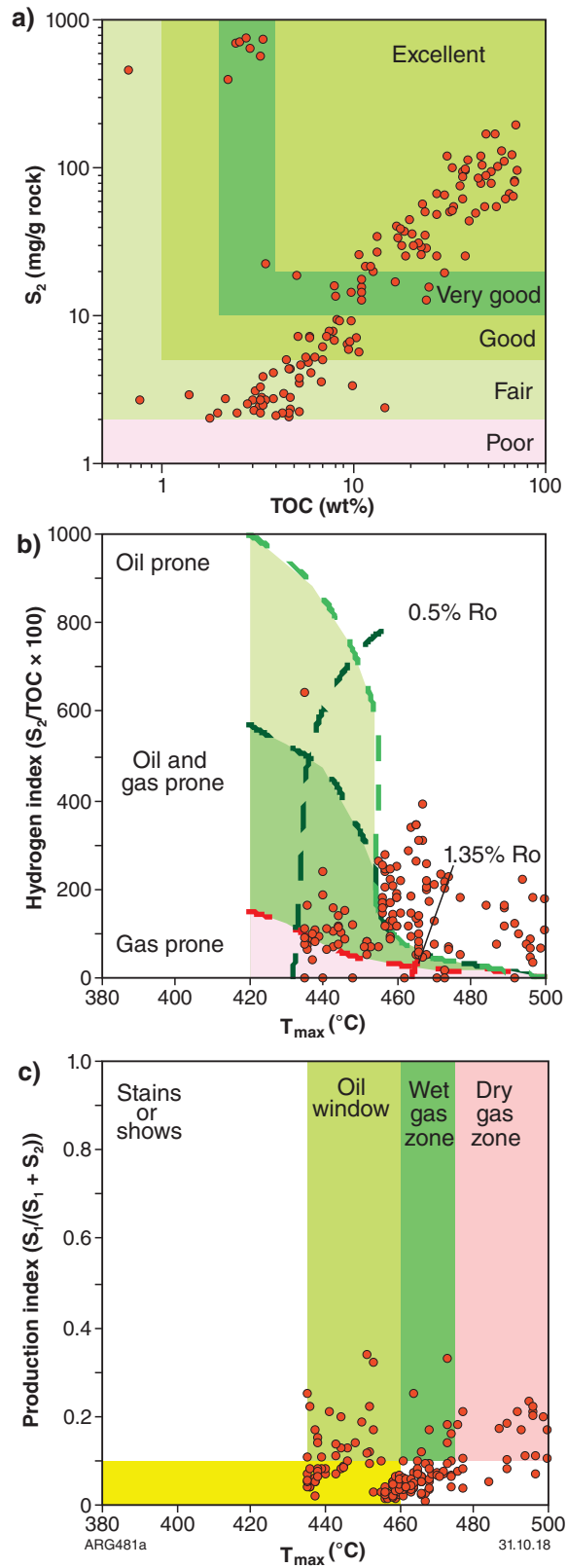
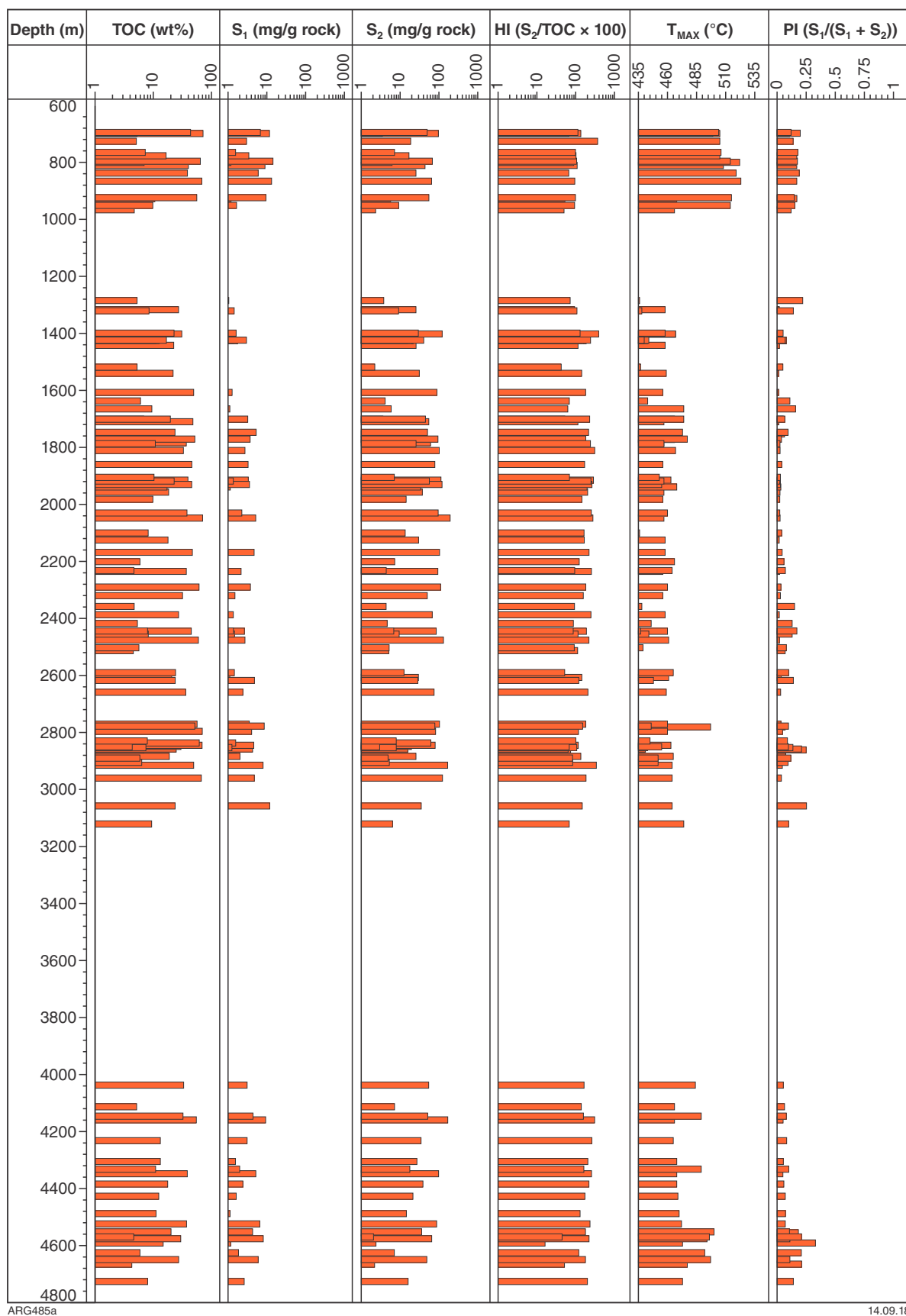


Figure 12. Summary of Rock-Eval data of Perth Basin Permian source-rock samples, showing:
a) generating potential; b) kerogen type;
c) thermal maturity



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Figure 13. TOC and Rock-Eval pyrolysis composite log of Permian source-rock samples from well data in the Perth Basin

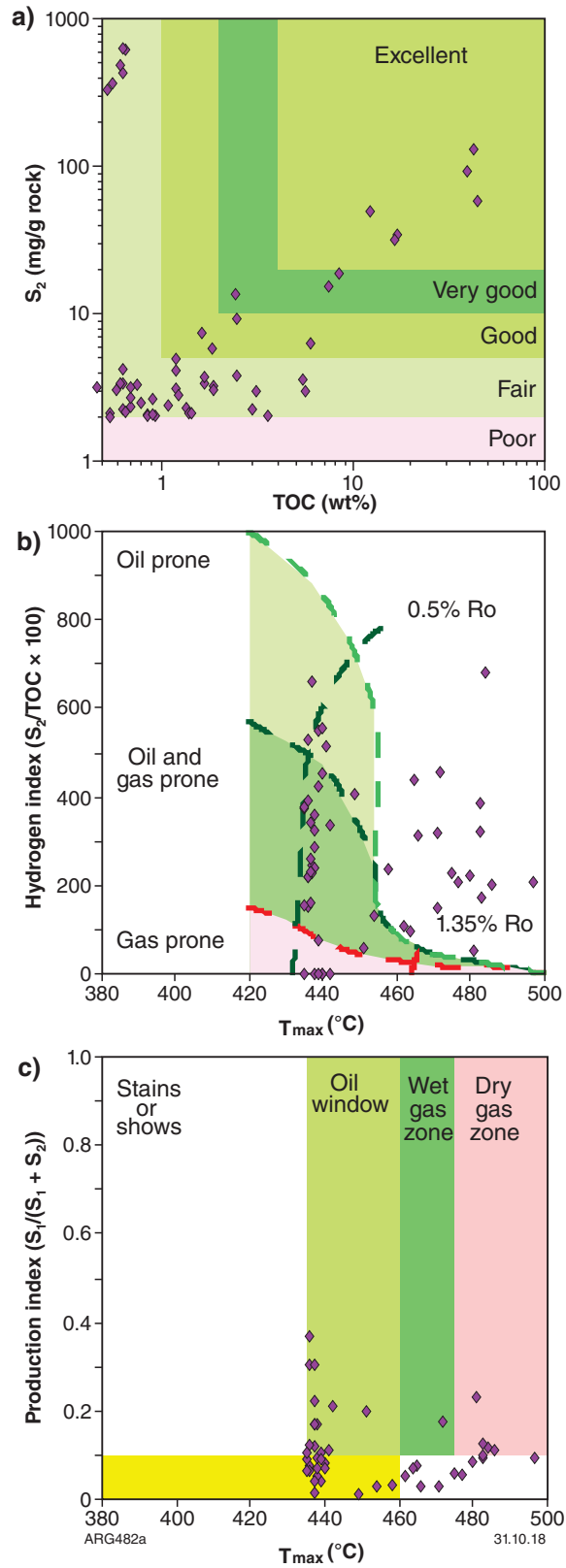


Figure 14. Summary of Rock-Eval data of Triassic source-rock samples in the Perth Basin, showing: a) generating potential; b) kerogen type; c) thermal maturity

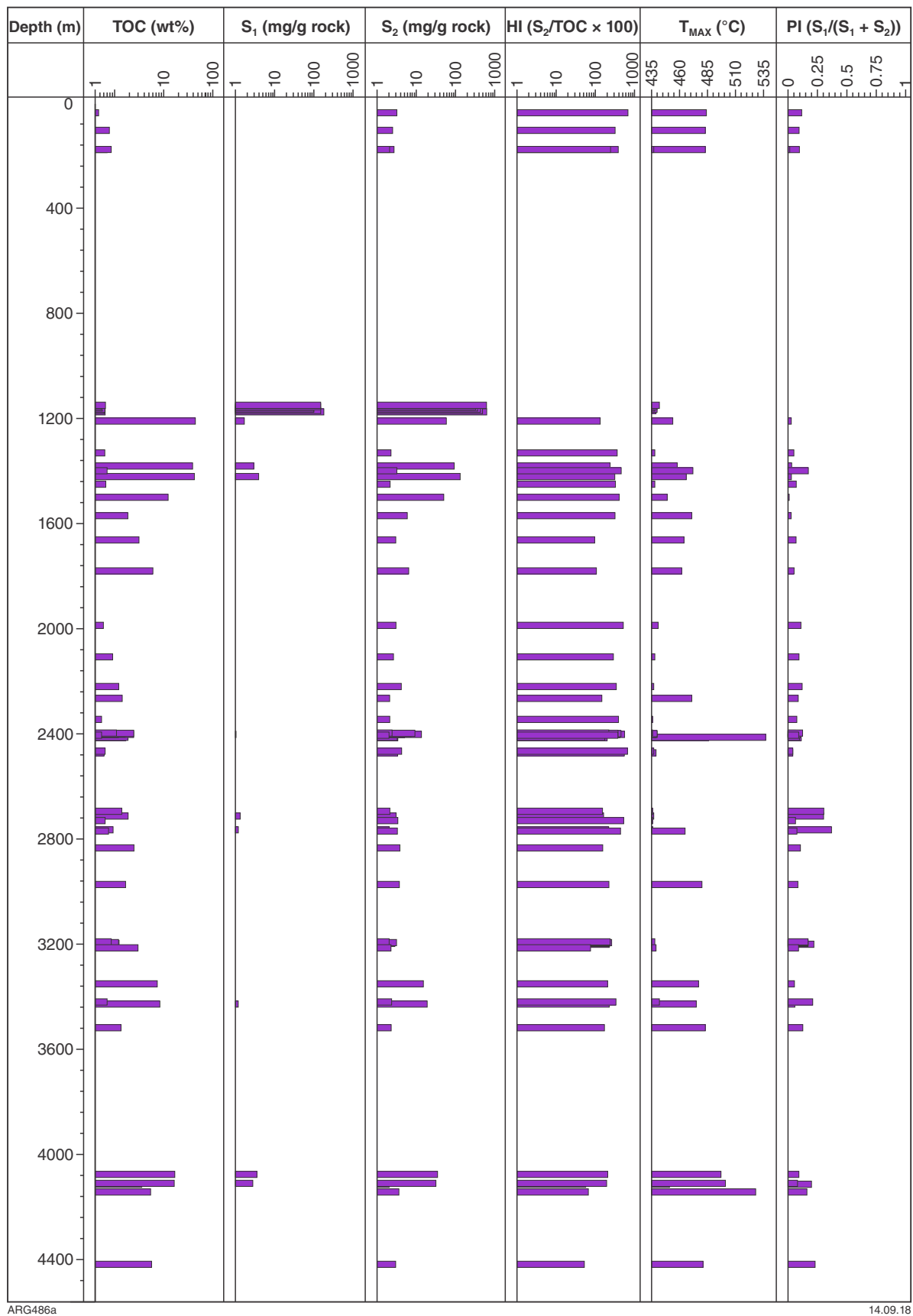


Figure 15. TOC and Rock-Eval pyrolysis composite log of Triassic source-rock samples from well data in the Perth Basin

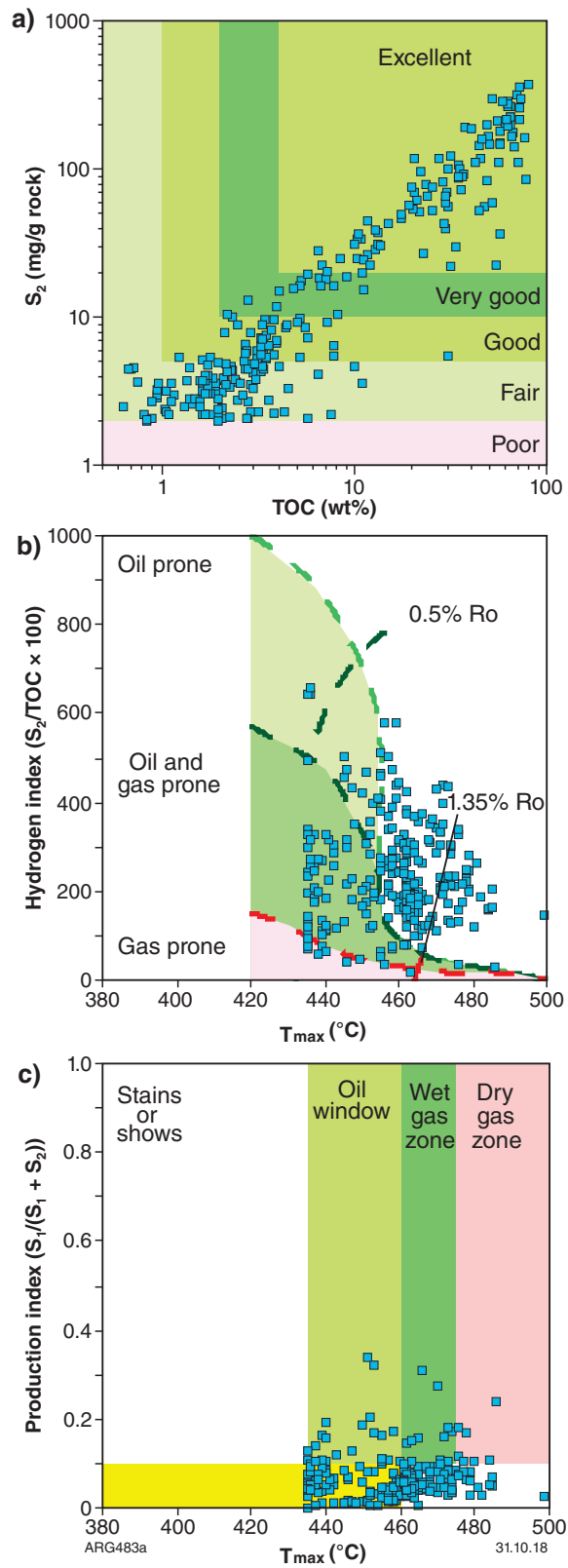


Figure 16. Summary of Rock-Eval data of Jurassic source-rock samples in the Perth Basin, showing: a) generating potential; b) kerogen type; c) thermal maturity



Figure 17. TOC and Rock-Eval pyrolysis composite log of Jurassic source-rock samples from well data in the Perth Basin

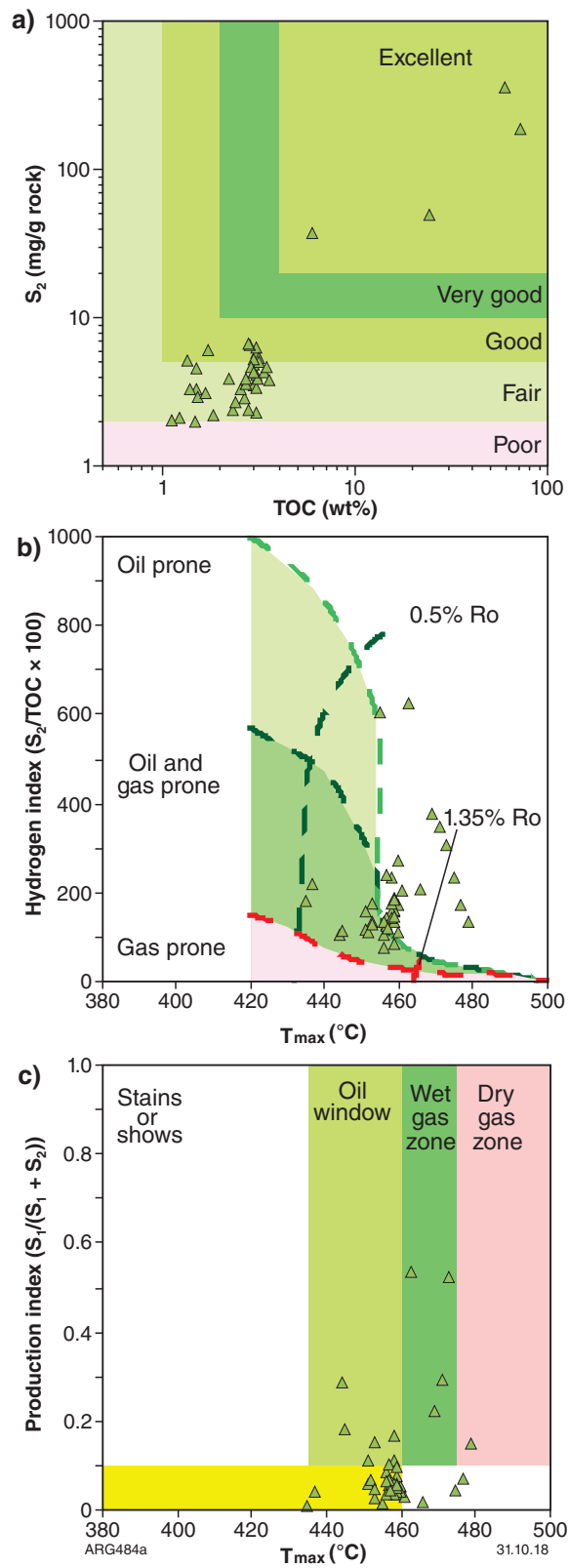


Figure 18. Summary of Rock-Eval data of Cretaceous source-rock samples in the Perth Basin, showing: a) generating potential; b) kerogen type; c) thermal maturity

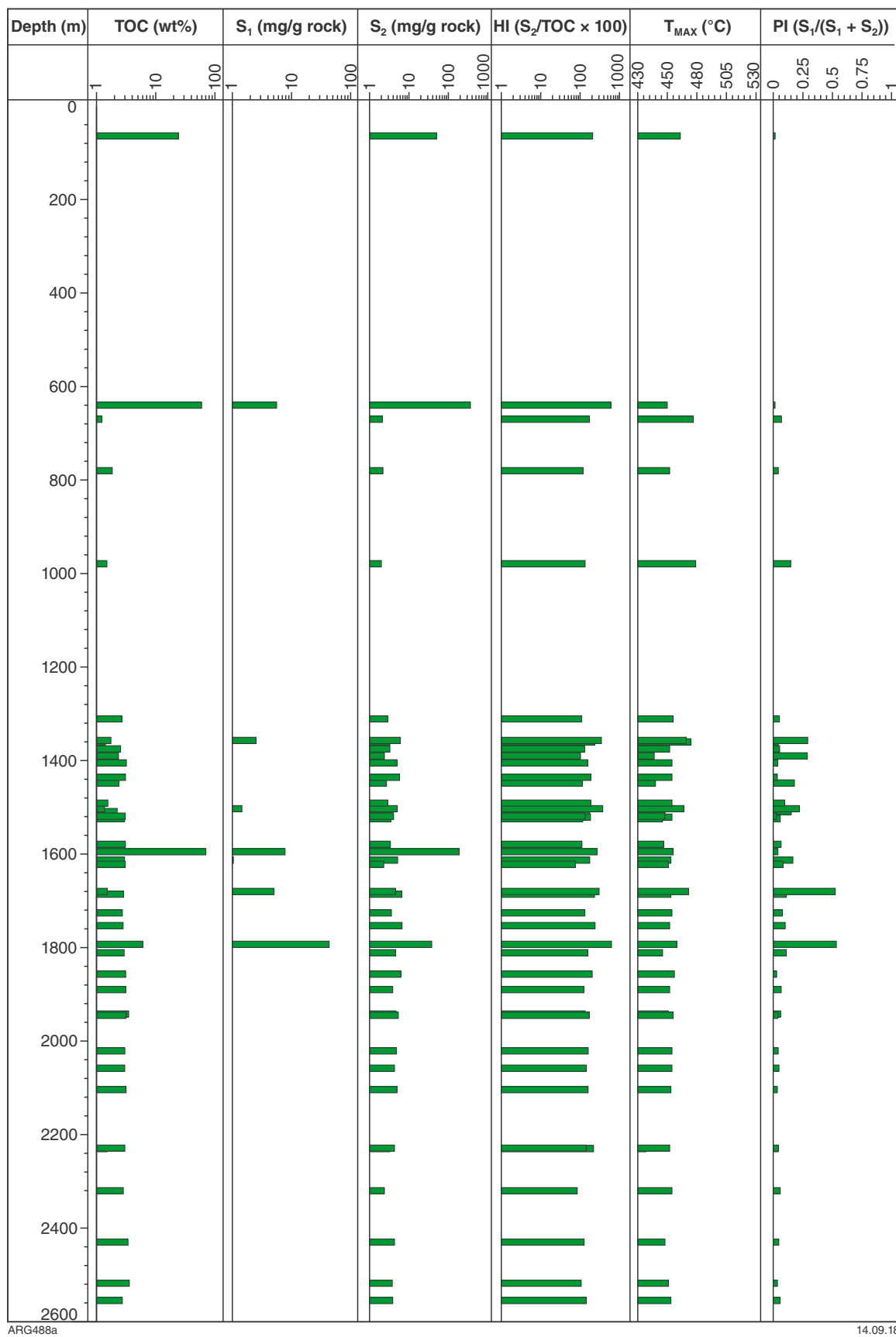
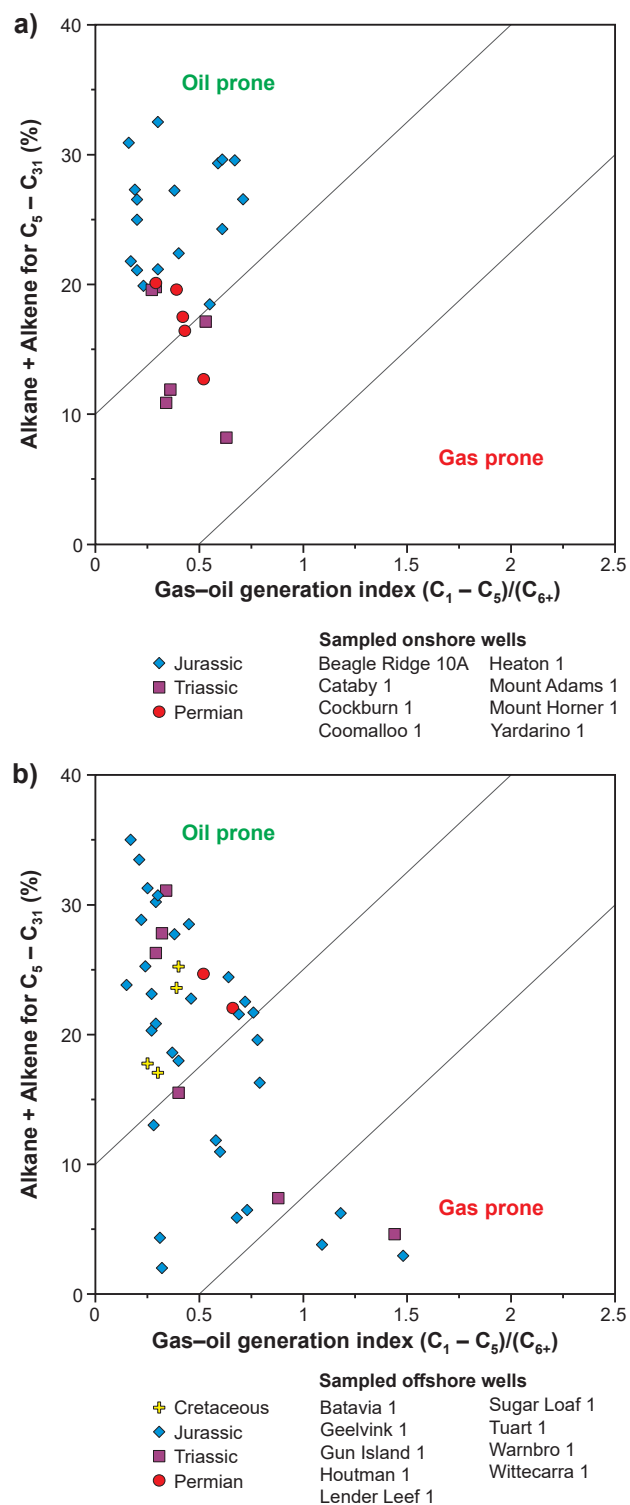


Figure 19. TOC and Rock-Eval pyrolysis composite log of Cretaceous source-rock samples from well data in the Perth Basin



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Figure 20. Pyrolysis-gas chromatography typing of Permian, Triassic, Jurassic, and Cretaceous samples

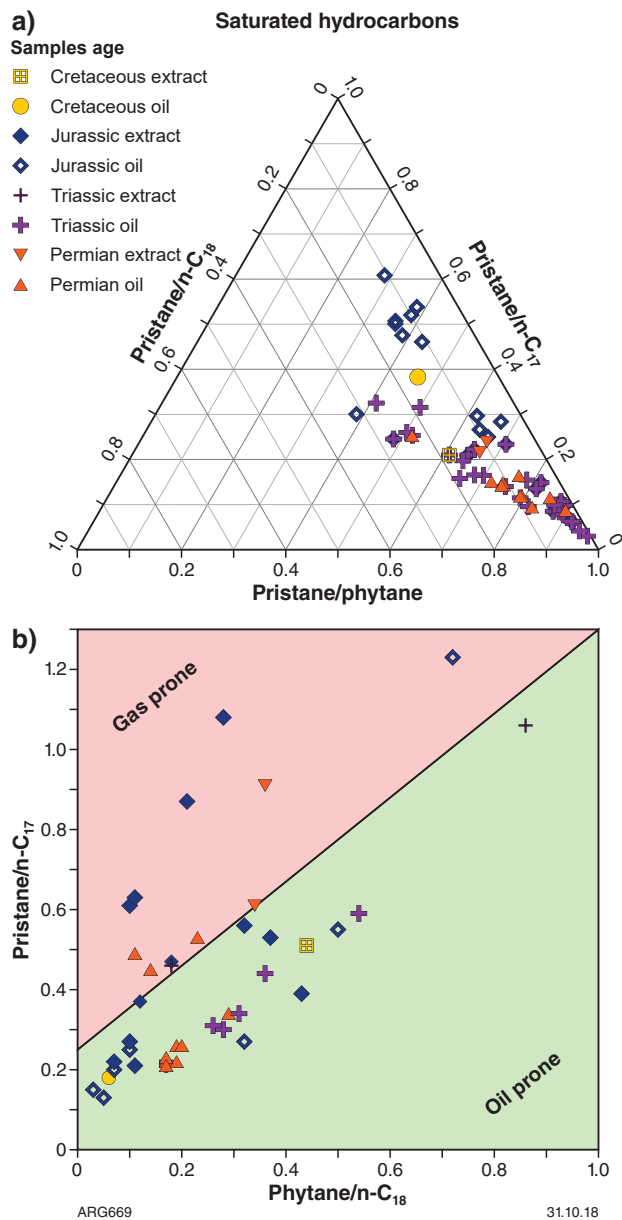


Figure 21. Gas chromatography typing of Permian, Triassic, Jurassic, and Cretaceous samples

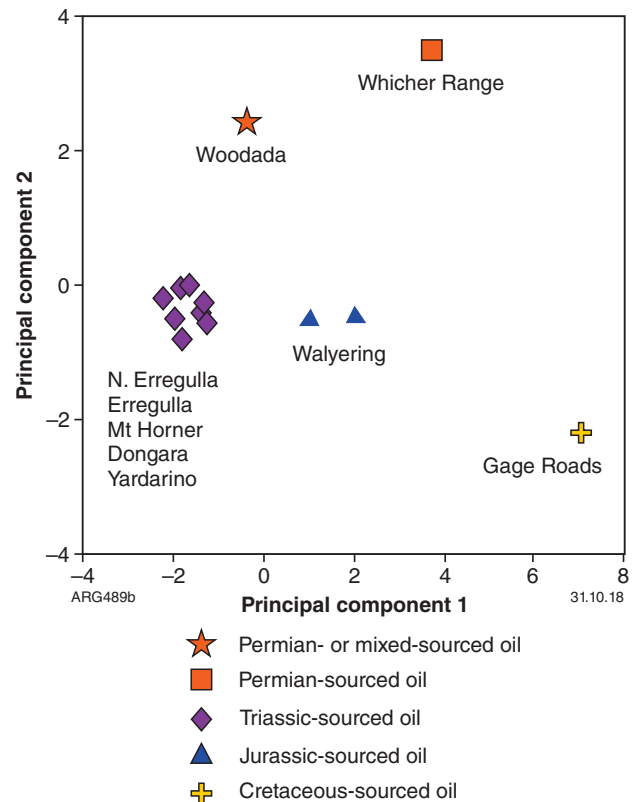


Figure 22. Chemometric characterization of crude oil in the Perth Basin. Data from GeoMark and AGSO (1996)

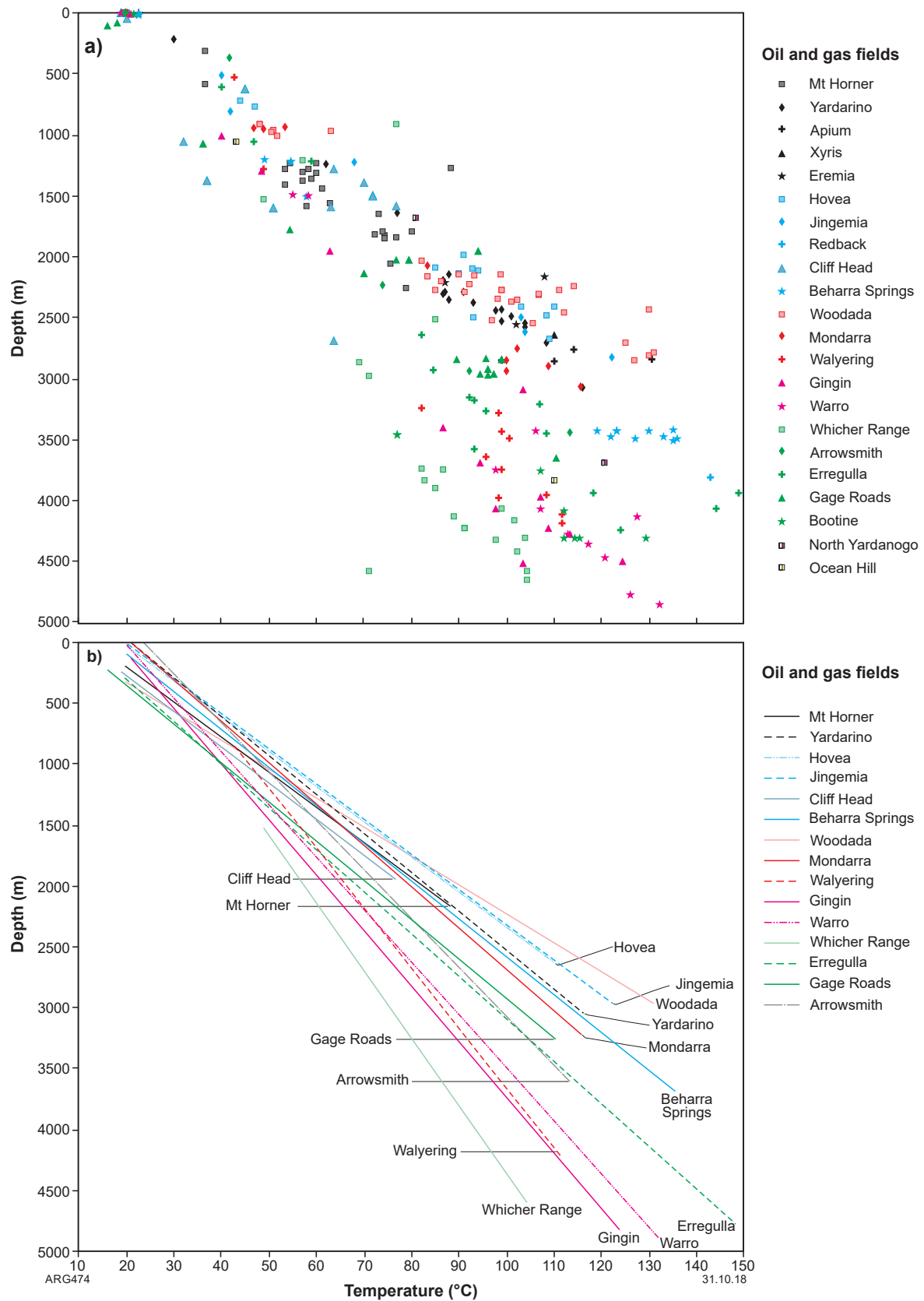


Figure 23. Estimated subsurface temperatures of the Perth Basin. Data from Hot Dry Rocks Ltd (2008)

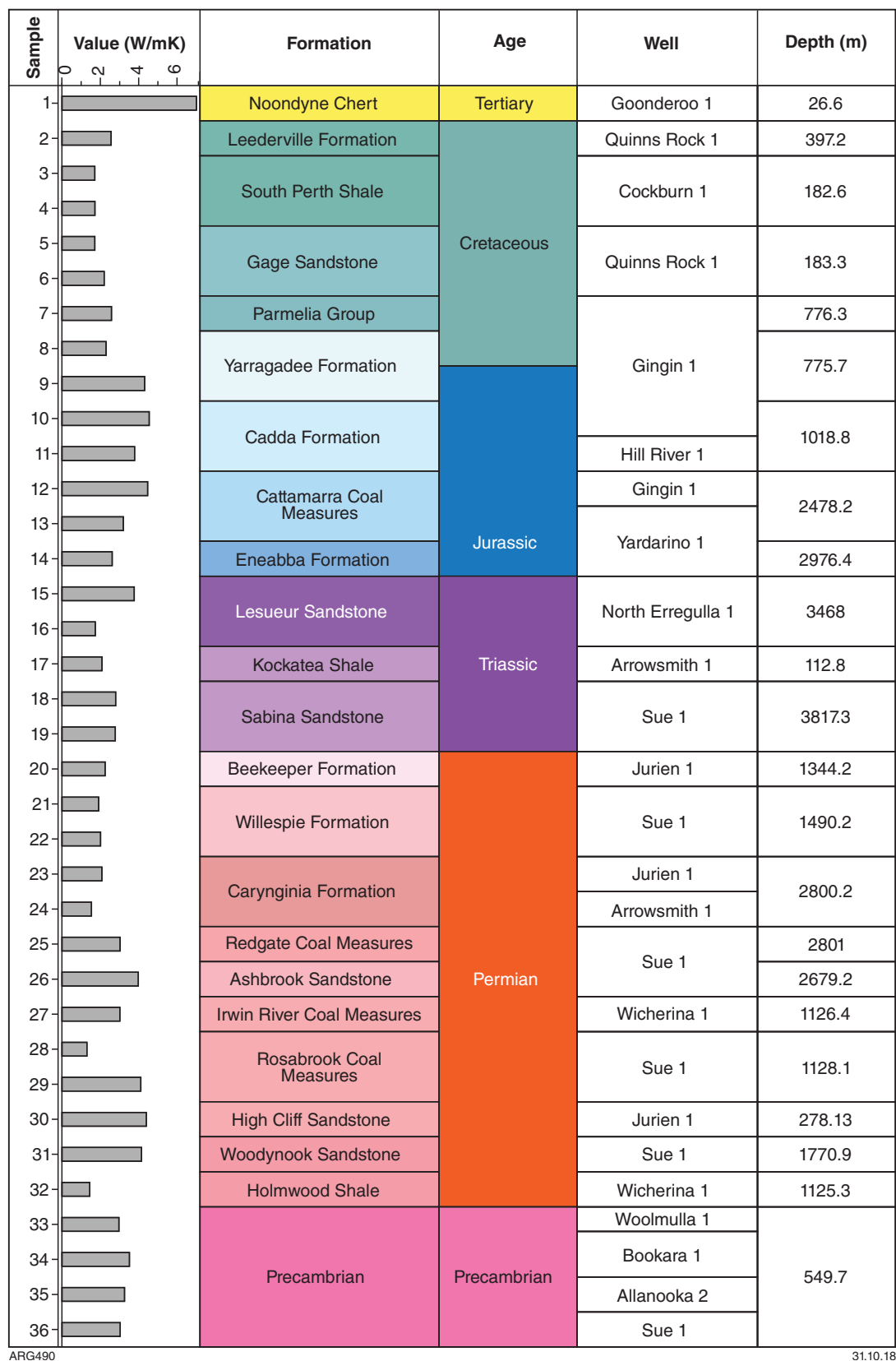


Figure 24. Measured thermal conductivity of rock units in the Perth Basin. Data from Hot Dry Rocks Ltd (2008)

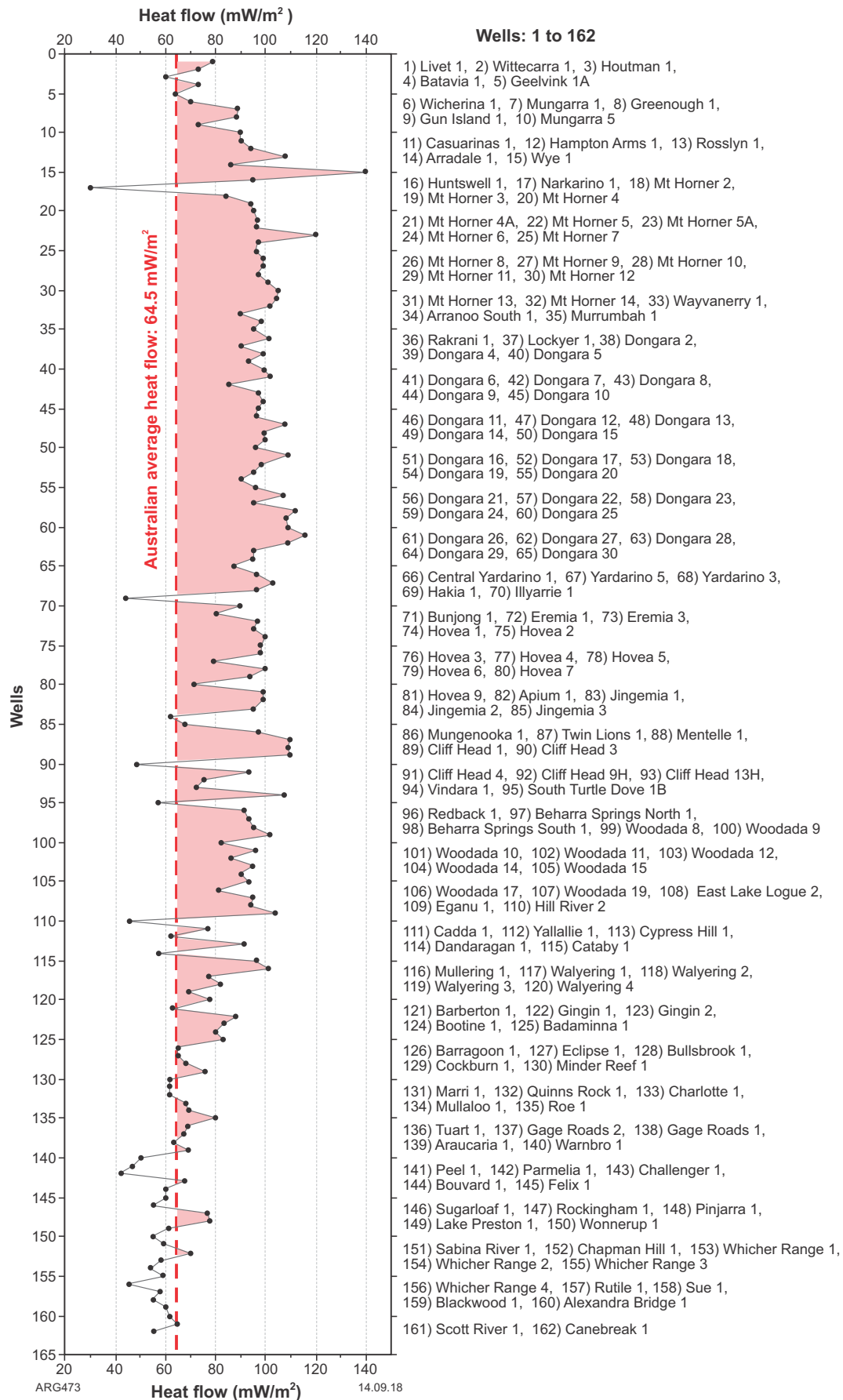


Figure 25. Estimated present-day heat flow in the Perth Basin, based on 1D modelling of well data. Data from Hot Dry Rocks Ltd (2008)

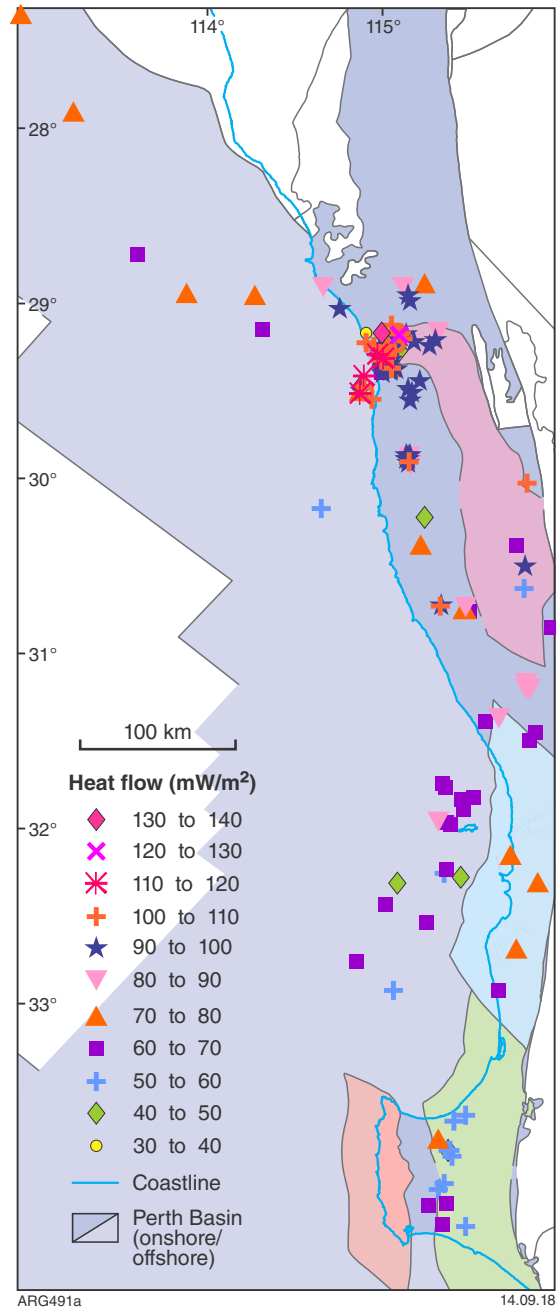


Figure 26. Map of Perth Basin, showing 1D-modelled, present-day heat flow

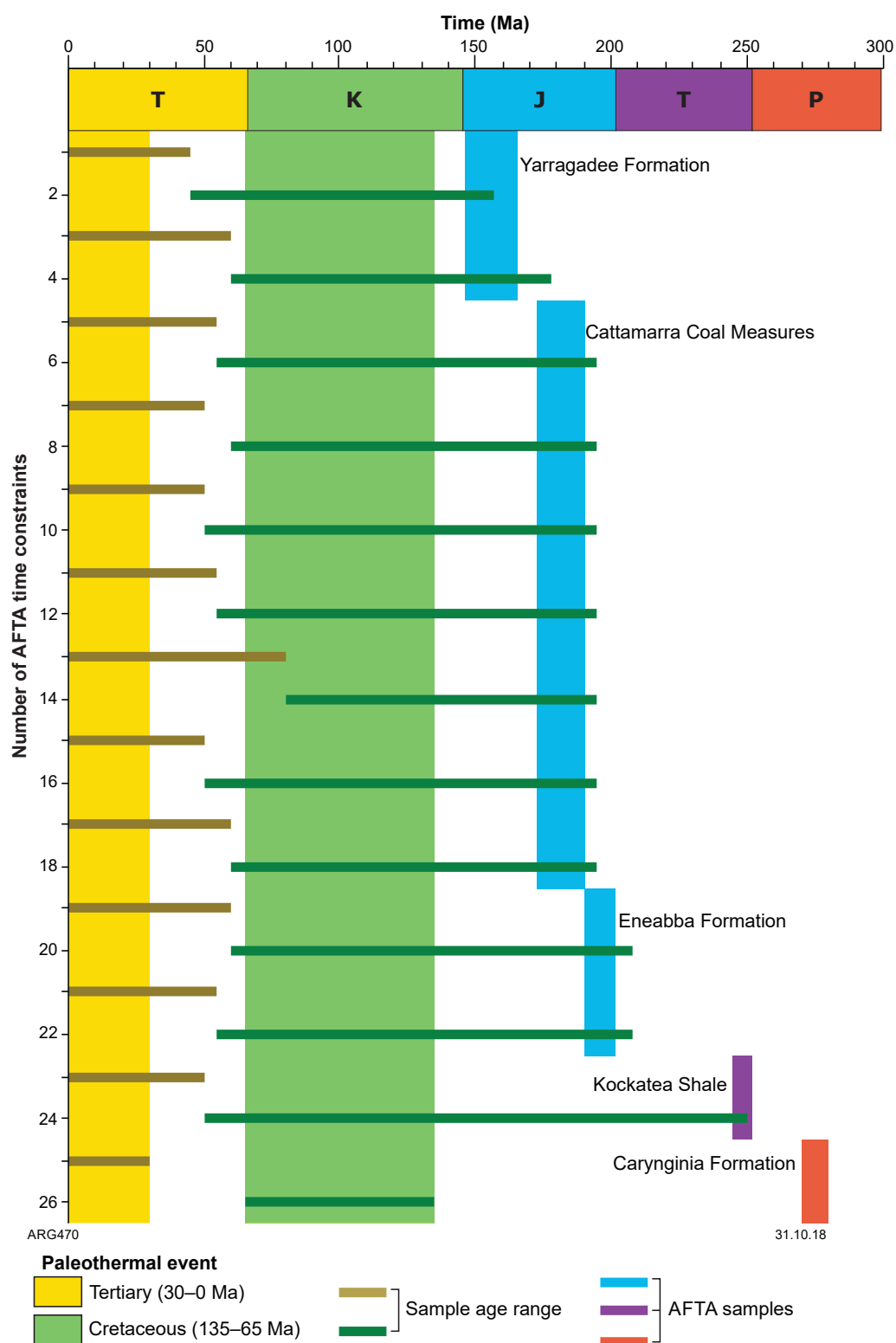


Figure 27. Apatite fission track analysis (AFTA) regional cooling events in the Perth Basin

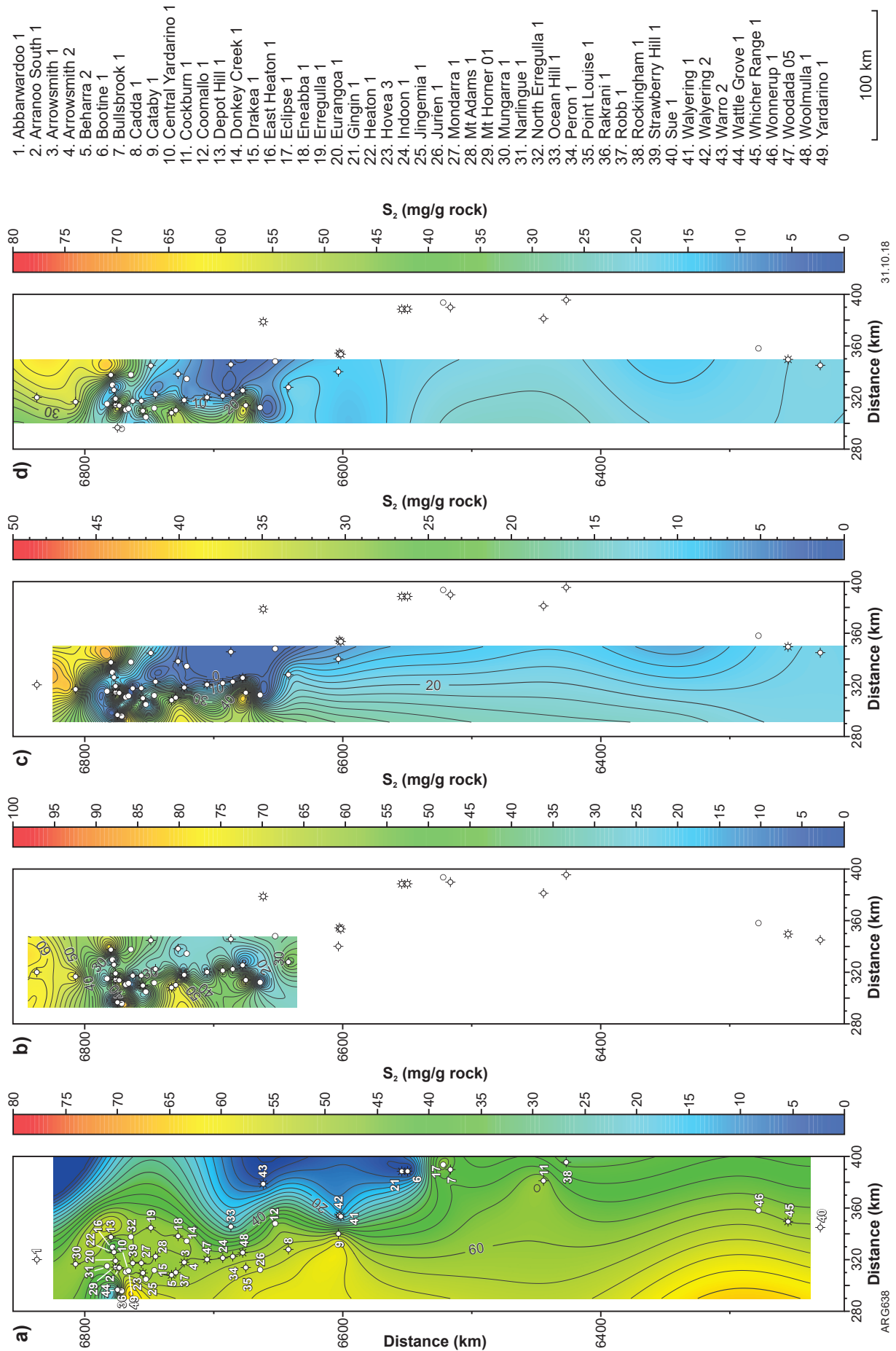


Figure 28. Maps of the Perth Basin, showing the distribution of the generating potential S_2 within the: a) Jurassic Cattamarra Coal Measures; b) Triassic Kockatea Shale; c) Permian Carynginia Formation; d) Permian Irwin River Coal Measures

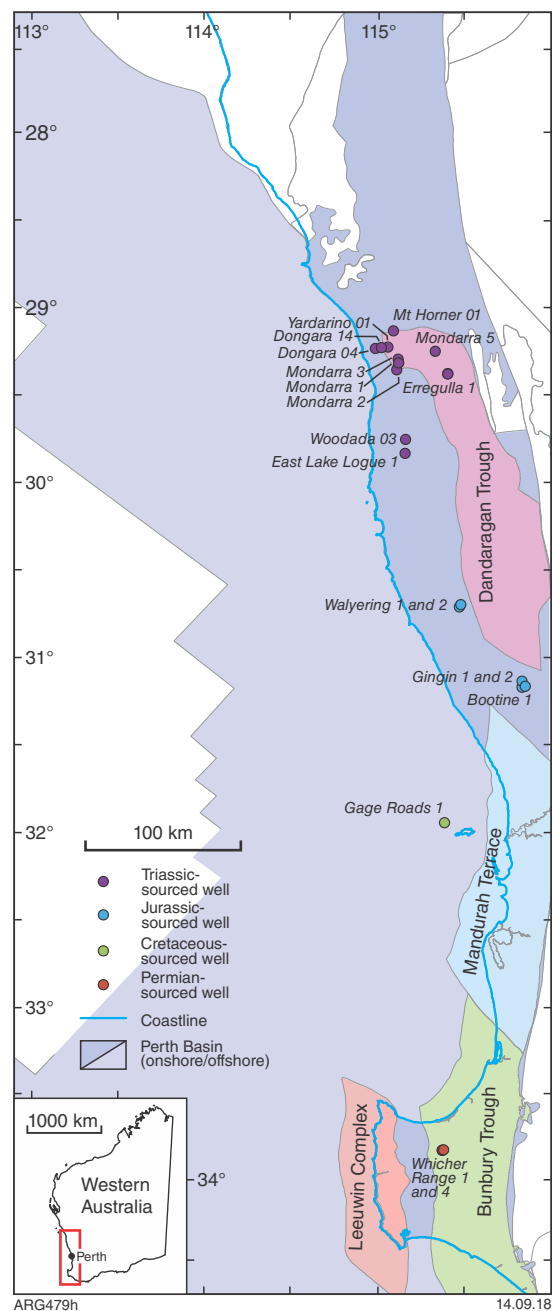


Figure 29. Map of Perth Basin, showing the distribution of petroleum field wells and their petroleum source-rock ages located in the Triassic Kockatea Shale, Jurassic Cattamarra Coal Measures, Permian Carynginia Formation and Irwin River Coal Measures, and Cretaceous source rocks

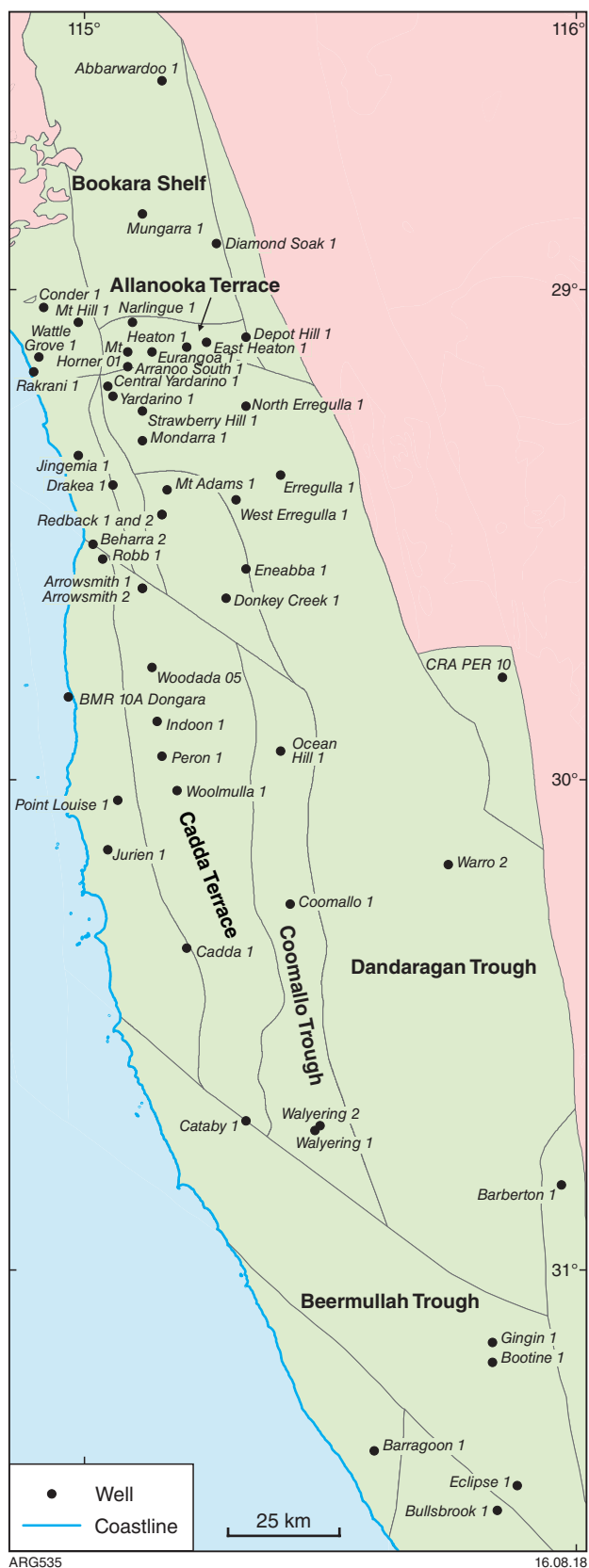


Figure 30. Map of the northern onshore Perth Basin, showing structural elements, selected petroleum wells, and the location of well correlation A–A' shown in Figure 31

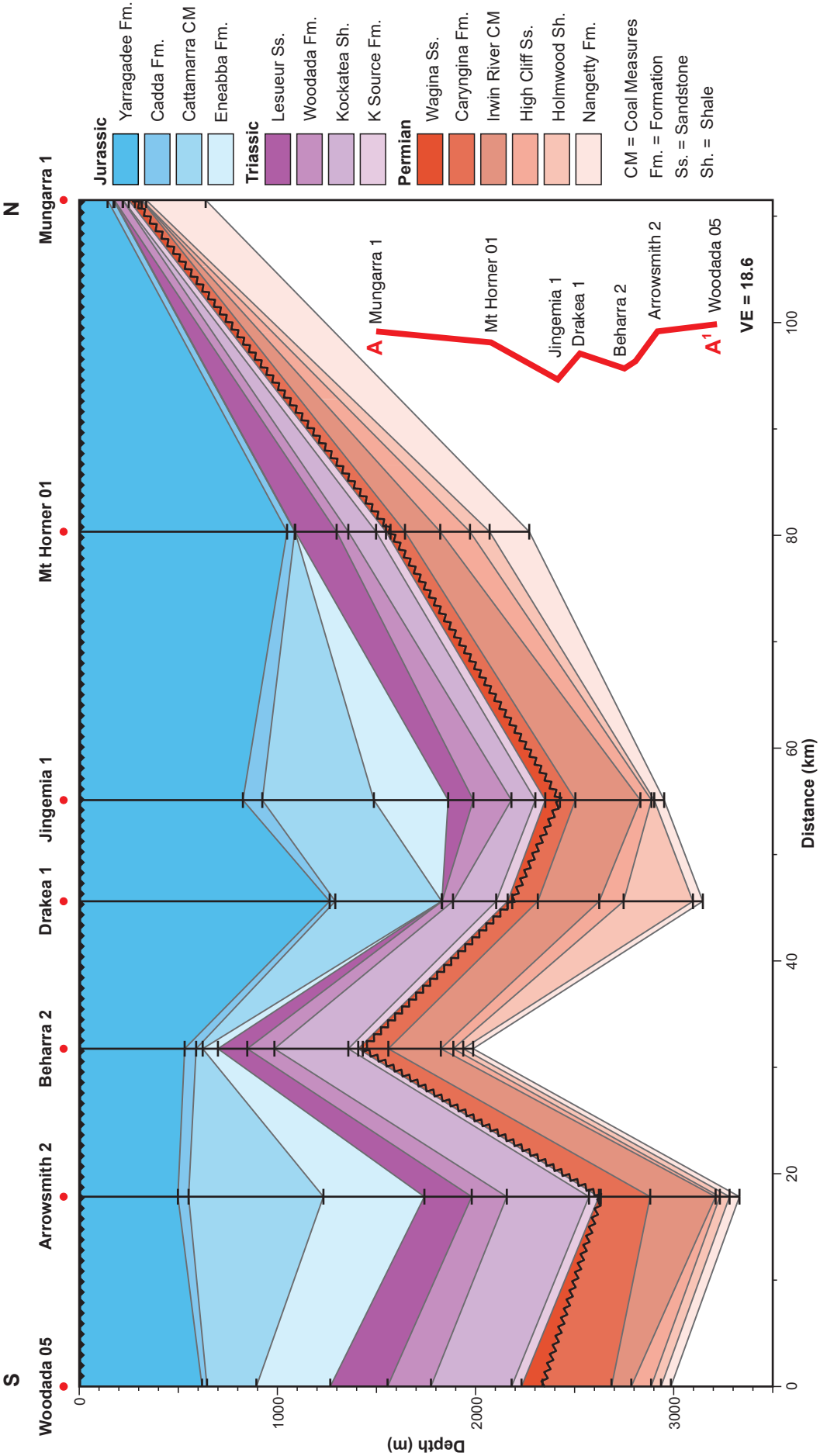


Figure 31. Cross-section A-A' of Figure 30, showing the well correlation from north to south (Mungarra 1 to Woodada 5) and depicting the stratigraphy in the BasinView and 2D BasinMod well models

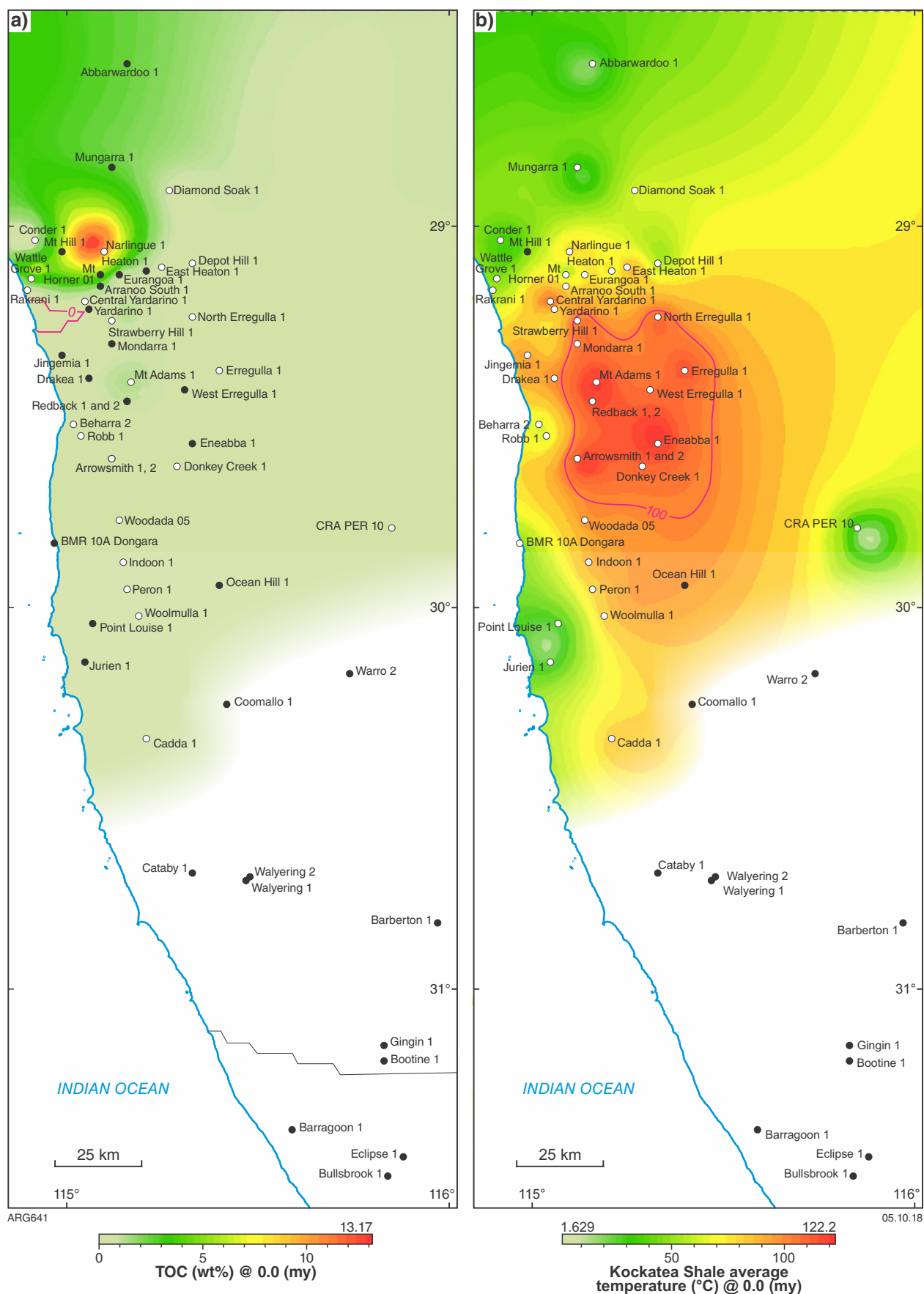


Figure 32. Maps of the Northern onshore Perth Basin based on basin modelling: a) distribution of organic richness, using measured TOC of the Kockatea Shale; b) distribution of the temperature at bottom of the Kockatea Shale. Data wells are represented by white circles

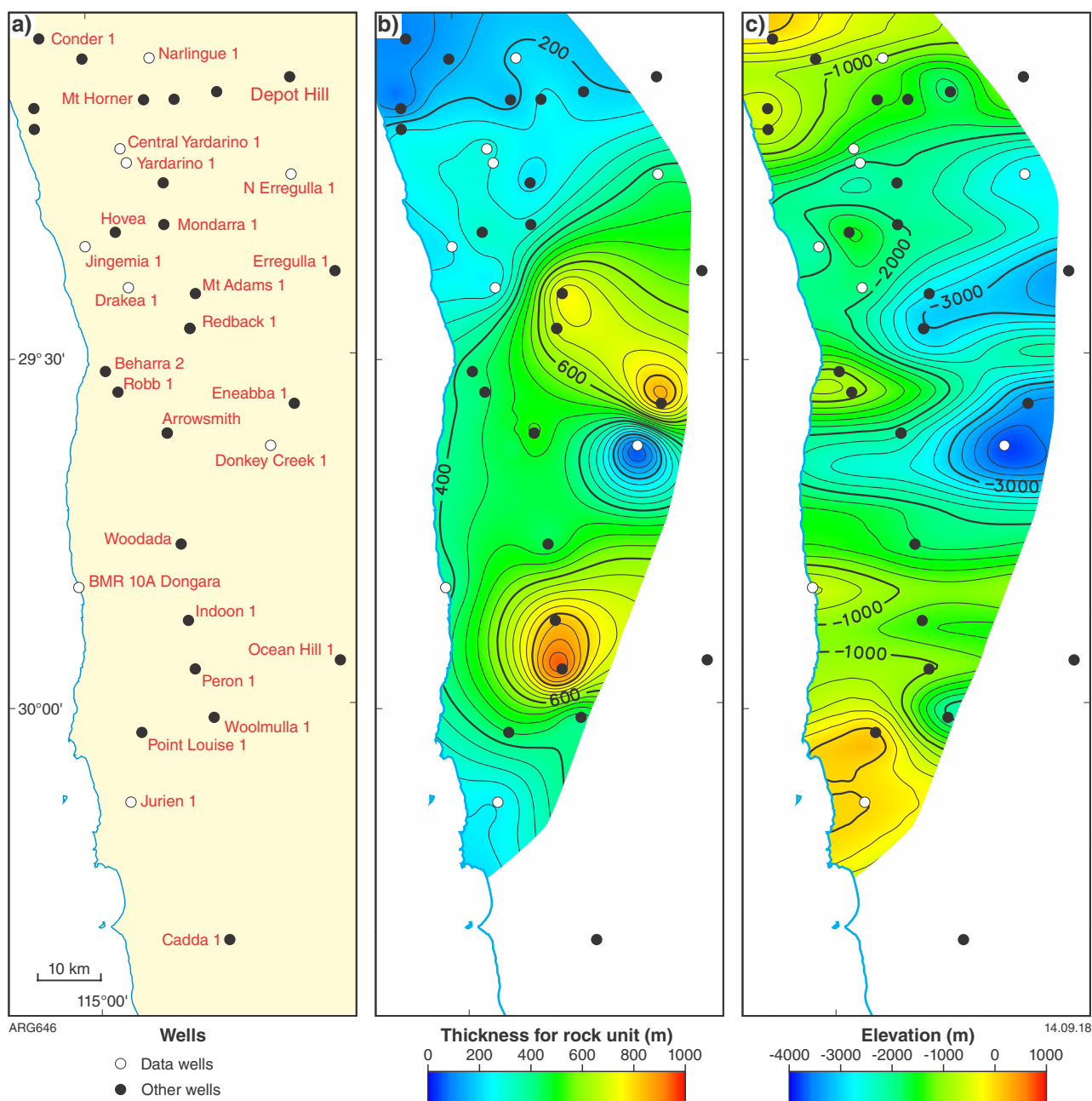


Figure 33. Maps of the Perth Basin, summarizing the Kockatea Shale modelling results: a) location of wells; b) total thickness; c) elevation

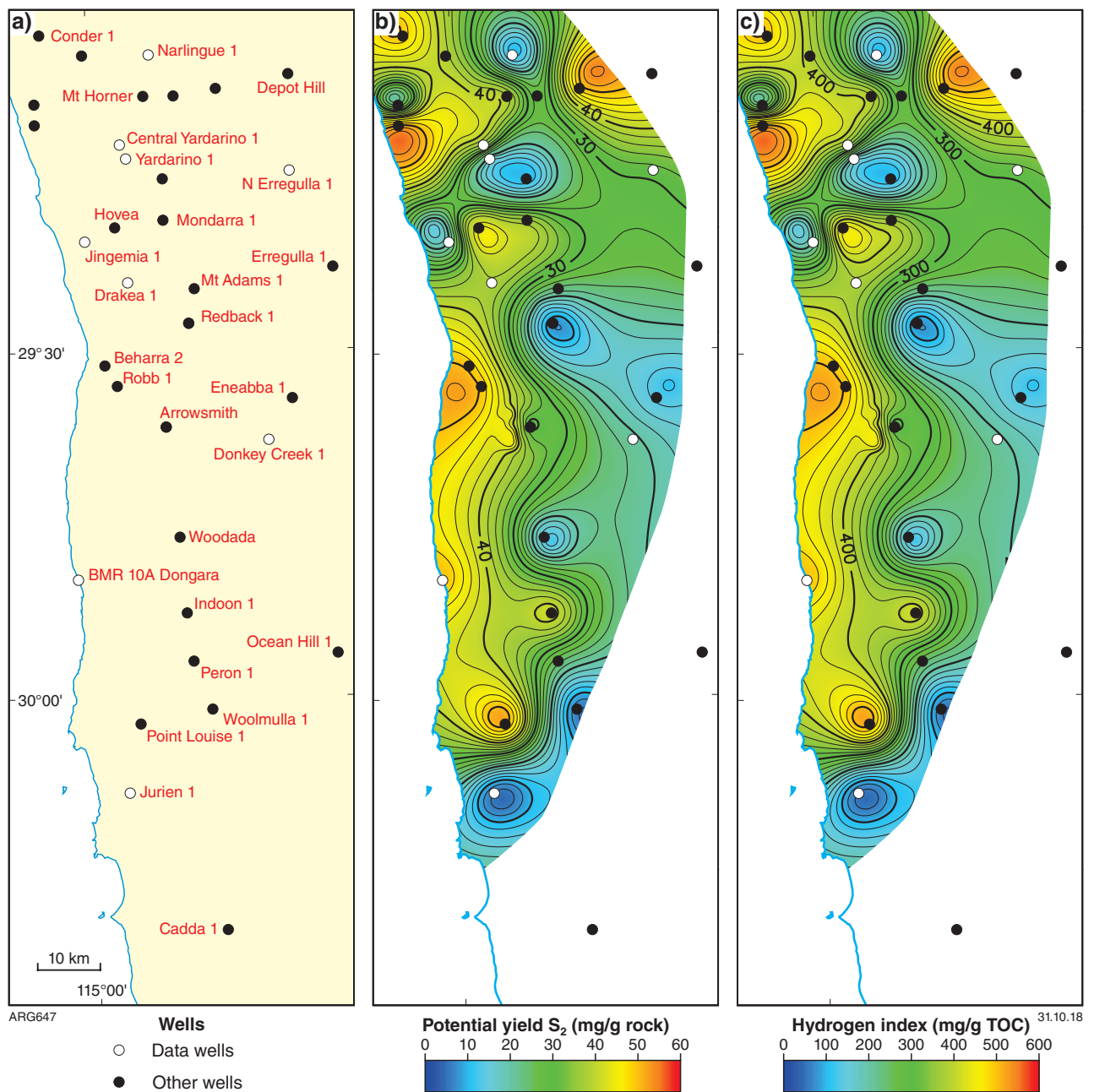


Figure 34. Maps of the Perth Basin, summarizing the Kockatea Shale source-rock potential modelling results: a) location of wells; b) generating potential S_2 ; c) hydrogen index

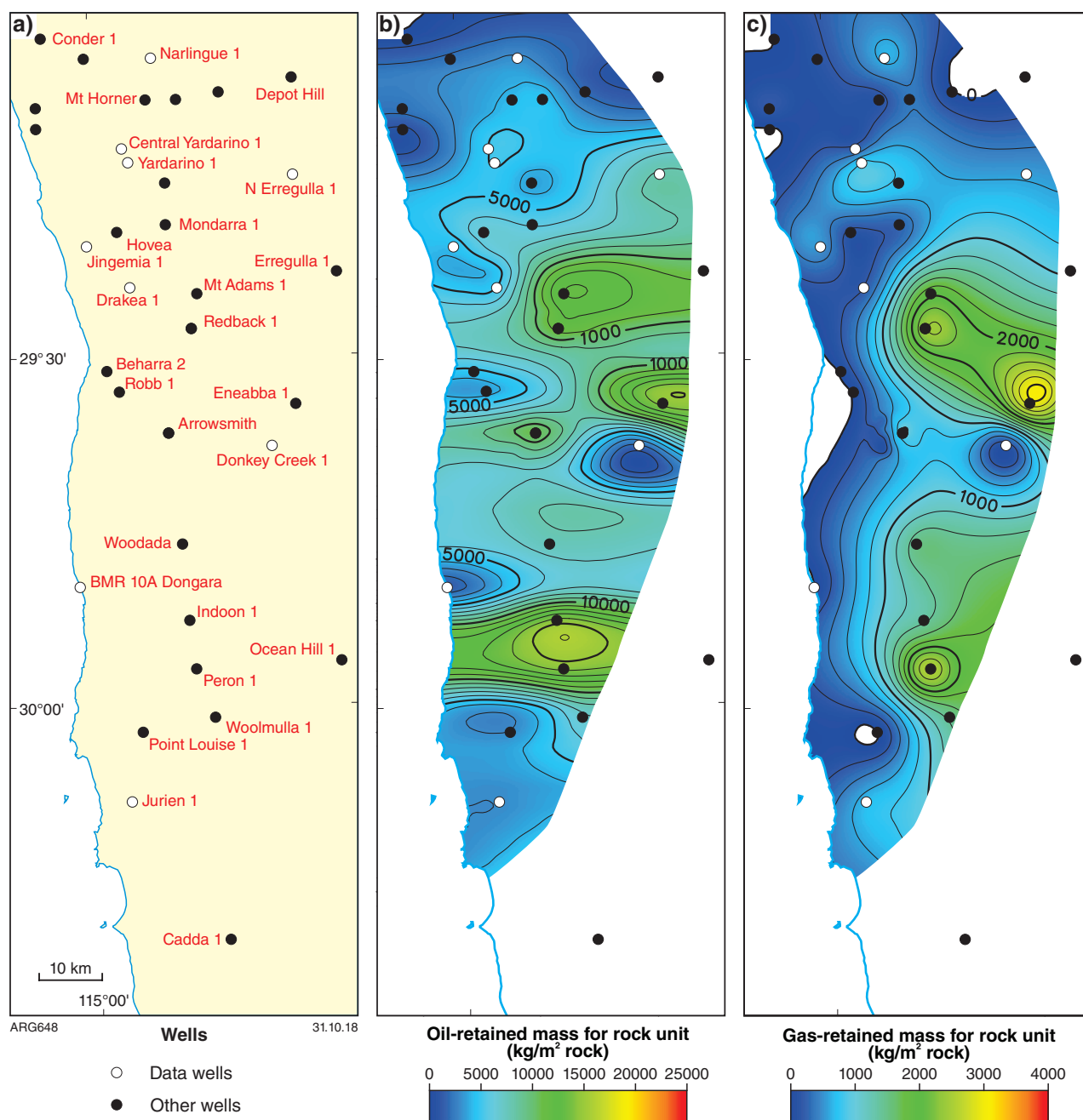


Figure 35. Maps of Perth Basin, summarizing the Kockatea Shale modelled retained hydrocarbons: a) location of wells; b) mass of oil retained per kg/m² of rock; c) mass of gas retained per kg/m² of rock

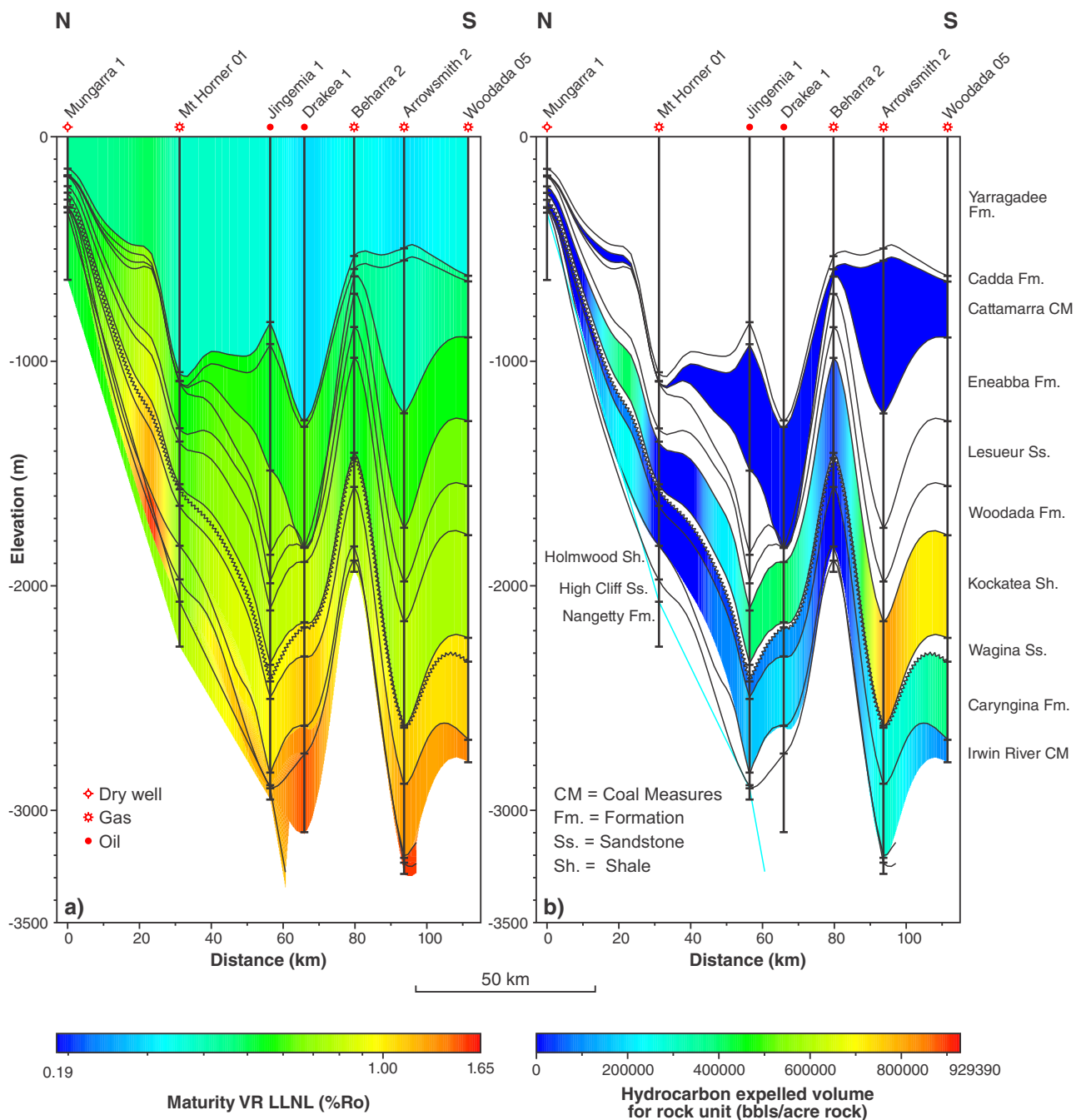


Figure 36. Cross-section A–A' of Figure 30, showing the well correlation from north to south (Mungarra 1 to Woodada 5), depicting:
a) VR maturity; b) expelled hydrocarbon volume of the Jurassic Cattamarra Coal Measures, Triassic Kockatea Shale, and Permian Carynginia Formation and Irwin River Coal Measures source beds. Based on the results of the BasinView modelling, the maximum expulsion was within the Arrowsmith area, followed by the Woodada area. Abbreviation: Maturity VR LLNL, maturity vitrinite reflectance Lawrence Livermore National Laboratory, US

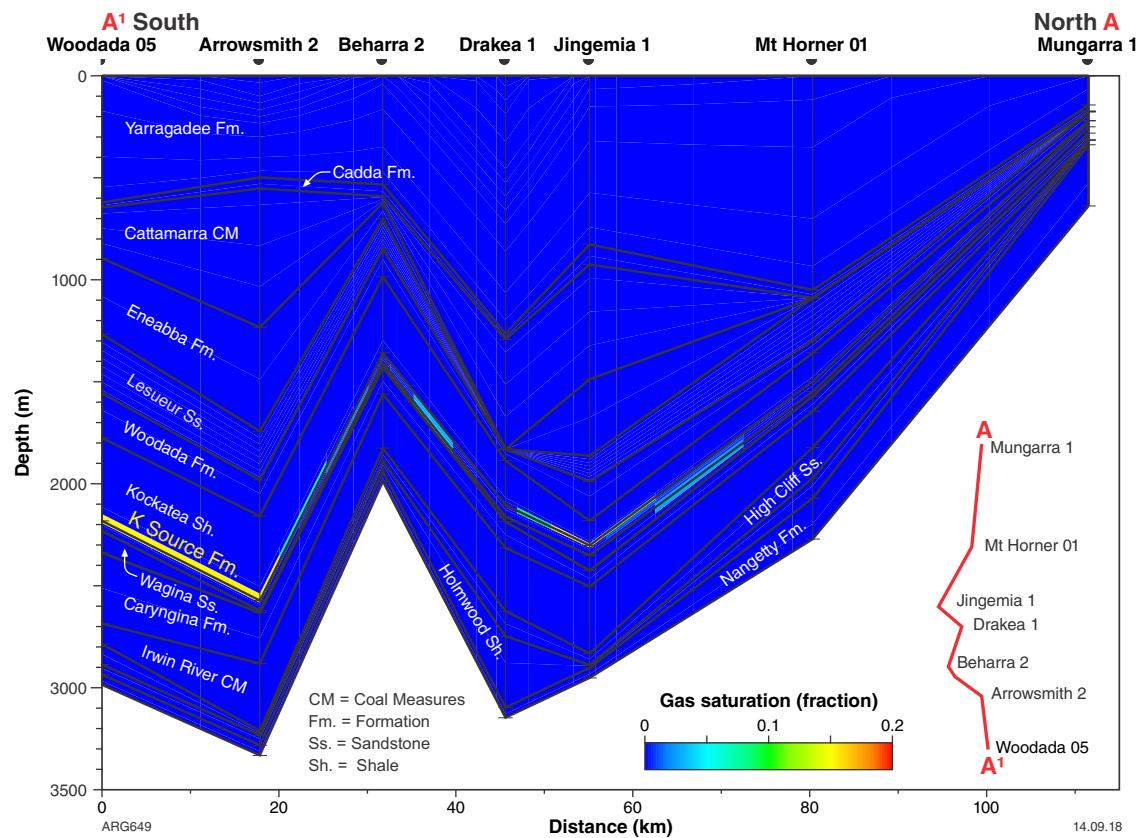


Figure 37. Cross-section A–A¹ of Figure 30, showing the well correlation from north to south well correlation (Mungarra 1 to Woodada 5), depicting present-day gas saturation within the Triassic Kockatea Shale, based on 2D basin modelling

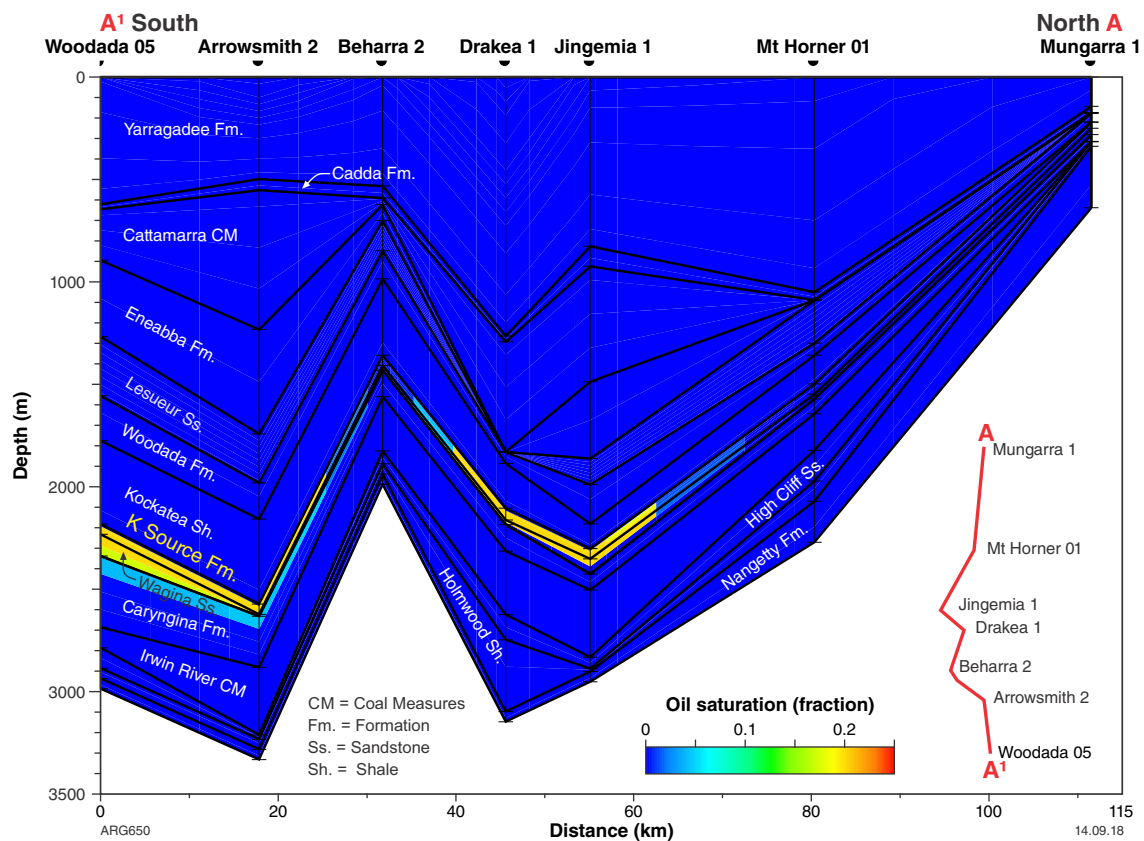


Figure 38. Cross-section A–A¹ of Figure 30, showing the well correlation from north to south (Mungarra 1 to Woodada 5), depicting present-day oil saturation within the Triassic Kockatea Shale, based on 2D basin modelling

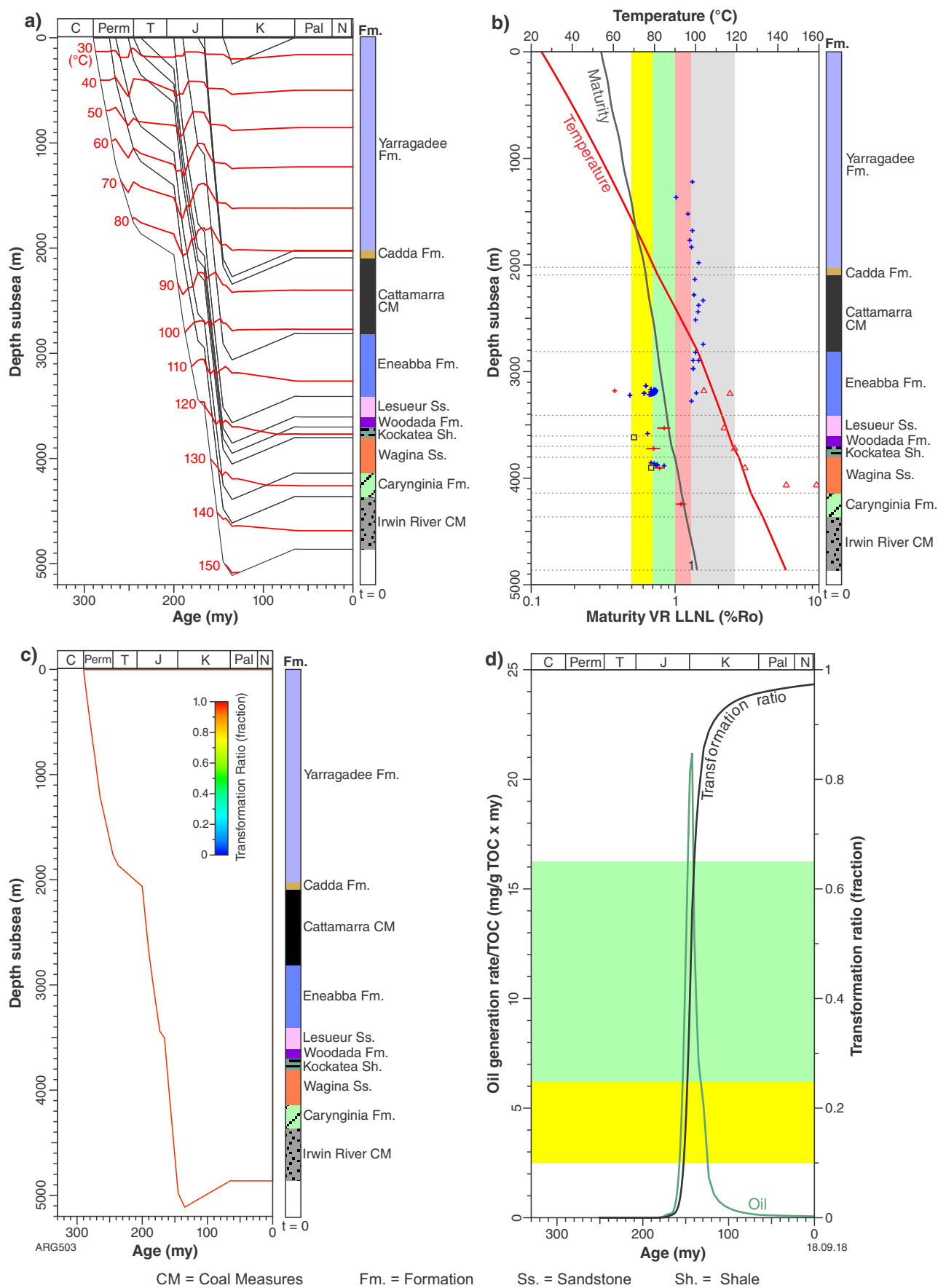


Figure 39. Petroleum system modelling of the Erregulla area (data from Erregulla wells), northern Perth Basin: a) burial history; b) maturity calibration; c) kerogen transformation vs. depth; d) kerogen transformation and oil generation rate vs. time. Abbreviation: Maturity VR LLNL, maturity vitrinite reflectance Lawrence Livermore National Laboratory, US

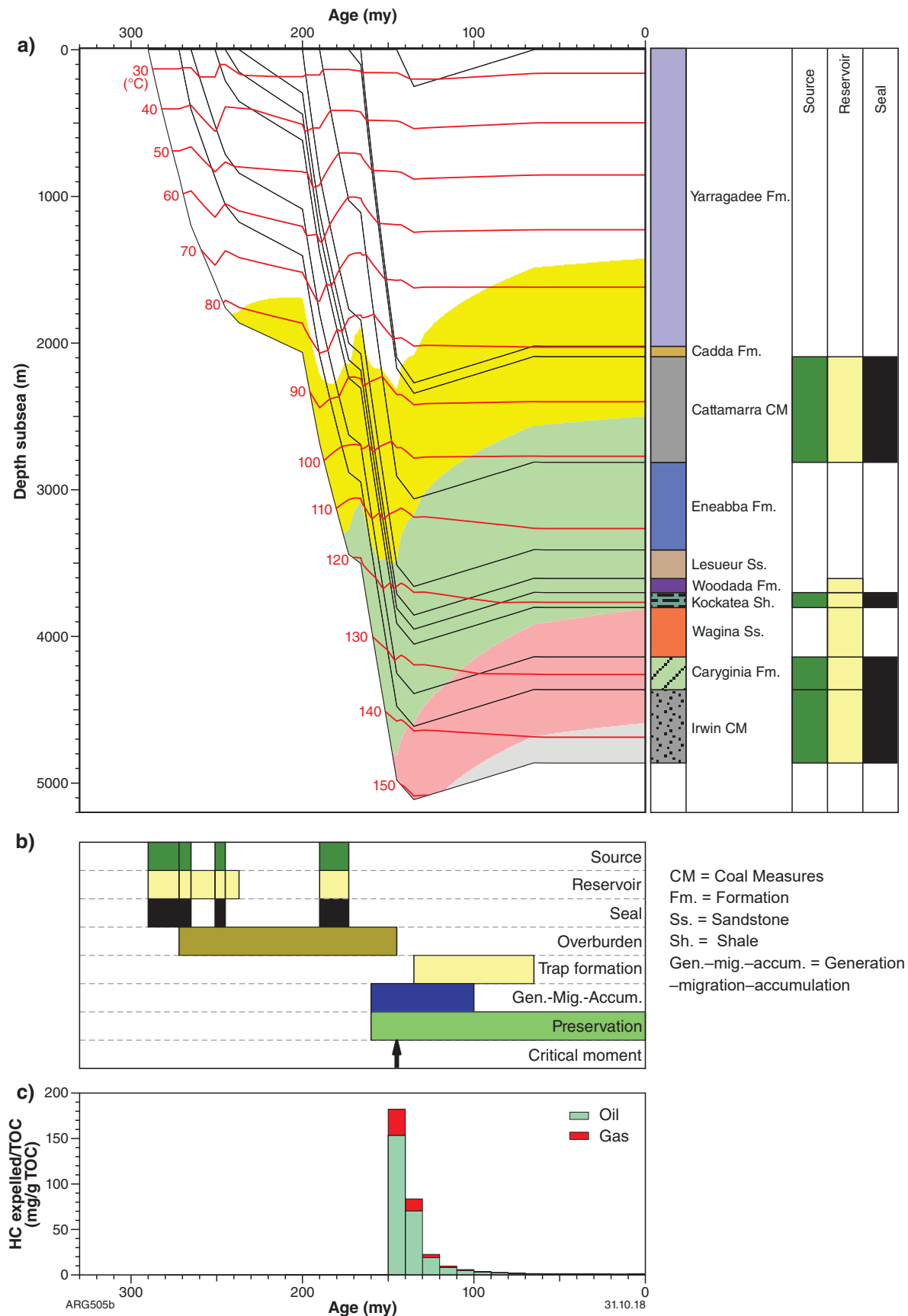


Figure 40. Petroleum system modelling of the Erregulla area (data from Erregulla wells) northern Perth Basin: a) burial history; b) petroleum system elements and timing; c) hydrocarbon expulsion timing from the Latest Permian – Triassic Kockatea Shale source beds

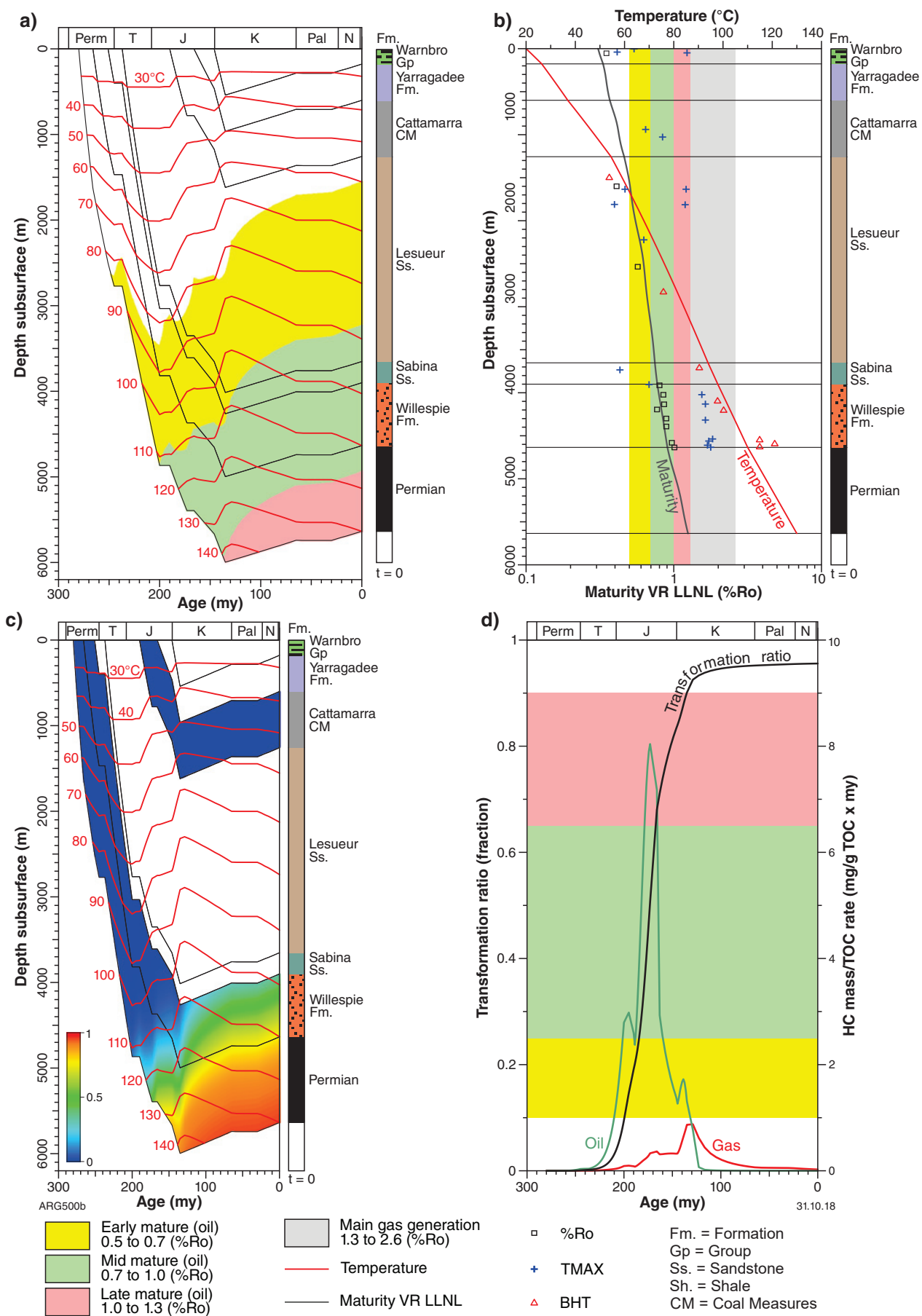


Figure 41. Petroleum system modelling of the Whicher Range area (data from Whicher Range wells) southern Perth Basin: a) burial history; b) maturity calibration c) kerogen transformation vs depth; d) kerogen transformation, oil, and gas generation rate vs time. Maturity VR LLNL, maturity vitrinite reflectance Lawrence Livermore National Laboratory, US

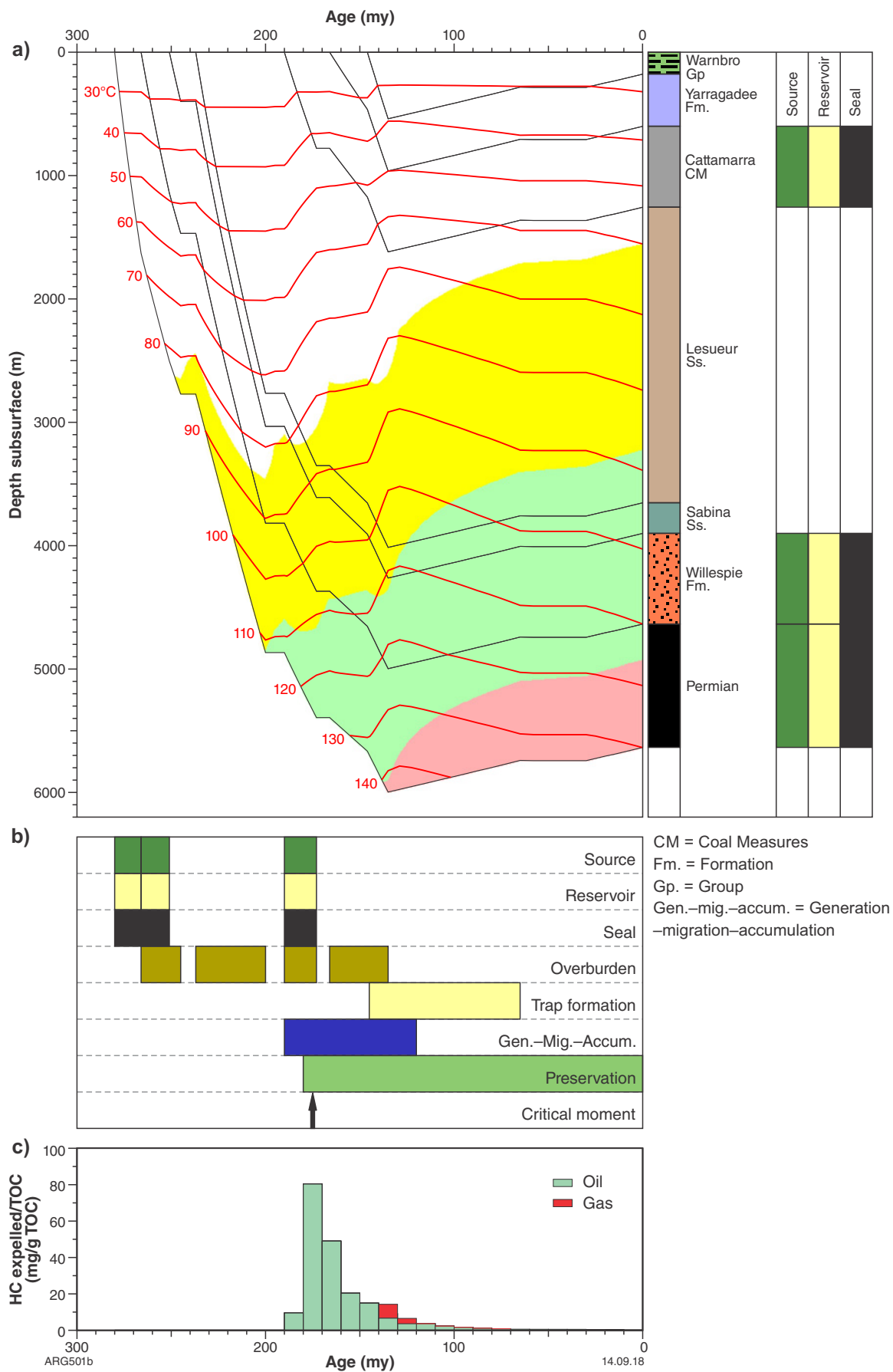


Figure 42. Petroleum system modelling of the Whicher Range area (data from Whicher Range wells) southern Perth Basin: a) burial history; b) petroleum system elements and timing; c) hydrocarbon expulsion timing from the Permian source beds

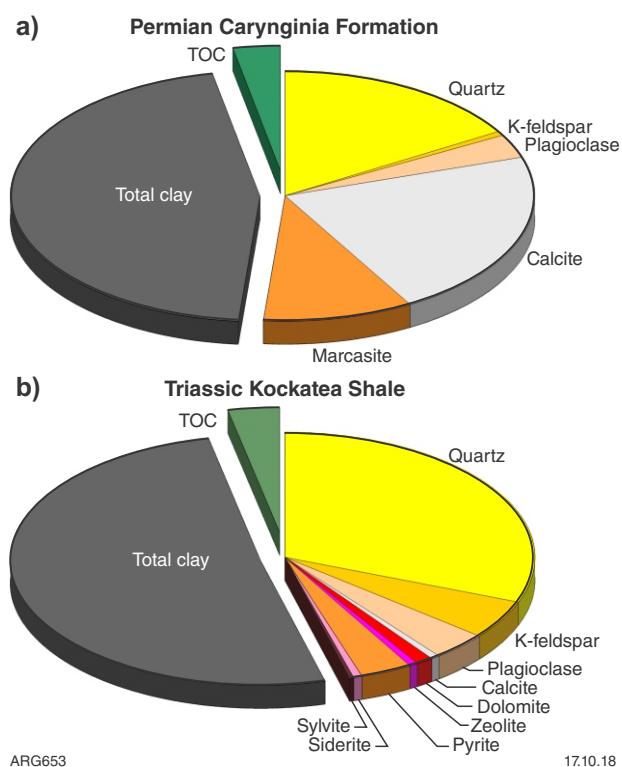
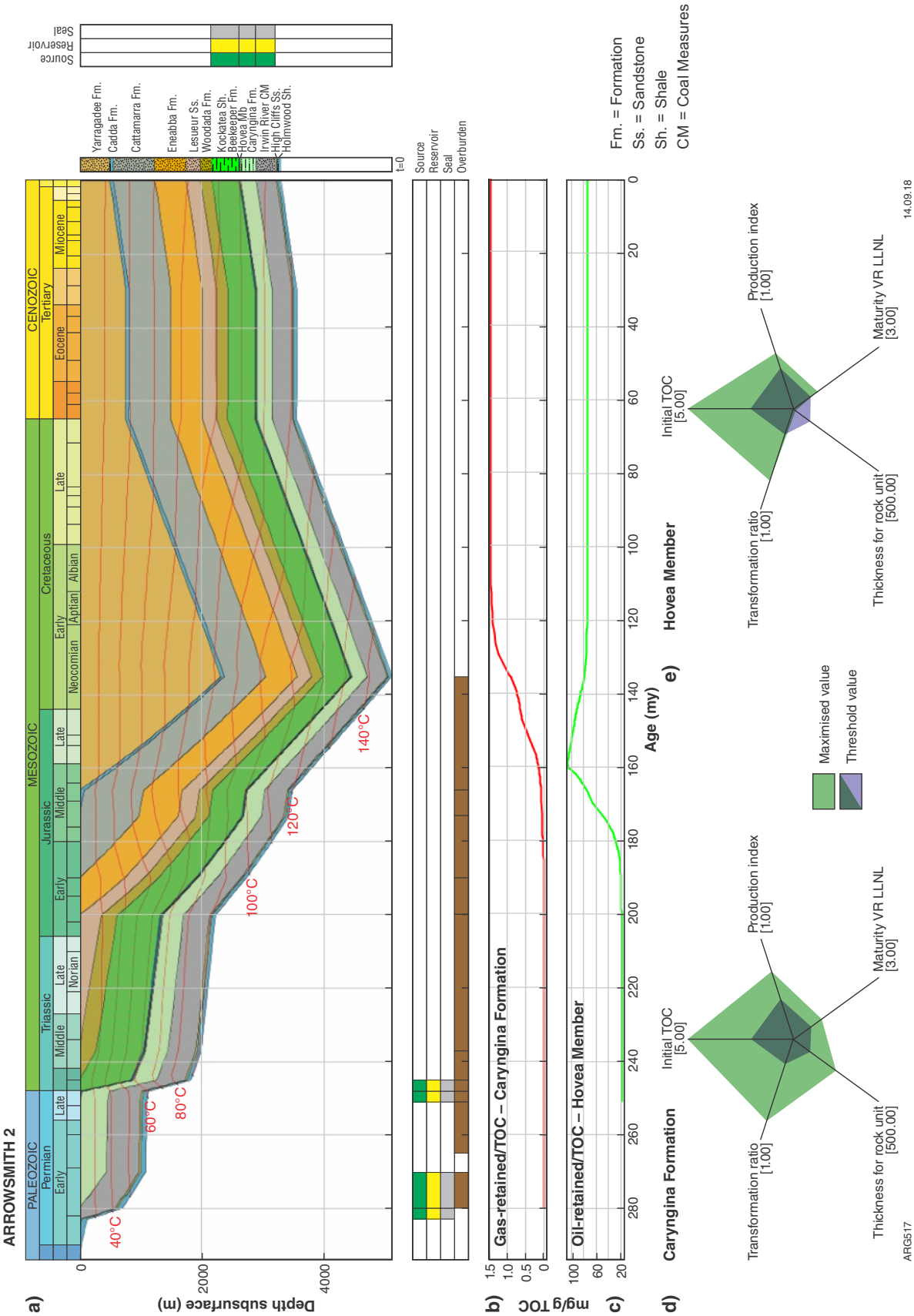


Figure 43. Summary of the mineral, clay, and kerogen content of: a) Permian Carynginia Formation; b) Triassic Kockatea Shale. These components are the key factors in characterizing shale reservoirs for fraccing (data from CoreLab, 2013)



APPENDICES

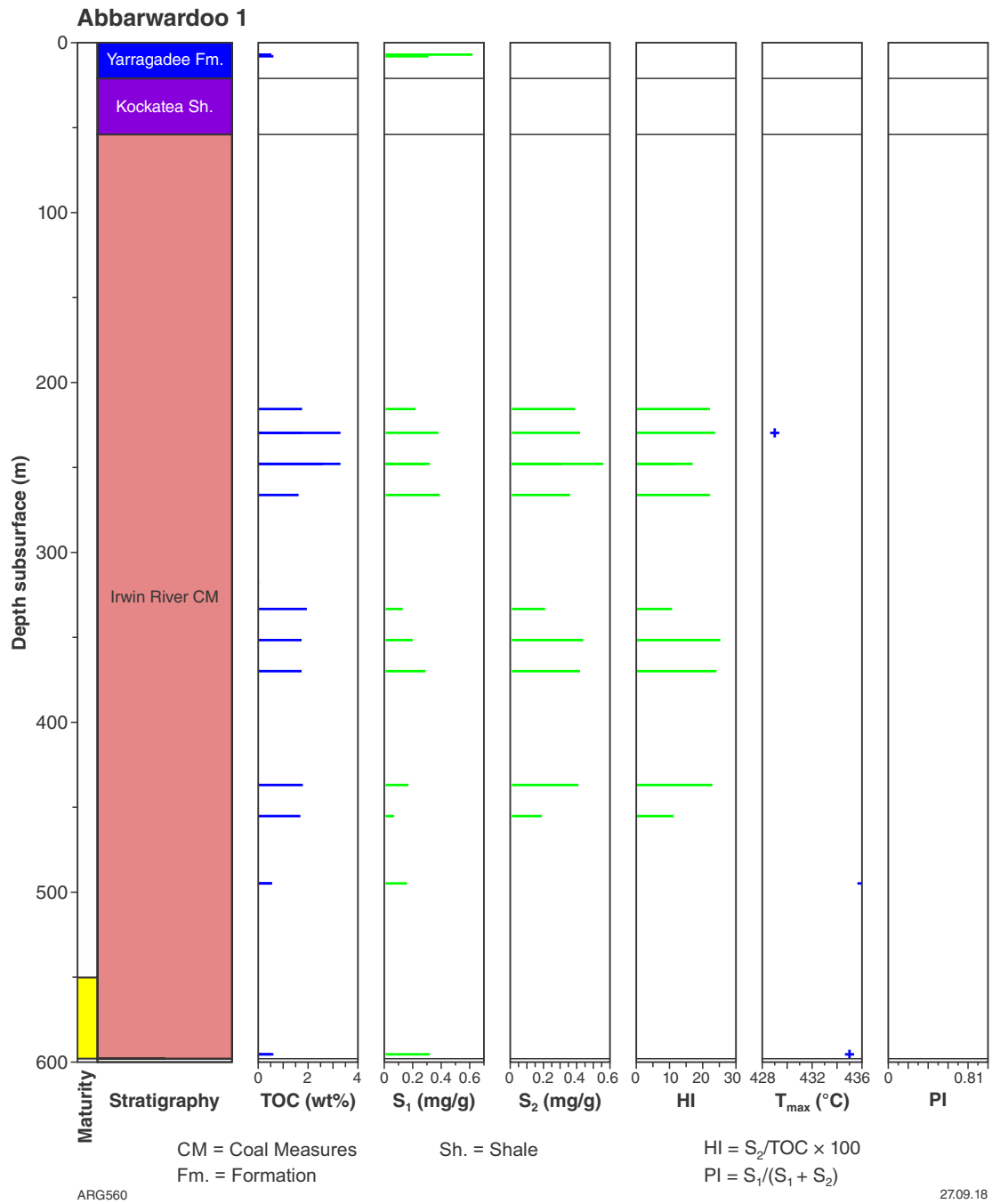
Appendix 1

REESA (Rock Eval Expert System Analysis) rules are used to filter out unreliable data. The rules were developed by Peter E Kenneth, Chevron Overseas Petroleum Inc. and David A Nelson of Chevron Corporation. These rules also apply to Appendix 2

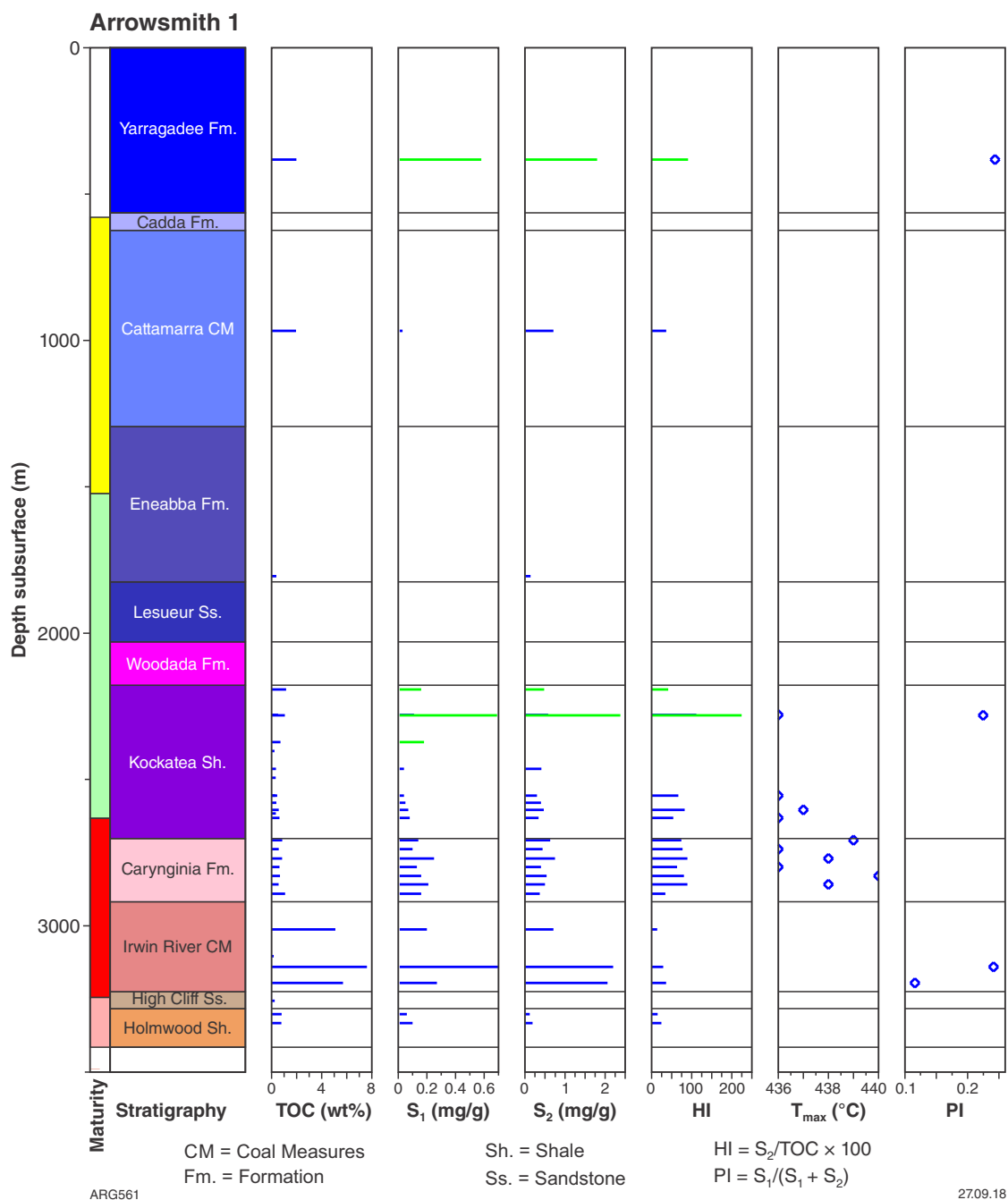
Rule 1	Reject T_{\max} if $T_{\max} = 0.0$
Rule 2	Reject T_{\max} if S_2 is less than tolerance (default 0.2 mg HC/g rock). This rule changes according to the precision of measurement of S_2
Rule 3	If TOC is less than tolerance (default 0.4 wt%), then reject T_{\max} , S_2/S_3 , HI, and OI. When TOC is not measured, rules rejecting T_{\max} based on low TOC are suppressed
Rule 4	If T_{\max} is below tolerance (default 395°C), reject T_{\max}
Rule 5	Reject PI if $(S_1 + S_2)$ less than tolerance (default 2 mg HC rock). This rule changes according to the precision of the measurement of S_1 , S_2 , and S_3
Rule 6	Reject T_{\max} if HI < tolerance (default 50 mg HC/g TOC), and TOC is greater than tolerance (default 1.0)
Rule 7	Reject HI if HI > tolerance (default 1100 mg HC/g TOC)
Rule 8	Reject OI if OI > tolerance (default 300 mg CO ₂ /g rock)
Rule 9	Reject all if depth > tolerance (default 20 000 ft)
Rule 10	All numerical values are user-changeable tolerances if $T_{\max} < 435^\circ\text{C}$, and if $PI > 0.2$, or if $((S_1/\text{TOC}) \times 1000) > 300$, or if $(S_1/S_2) > 0.3$, then: reject T_{\max} and flag S_1 , T_{\max} migrated
Rule 10b	Same conditions as Rule 10 and if $S_1 > \text{tolerance}$ (default 1 mg HC/g rock), accept PI and flag PI migrated
Rule 10c	Same conditions as Rule 10 and If TOC > tolerance (default 1 wt%) and $S_1 < \text{tolerance}$ (default 1 mg HC/g rock), accept HI, S_2 , OI, S_2/S_3 and flag HI, S_2 , OI, and S_2/S_3 migrated
Rule 10d	Same conditions as Rule 10 and: if TOC < tolerance (default 1 wt%), reject HI, S_2 , OI, S_2/S_3 and flag HI, S_2 , OI, and S_2/S_3 migrated
Rule 10e	Same conditions as Rule 10 and: if TOC > tolerance (default 1 wt%) and $S_1 > \text{tolerance}$ (default 1 mg HC/g rock), reject HI, S_2 , OI, and S_2/S_3
Rule 11	All numerical values are user-changeable tolerances: for $435^\circ\text{C} < T_{\max} < 460^\circ\text{C}$ and if $PI > 0.4$, then:
Rule 11a	Reject T_{\max} and flag S_1 , T_{\max} migrated
Rule 11b	Same conditions as Rule 11 and if $S_1 > \text{tolerance}$ (default 1 mg HC/g rock), accept PI and flag PI migrated
Rule 11c	Same conditions as Rule 11 and if TOC > tolerance (default 1 wt%) and $S_1 < \text{tolerance}$ (default 1 mg HC/g rock), accept HI, S_2 , OI, and S_2/S_3 and flag HI, S_2 , OI, and S_2/S_3 migrated
Rule 11d	Same conditions as Rule 11 and: if TOC < tolerance (default 1 wt%), reject HI, S_2 , OI, and S_2/S_3 and flag HI, S_2 , OI, and S_2/S_3 migrated
Rule 11e	Same conditions as Rule 11 and: if TOC > tolerance (default 1 wt%) and $S_1 > \text{tolerance}$ (default 1 mg HC/g rock), reject HI, S_2 , OI, and S_2/S_3
Rule 12a	If a sample T_{\max} is greater than 460°C and the following five sample T_{\max} values are smaller, then the sample T_{\max} is rejected
Rule 12b	If a sample T_{\max} is less than 435°C and the preceding five sample T_{\max} values are larger, then the sample T_{\max} is rejected
Rule 13	Reject T_{\max} if its value differs more than 8°C from current least squares regression line
Rule 14	Three-step method for calculating maturation:
Rule 14a	Select depth range covered by a line of best fit between accepted T_{\max} values of 435 and 460°C. Calculate average accepted HI in this depth range. If average HI in this range is >250 mg HC/g TOC, then top oil window is set to 445°C. If less than 250 mg HC/g TOC, then top oil window is set to 435°C
Rule 14b	Calculate the line of best fit for accepted PI in the depth range covered by the best fit line between accepted T_{\max} values of 435 and 460°C. Define top oil window where $PI = 0.1$
Rule 14c	Compare the best fit values for top of oil window based on T_{\max} (Step 1) and PI (Step 2). If they are within 2000 feet apart, then average or accept the value determined from the line of best fit, showing the least standard deviation

Appendix 2

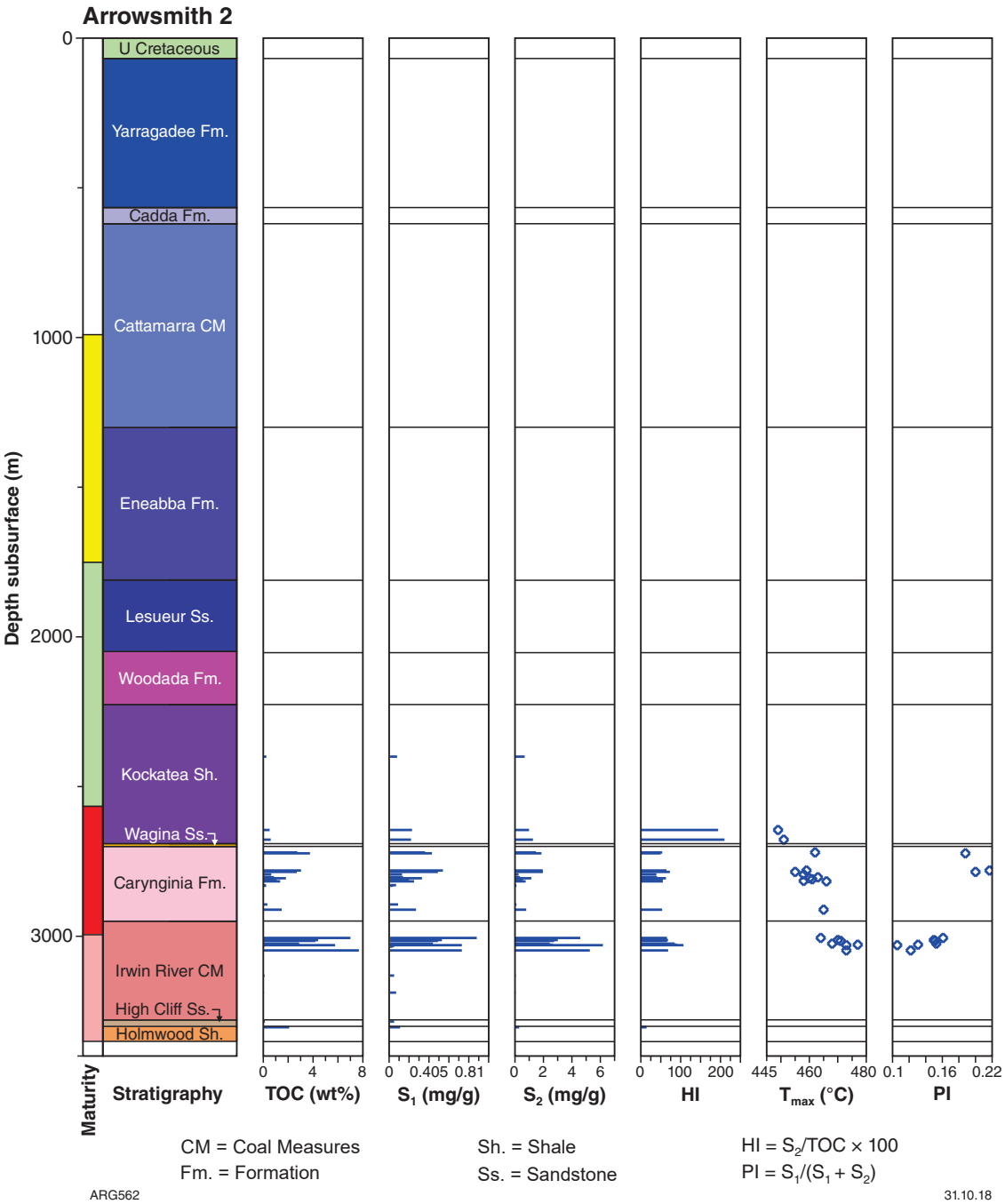
Geochemical logs of TOC and Rock-Eval data for 60 wells



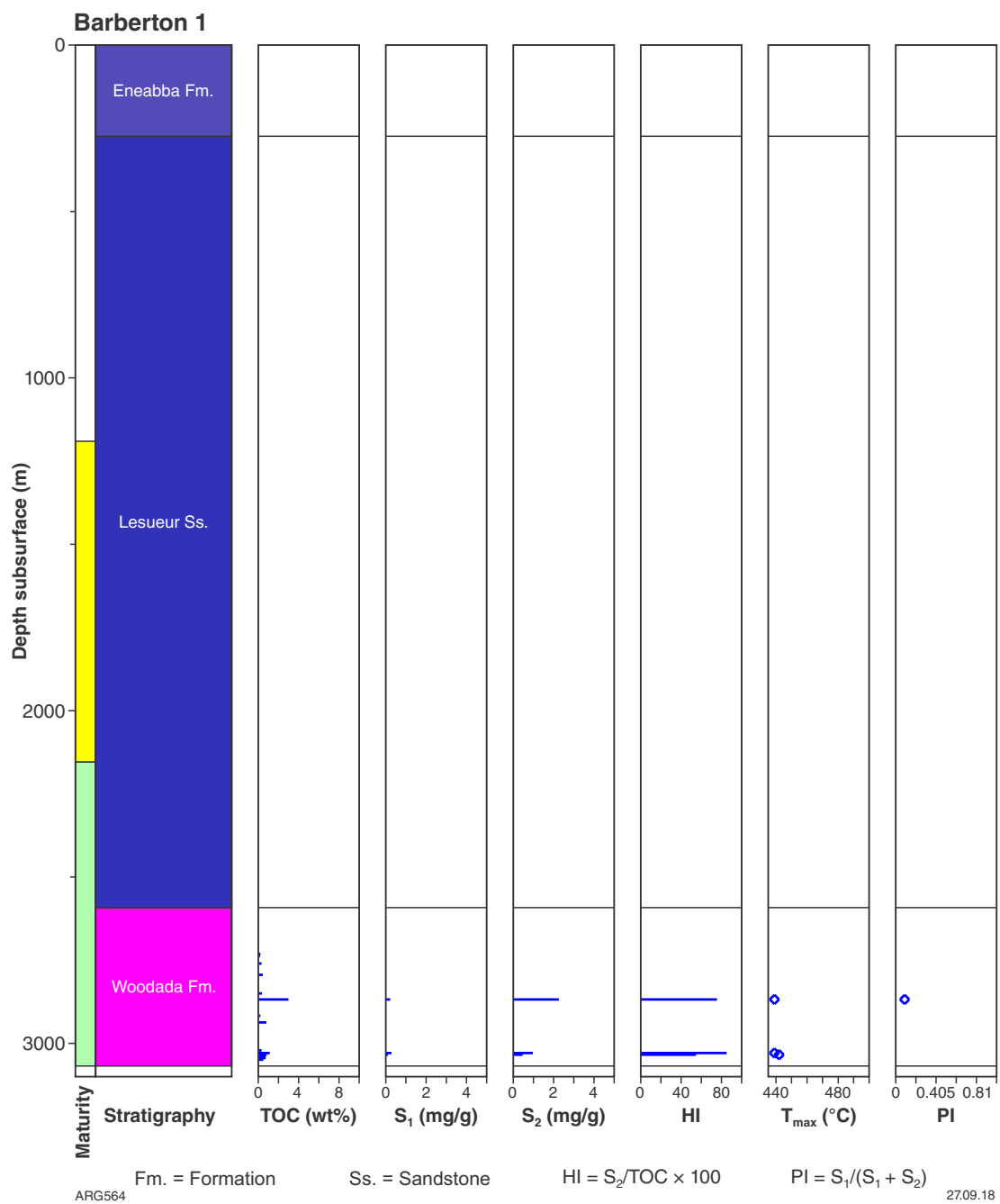
Appendix 2.1. Abbarwardoo 1 geochemical log of TOC and Rock-Eval pyrolysis data



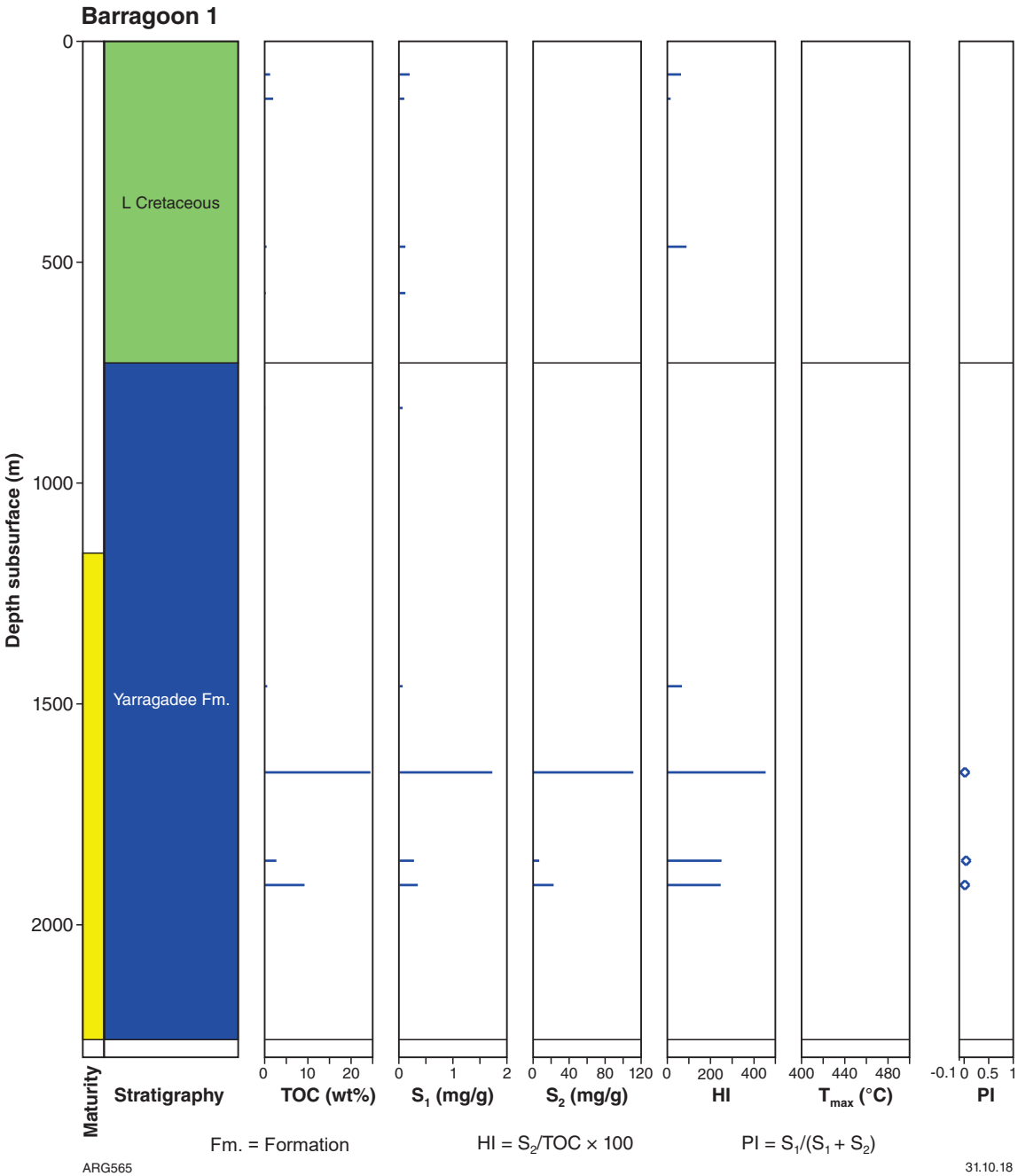
Appendix 2.2. Arrowsmith 1 geochemical log of TOC and Rock-Eval pyrolysis data



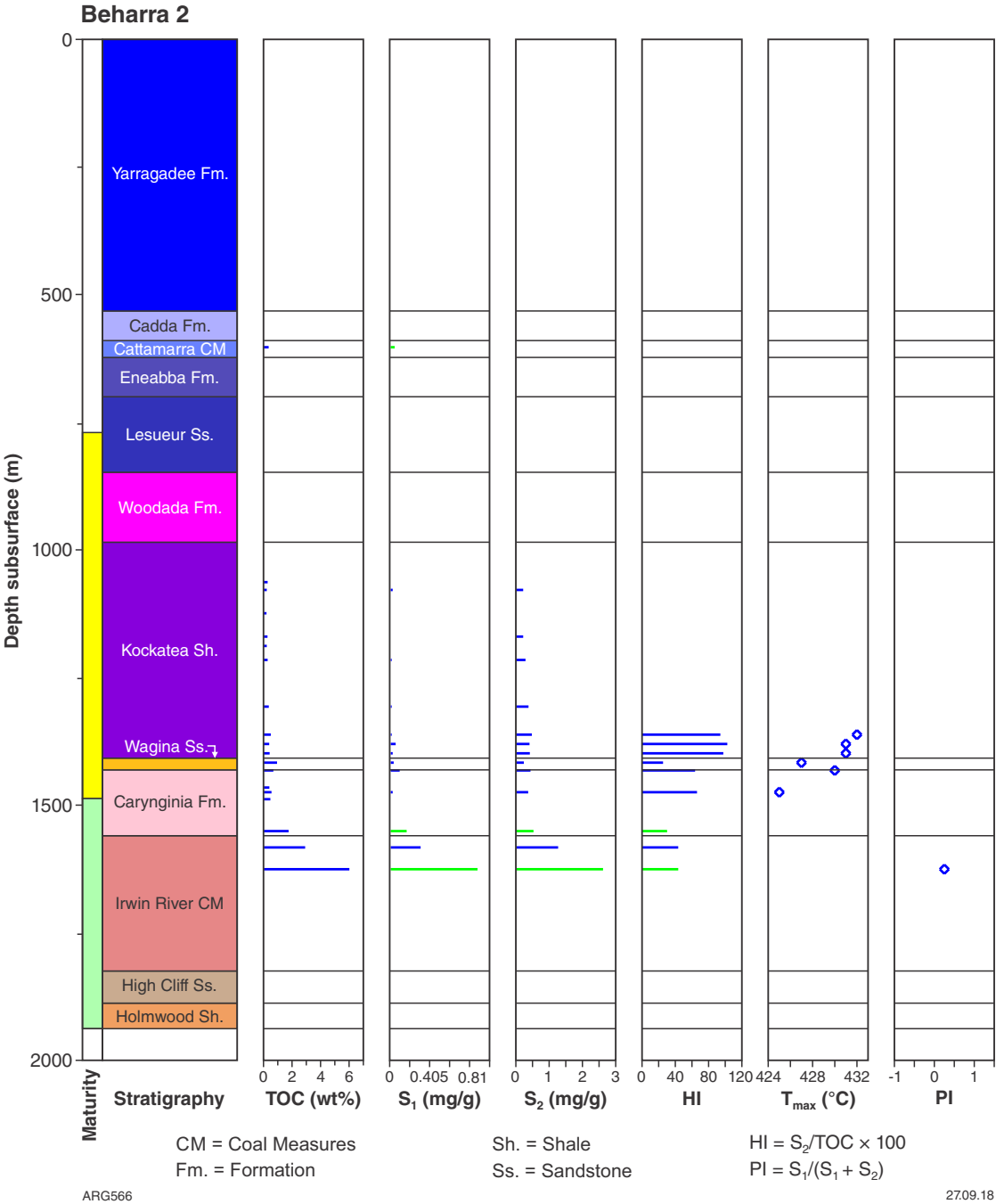
Appendix 2.3. Arrowsmith 2 geochemical log of TOC and Rock-Eval pyrolysis data



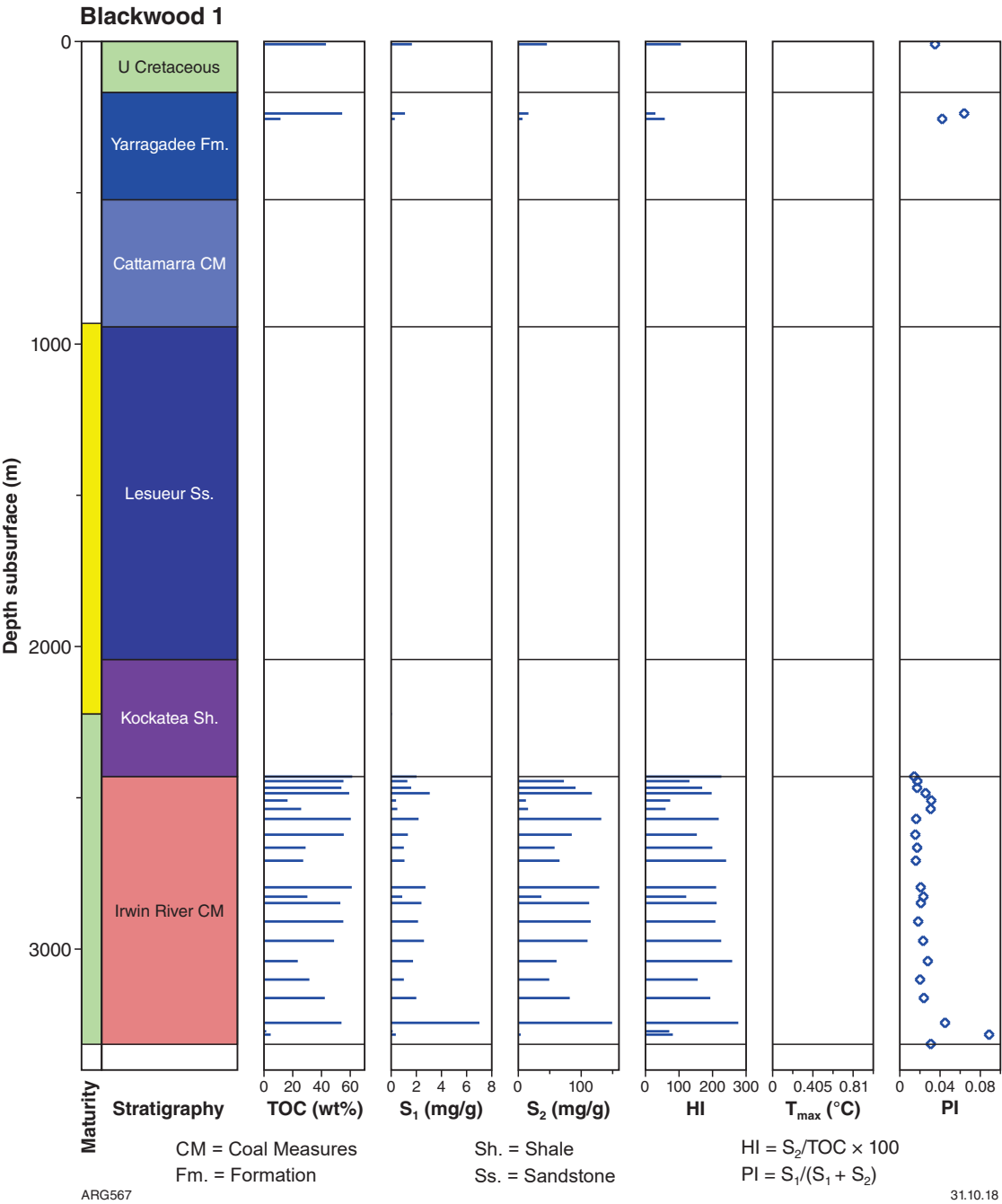
Appendix 2.4. Barberton 1 geochemical log of TOC and Rock-Eval pyrolysis data



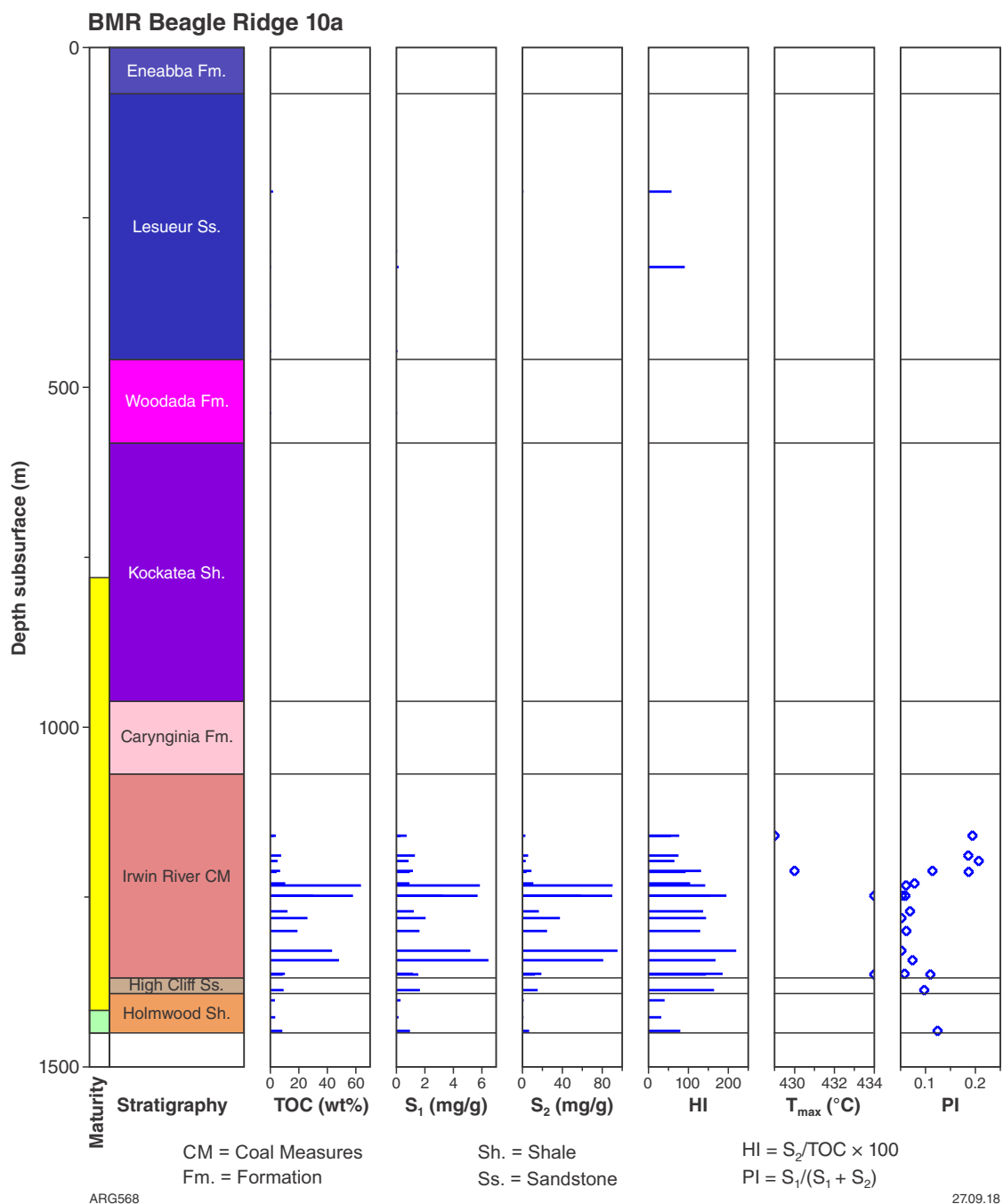
Appendix 2.5. Barragoon 1 geochemical log of TOC and Rock-Eval pyrolysis data



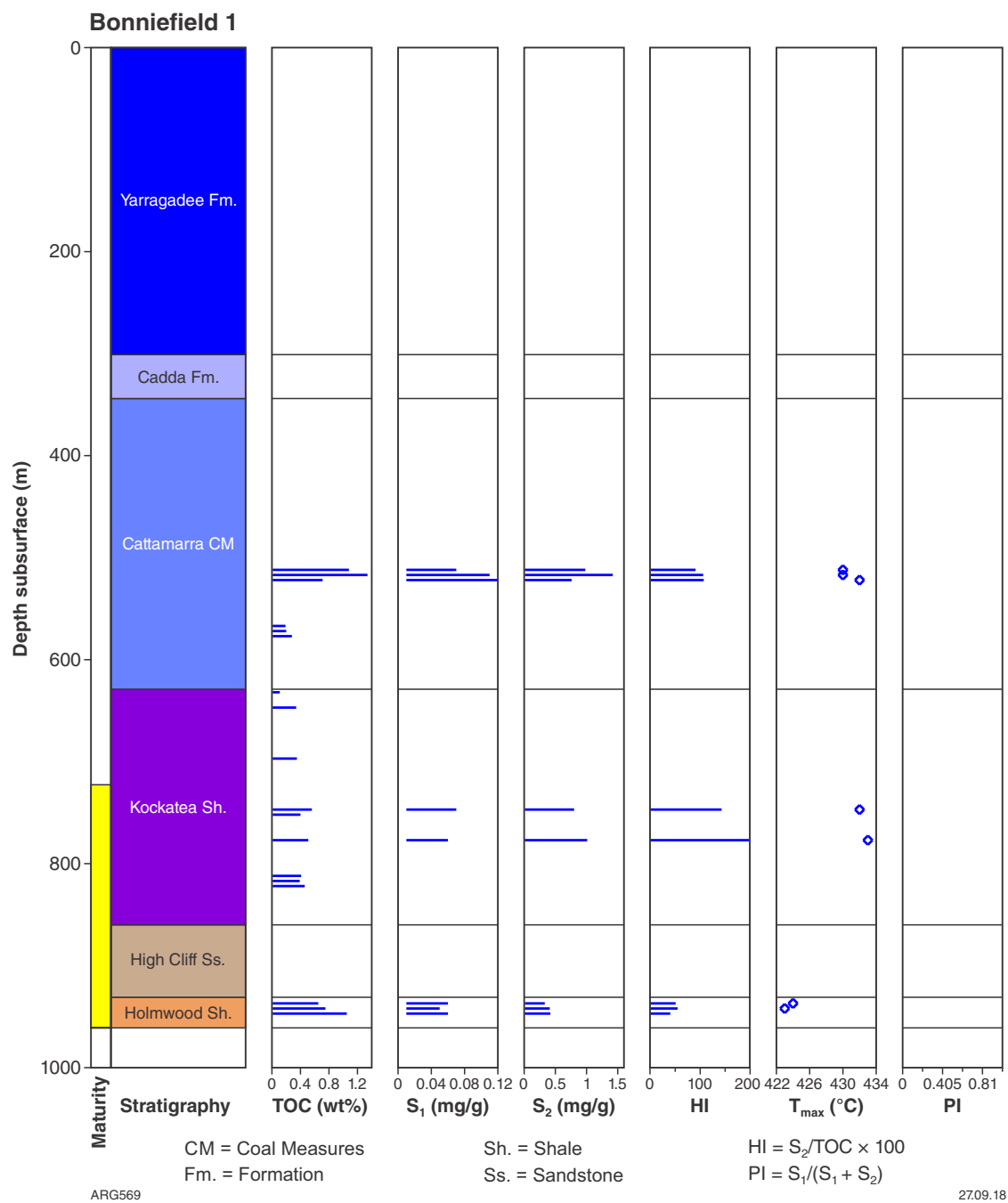
Appendix 2.6. Beharra 2 geochemical log of TOC and Rock-Eval pyrolysis data



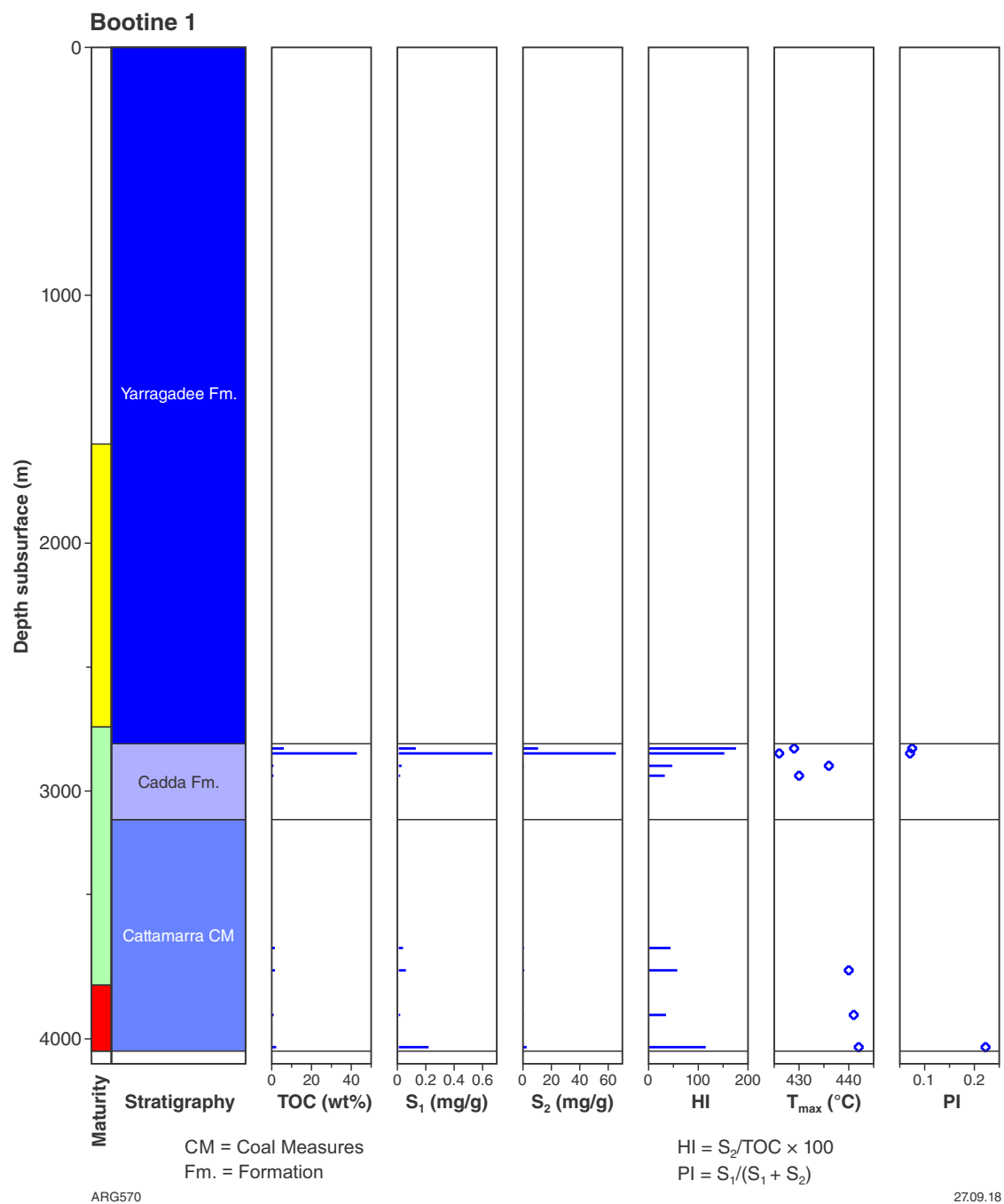
Appendix 2.7. Blackwood 1 geochemical log of TOC and Rock-Eval pyrolysis data



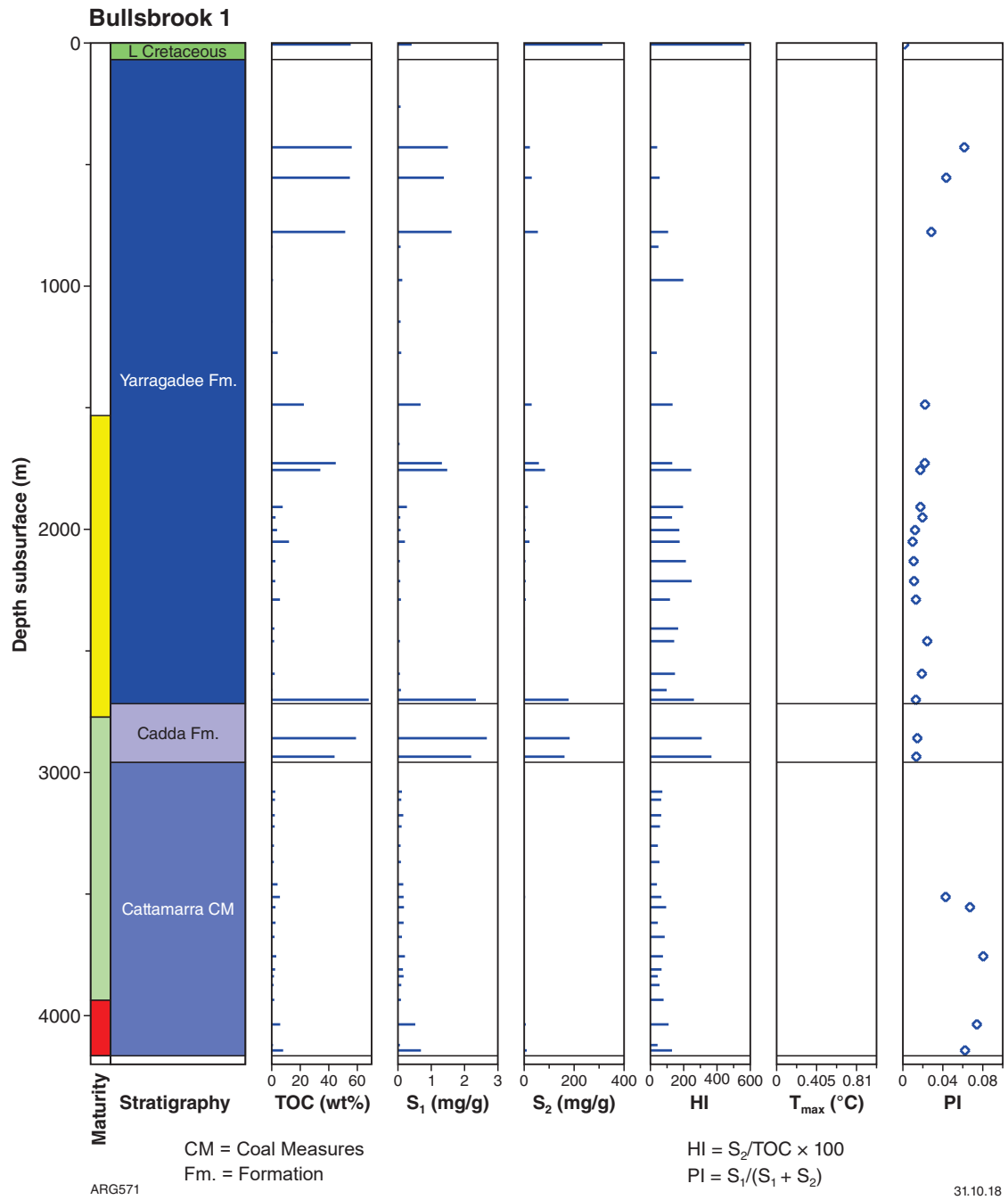
Appendix 2.8. BMR 10A Dongara geochemical log of TOC and Rock-Eval pyrolysis data



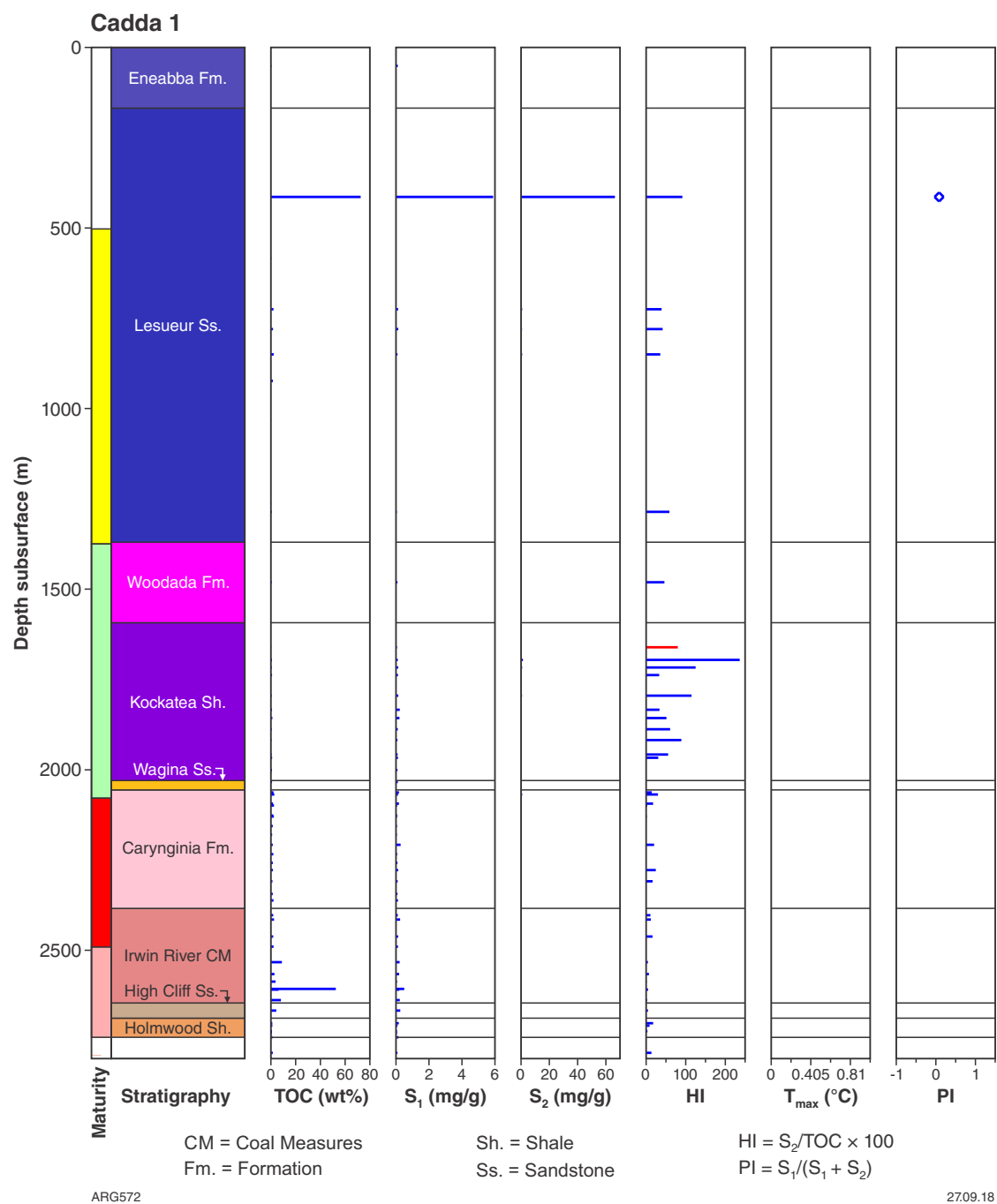
Appendix 2.9. Bonniefield 1 geochemical log of TOC and Rock-Eval pyrolysis data



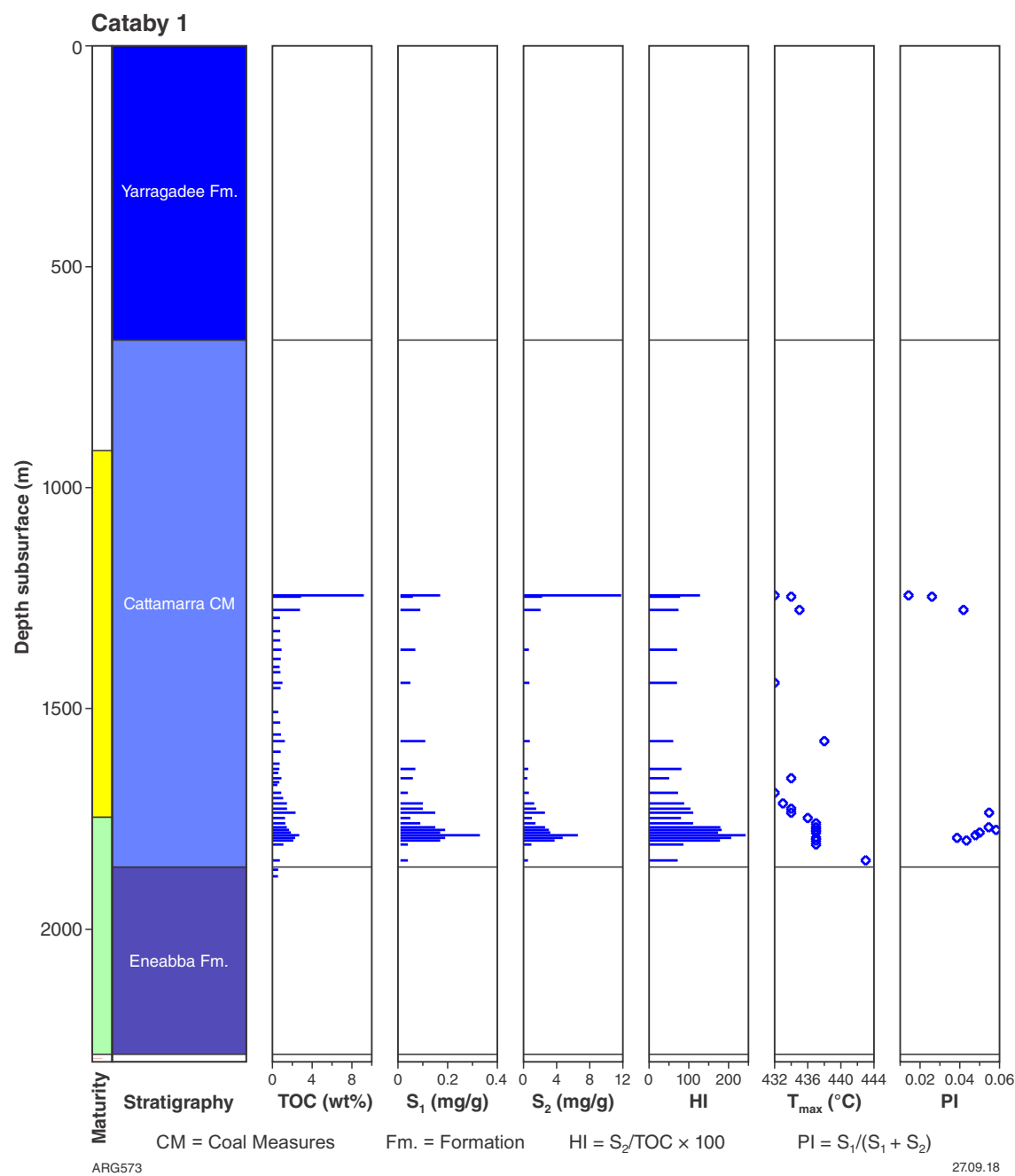
Appendix 2.10. Bootline 1 geochemical log of TOC and Rock-Eval pyrolysis data



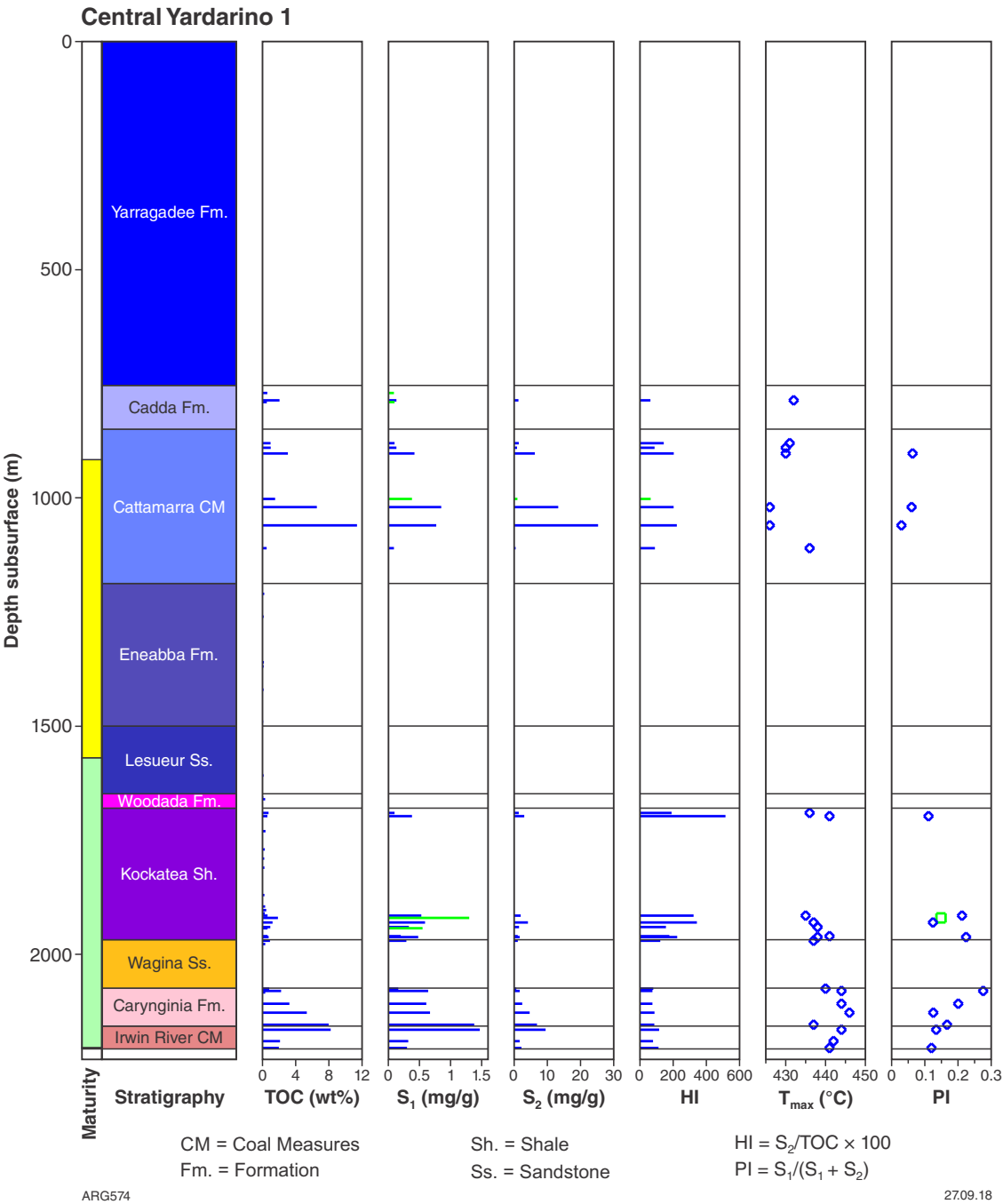
Appendix 2.11. Bullsbrook 1 geochemical log of TOC and Rock-Eval pyrolysis data



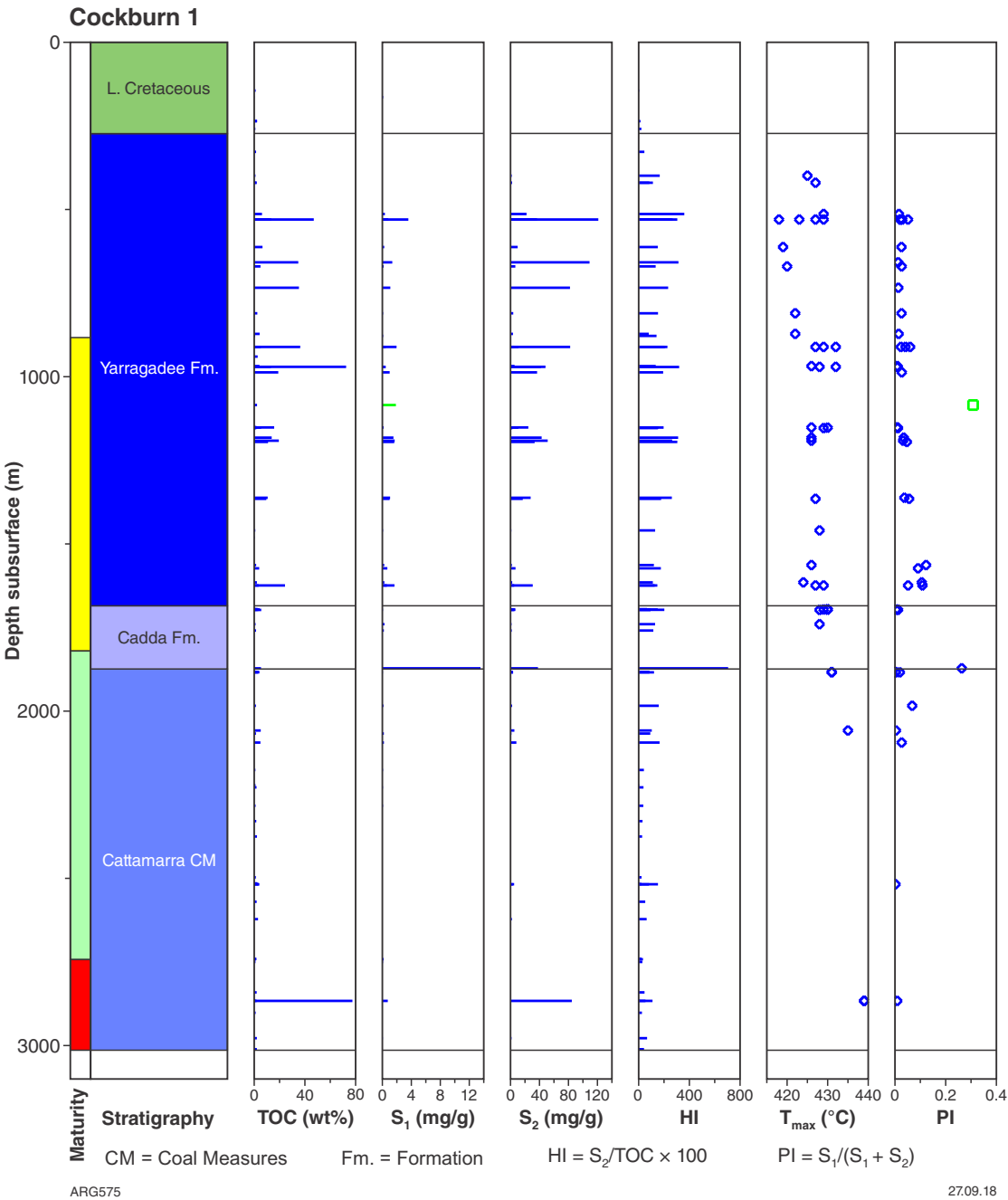
Appendix 2.12. Cadda 1 geochemical log of TOC and Rock-Eval pyrolysis data



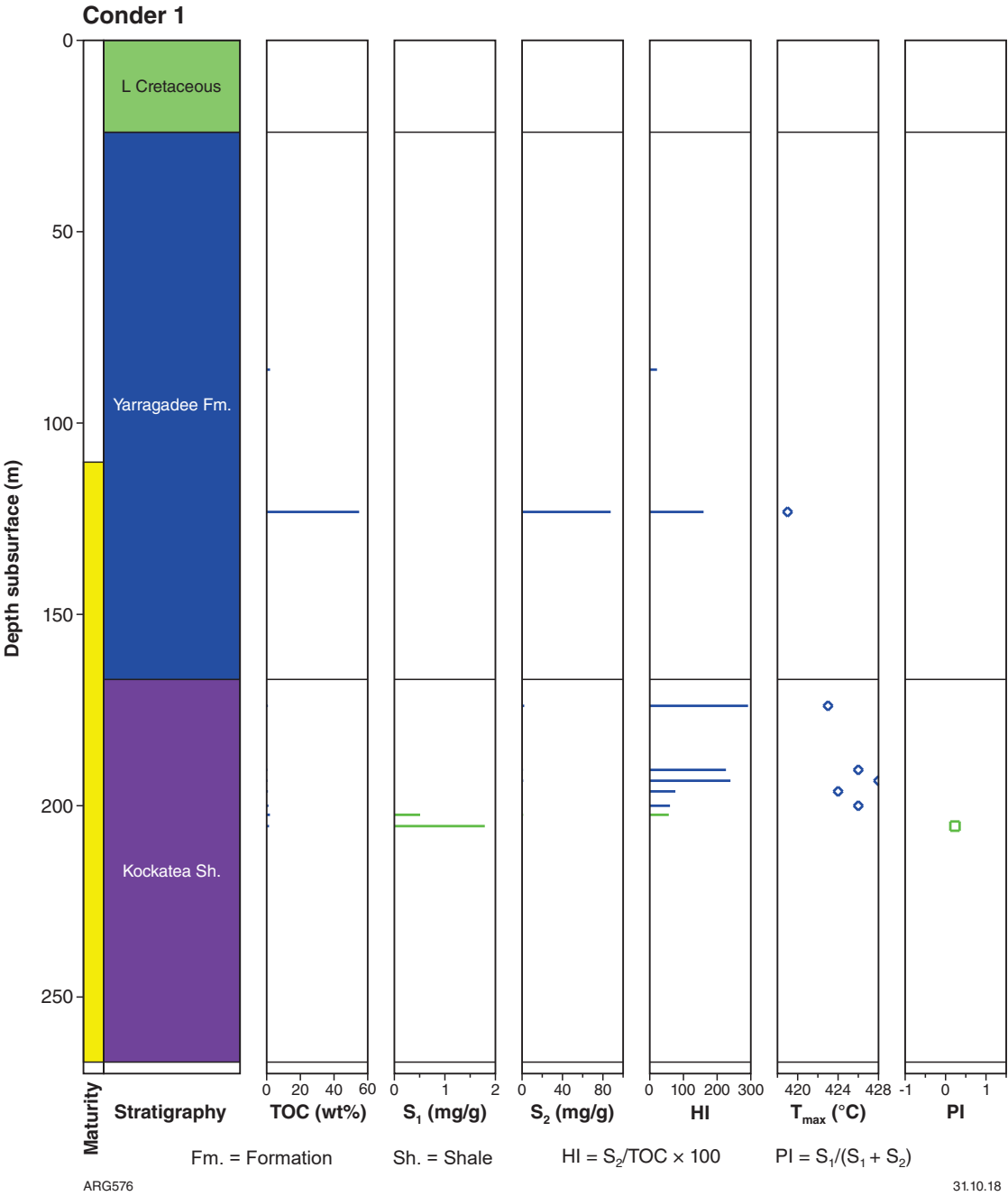
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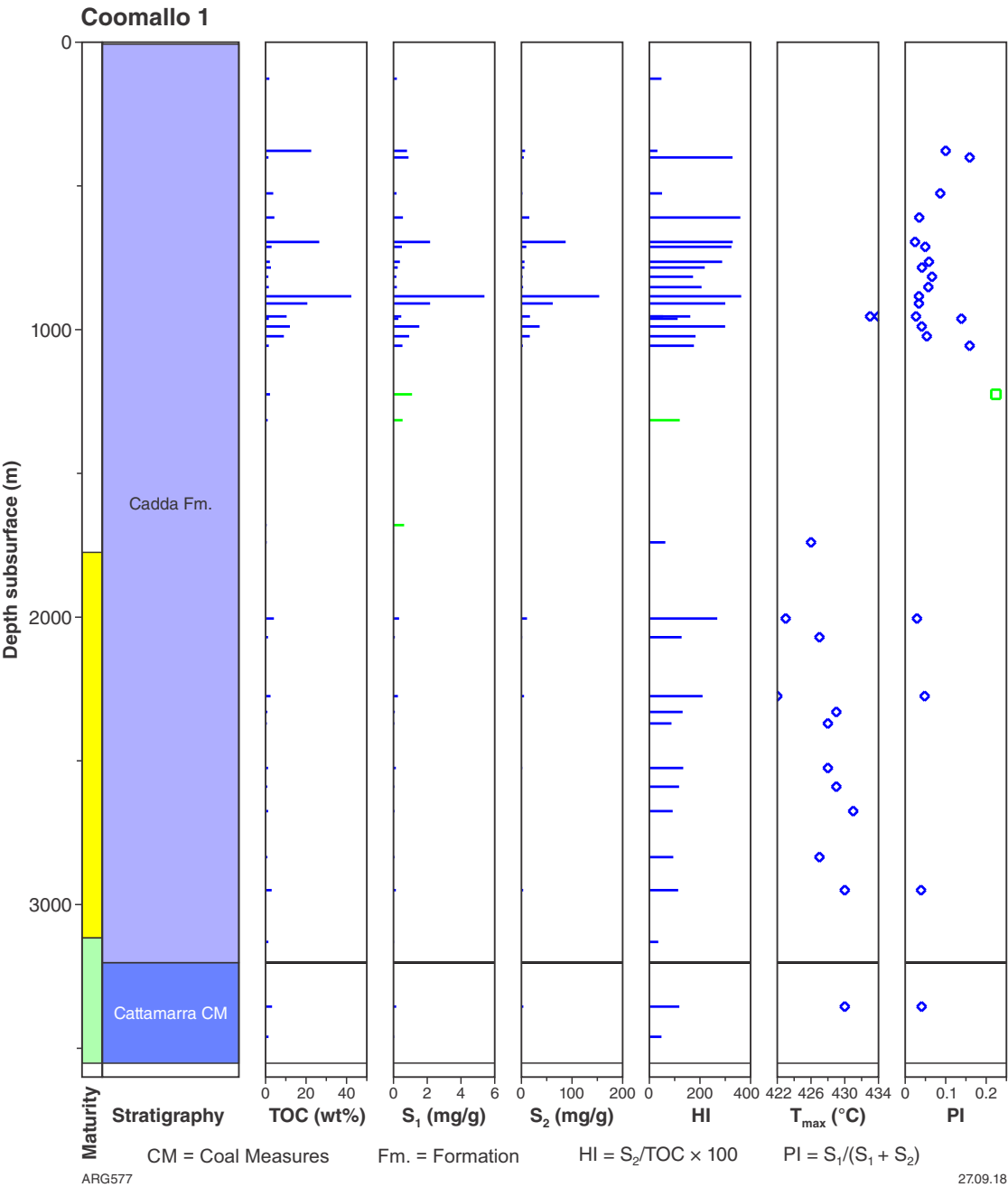
Appendix 2.14. Central Yardarino 1 geochemical log of TOC and Rock-Eval pyrolysis data



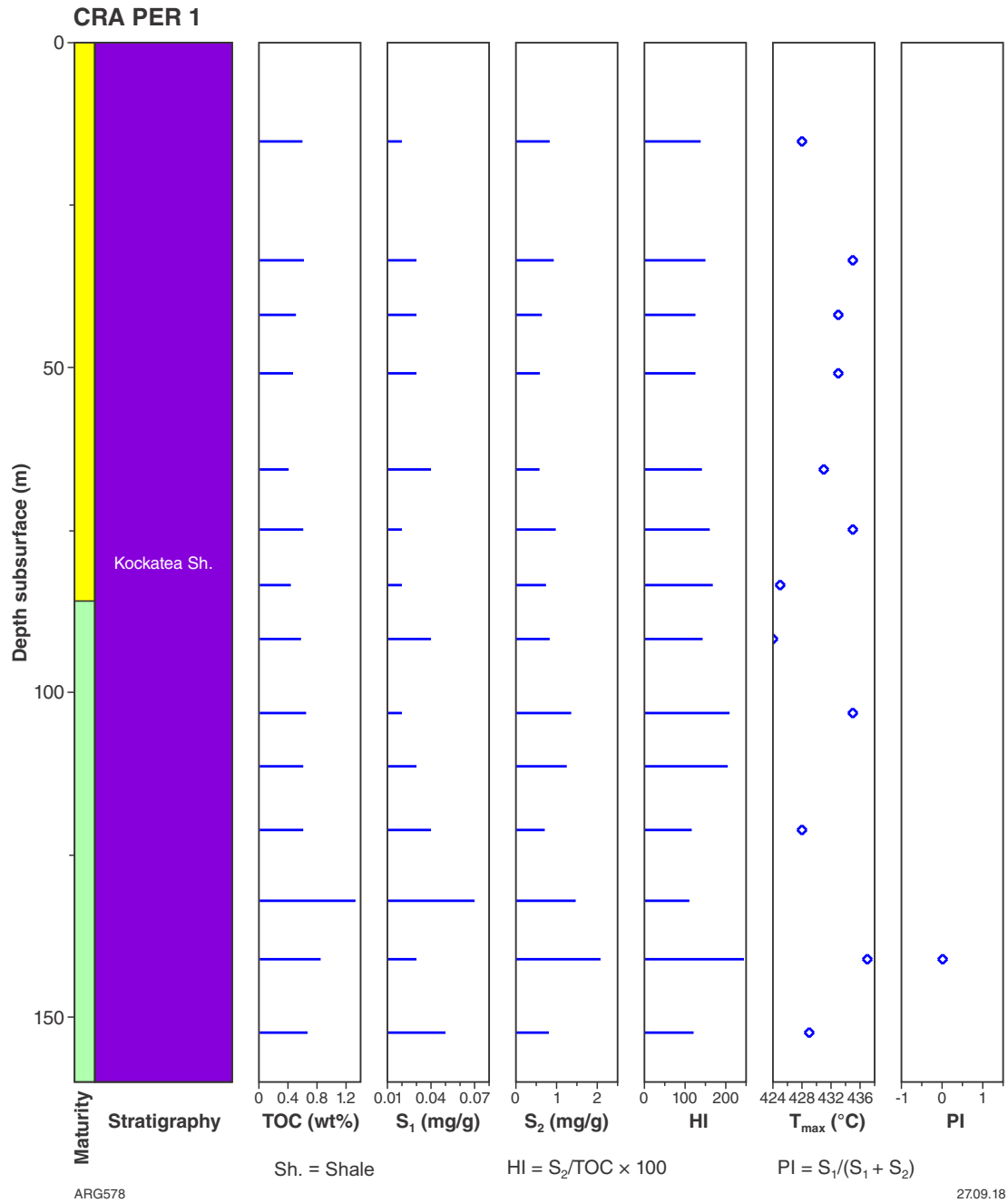
Appendix 2.15. Cockburn 1 geochemical log of TOC and Rock-Eval pyrolysis data



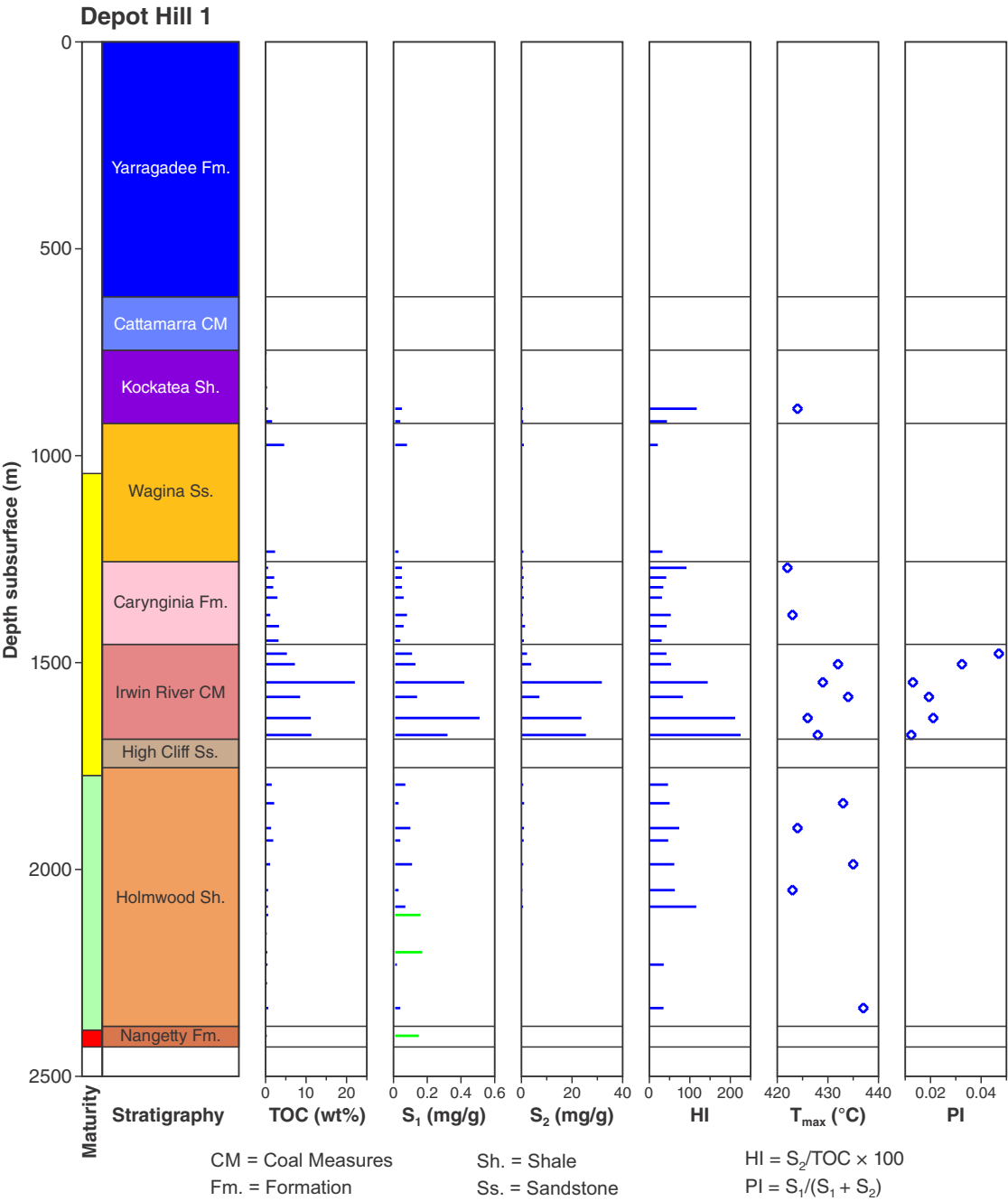
Appendix 2.16. Conder 1 geochemical log of TOC and Rock-Eval pyrolysis data



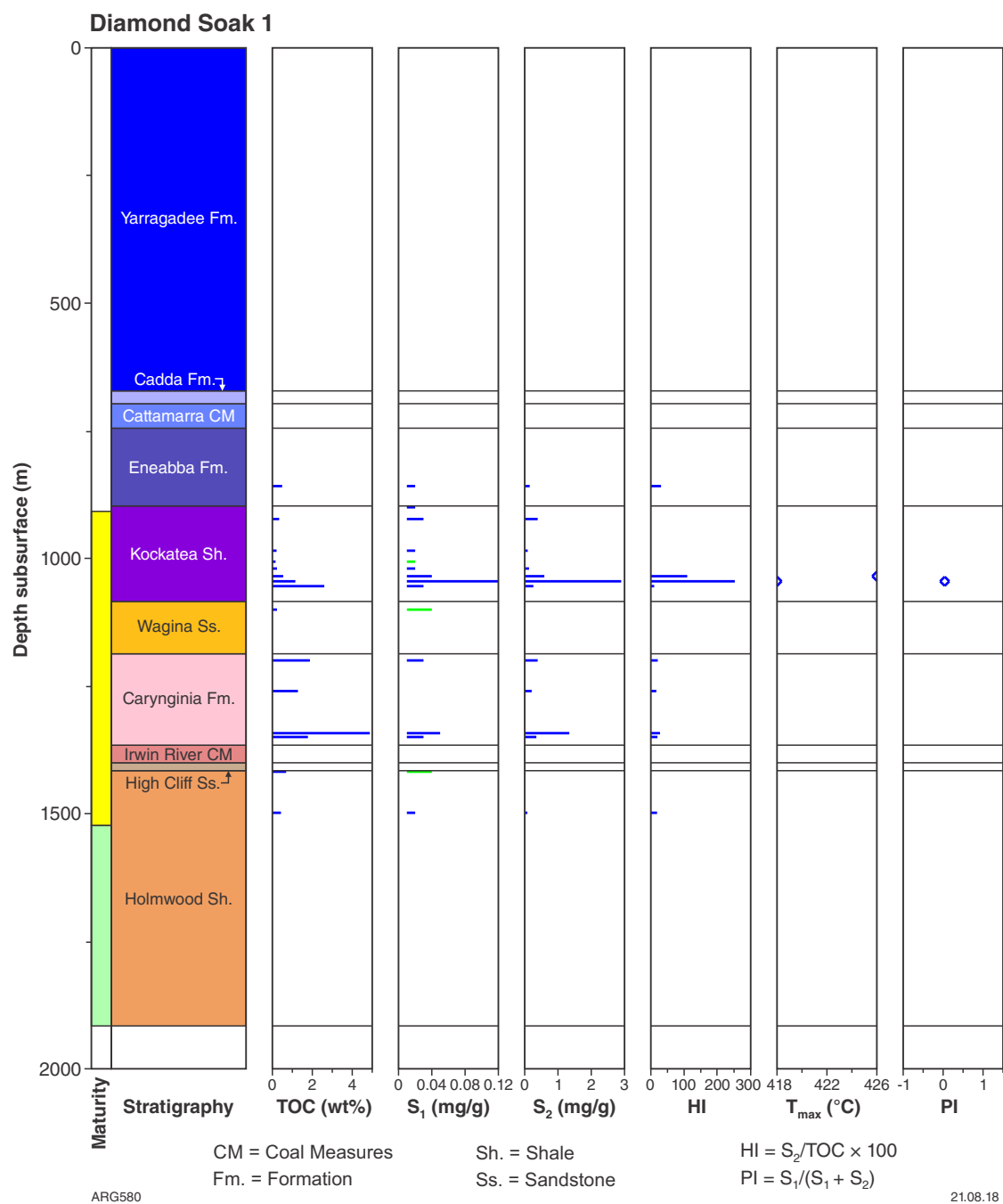
Appendix 2.17. Coomallo 1 geochemical log of TOC and Rock-Eval pyrolysis data



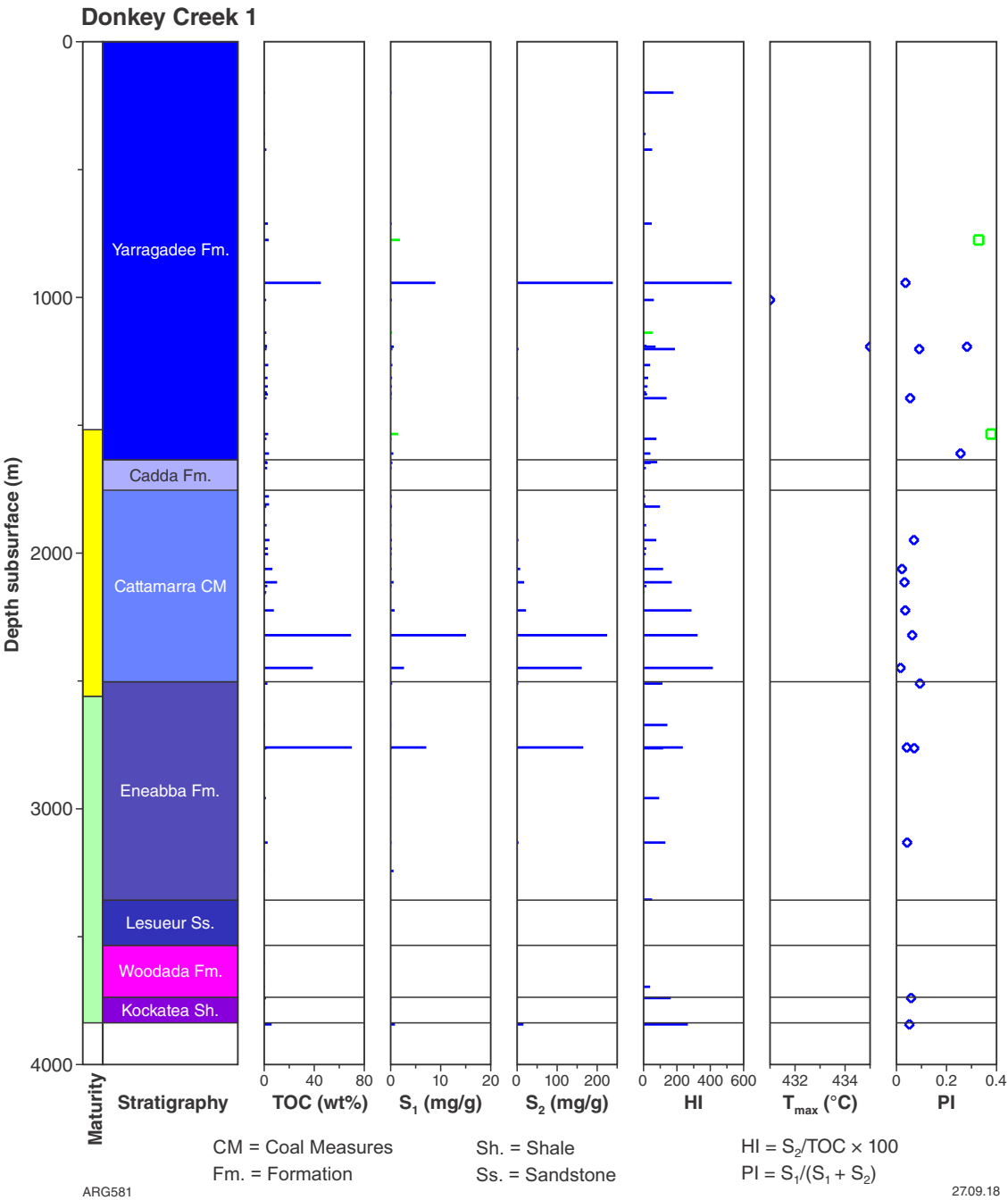
Appendix 2.18. CRA PER 10 geochemical log of TOC and Rock-Eval pyrolysis data



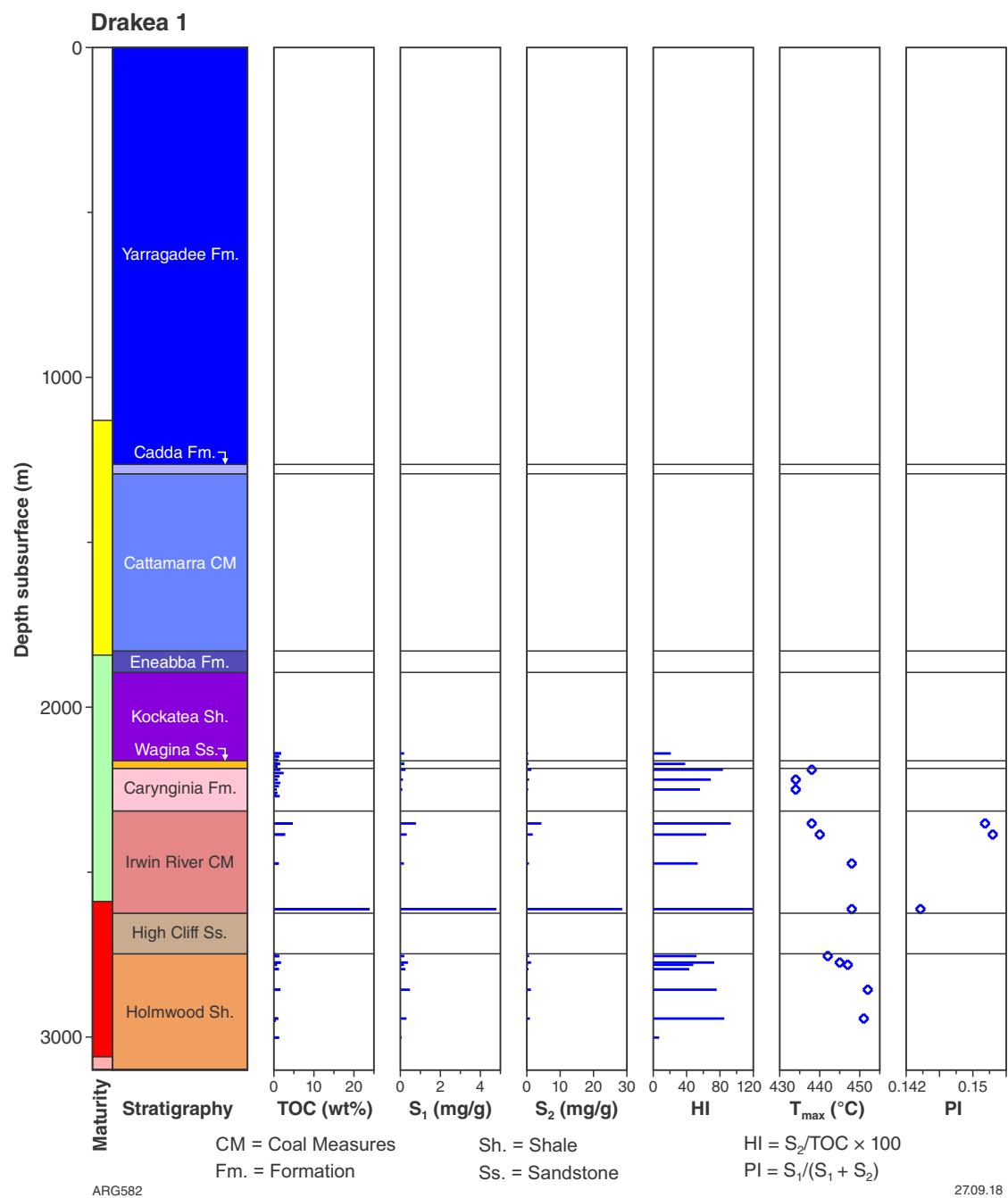
Appendix 2.19. Depot Hill 1 geochemical log of TOC and Rock-Eval pyrolysis data



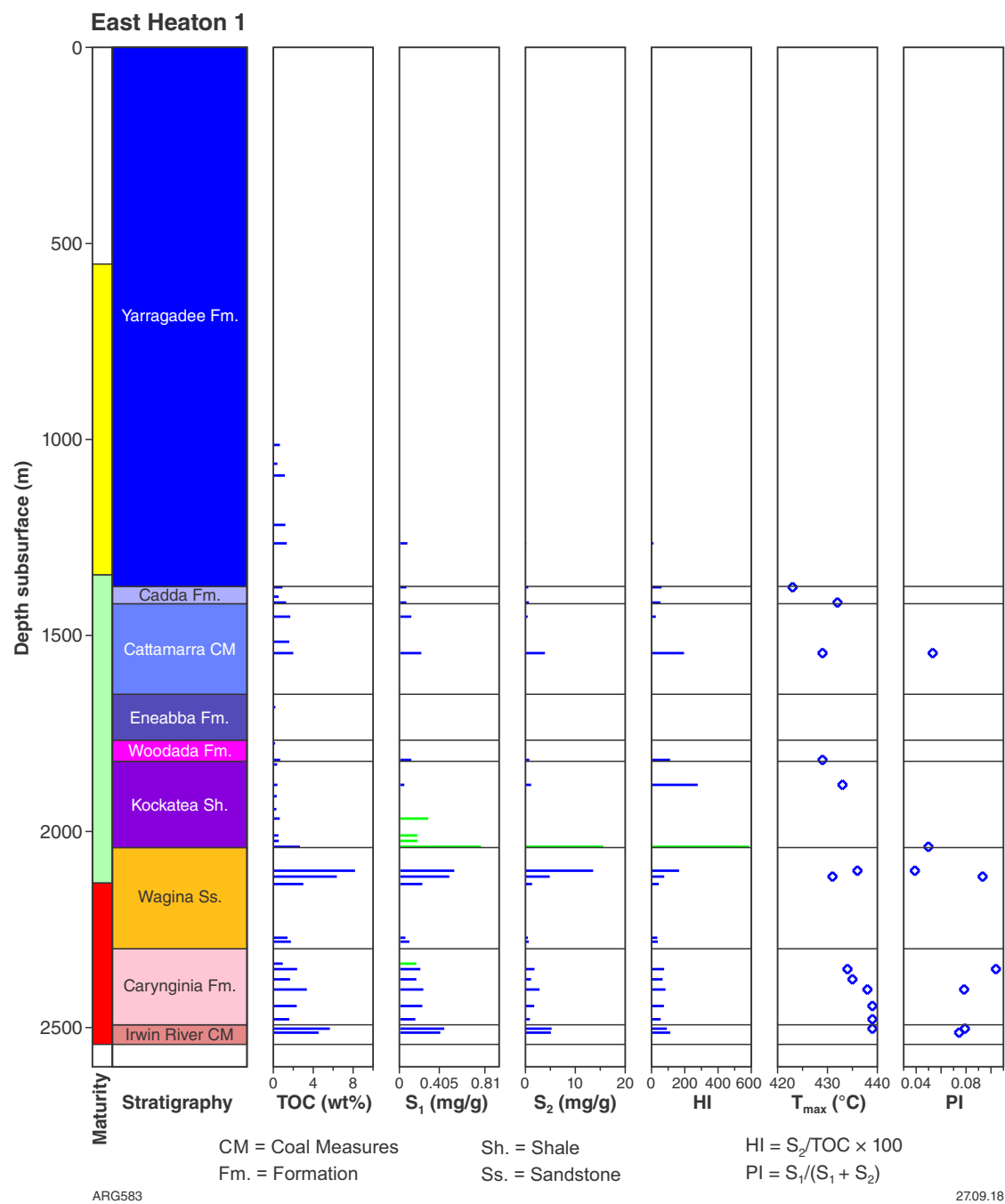
Appendix 2.20. Diamond Soak 1 geochemical log of TOC and Rock-Eval pyrolysis data



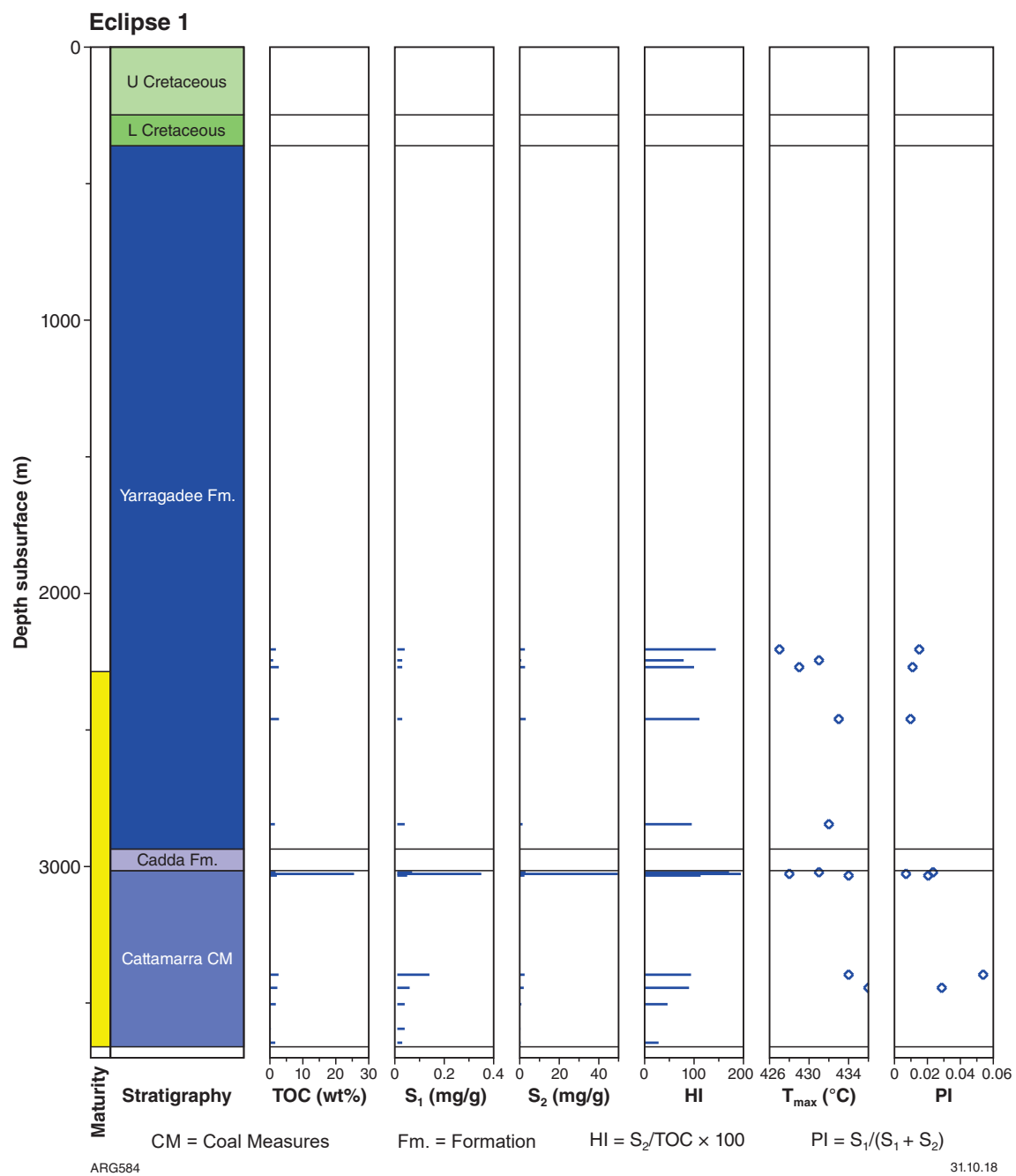
Appendix 2.21. Donkey Creek 1 geochemical log of TOC and Rock-Eval pyrolysis data



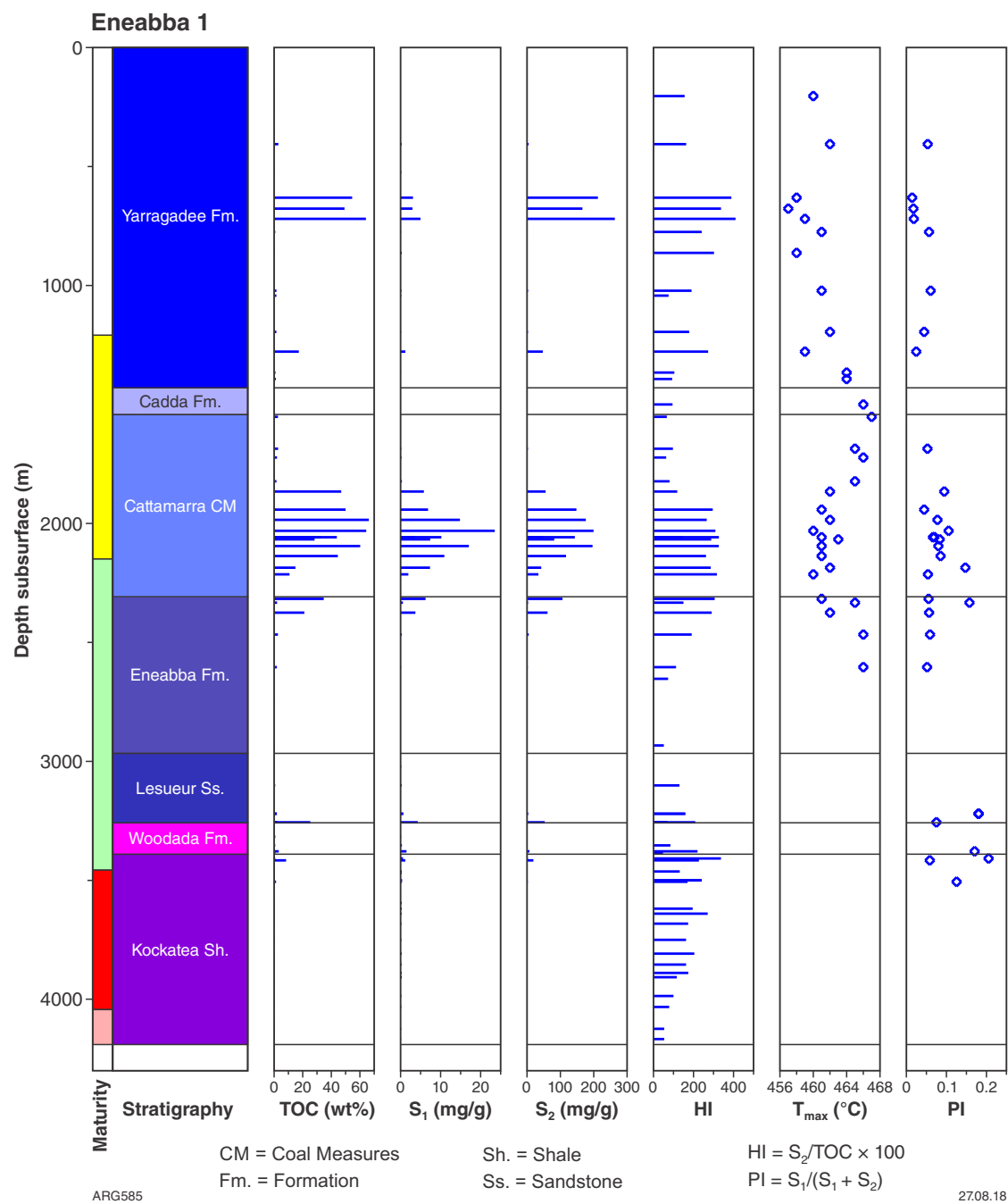
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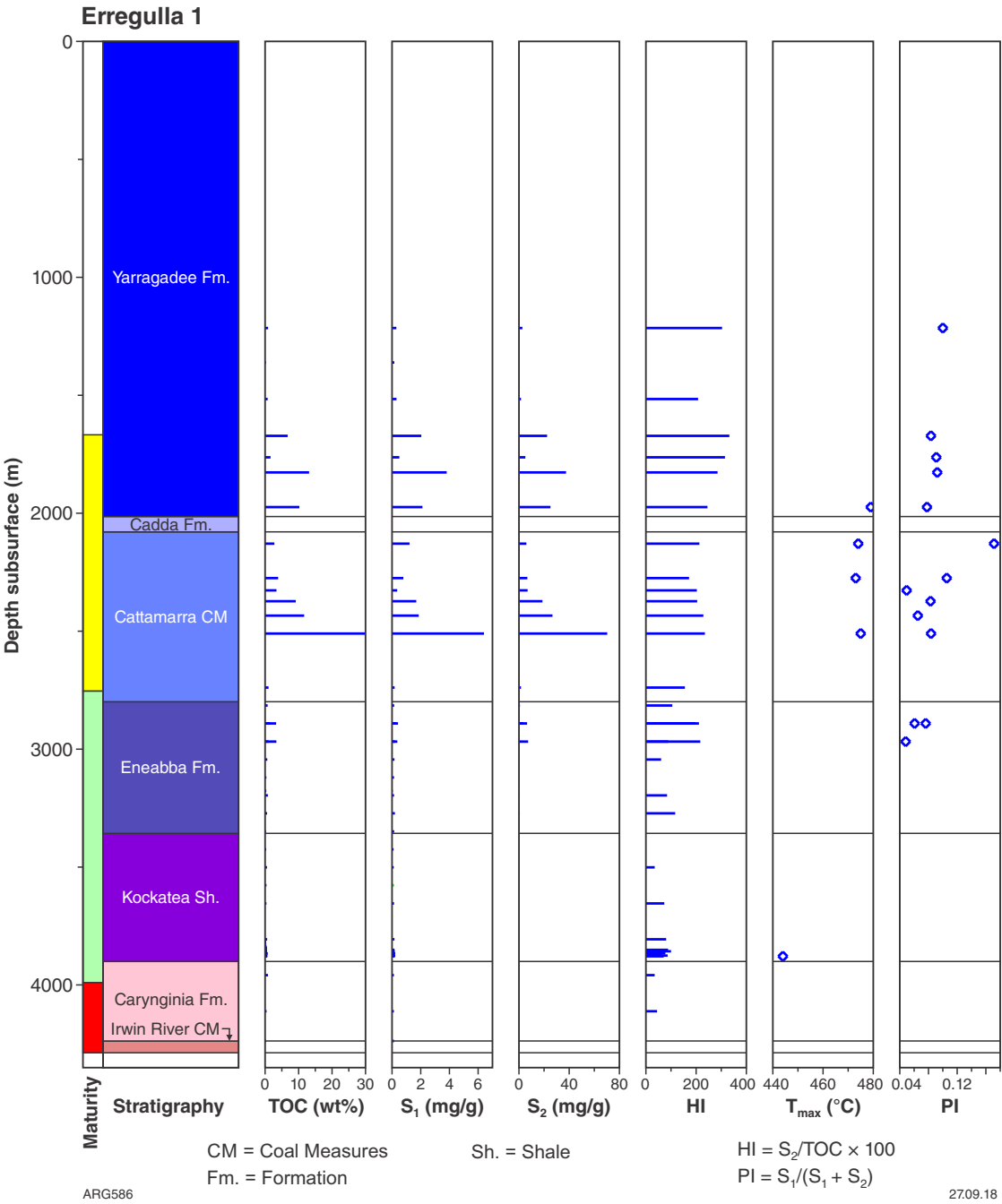
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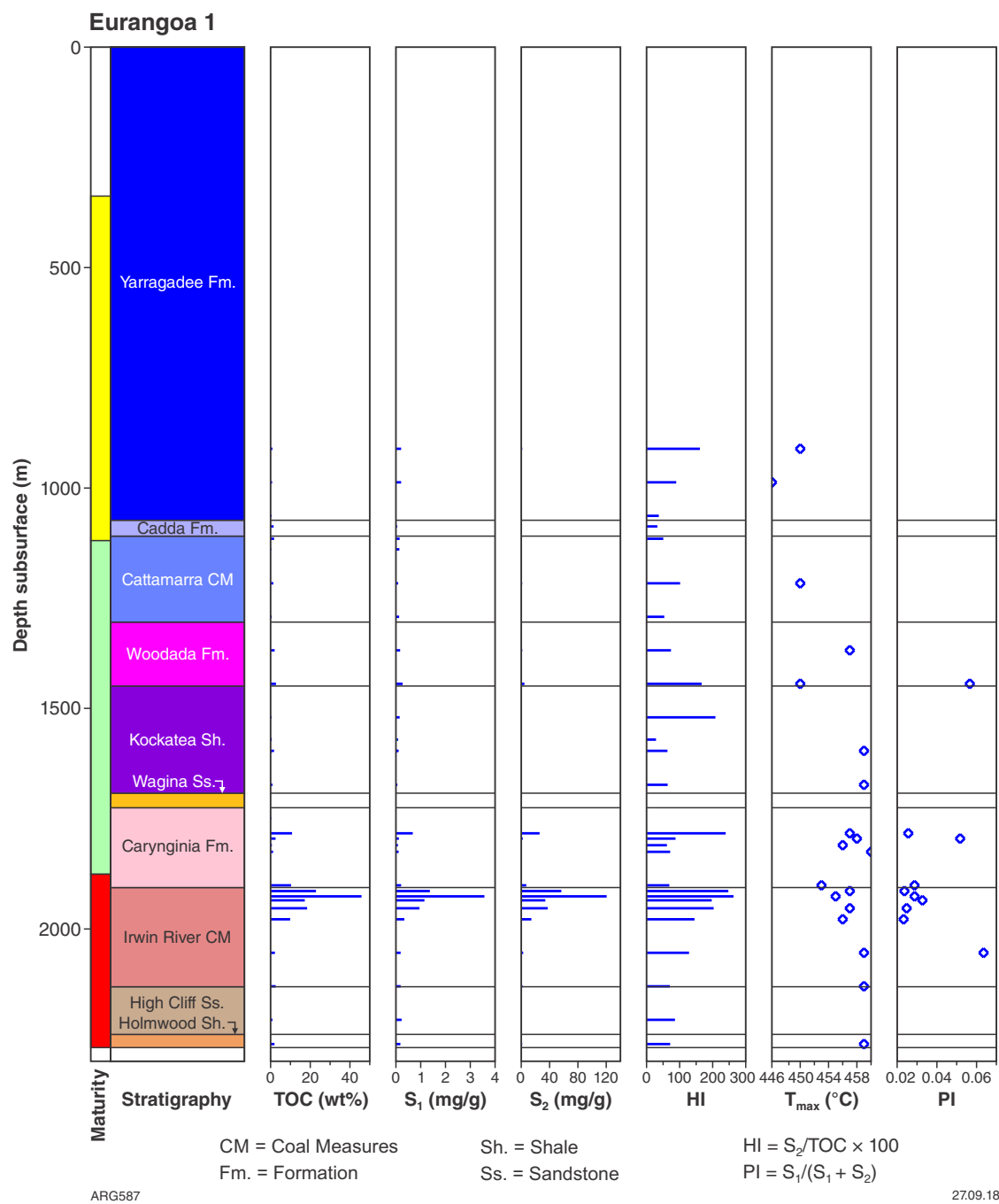
Appendix 2.24. Eclipse 1 geochemical log of TOC and Rock-Eval pyrolysis data



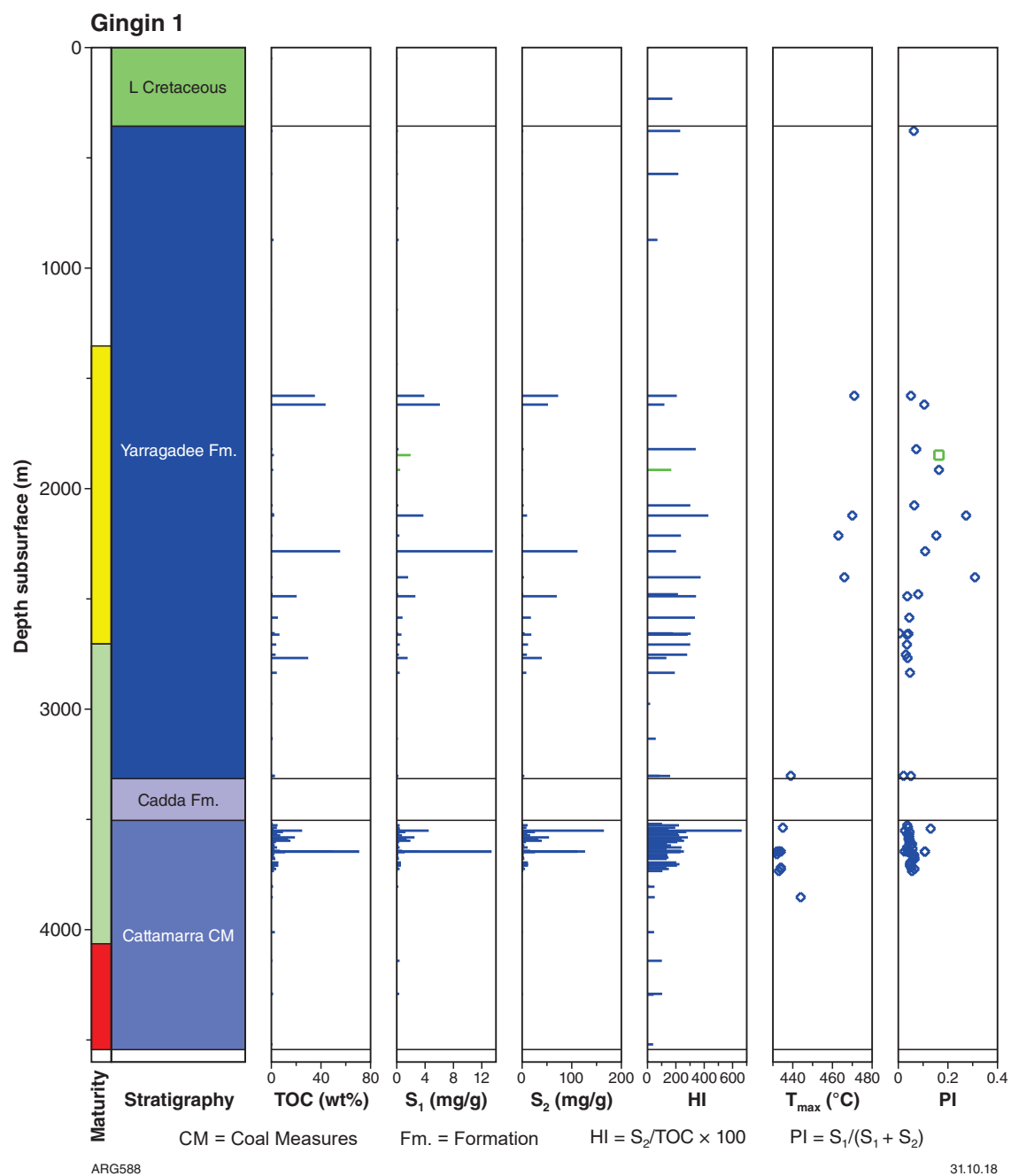
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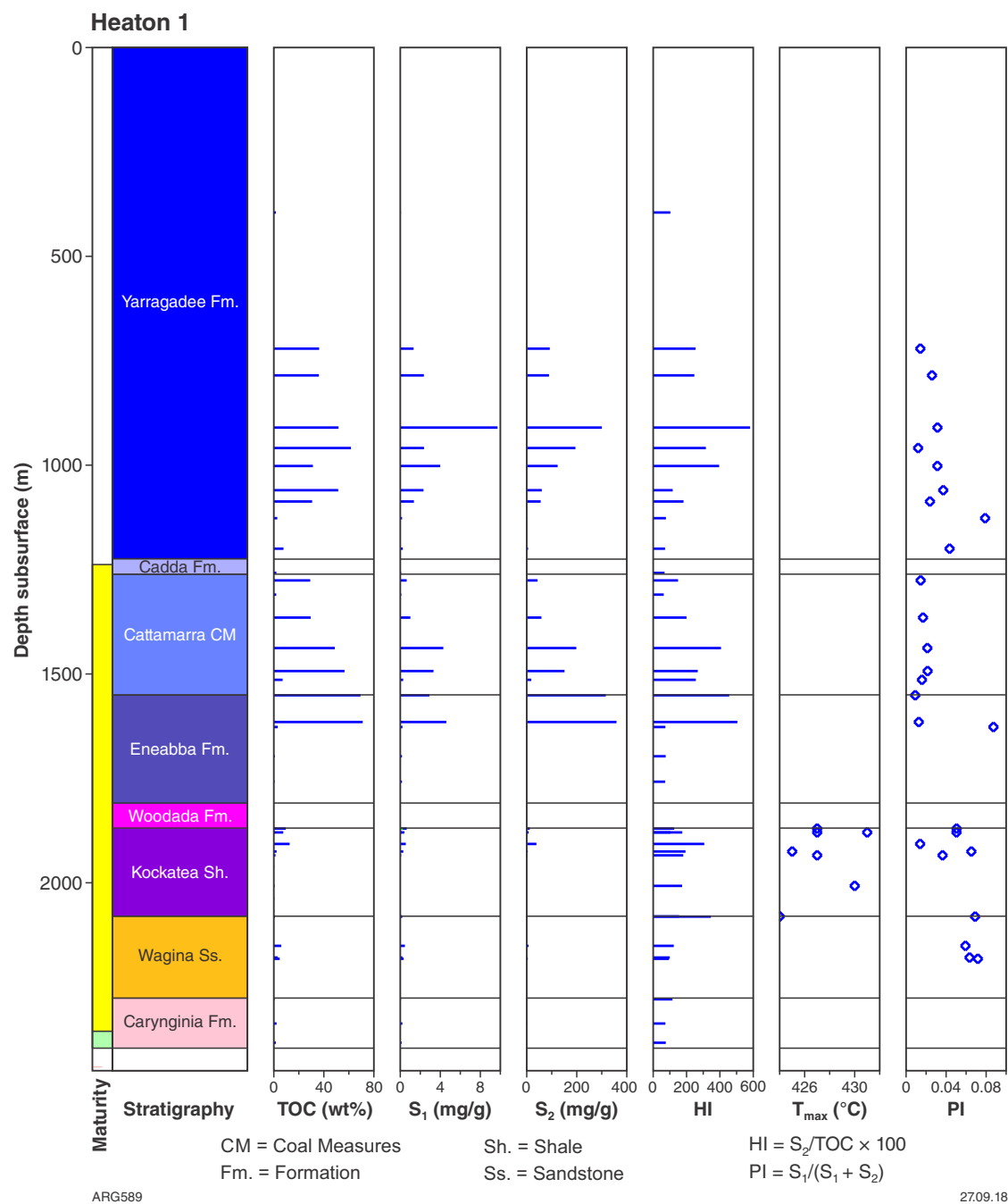
Appendix 2.26. Erregulla 1 geochemical log of TOC and Rock-Eval pyrolysis data



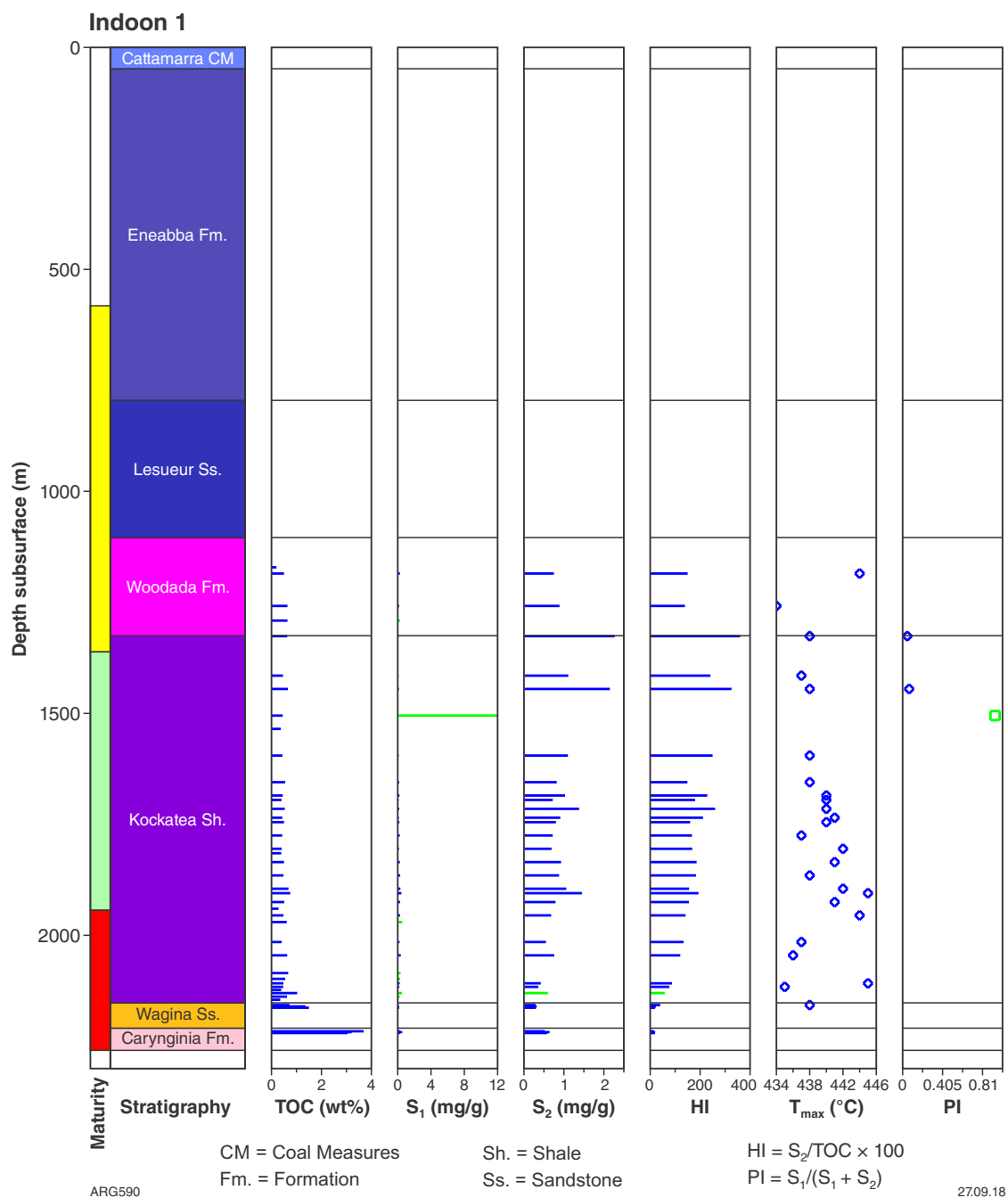
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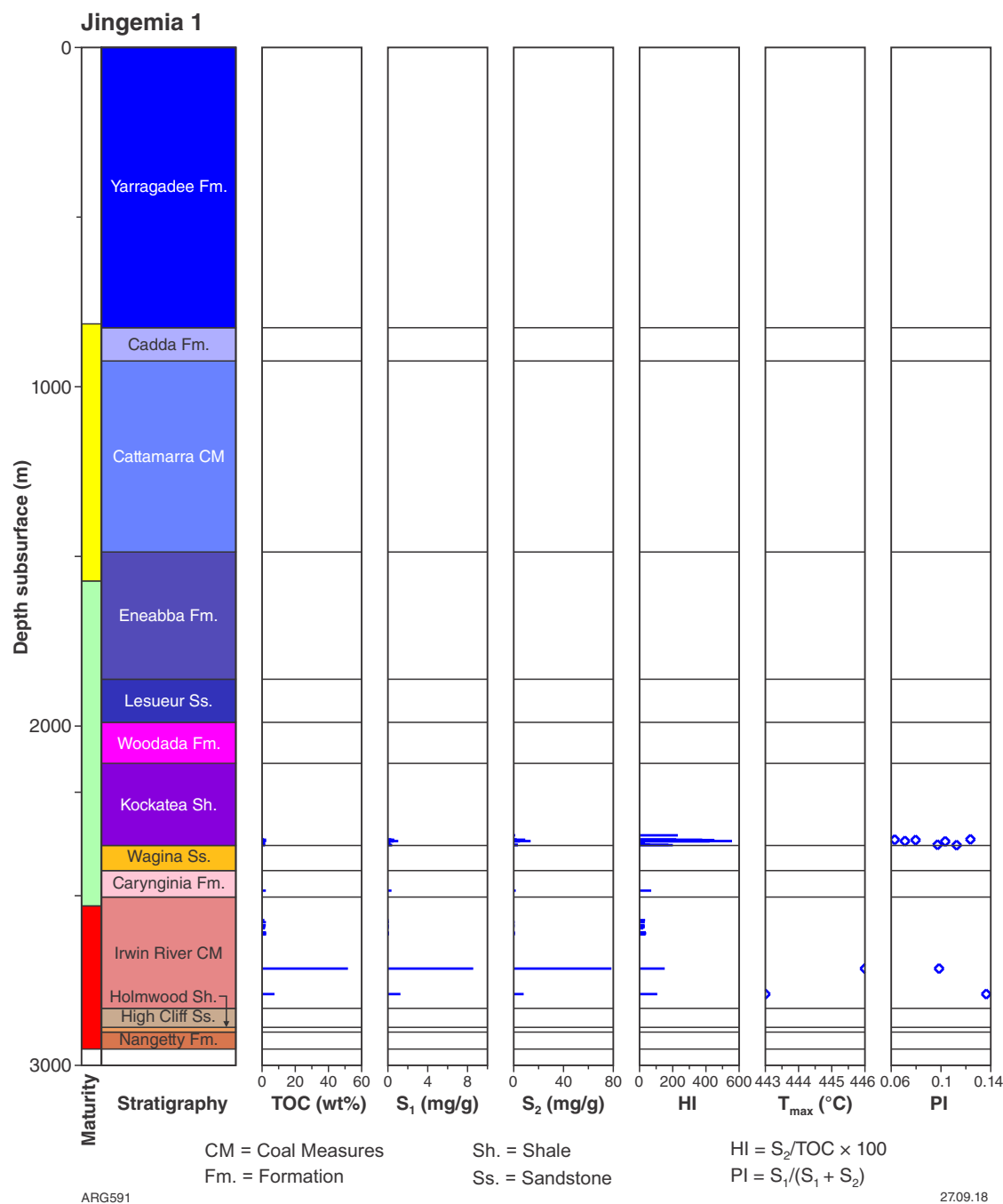
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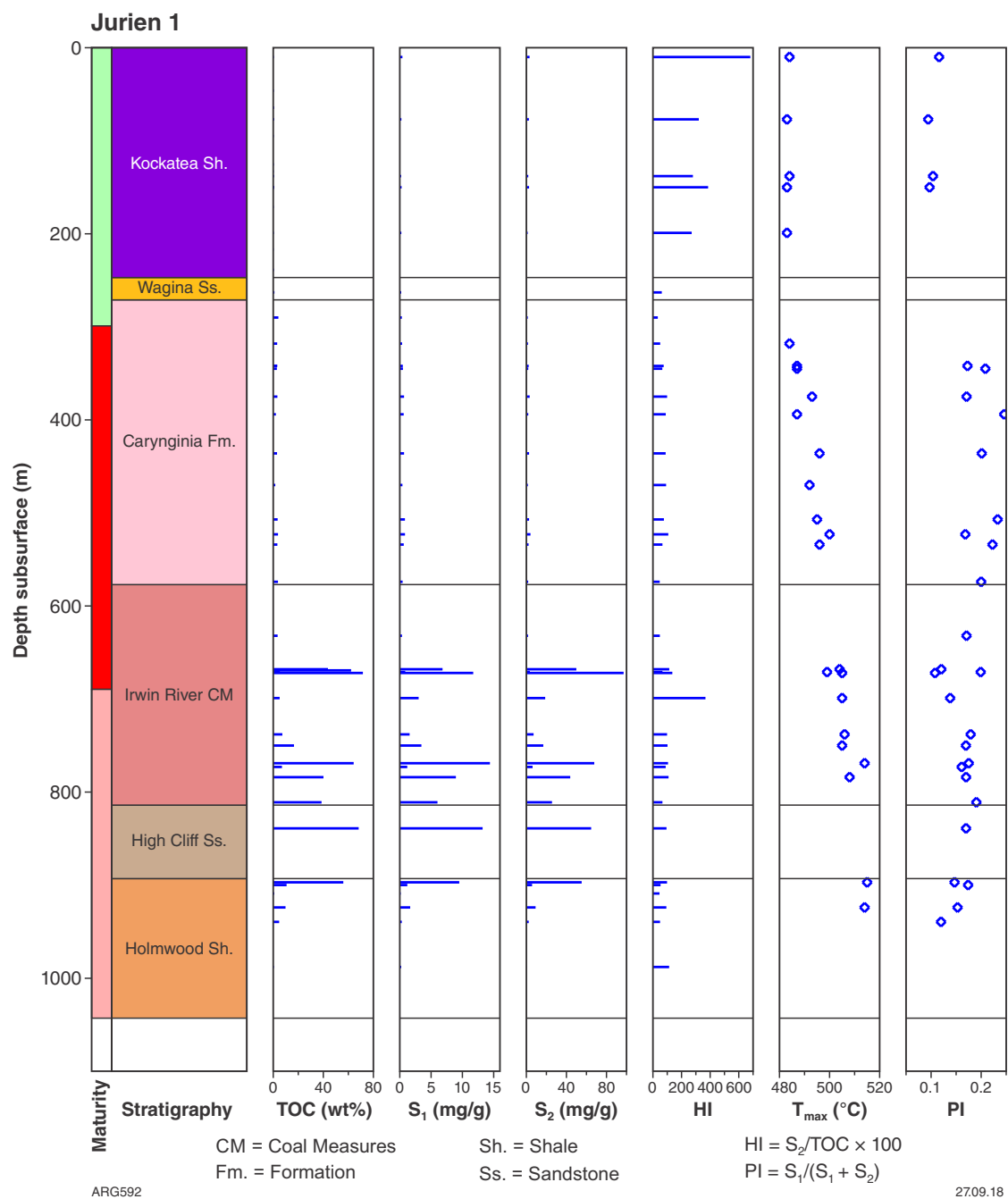
Appendix 2.29. Heaton 1 geochemical log of TOC and Rock-Eval pyrolysis data



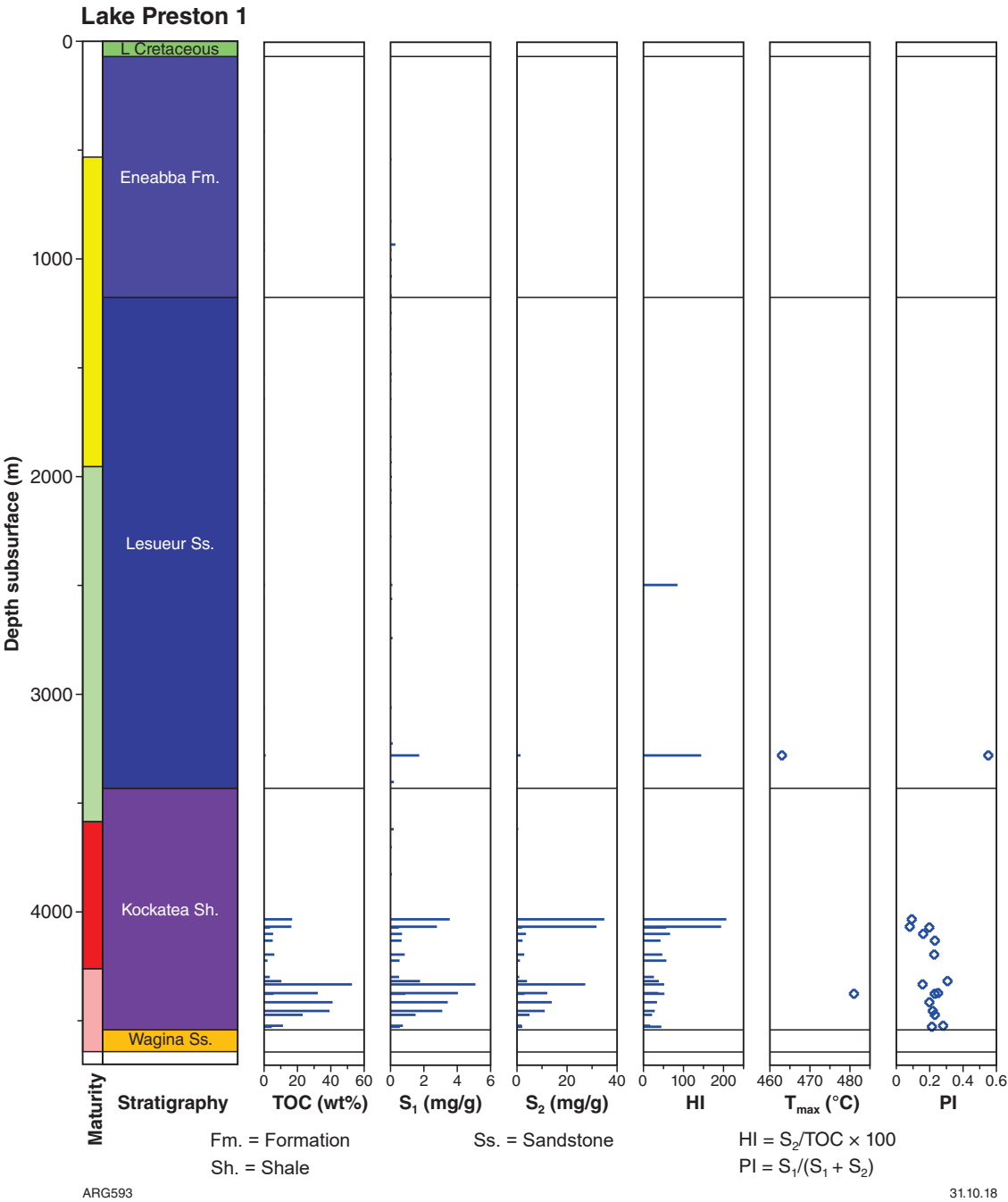
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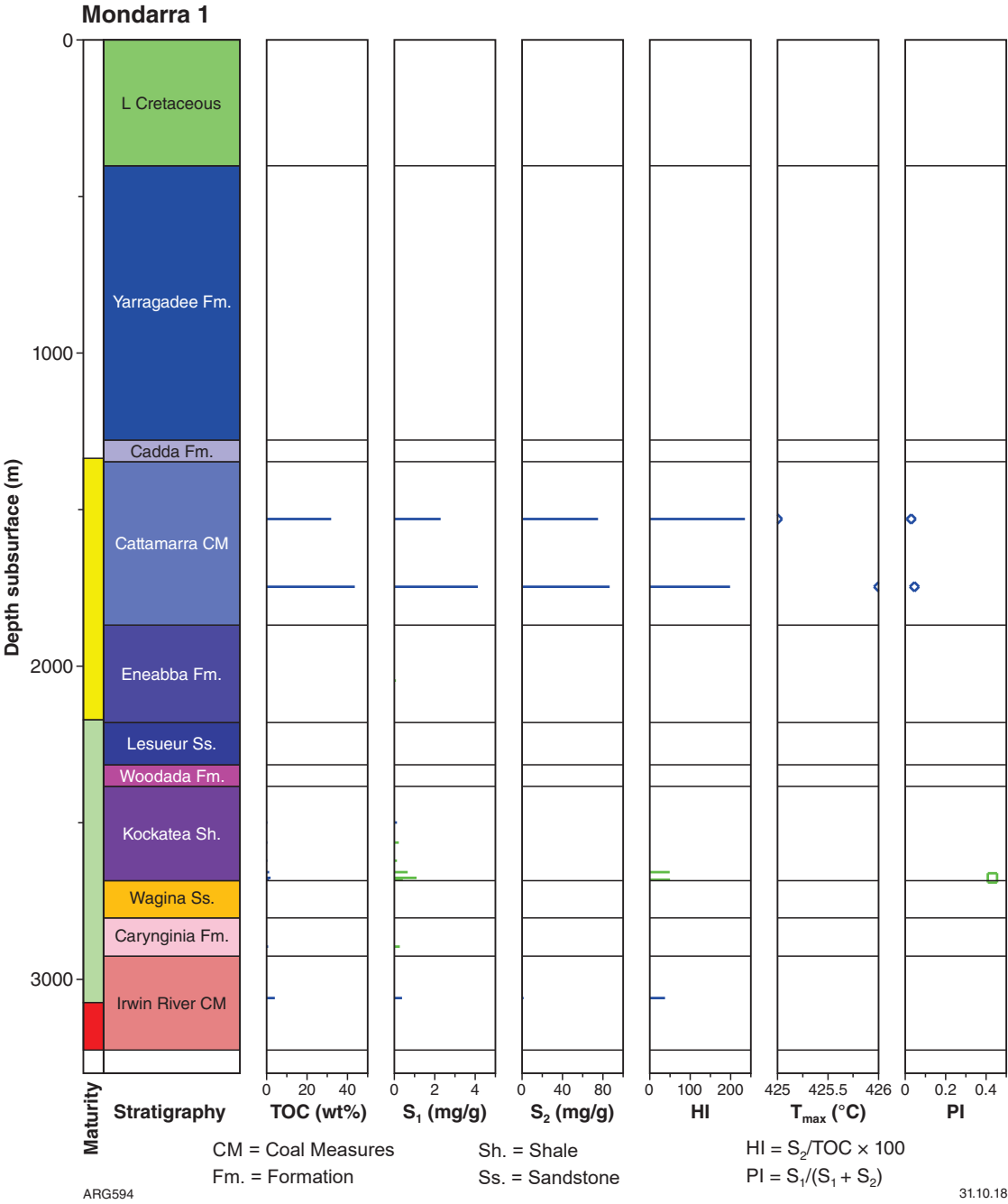
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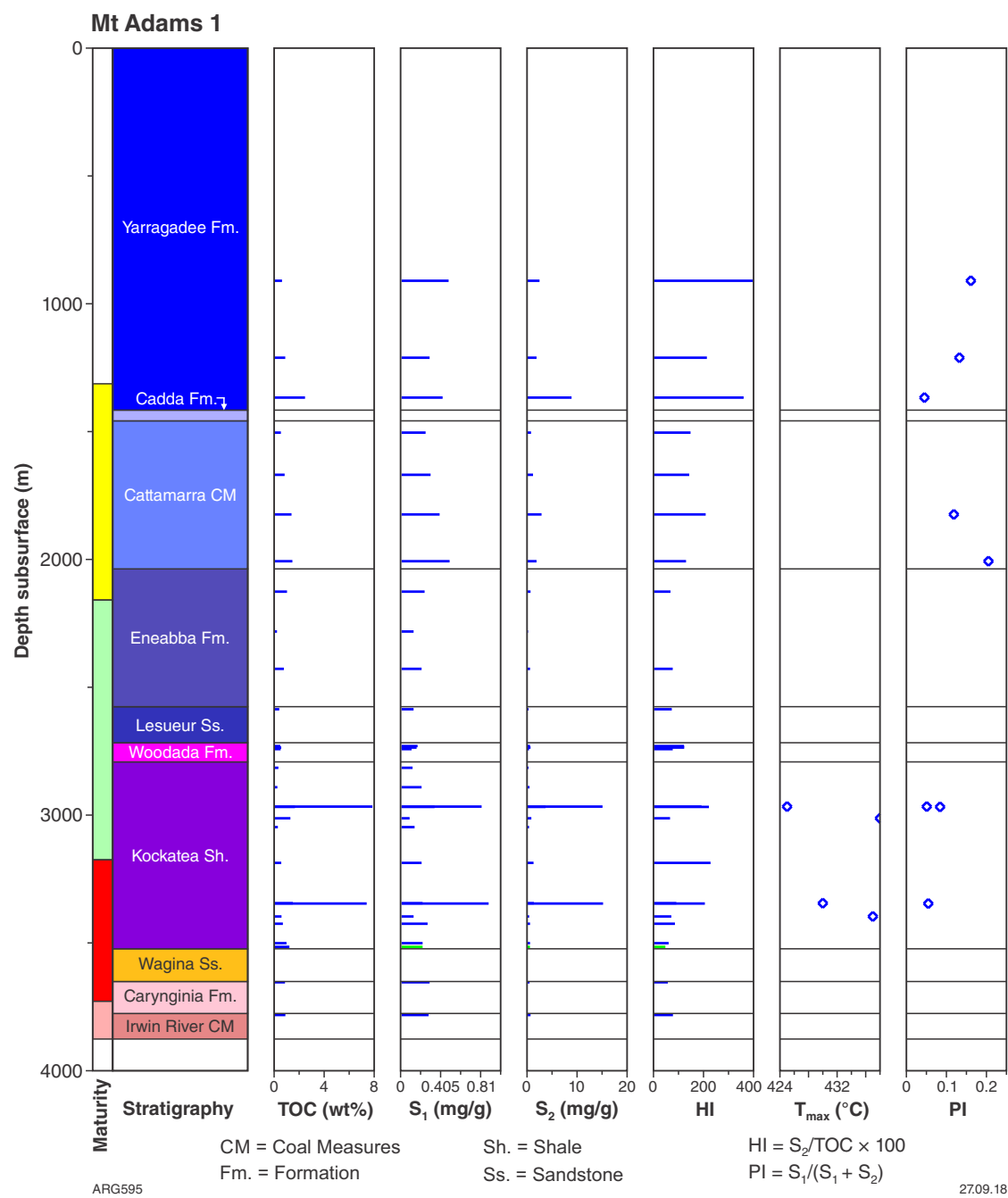
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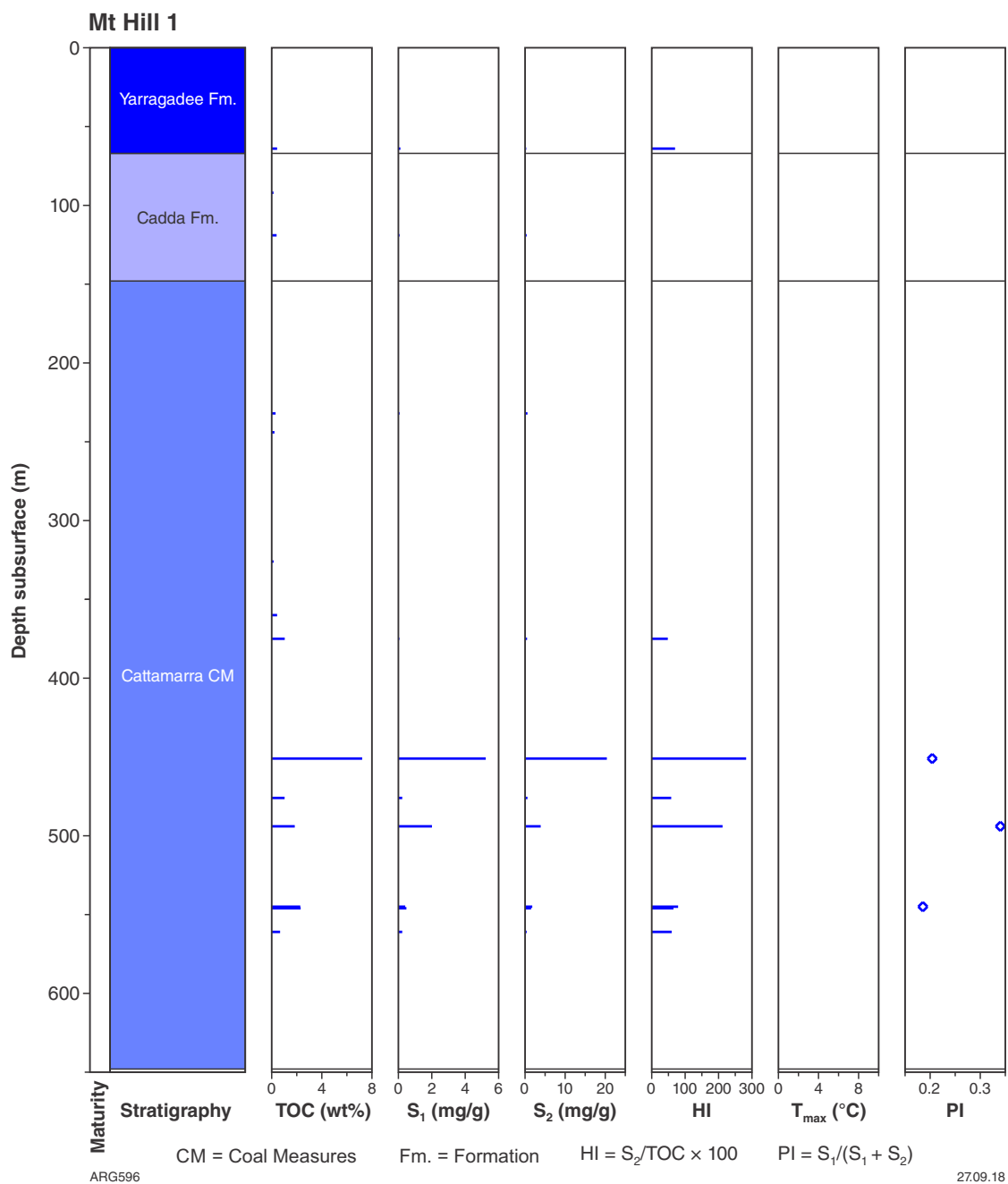
Appendix 2.33. Lake Preston 1 geochemical log of TOC and Rock-Eval pyrolysis data



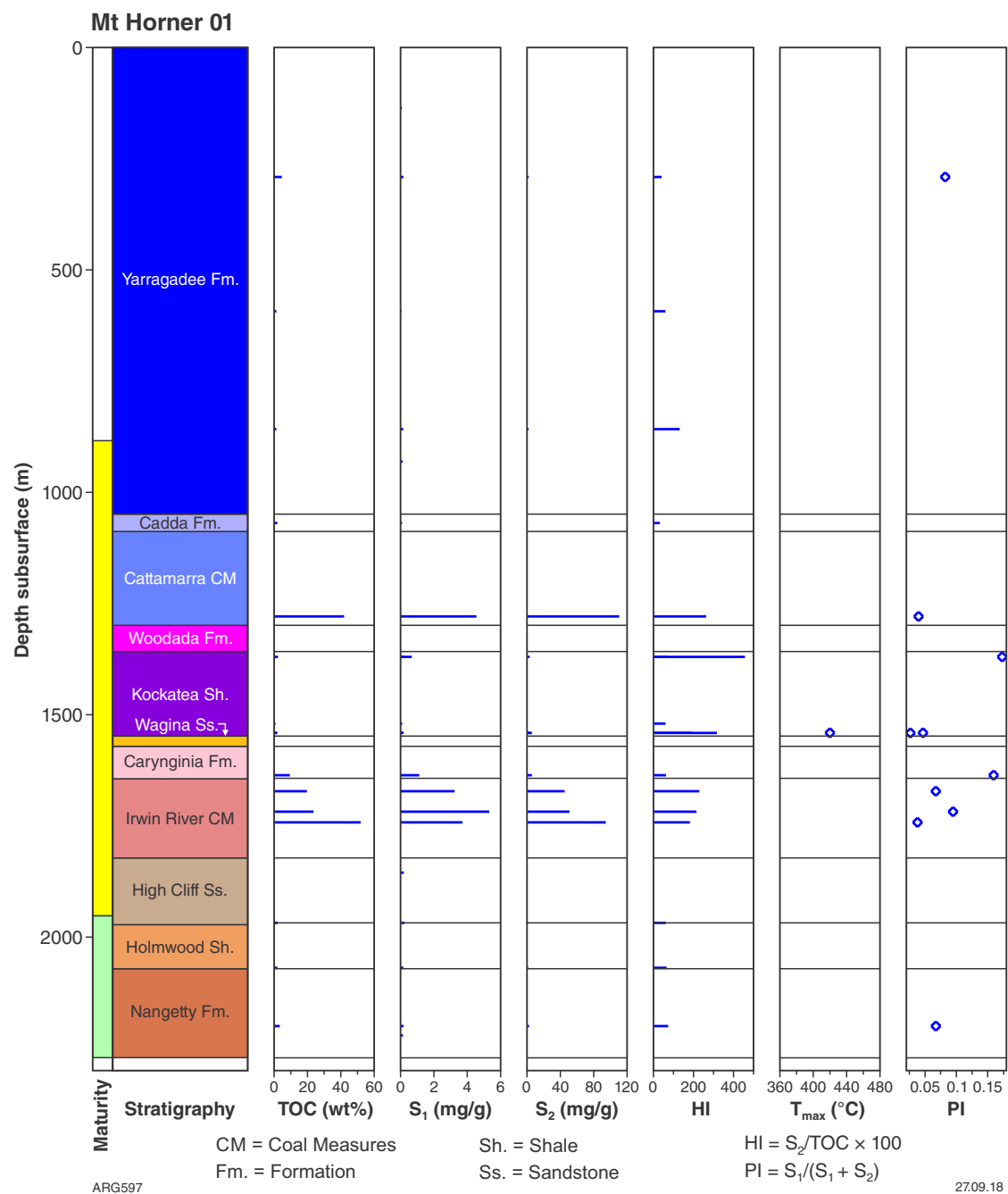
Appendix 2.34. Mondarra 1 geochemical log of TOC and Rock-Eval pyrolysis data



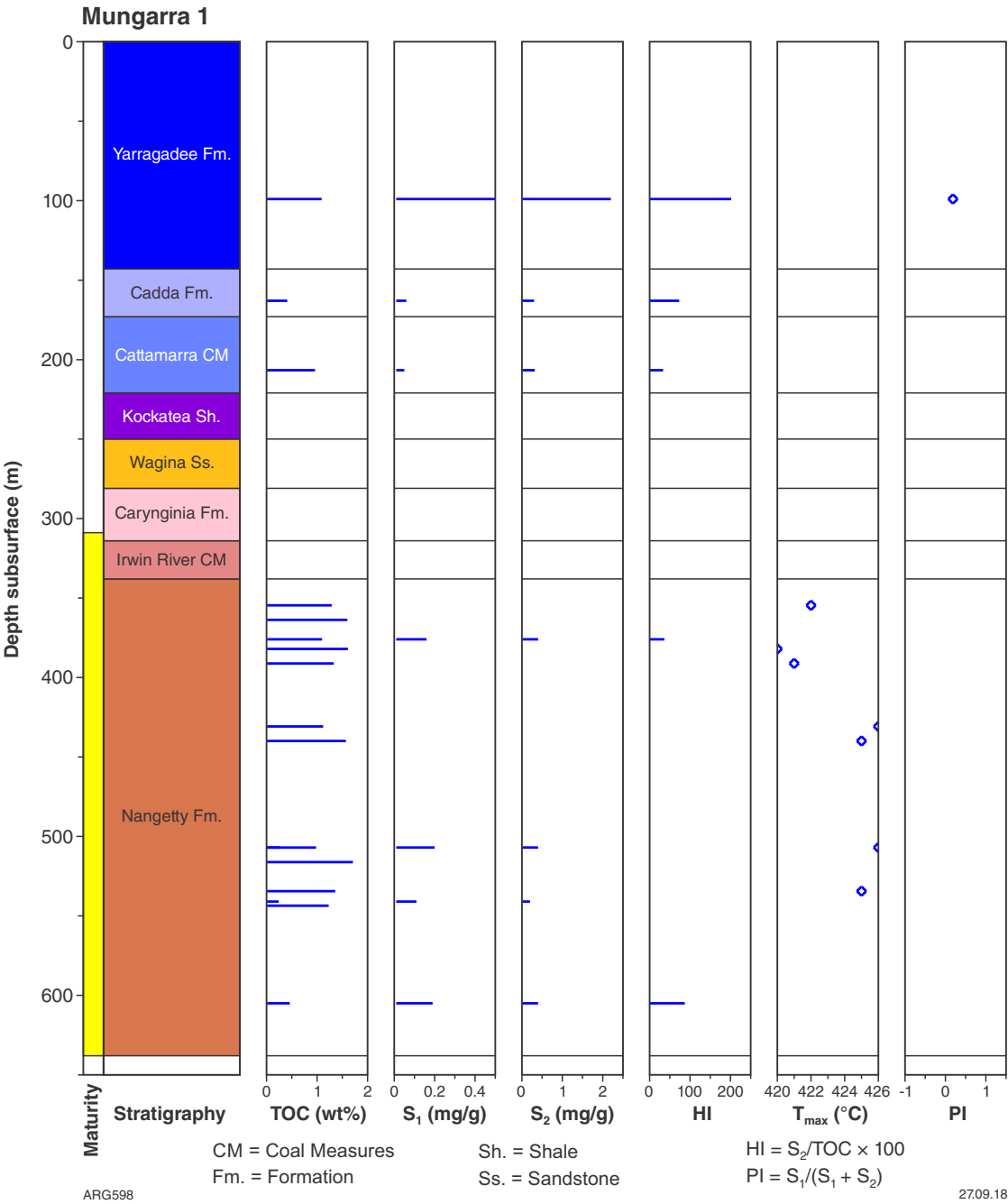
Appendix 2.35. Mt Adams 1 geochemical log of TOC and Rock-Eval pyrolysis data



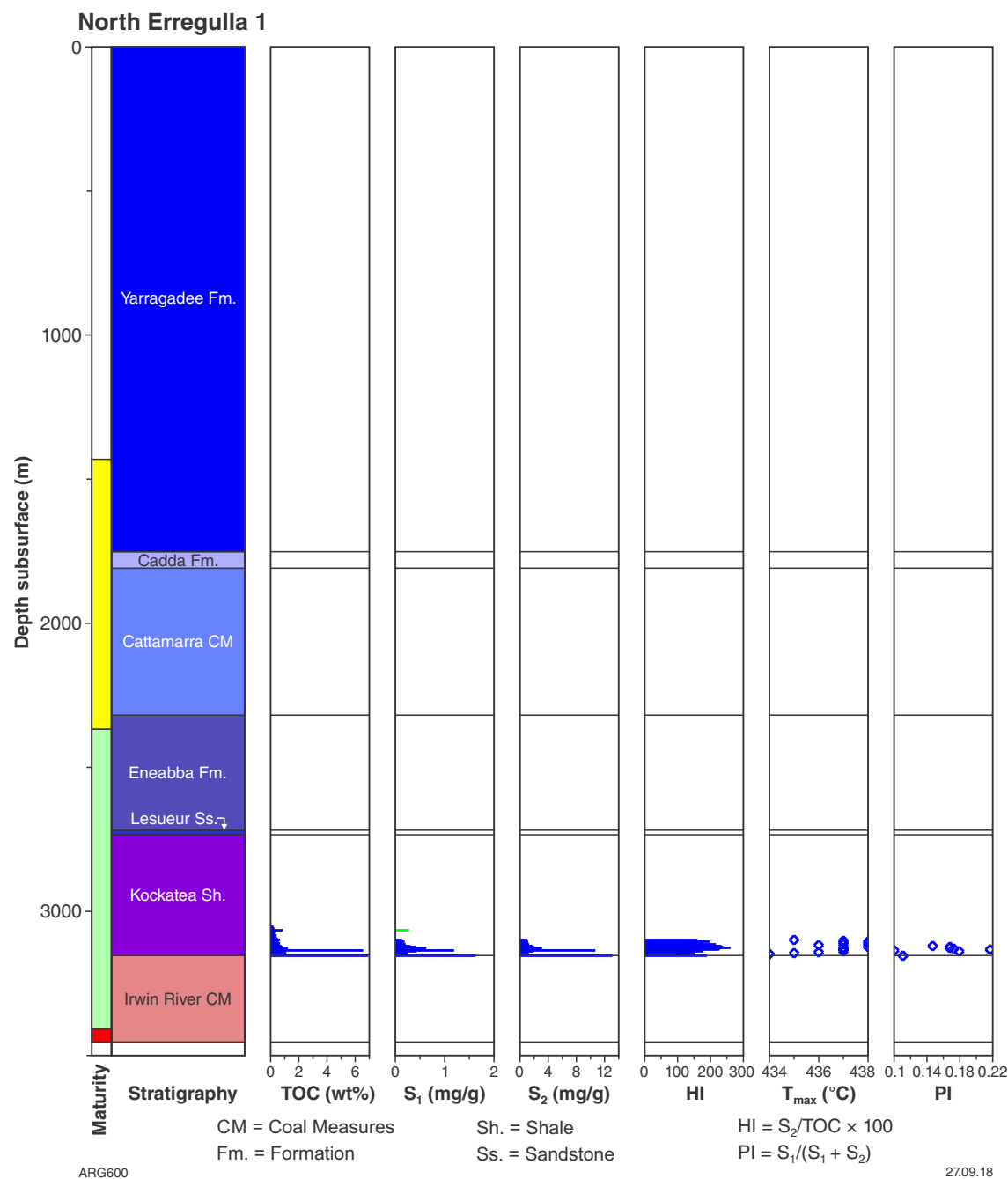
Appendix 2.36. Mt Hill 1 geochemical log of TOC and Rock-Eval pyrolysis data



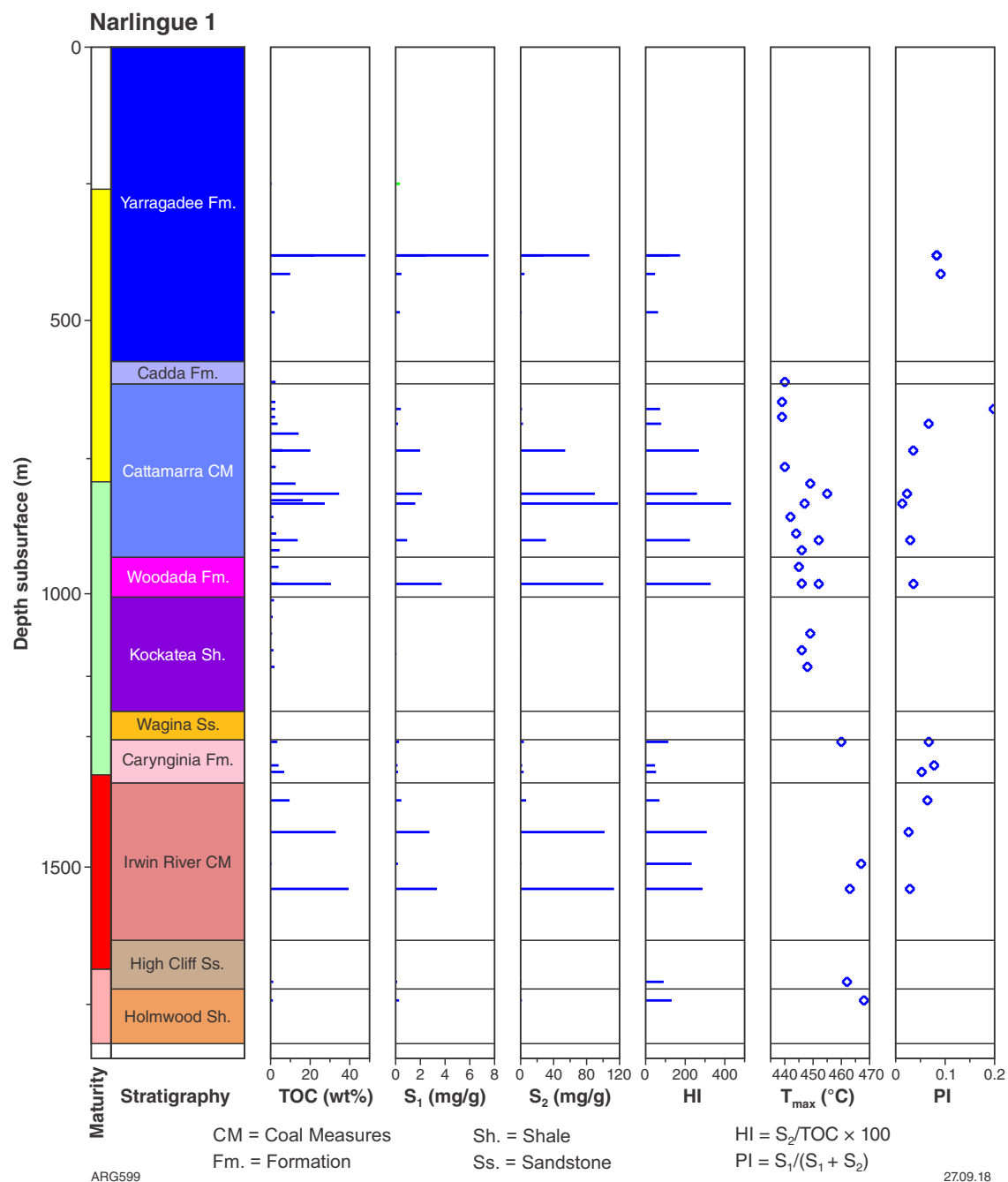
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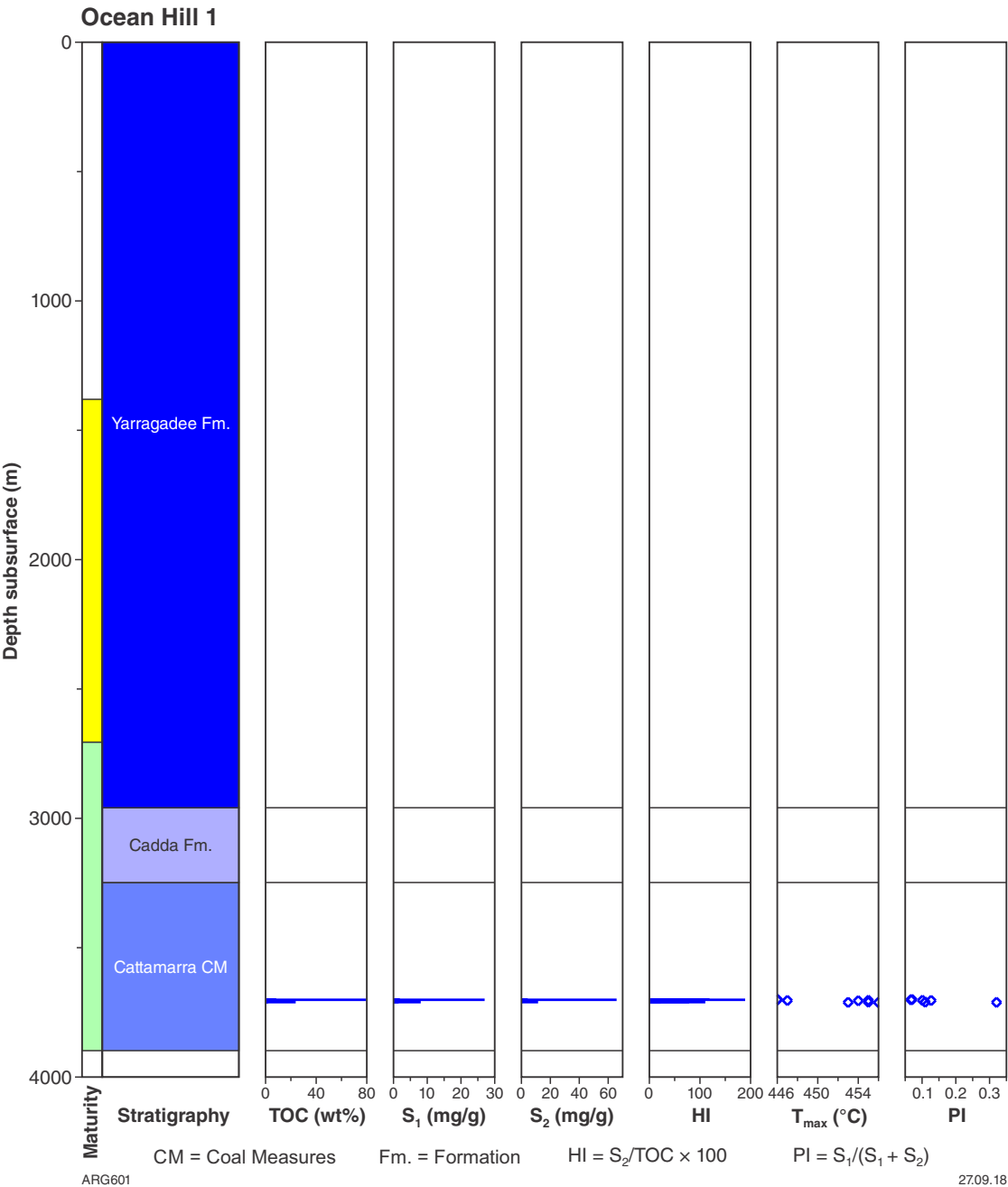
Appendix 2.38. Mungarra 1 geochemical log of TOC and Rock-Eval pyrolysis data



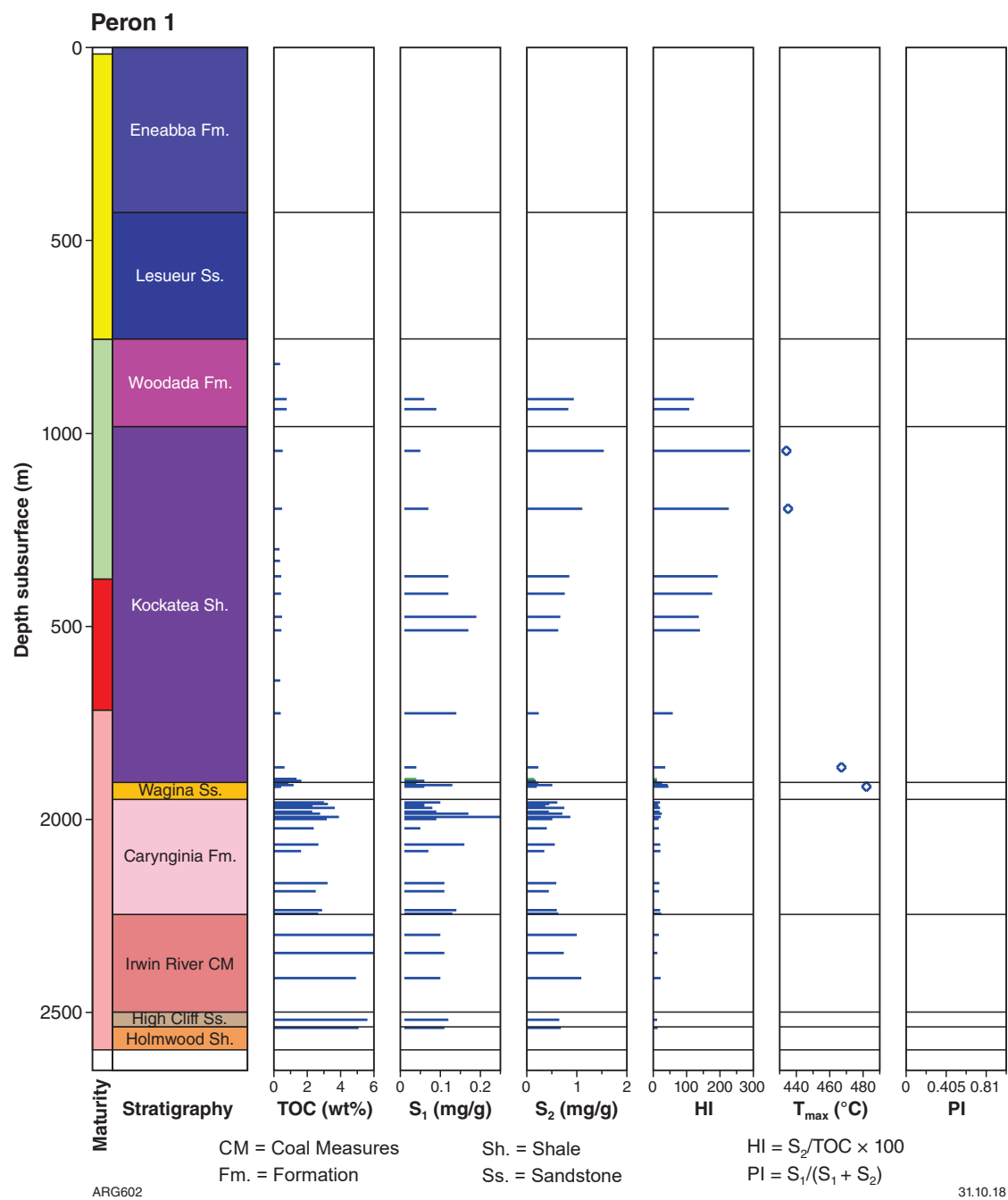
Appendix 2.39. North Erregulla 1 geochemical log of TOC and Rock-Eval pyrolysis data



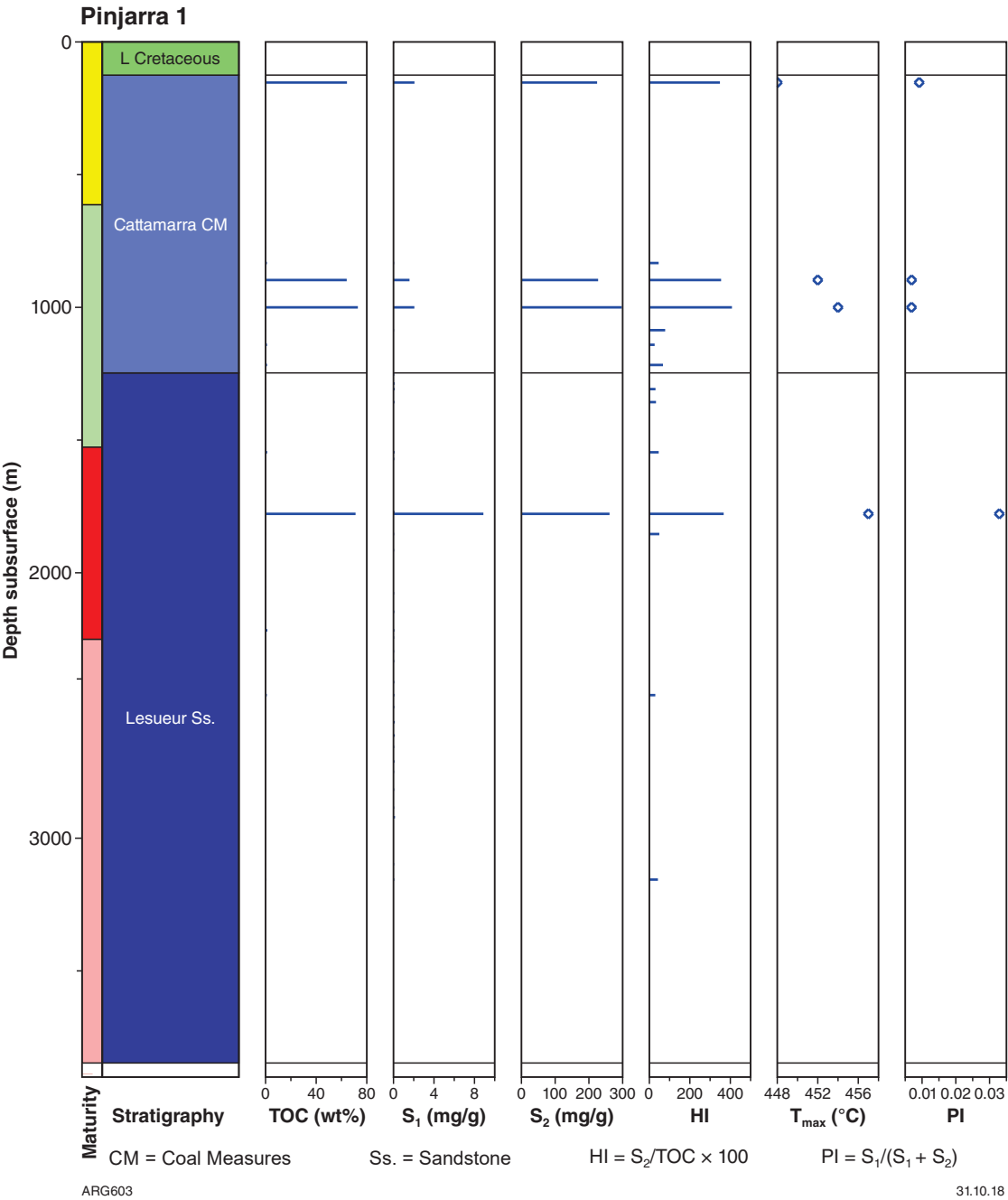
Appendix 2.40. Narlingue 1 geochemical log of TOC and Rock-Eval pyrolysis data



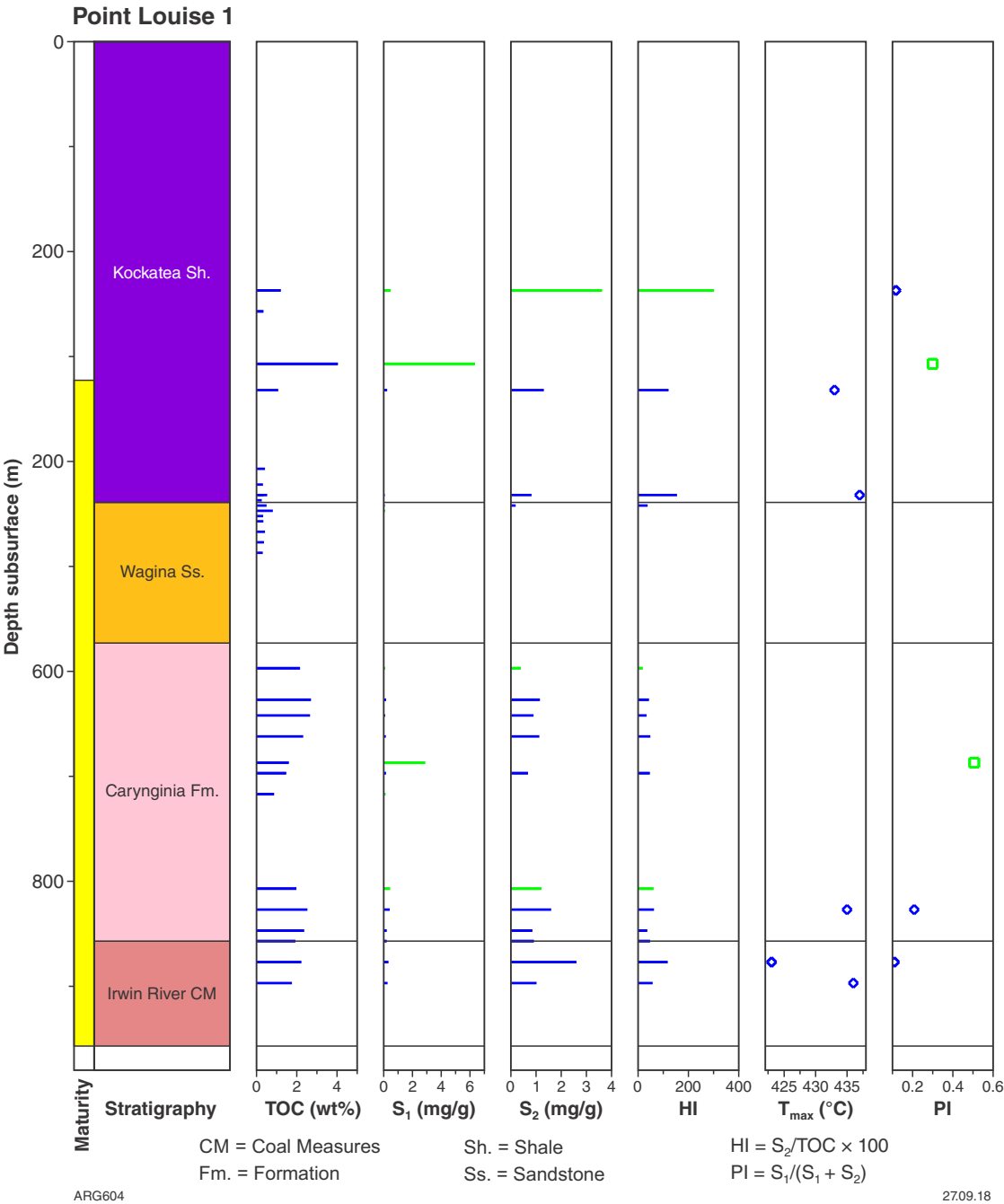
Appendix 2.41. Ocean Hill 1 geochemical log of TOC and Rock-Eval pyrolysis data



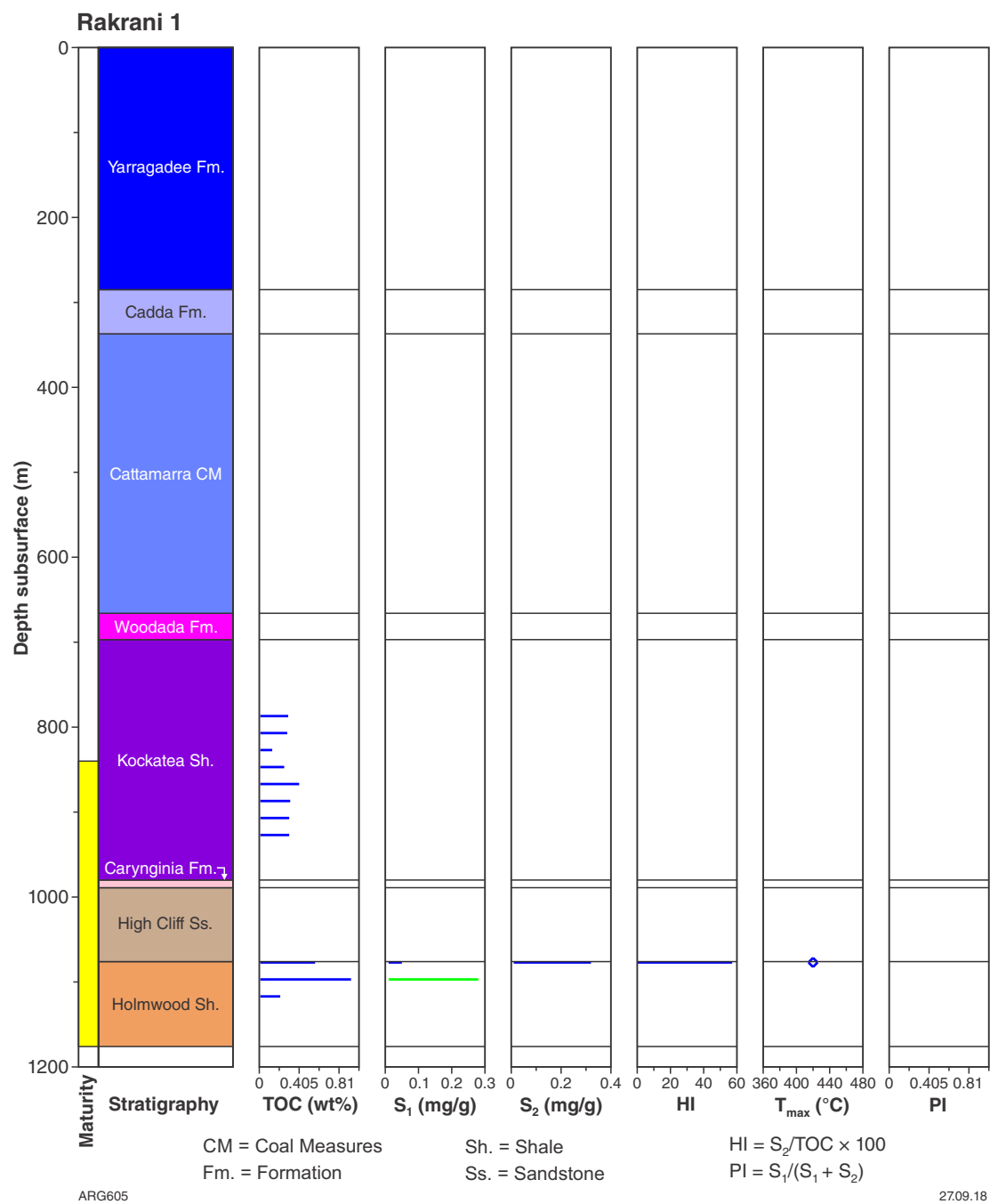
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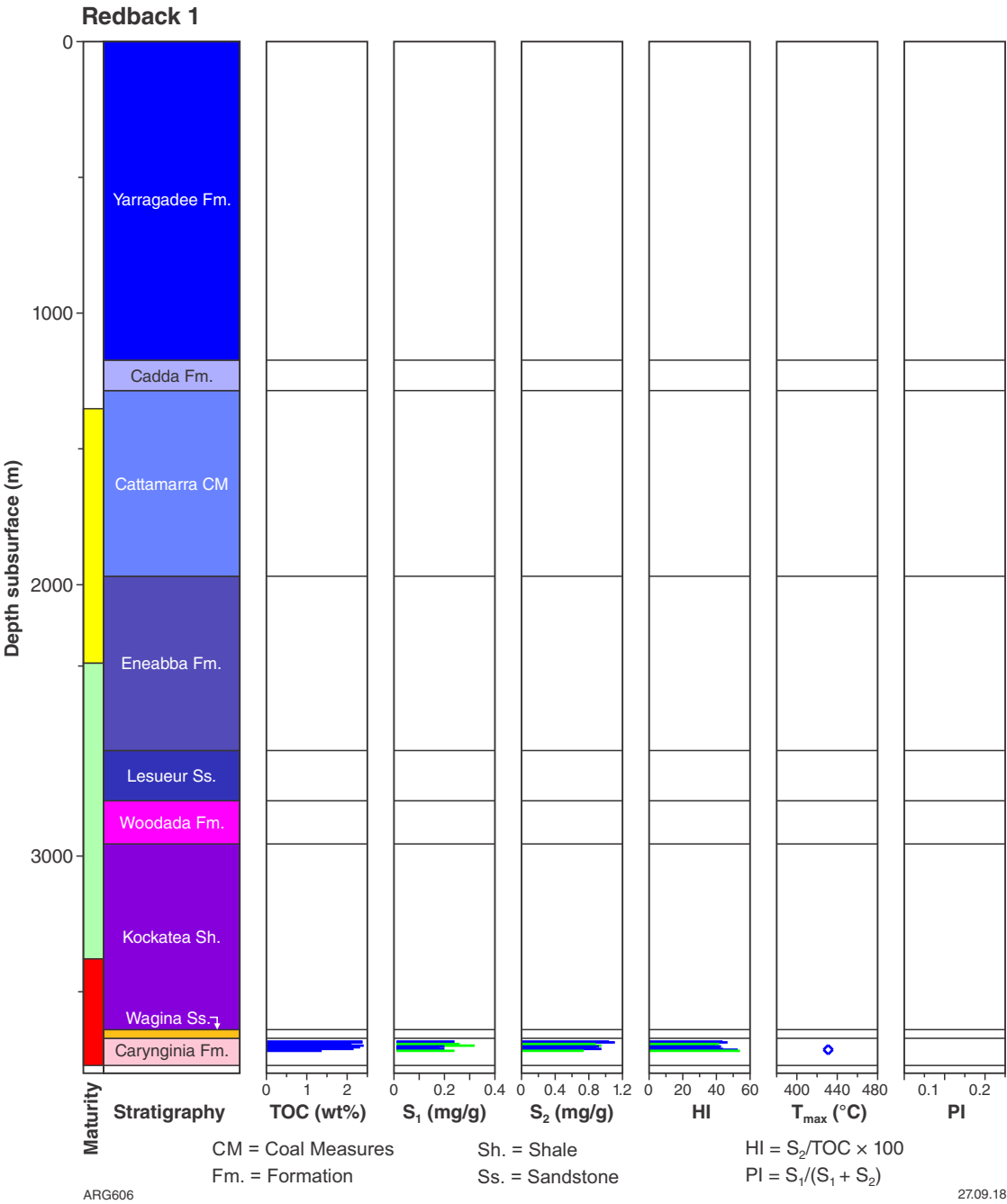
Appendix 2.43. Pinjarra 1 geochemical log of TOC and Rock-Eval pyrolysis data



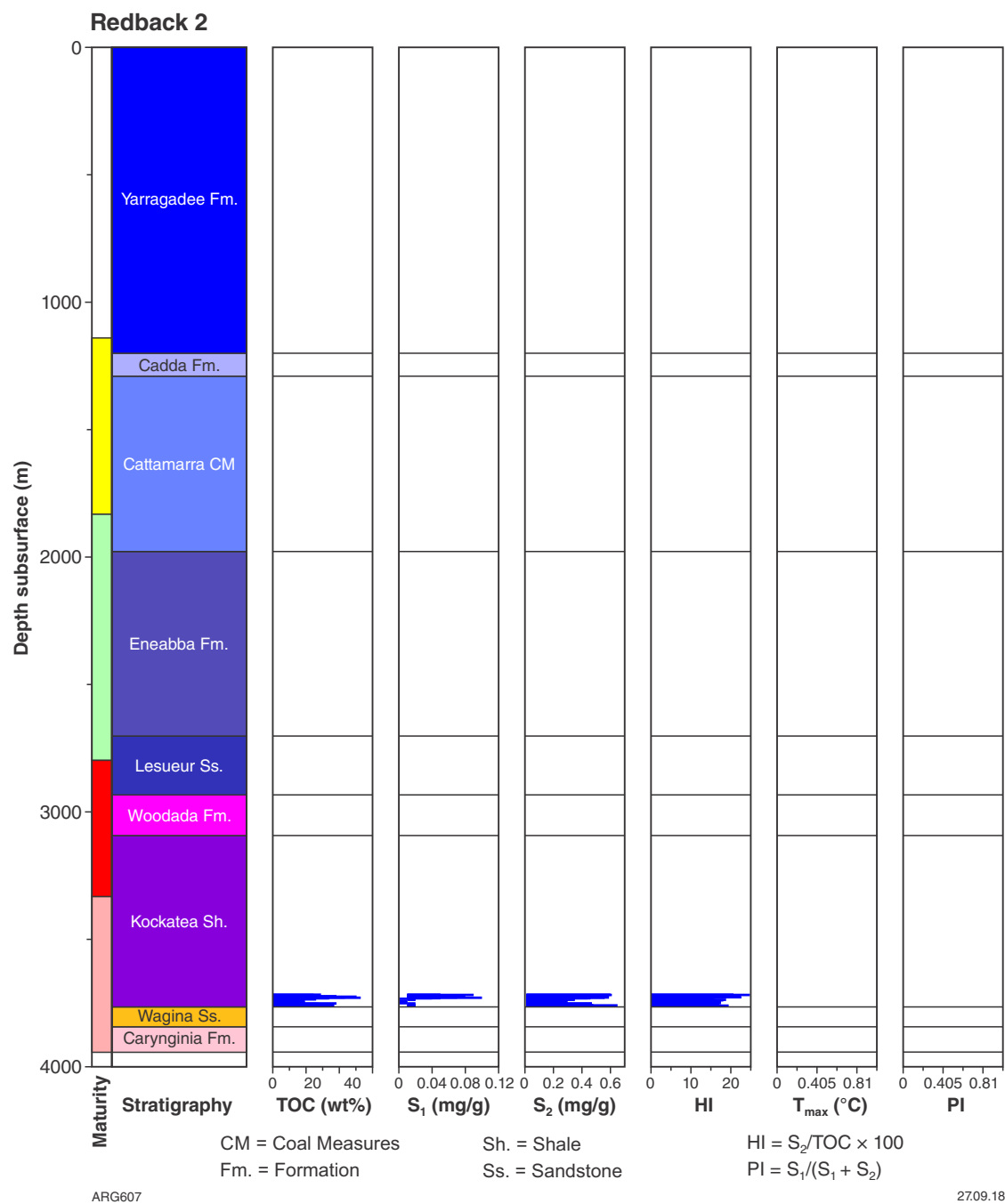
Appendix 2.44. Point Louise 1 geochemical log of TOC and Rock-Eval pyrolysis data



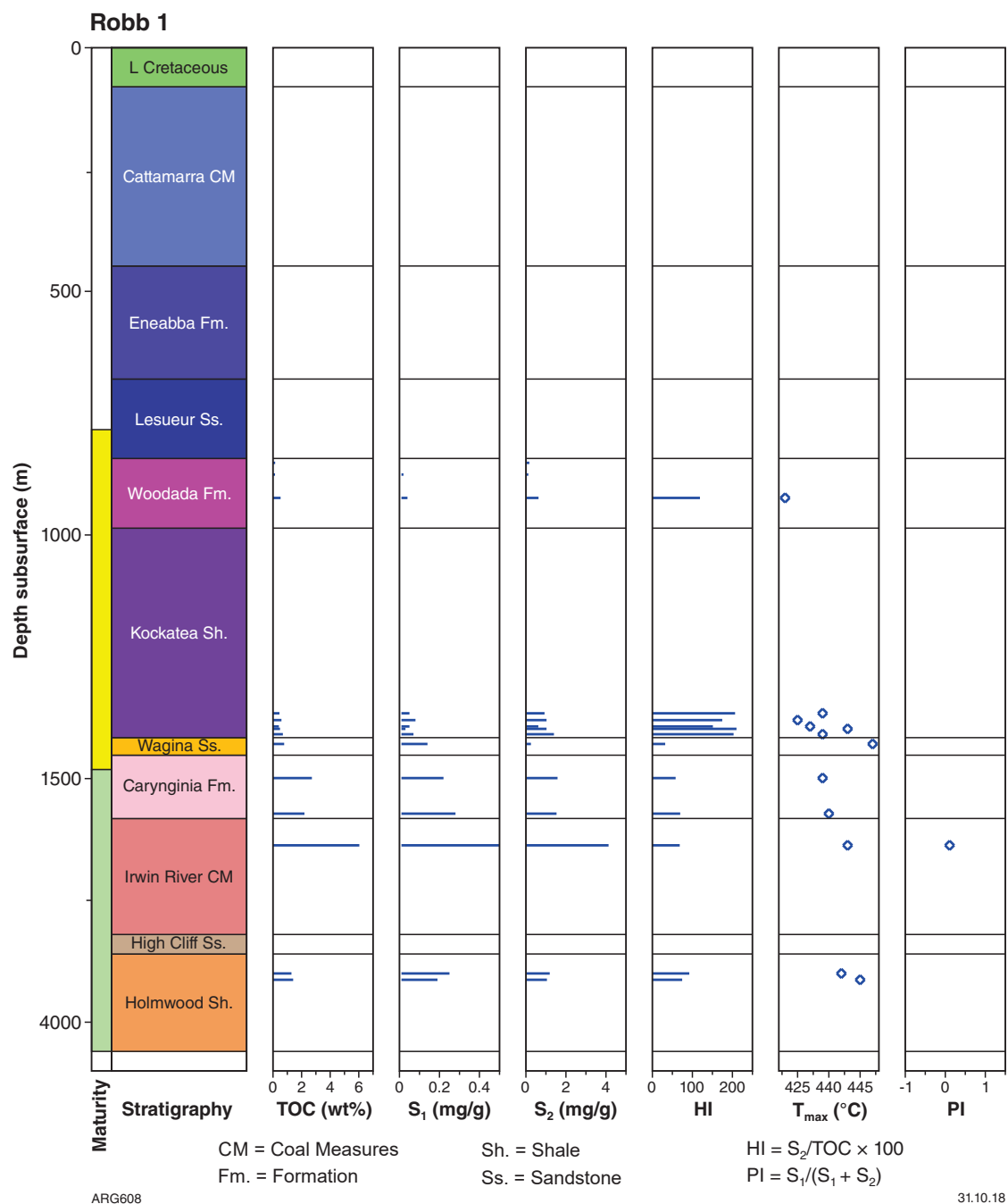
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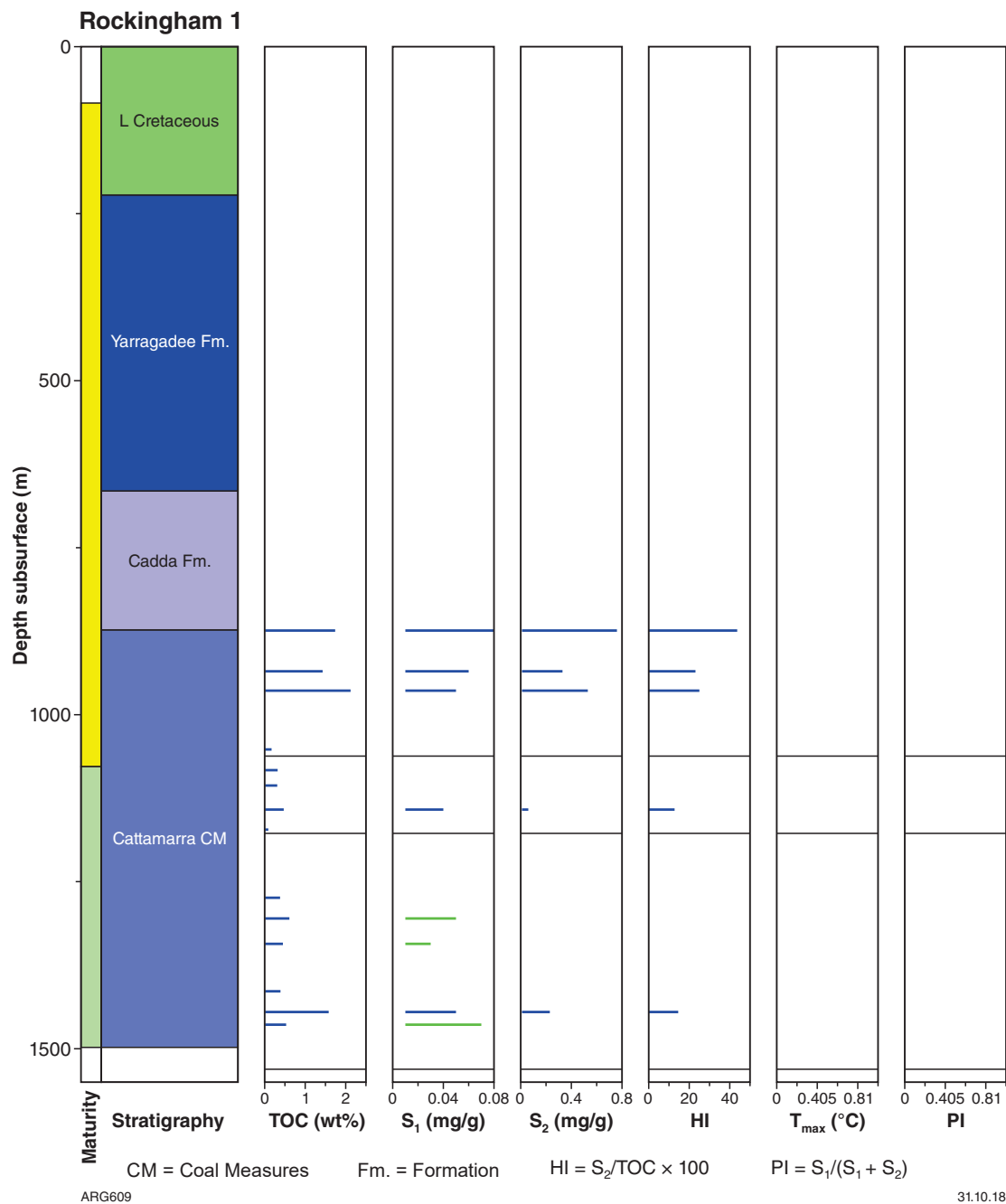
Appendix 2.46. Redback 1 geochemical log of TOC and Rock-Eval pyrolysis data



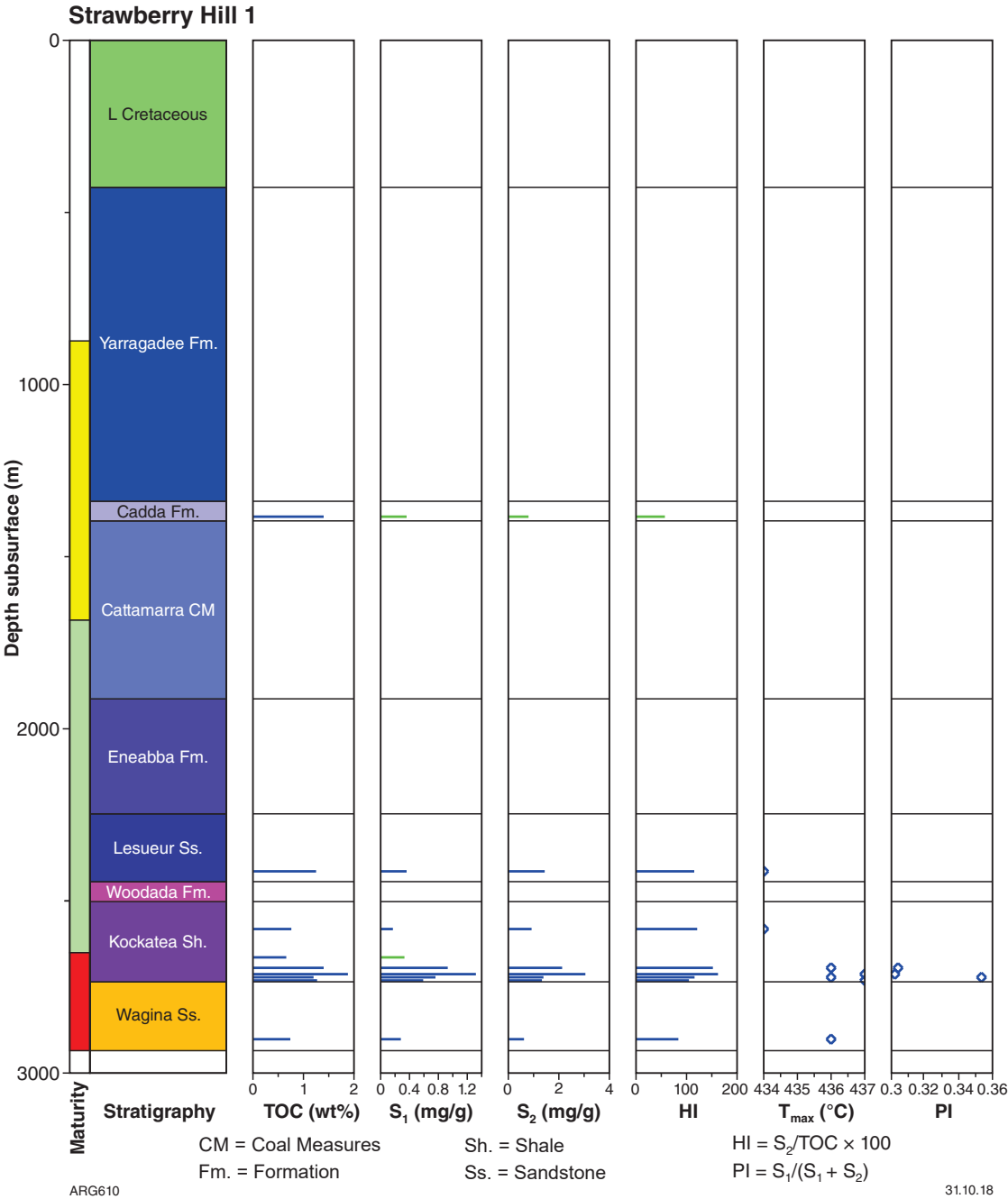
Appendix 2.47. Redback 2 geochemical log of TOC and Rock-Eval pyrolysis data



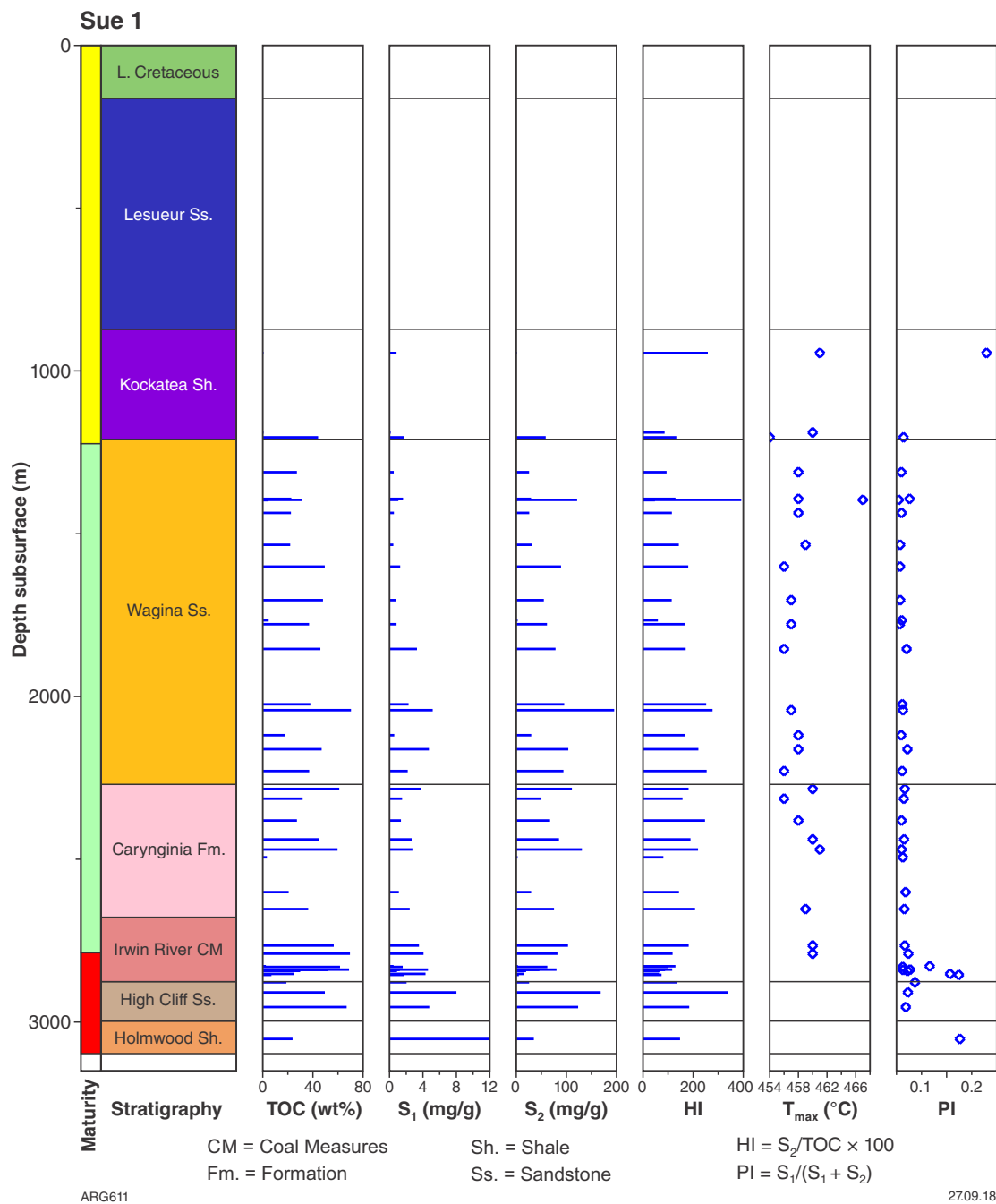
Appendix 2.46. Robb 1 geochemical log of TOC and Rock-Eval pyrolysis data



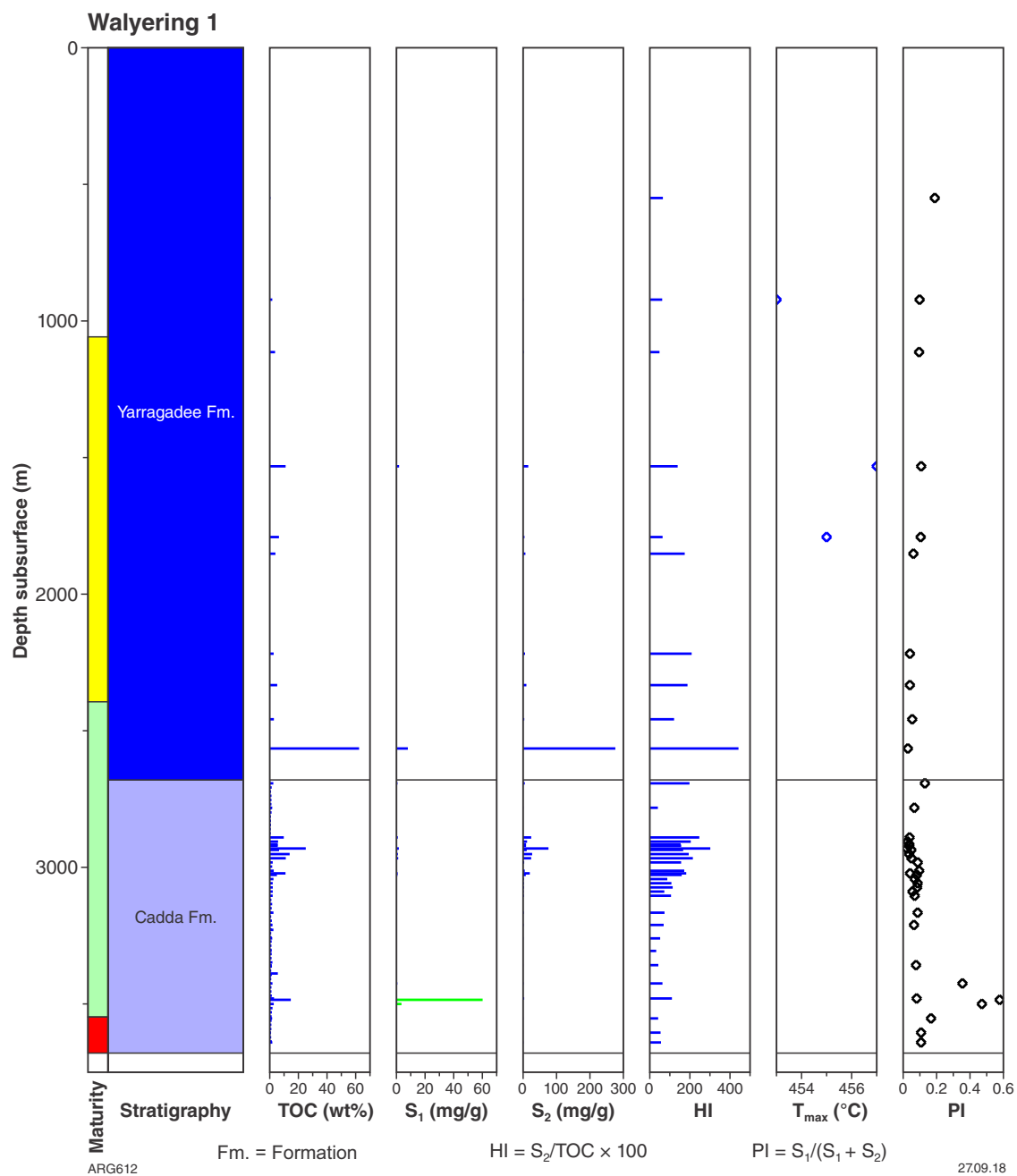
Appendix 2.49. Rockingham 1 geochemical log of TOC and Rock-Eval pyrolysis data



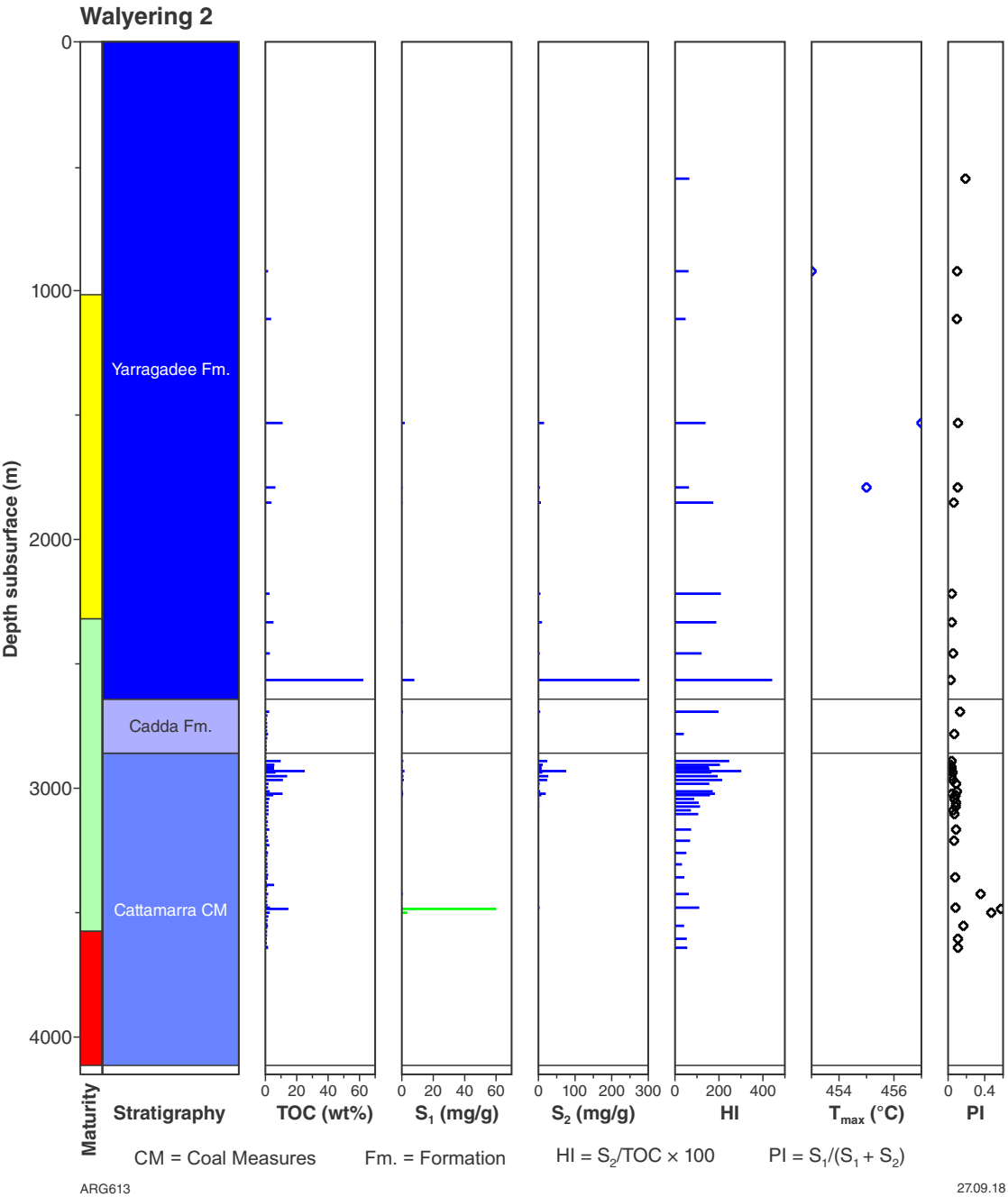
Appendix 2.50. Strawberry Hill 1 geochemical log of TOC and Rock-Eval pyrolysis data



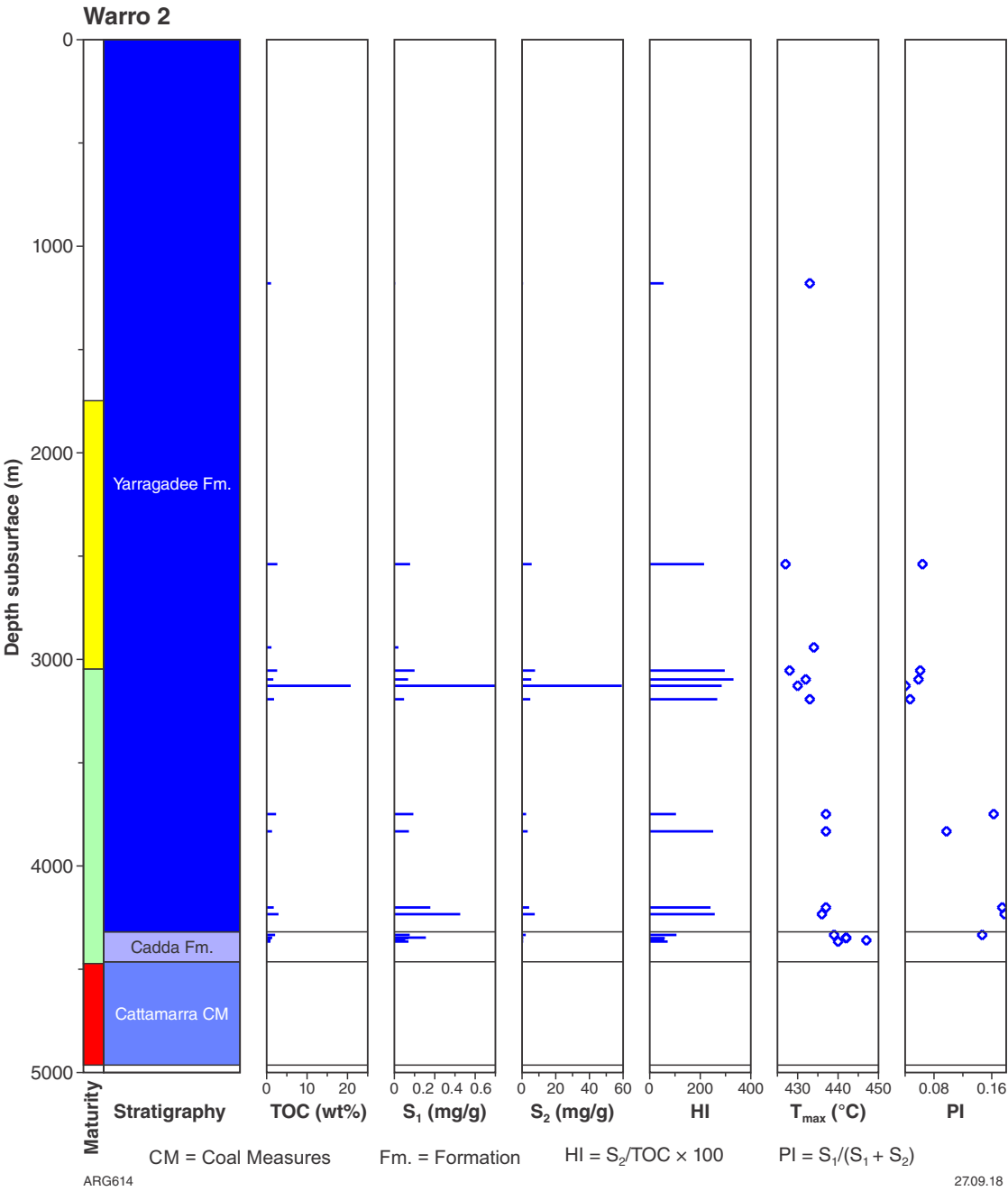
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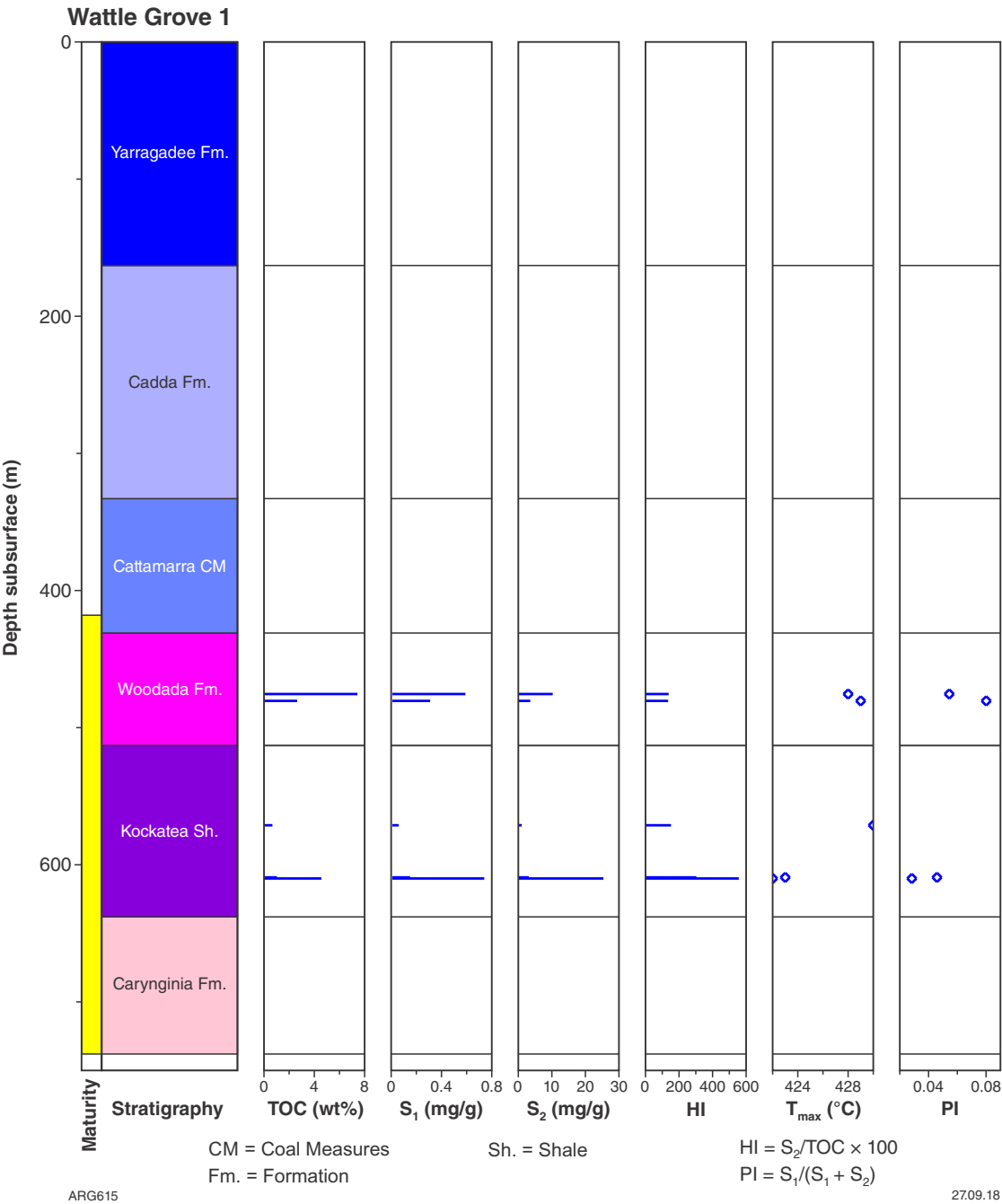
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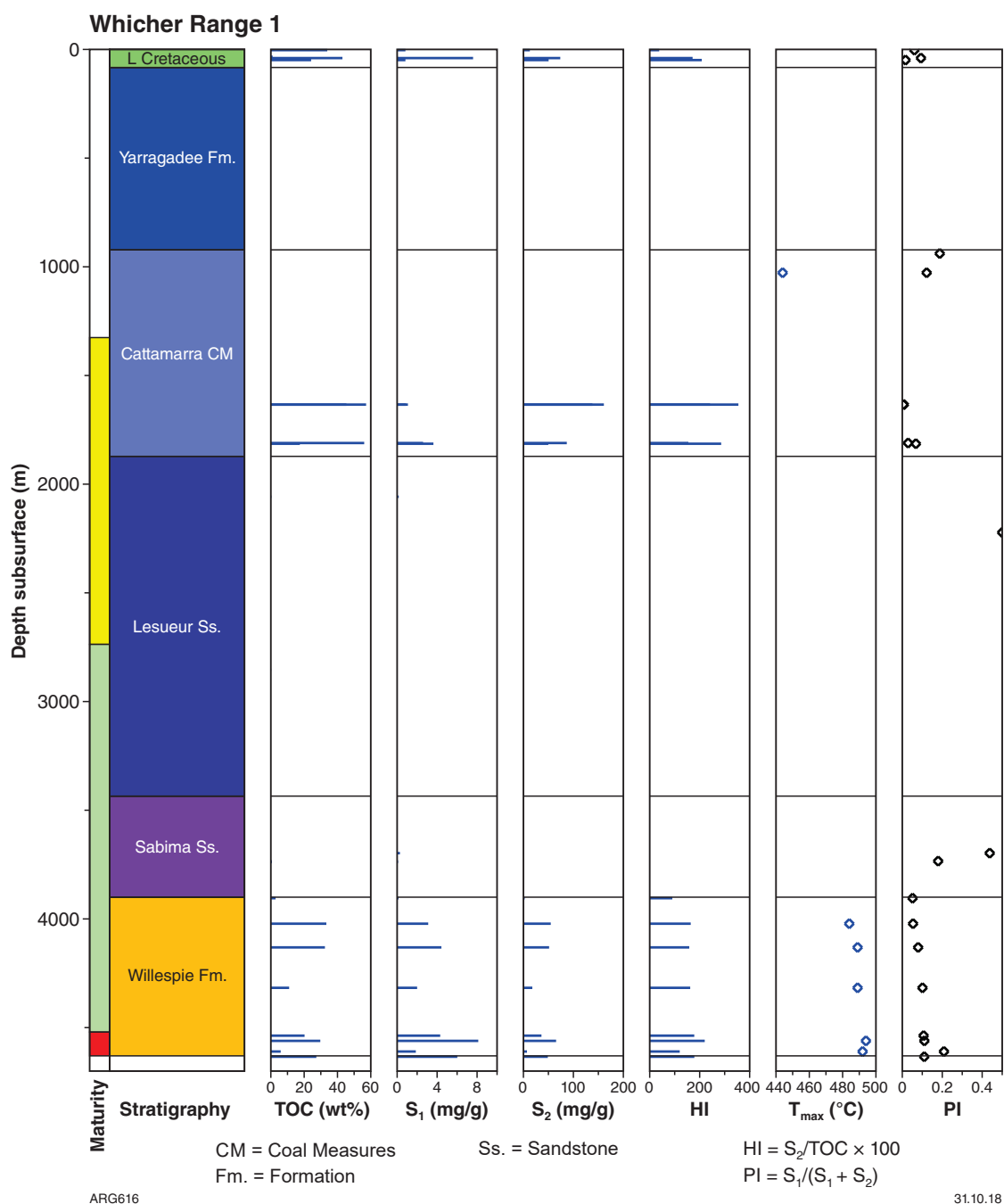
Appendix 2.53. Walyering 2 geochemical log of TOC and Rock-Eval pyrolysis data



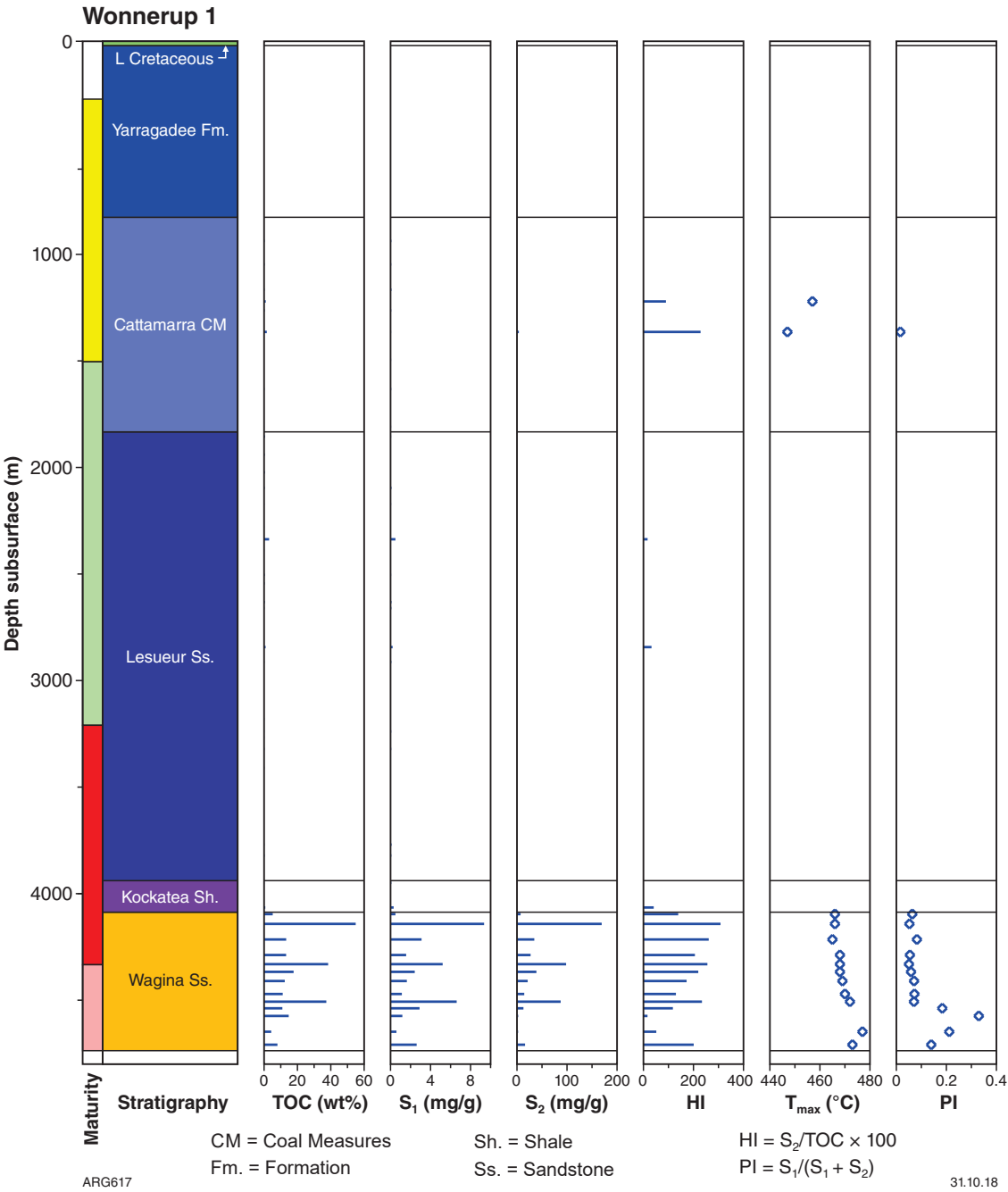
Appendix 2.54. Warro 2 geochemical log of TOC and Rock-Eval pyrolysis data



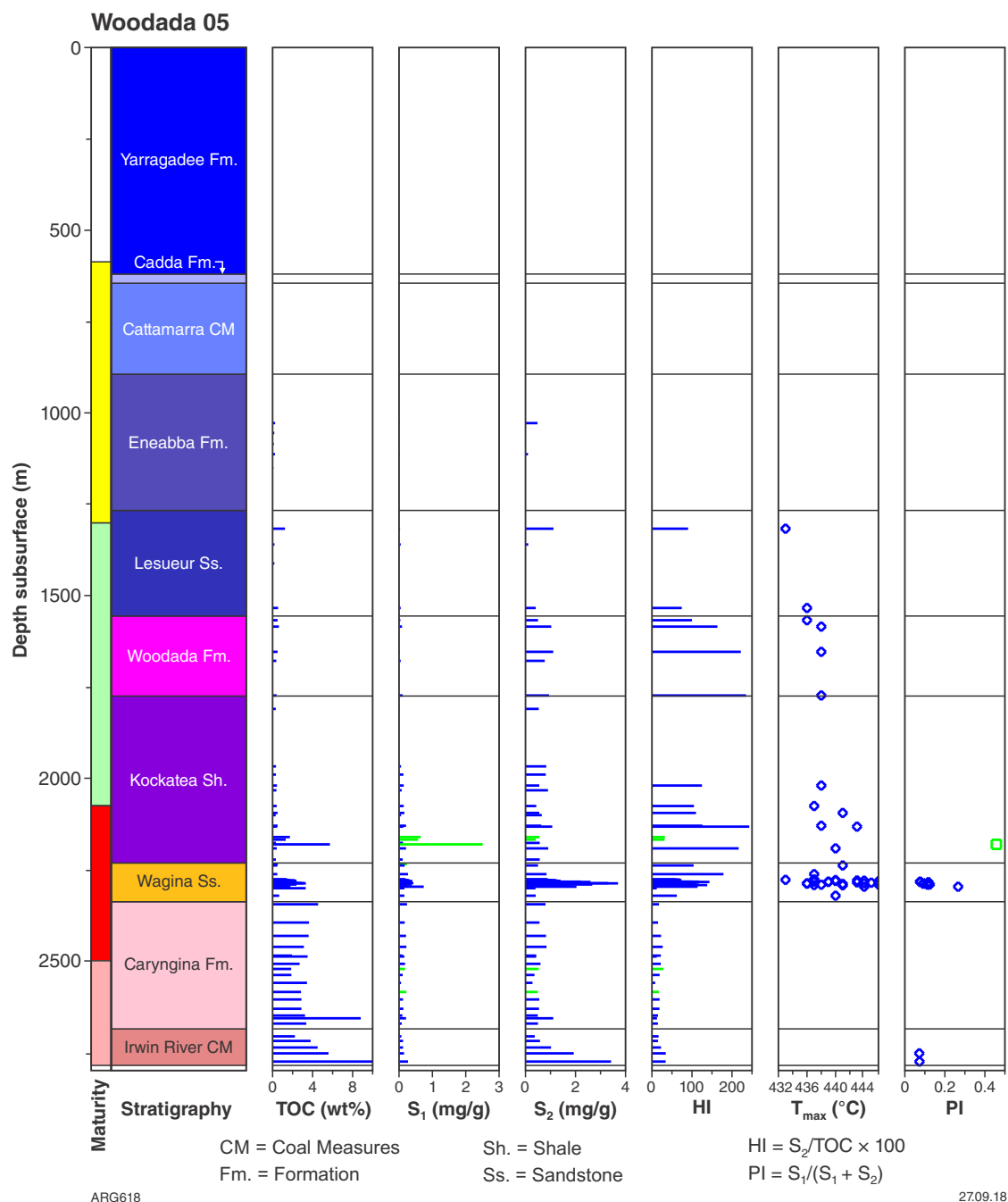
Appendix 2.55. Wattle Grove 1 geochemical log of TOC and Rock-Eval pyrolysis data



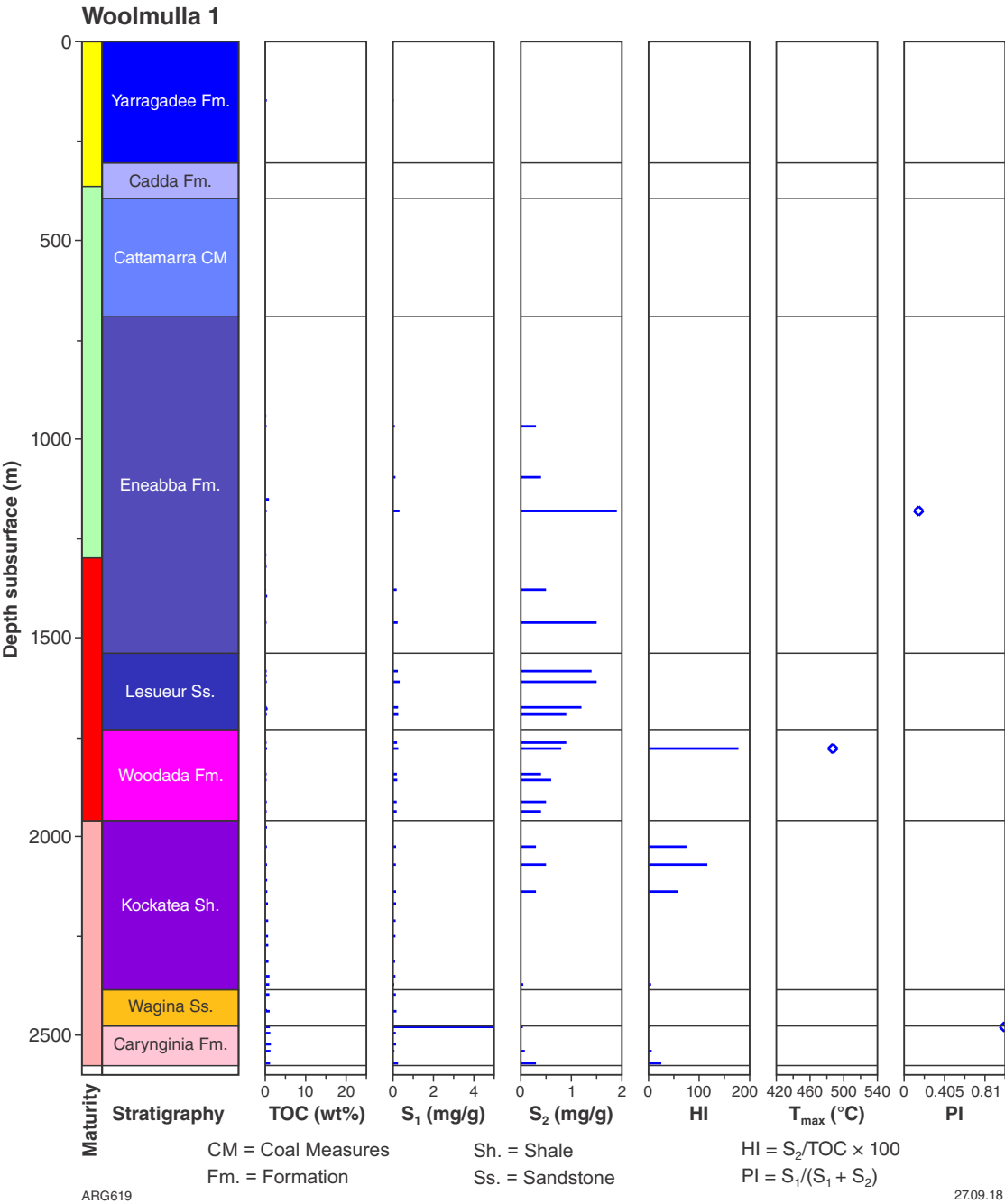
Appendix 2.56. Whicher Range 1 geochemical log of TOC and Rock-Eval pyrolysis data



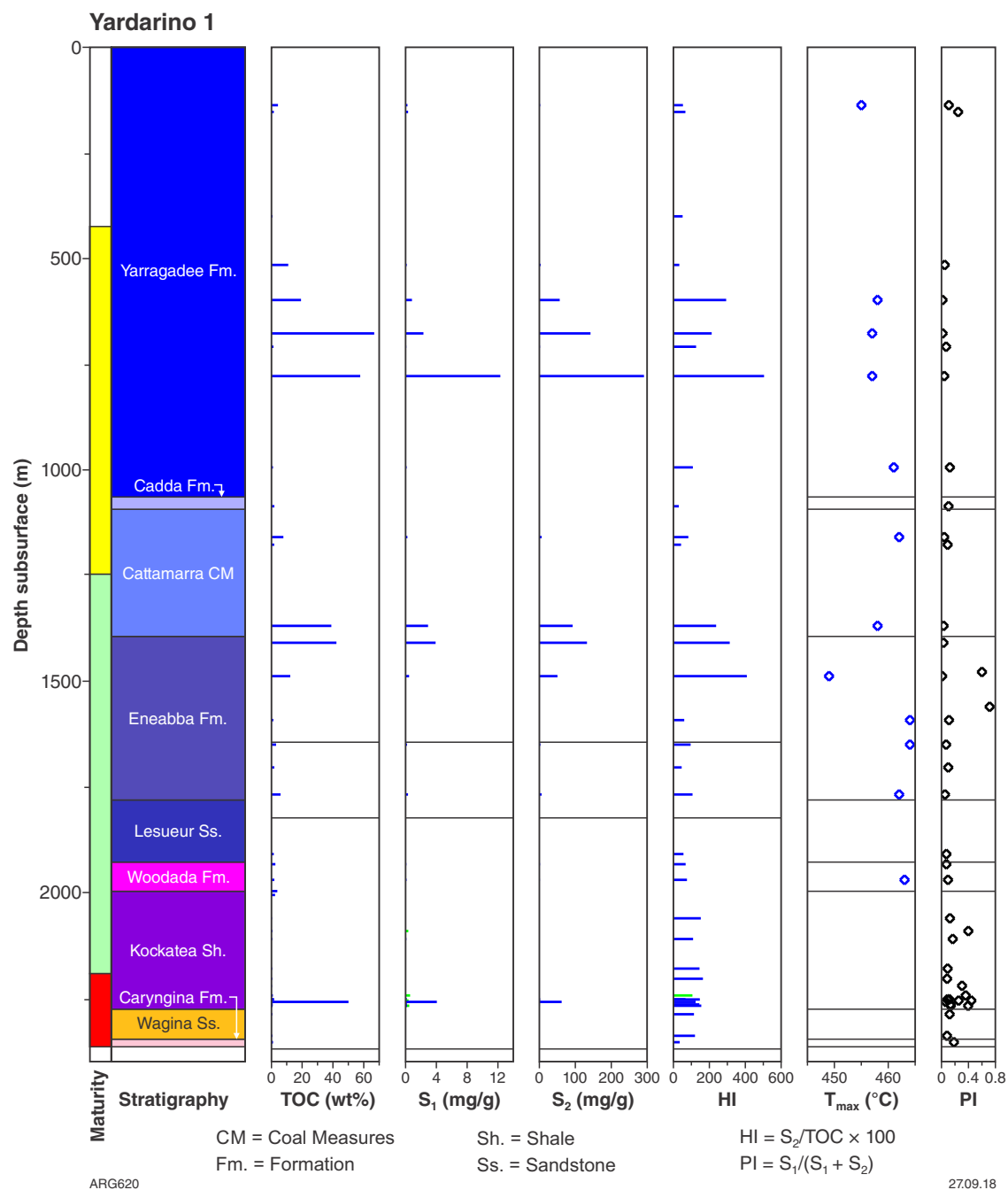
Appendix 2.57. Wonnerup 1 geochemical log of TOC and Rock-Eval pyrolysis data



Appendix 2.58. Woodada 05 geochemical log of TOC and Rock-Eval pyrolysis data



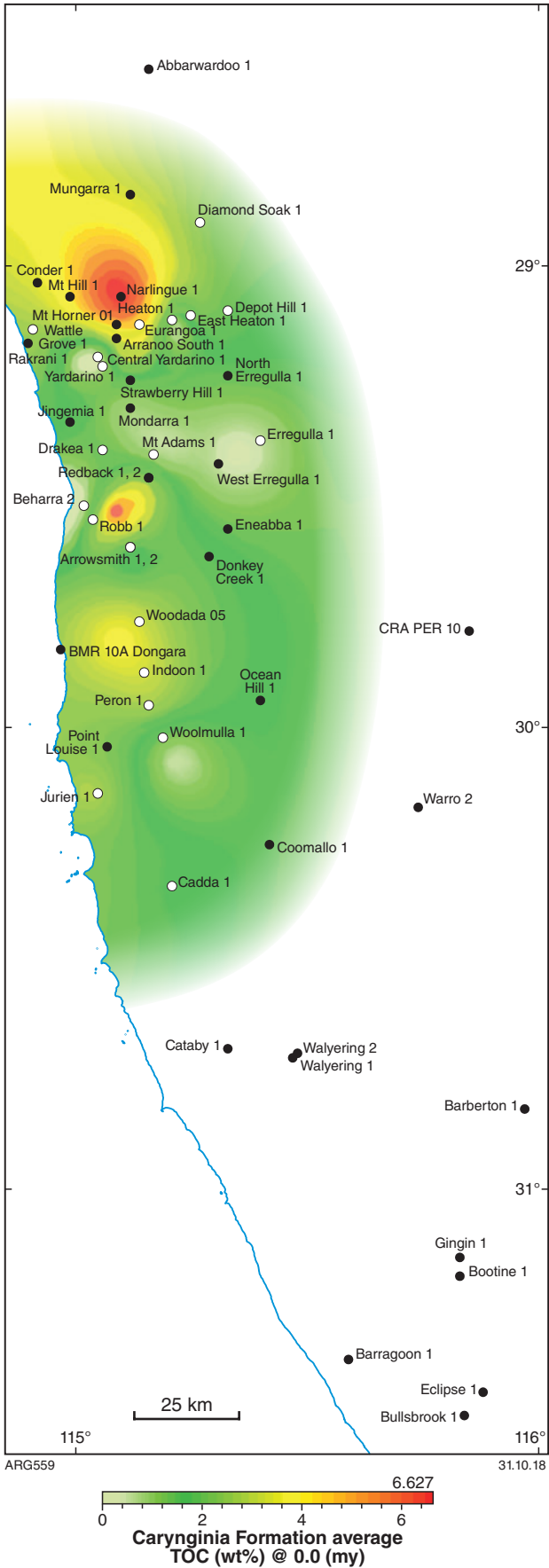
Appendix 2.59. Woolmulla 1 geochemical log of TOC and Rock-Eval pyrolysis data



Appendix 2.60. Yardarino 1 geochemical log of TOC and Rock-Eval pyrolysis data

Appendix 3

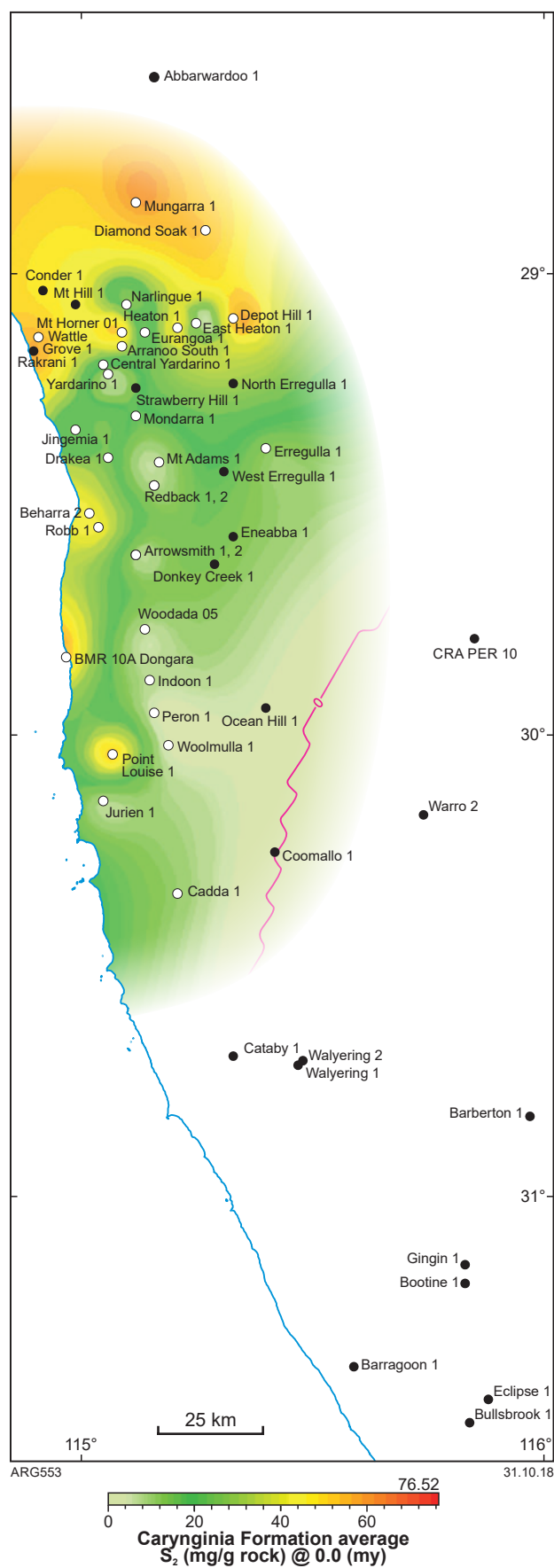
Maps of the Carynginia Formation, Kockatea Shale, and the Cattamarra Coal Measures, showing distribution of measured TOC, measured and calculated Rock-Eval parameter S_2 mg/g TOC, hydrogen index, production index, transformation ratio, calculated temperature, and temperature maximum within the northern Perth Basin



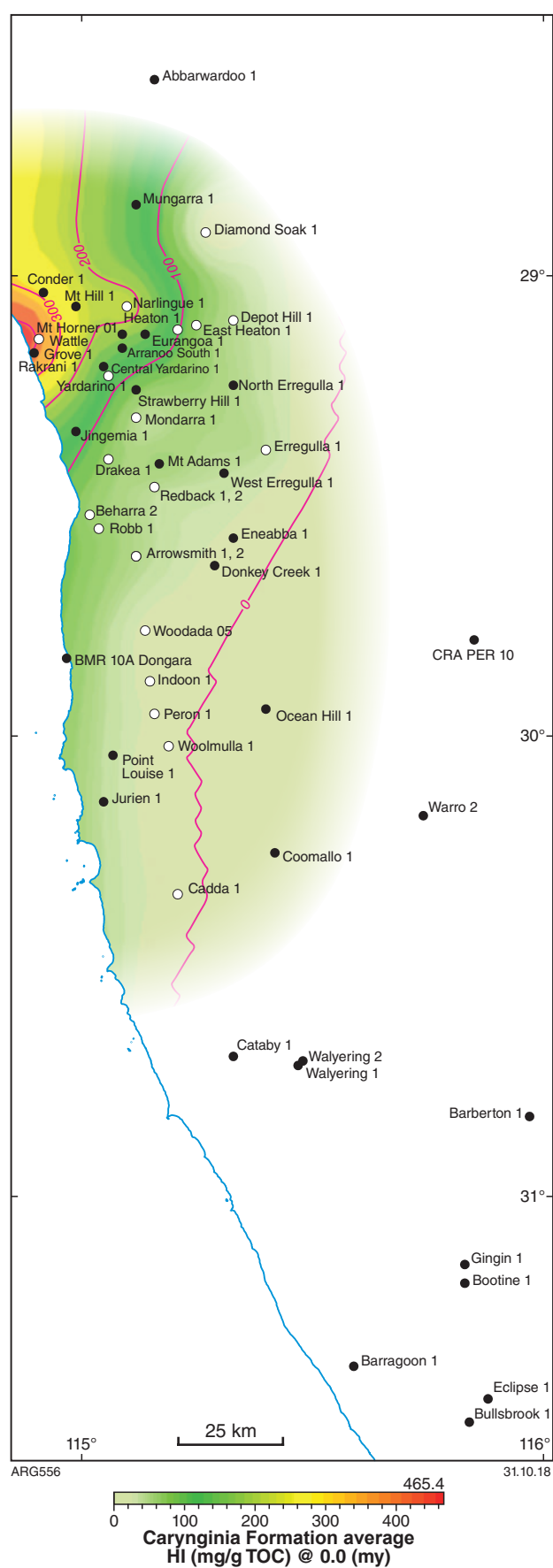
Appendix 3.1. Map of the Carynginia Formation, showing the distribution of measured TOC within the northern Perth Basin. Data wells are represented by white circles



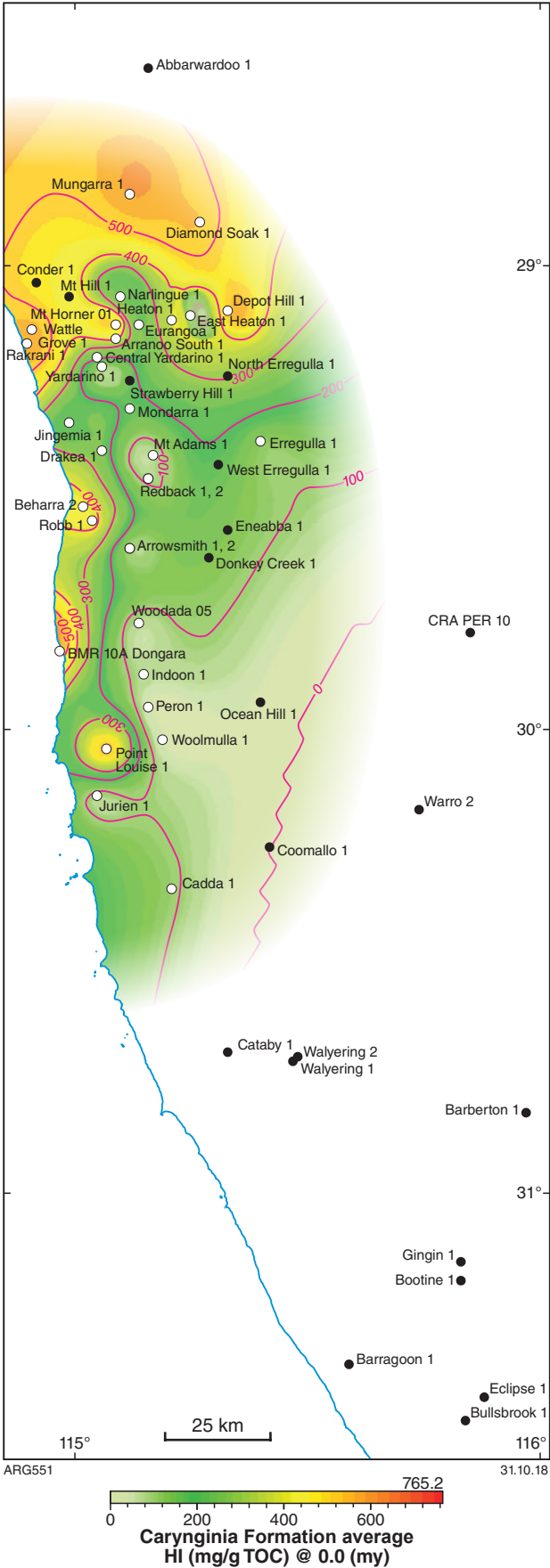
Appendix 3.2. Map of the Carynginia Formation showing the distribution of measured Rock-Eval parameter S_2 mg/g TOC within the northern Perth Basin. Data wells are represented by white circles



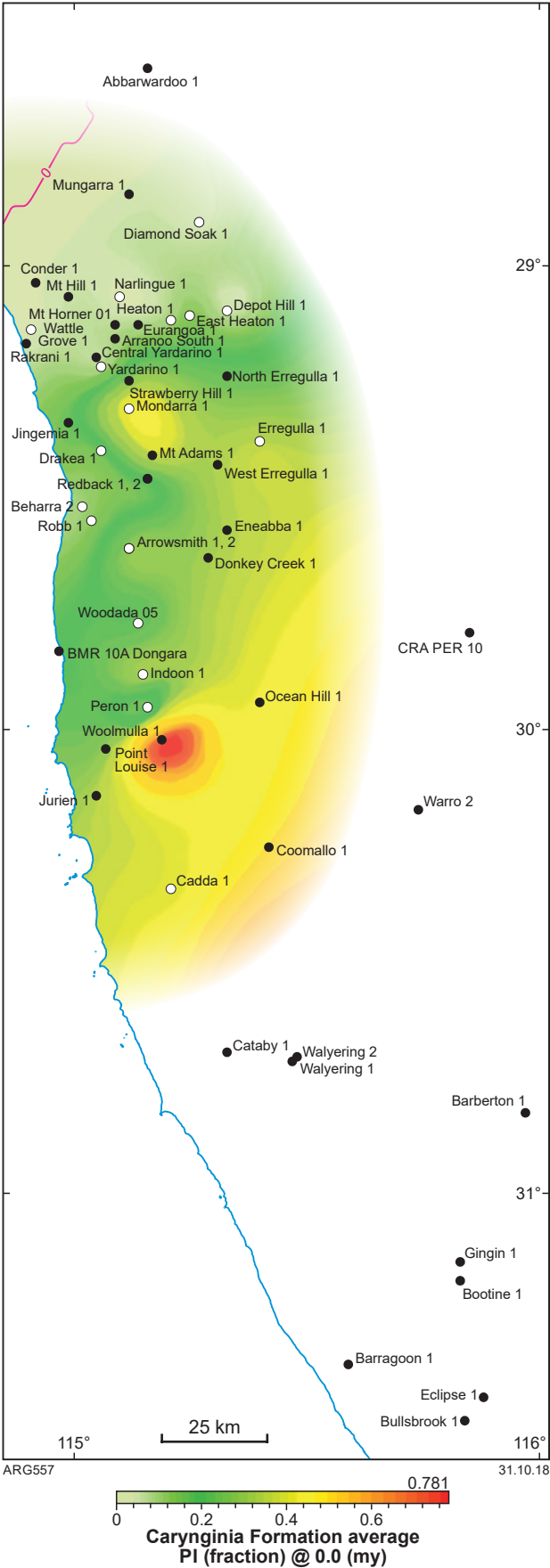
Appendix 3.3. Map of the Carynginia Formation showing the distribution of calculated Rock-Eval parameter S_2 mg/g TOC within the northern Perth Basin. Data wells are represented by white circles



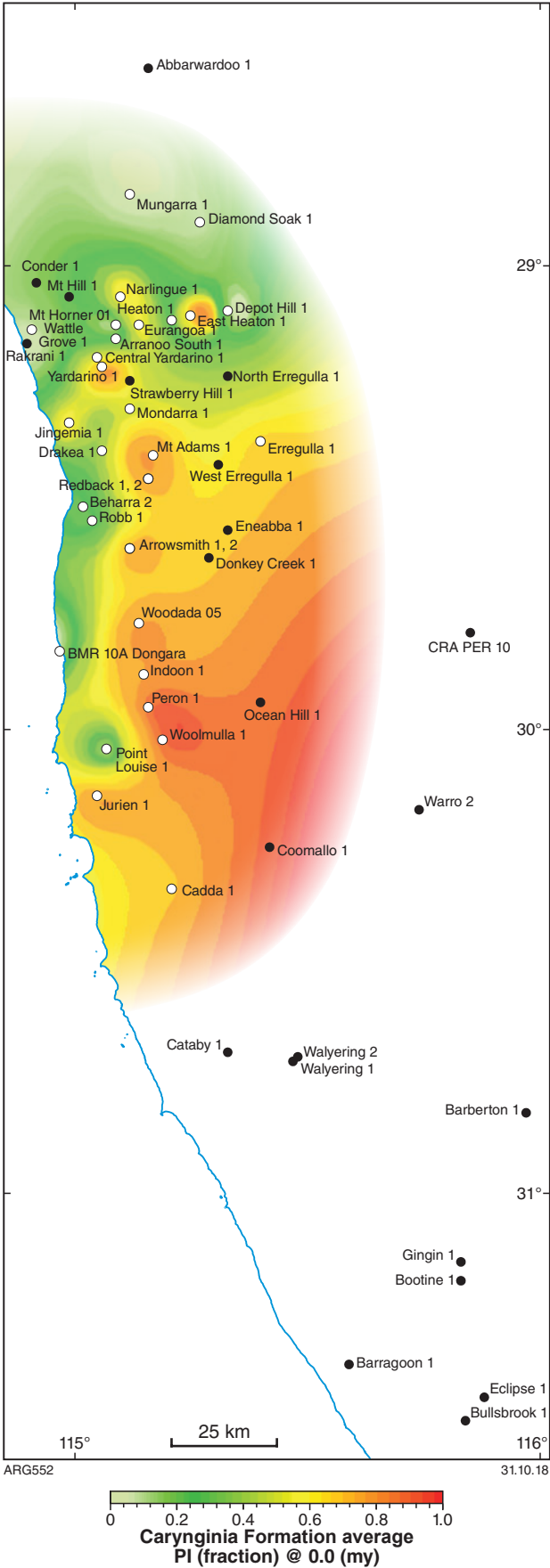
Appendix 3.4. Map of the Carynginia Formation showing the distribution of measured Rock-Eval parameter hydrogen index within the northern Perth Basin. Data wells are represented by white circles



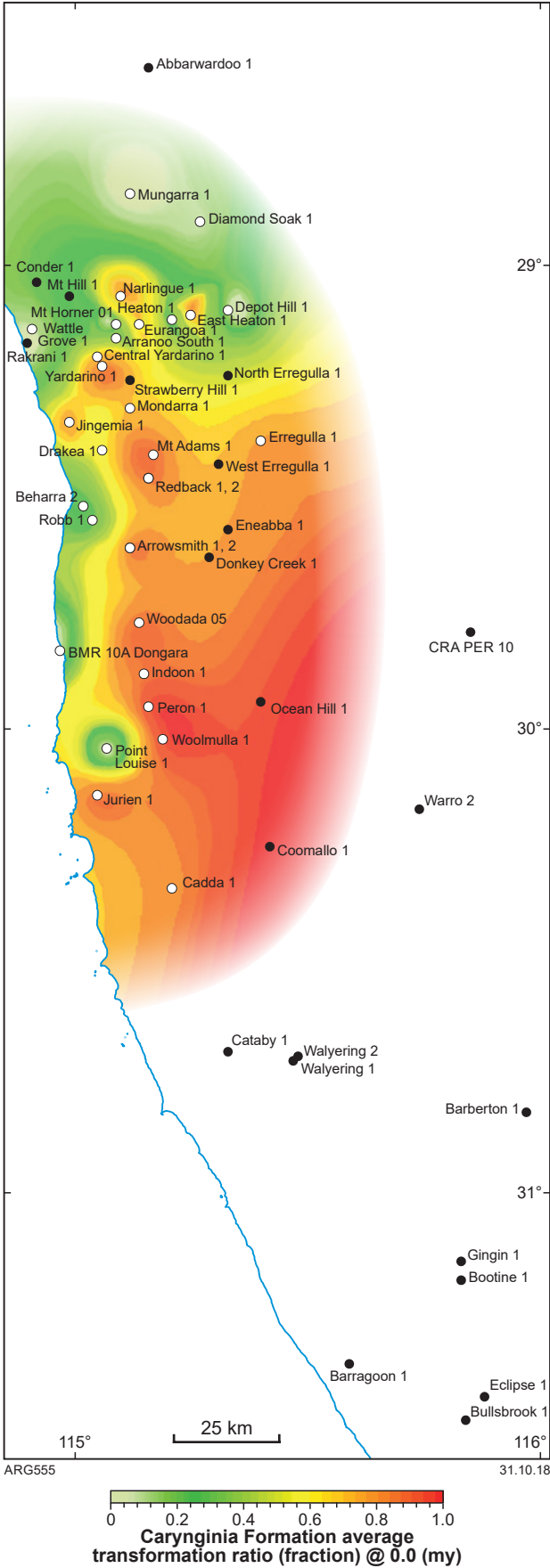
Appendix 3.5. Map of the Carynginia Formation showing the distribution of calculated Rock-Eval parameter hydrogen index within the northern Perth Basin. Data wells are represented by white circles



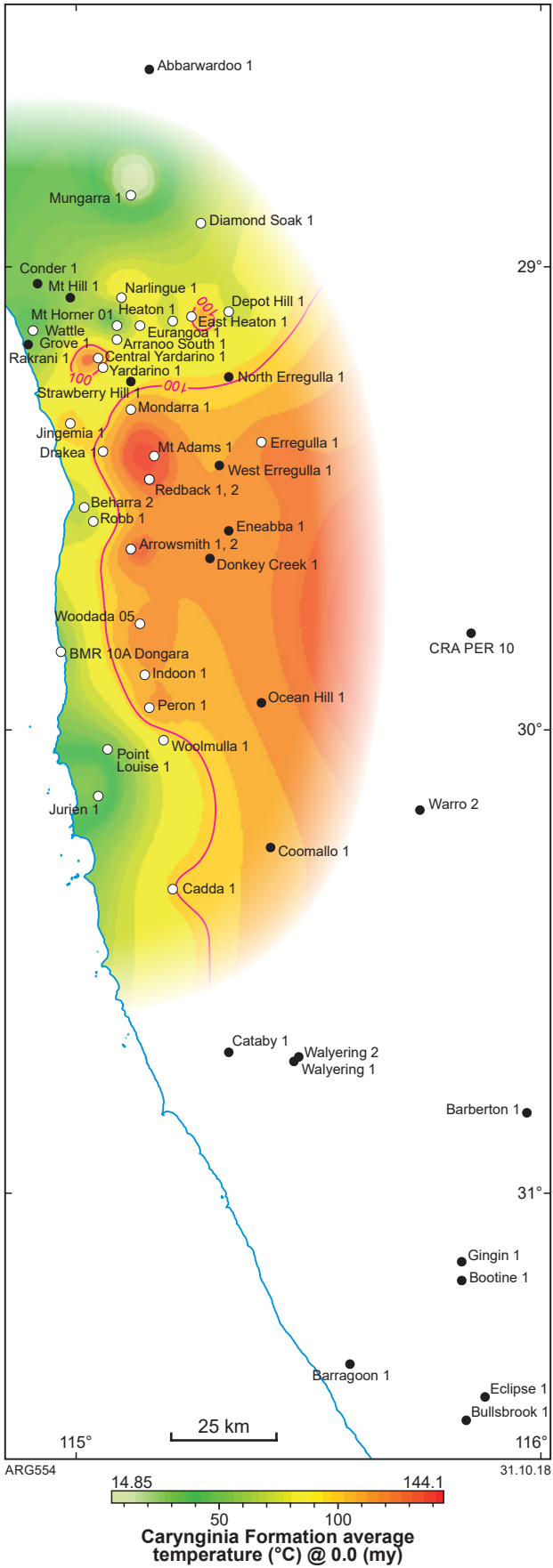
Appendix 3.6. Map of the Carynginia Formation showing the distribution of measured Rock-Eval parameter production index within the northern Perth Basin. Data wells are represented by white circles



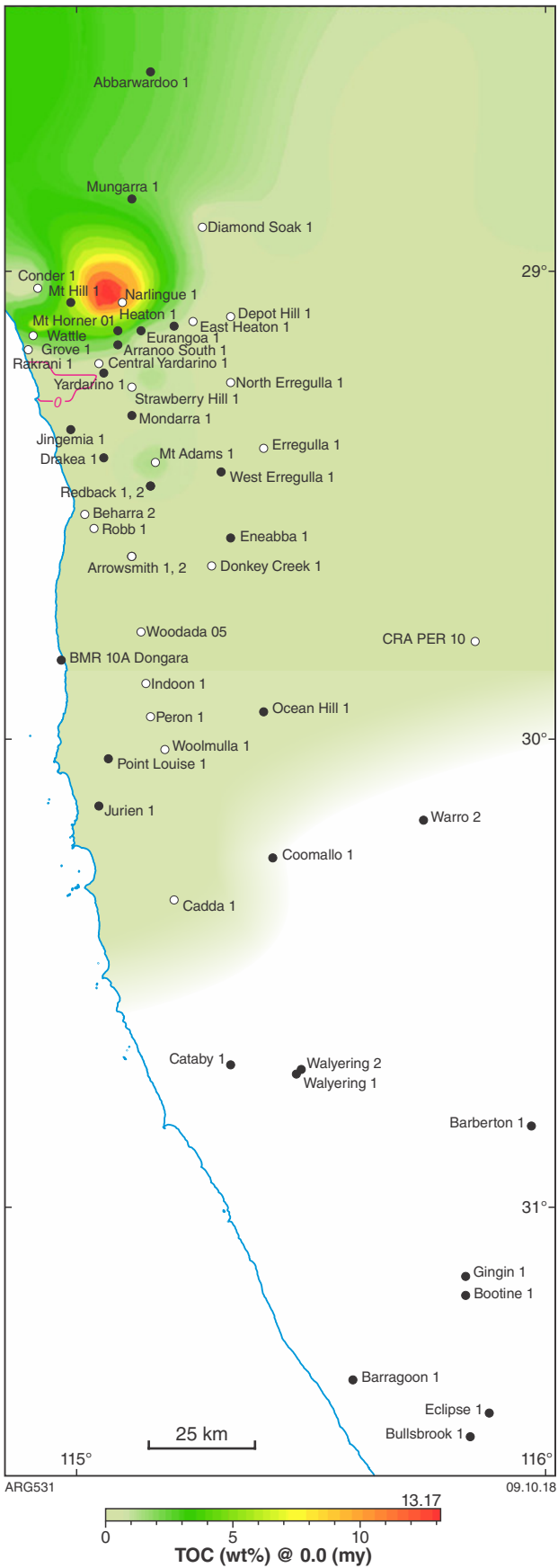
Appendix 3.7. Map of the Carynginia Formation showing the distribution of calculated Rock-Eval parameter production index within the northern Perth Basin. Data wells are represented by white circles



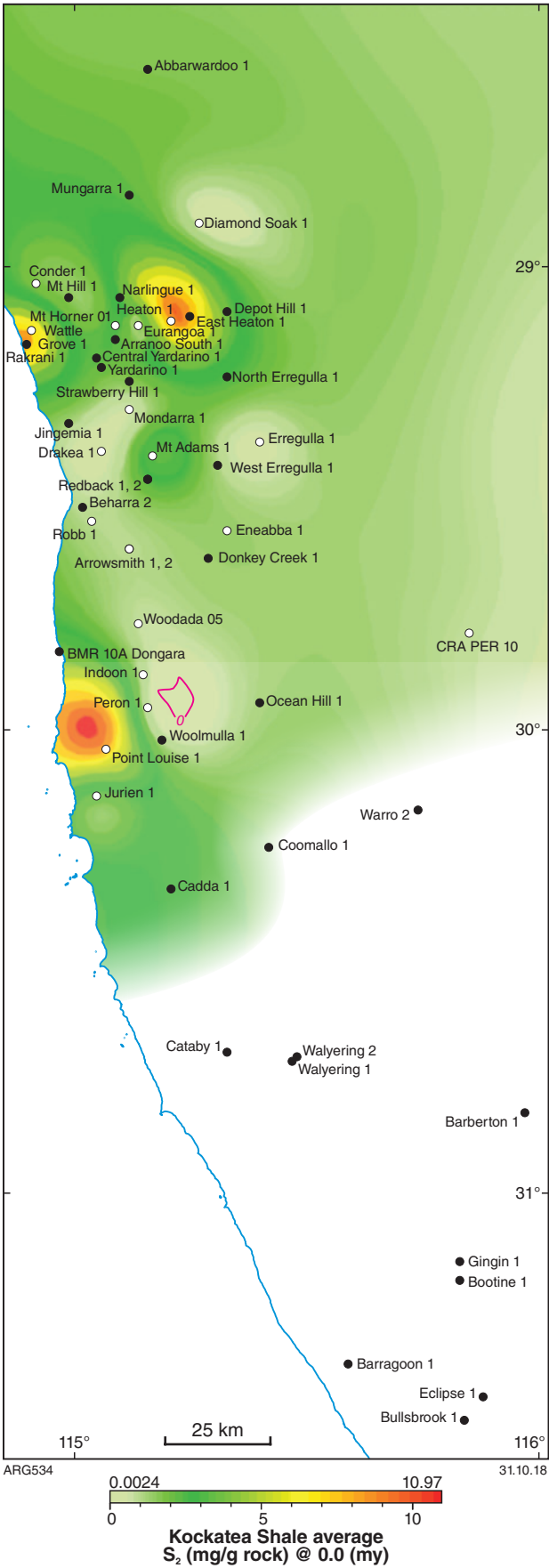
Appendix 3.8. Map of the Carynginia Formation showing the distribution of calculated Rock-Eval parameter transformation ratio within the northern Perth Basin. Data wells are represented by white circles



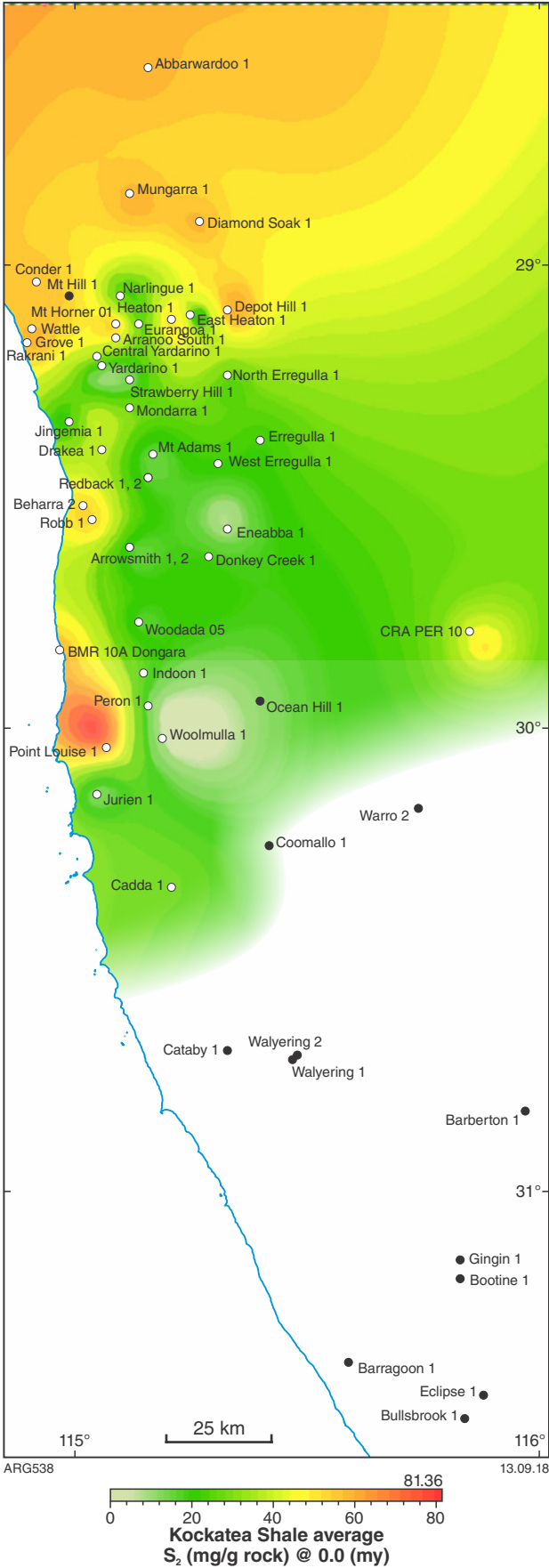
Appendix 3.9. Map of the Carynginia Formation showing the distribution of calculated temperature within the northern Perth Basin. Data wells are represented by white circles



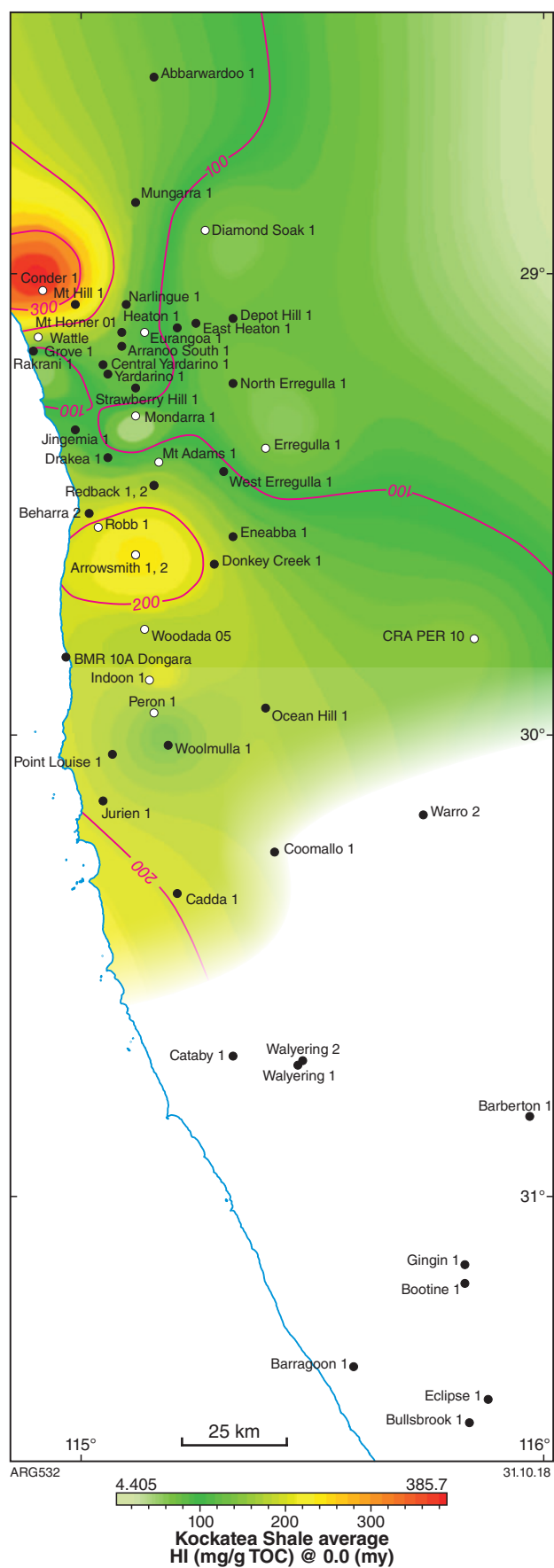
Appendix 3.10. Map of the Kockatea Shale showing the distribution of measured TOC within the northern Perth Basin. Data wells are represented by white circles



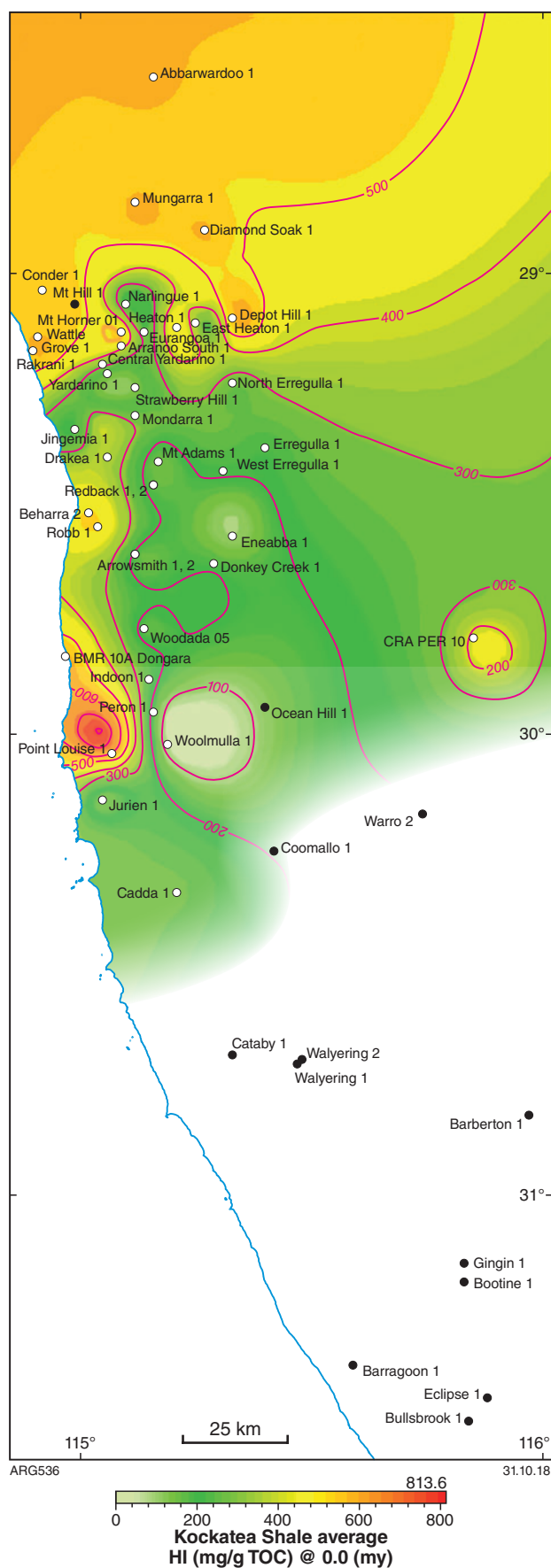
Appendix 3.11. Map of the Kockatea Shale showing the distribution of measured Rock-Eval parameter S_2 mg/g TOC within the northern Perth Basin. Data wells are represented by white circles



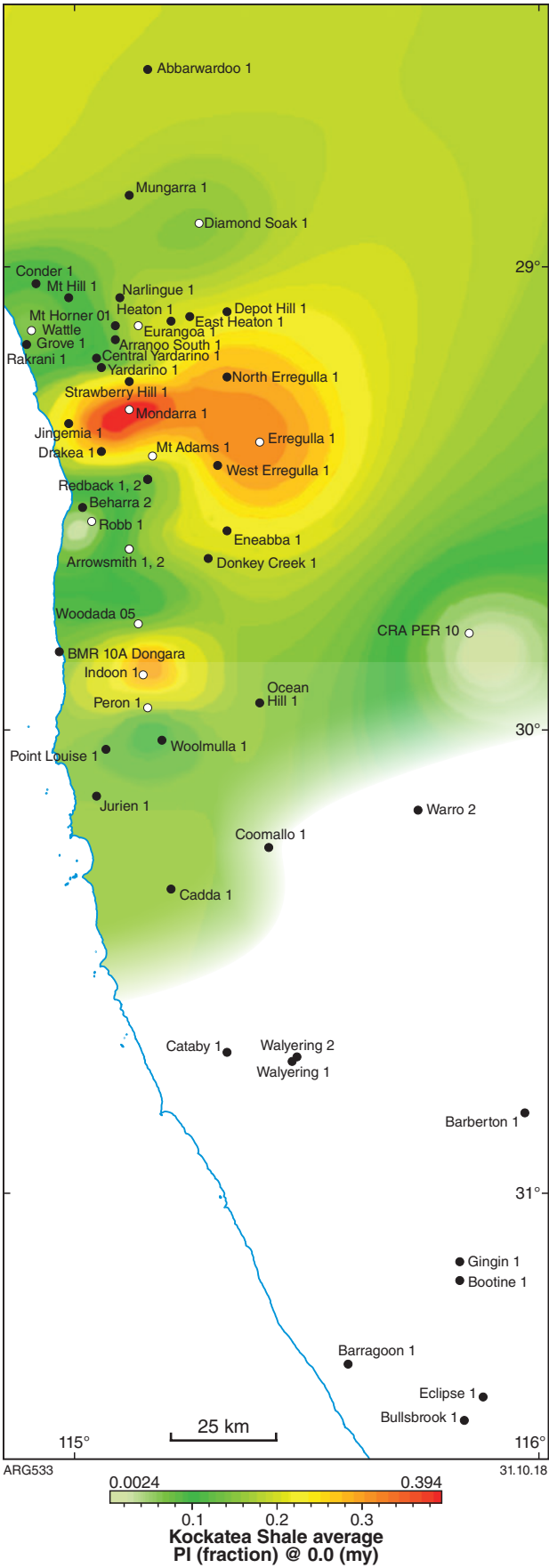
Appendix 3.12. Map of the Kockatea Shale showing the distribution of calculated Rock-Eval parameter S_2 mg/g TOC within the northern Perth Basin. Data wells are represented by white circles



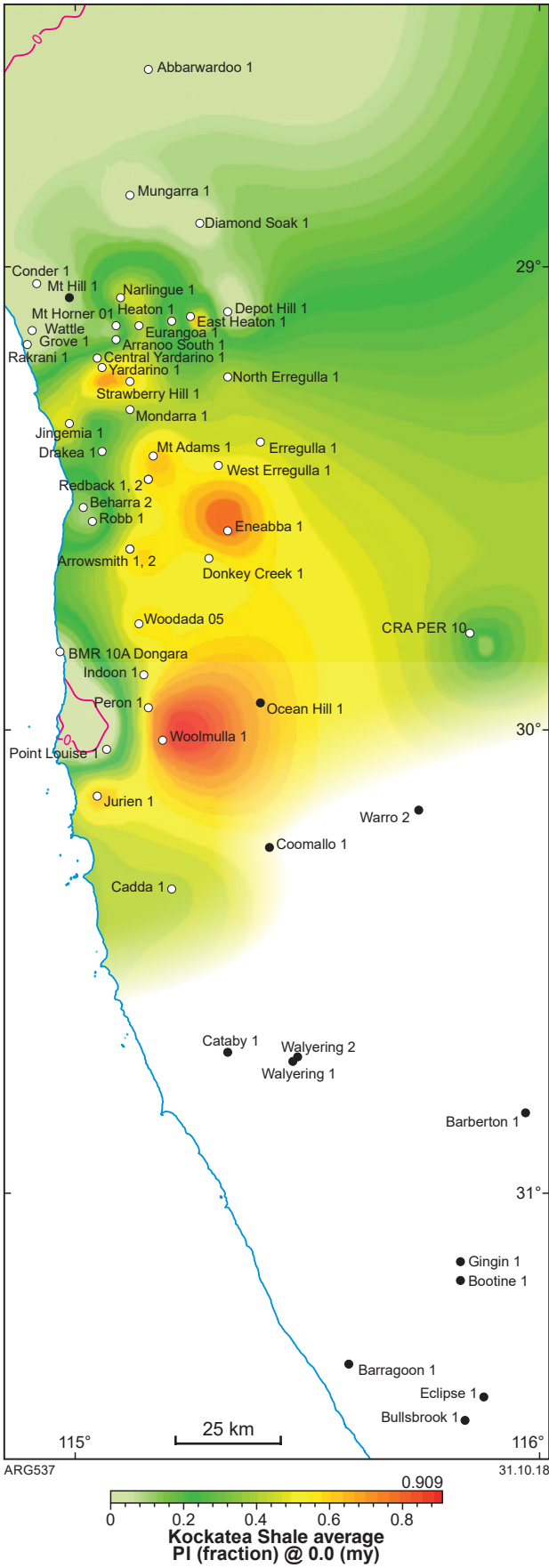
Appendix 3.13. Map of the Kockatea Shale showing the distribution of measured Rock-Eval parameter hydrogen index within the northern Perth Basin. Data wells are represented by white circles



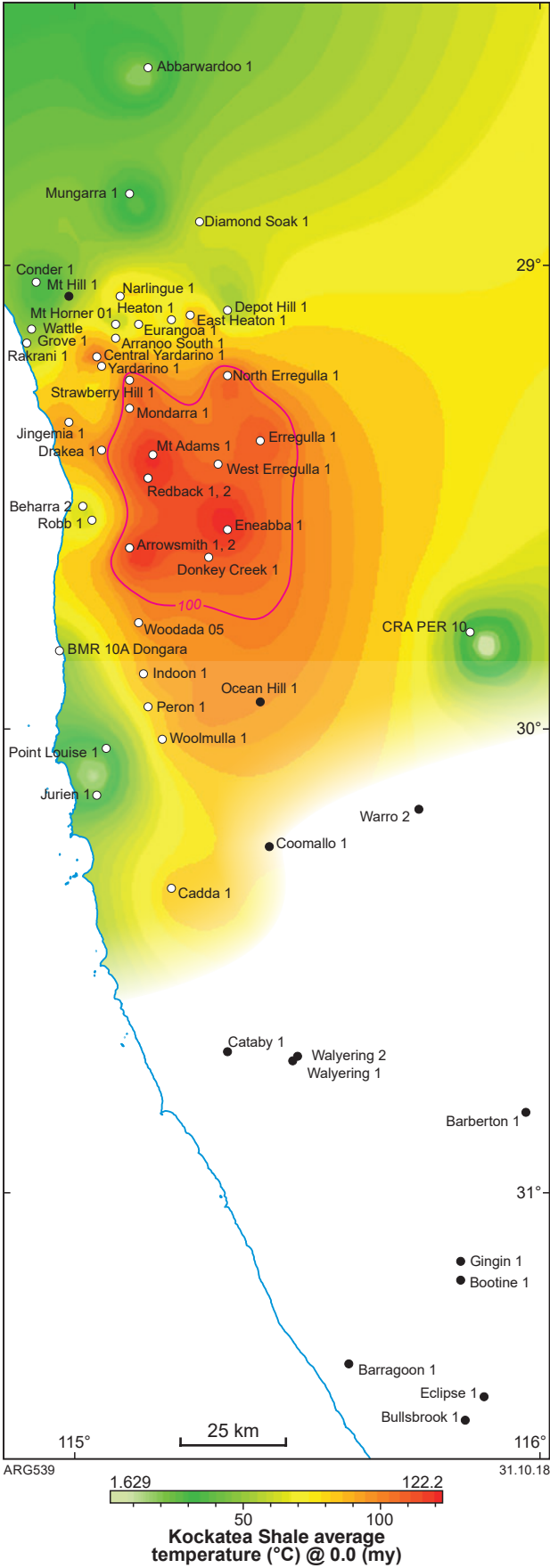
Appendix 3.14. Map of the Kockatea Shale showing the distribution of calculated Rock-Eval parameter hydrogen index within the northern Perth Basin. Data wells are represented by white circles



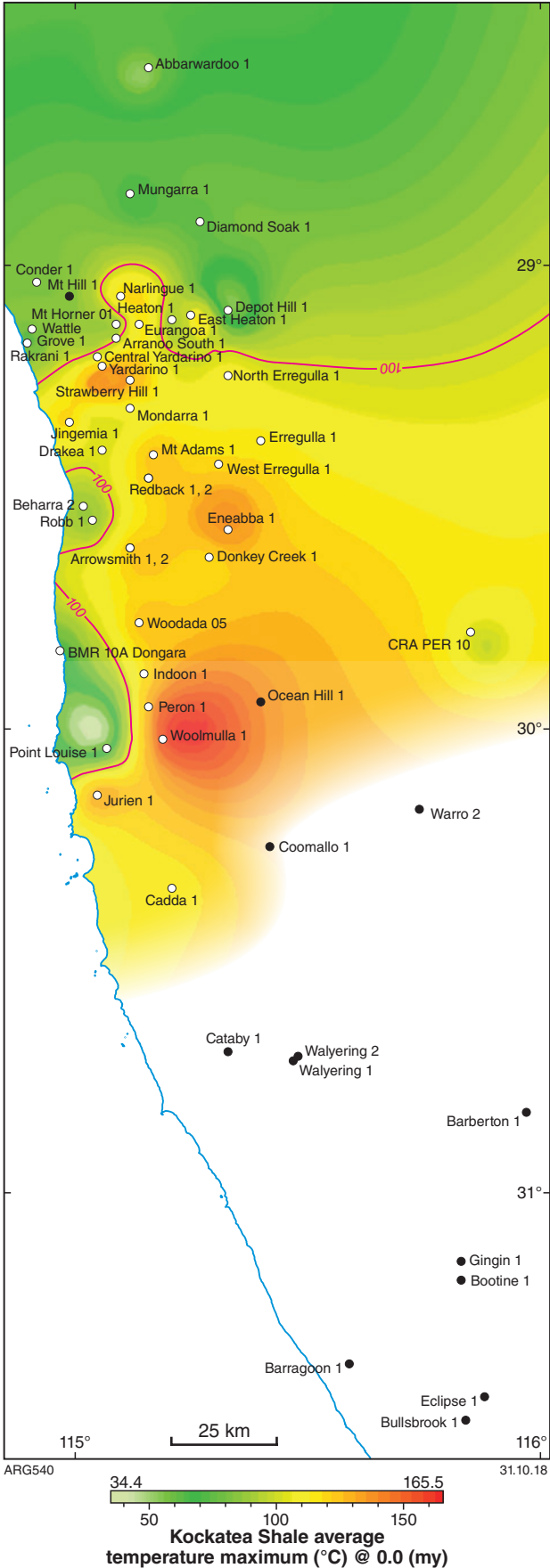
Appendix 3.15. Map of the Kockatea Shale showing the distribution of measured Rock-Eval parameter production index within the northern Perth Basin. Data wells are represented by white circles



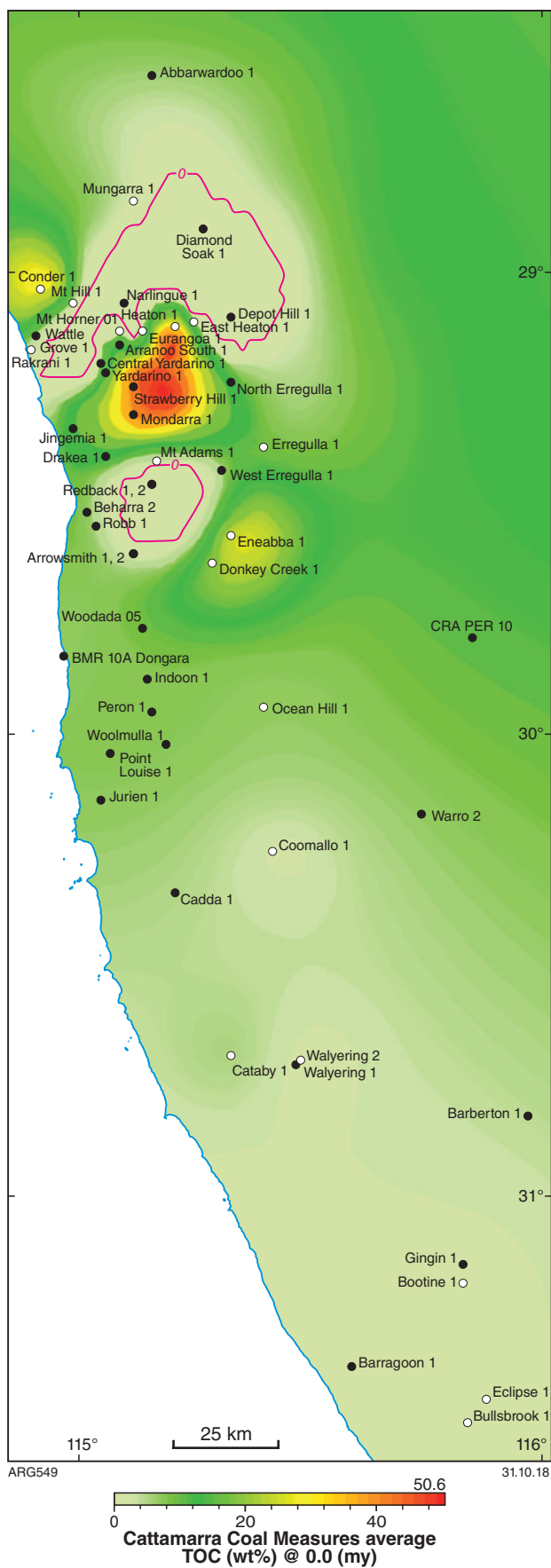
Appendix 3.16. Map of the Kockatea Shale showing the distribution of calculated Rock-Eval parameter production index within the northern Perth Basin. Data wells are represented by white circles



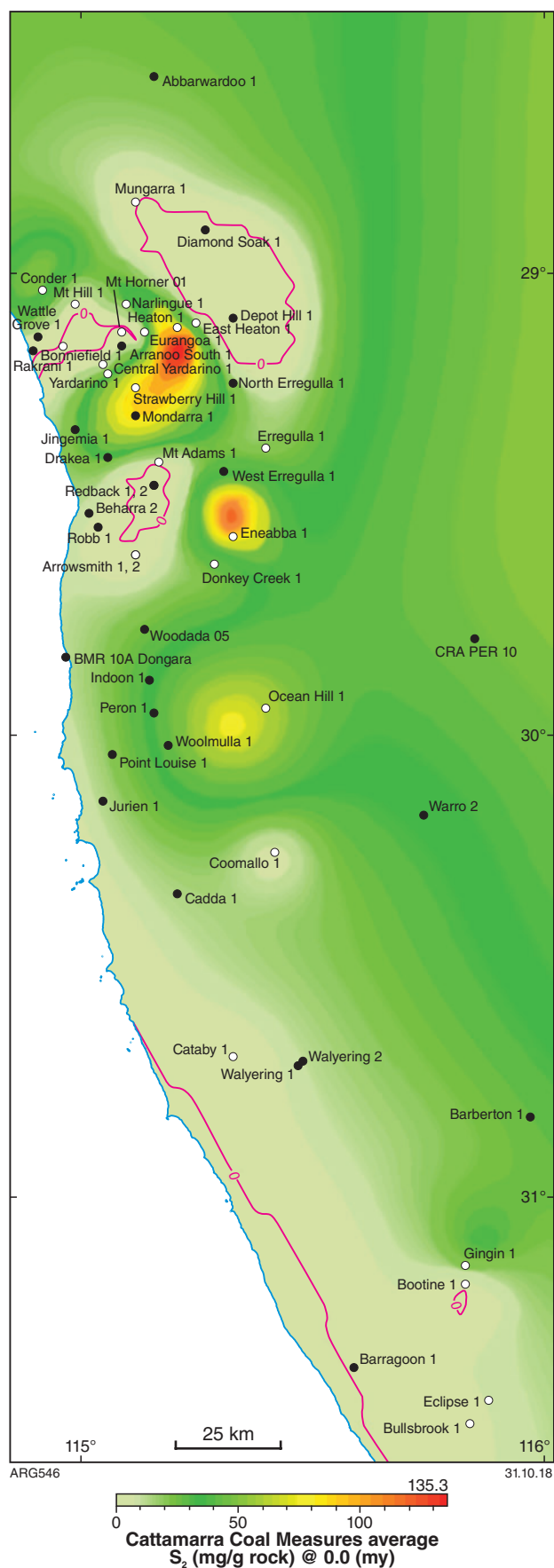
Appendix 3.17. Map of the Kockatea Shale showing the distribution of temperature within the northern Perth Basin. Data wells are represented by white circles



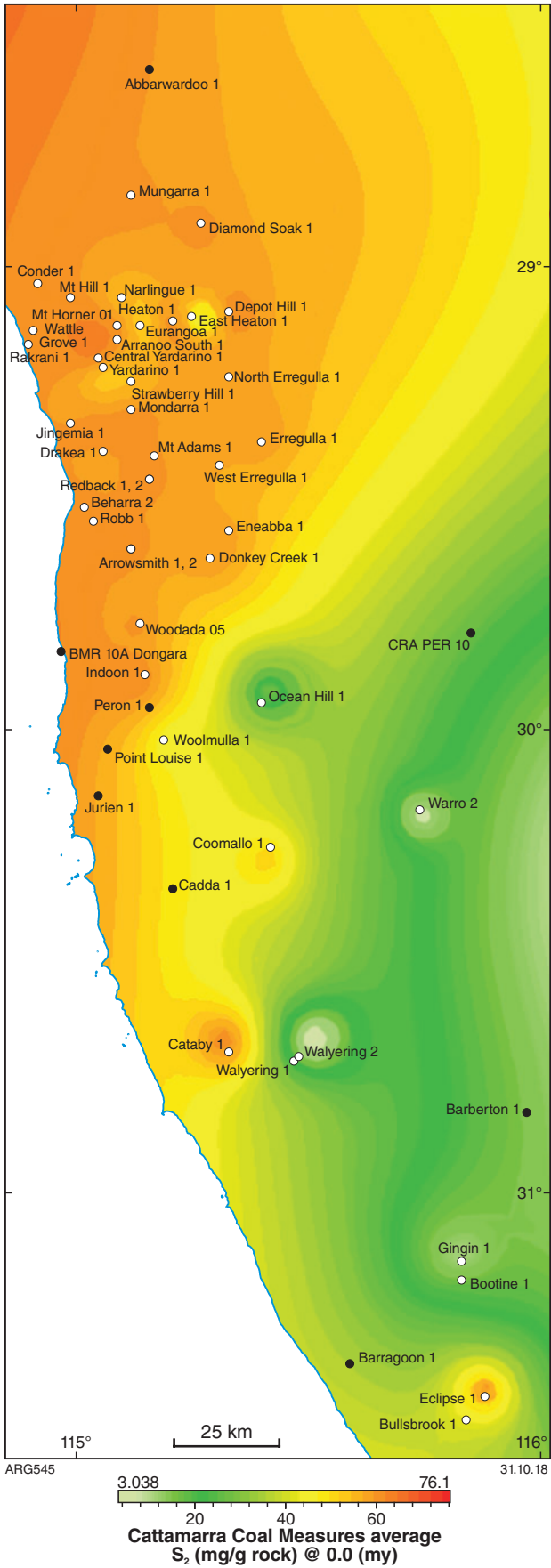
Appendix 3.18. Map of the Kockatea Shale showing the distribution of temperature max within the northern Perth Basin. Data wells are represented by white circles



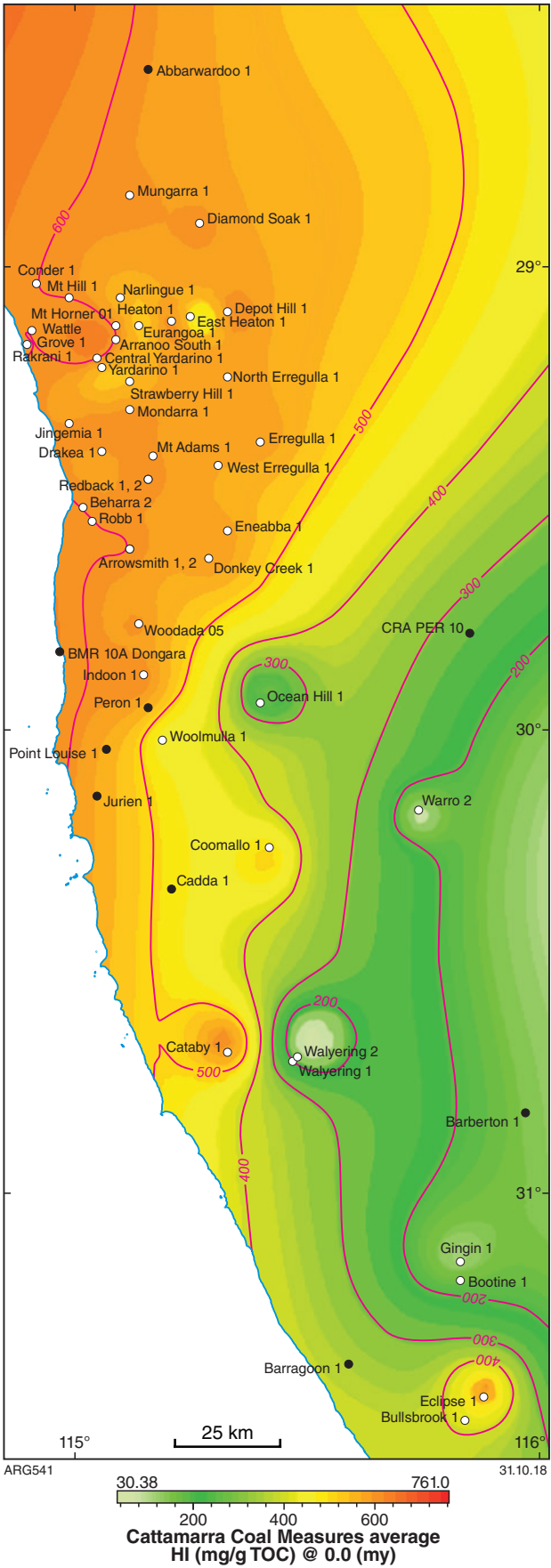
Appendix 3.19. Map of the Cattamarra Coal Measures showing the distribution of measured TOC within the northern Perth Basin. Data wells are represented by white circles



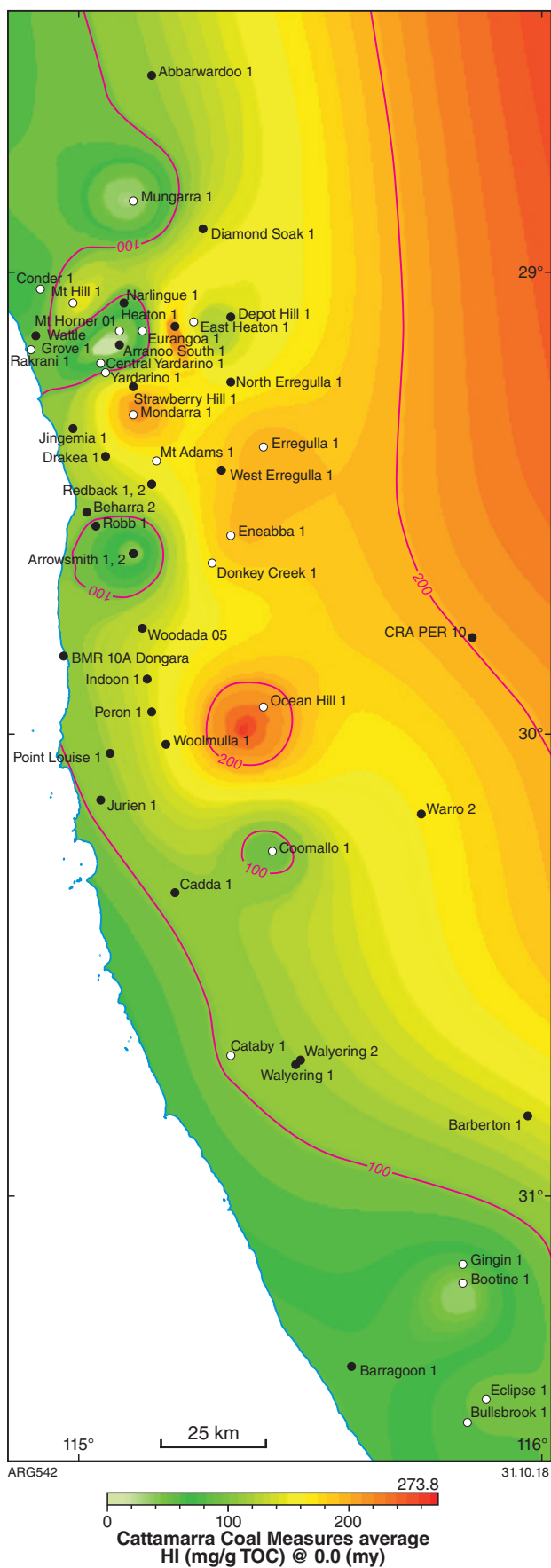
Appendix 3.20. Map of the Cattamarra Coal Measures showing the distribution of measured Rock-Eval parameter S_2 mg/g TOC within the northern Perth Basin. Data wells are represented by white circles



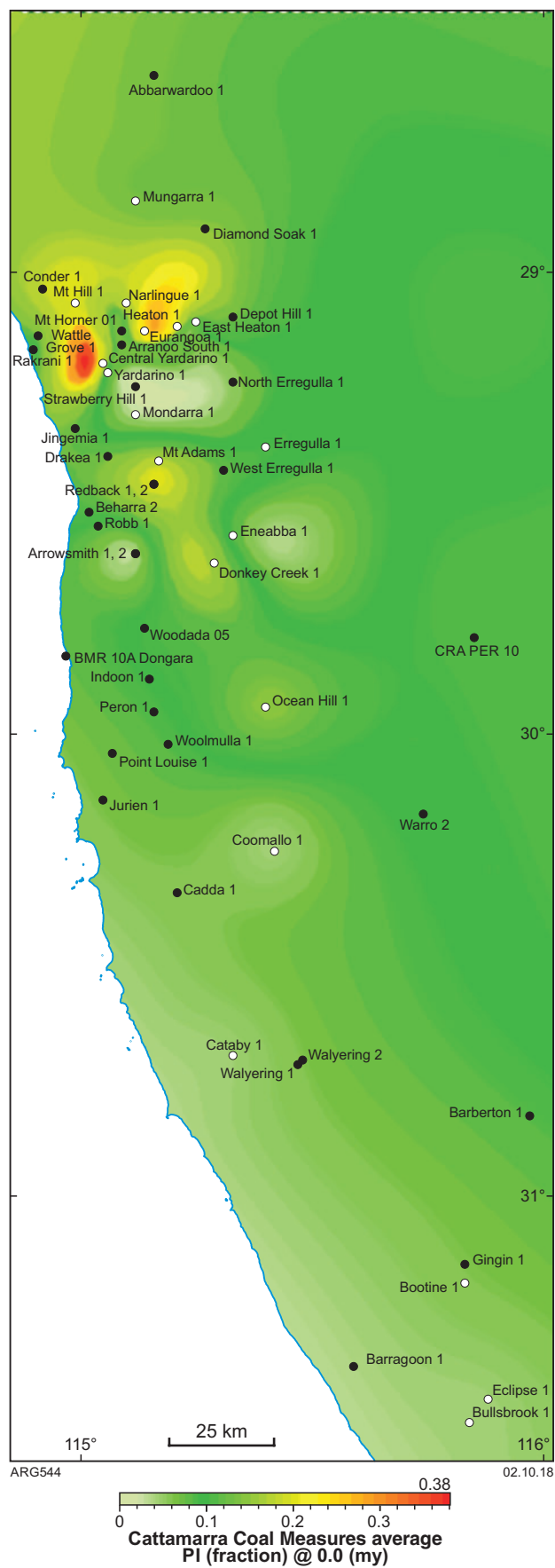
Appendix 3.21. Map of the Cattamarra Coal Measures showing the distribution of calculated Rock-Eval parameter S_2 mg/g TOC within the northern Perth Basin. Data wells are represented by white circles



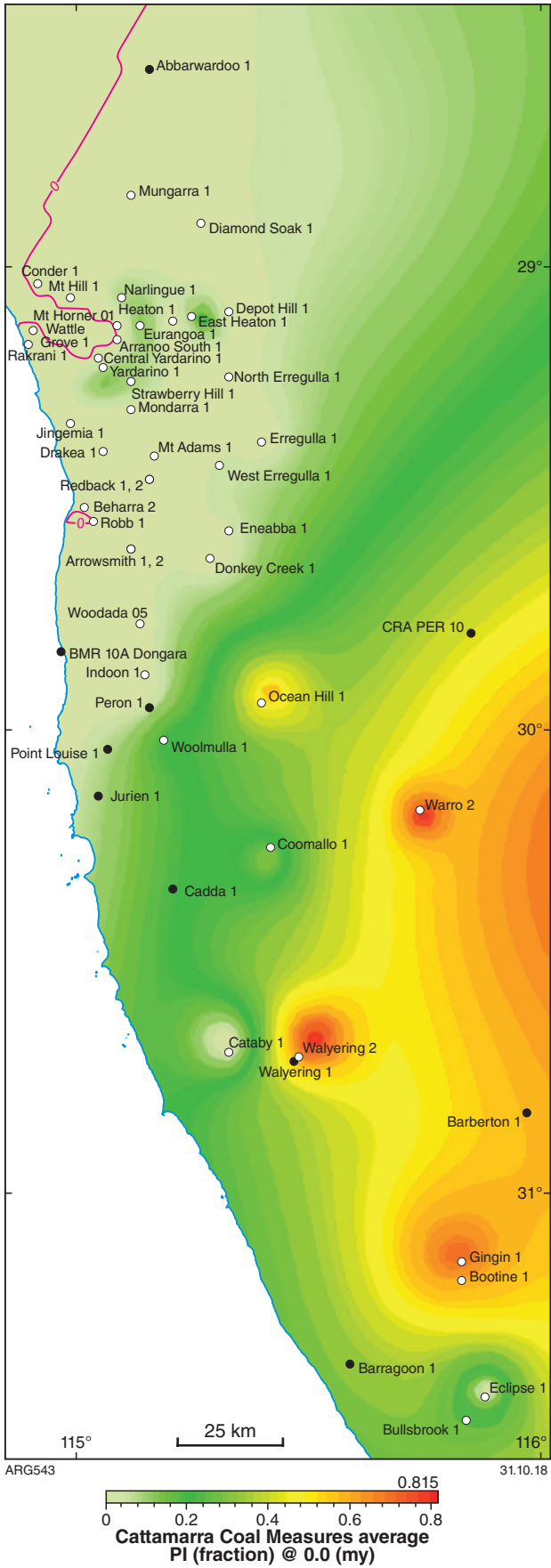
Appendix 3.22. Map of the Cattamarra Coal Measures showing the distribution of measured Rock-Eval parameter hydrogen index within the northern Perth Basin. Data wells are represented by white circles



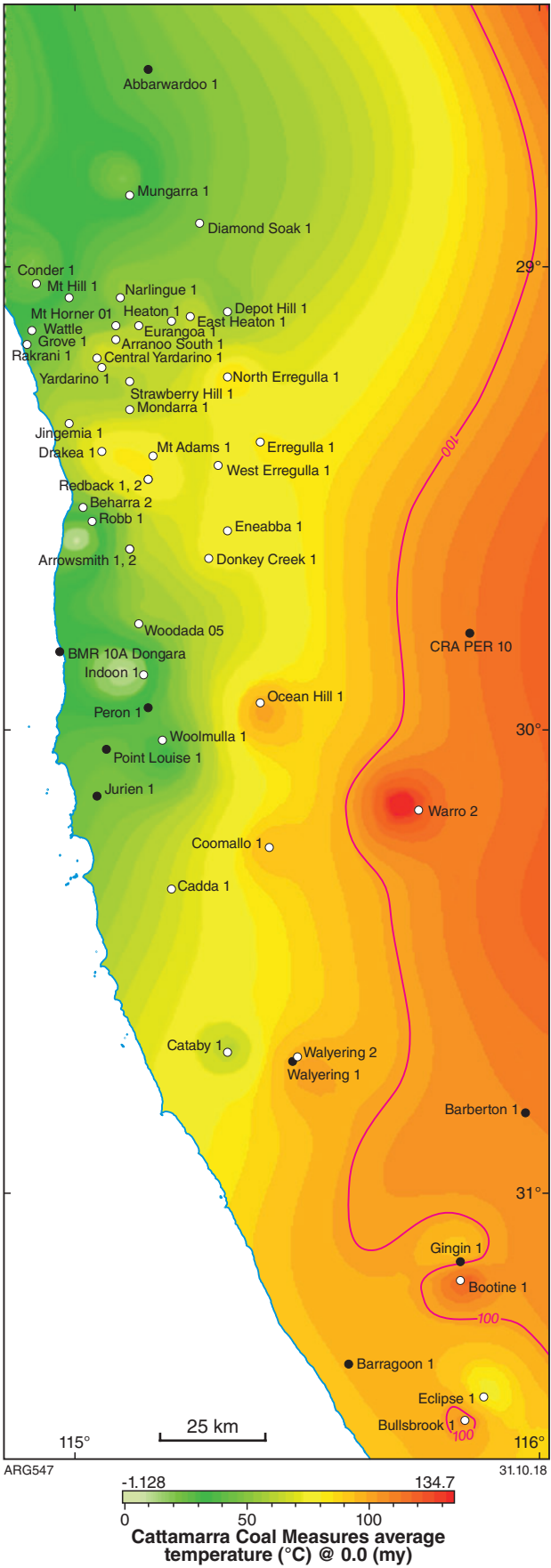
Appendix 3.23. Map of the Cattamarra Coal Measures showing the distribution of calculated Rock-Eval parameter hydrogen index within the northern Perth Basin. Data wells are represented by white circles



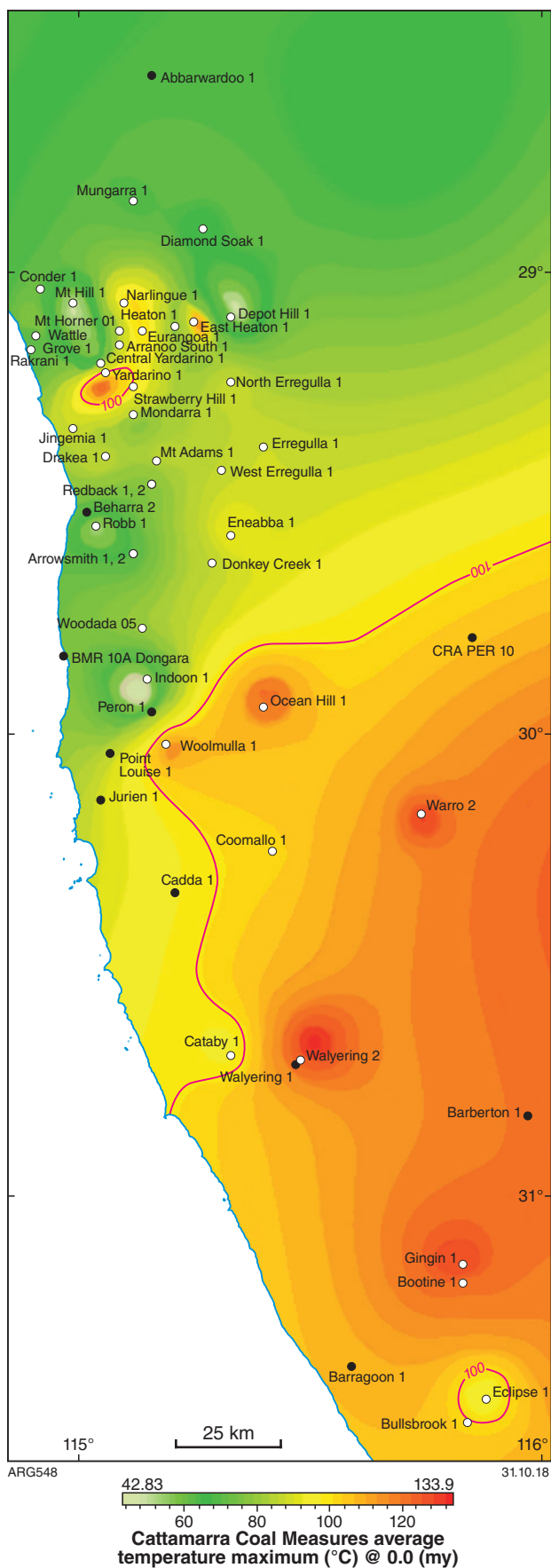
Appendix 3.24. Map of the Cattamarra Coal Measures showing the distribution of measured Rock-Eval parameter production index within the northern Perth Basin. Data wells are represented by white circles



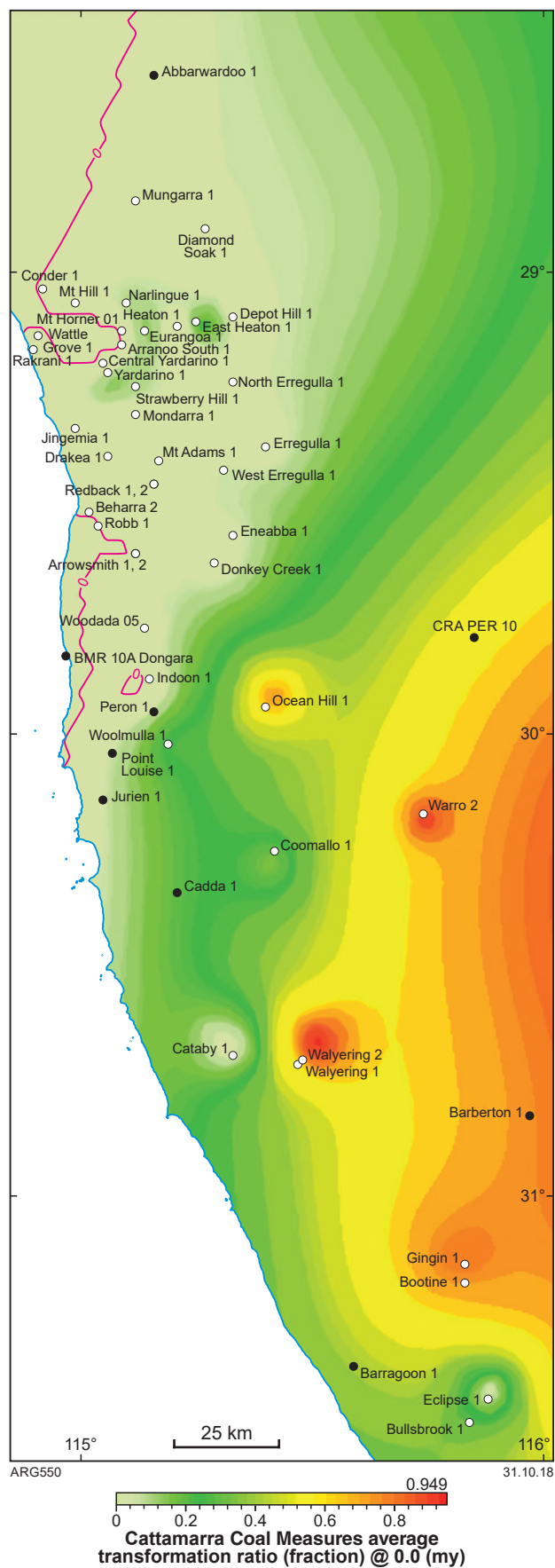
Appendix 3.25. Map of the Cattamarra Coal Measures showing the distribution of calculated Rock-Eval parameter production index within the northern Perth Basin. Data wells are represented by white circles



Appendix 3.26. Map of the Cattamarra Coal Measures showing the distribution of temperature within the northern Perth Basin. Data wells are represented by white circles



Appendix 3.27. Map of the Cattamarra Coal Measures showing the distribution of temperature max within the northern Perth Basin. Data wells are represented by white circles

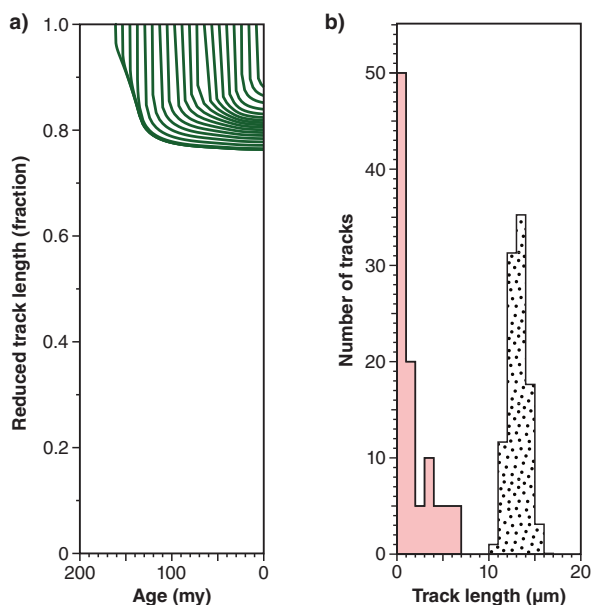


Appendix 3.28. Map of the Cattamarra Coal Measures showing the distribution of calculated Rock-Eval parameter transformation ratio within the northern Perth Basin. Data wells are represented by white circles

Appendix 4

Apatite fission track data for a total of 14 samples, five each from Arranoo South 1, Cataby 1, West Erregulla 1 from the Jurassic Yarragadee Formation, Cattamarra Coal Measures, Eneabba Formation, Permian Wagina Sandstone, and Irwin River Coal Measures

Arranoo South 1



ARG624

Durango apatite fission track sample depth = 750 m

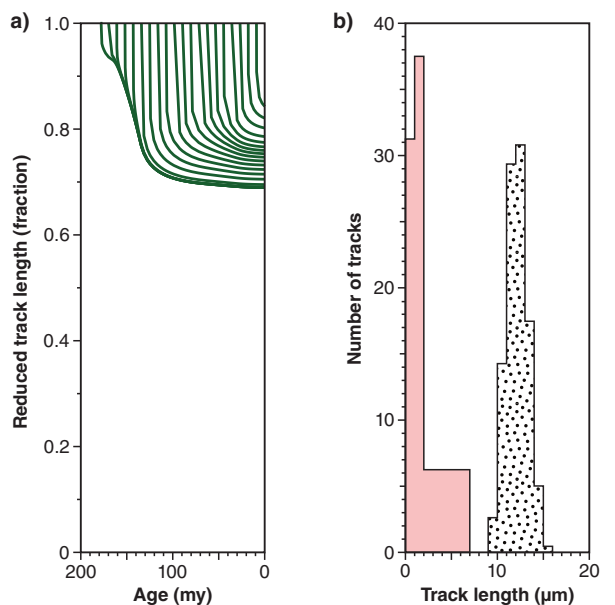
Measured mean = 1.85 μm
Standard deviation = 1.82 μm

Calculated mean = 13.16 μm
Standard deviation = 1.03 μm

Reduced length
Temperature
Fission track age

Appendix 4.1. Plot of basic apatite fission track data of the Yarragadee Formation (750 m) sample from Arranoo South 1

Arranoo South 1



ARG625

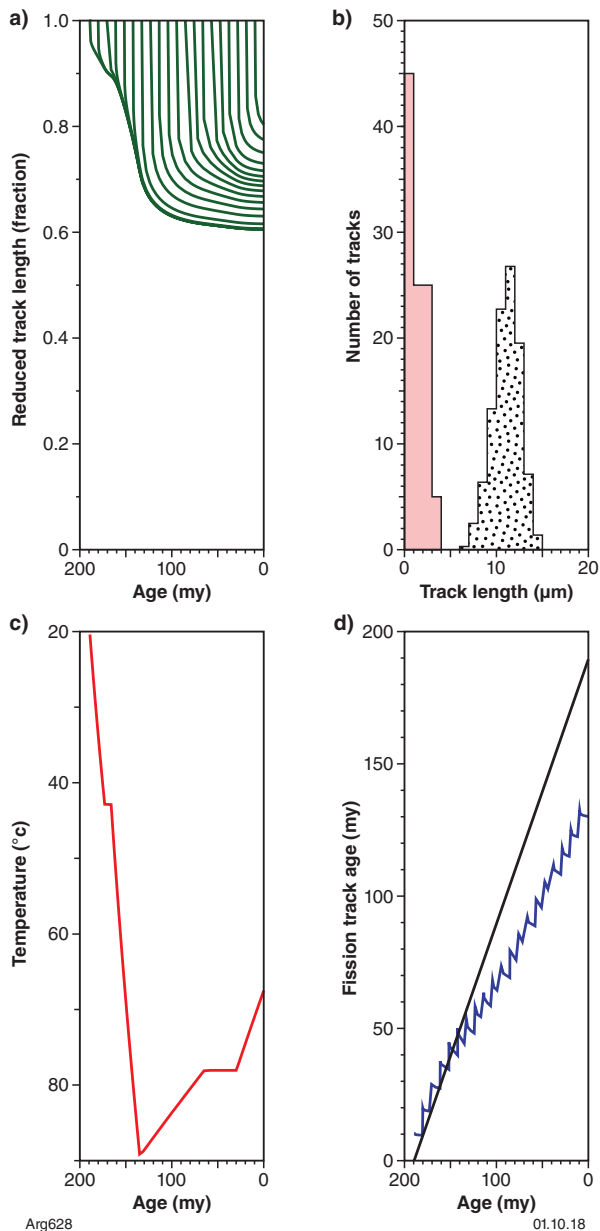
Durango apatite fission track sample depth = 1050 m

Measured mean = 2.13 μm
Standard deviation = 1.83 μm

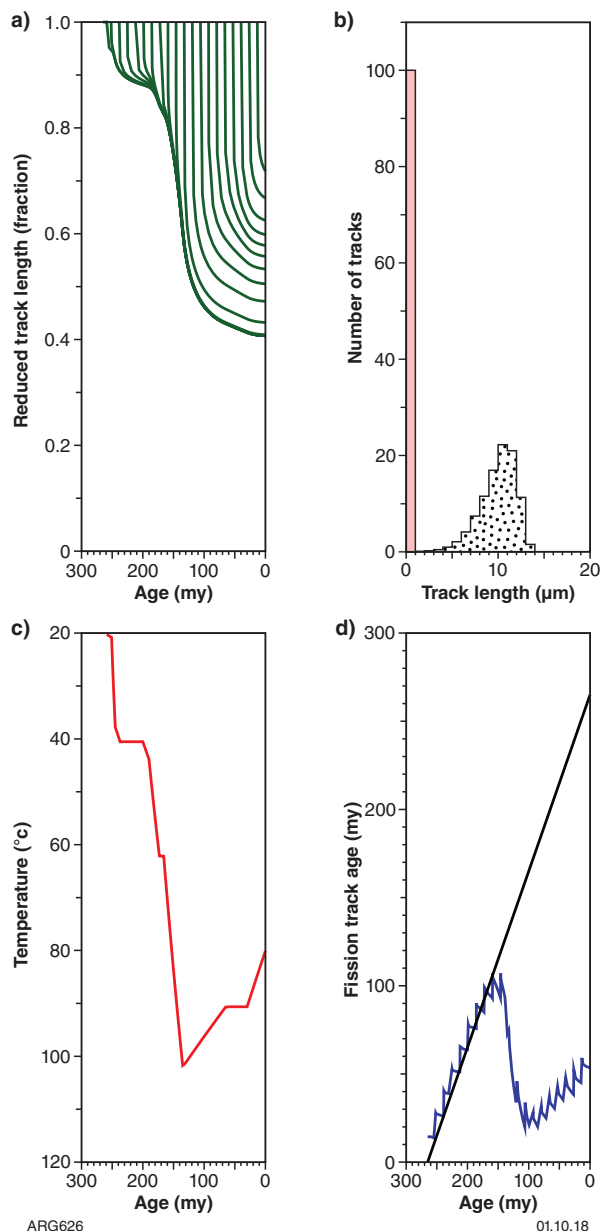
Calculated mean = 12.13 μm
Standard deviation = 1.18 μm

Reduced length
Temperature
Fission track age

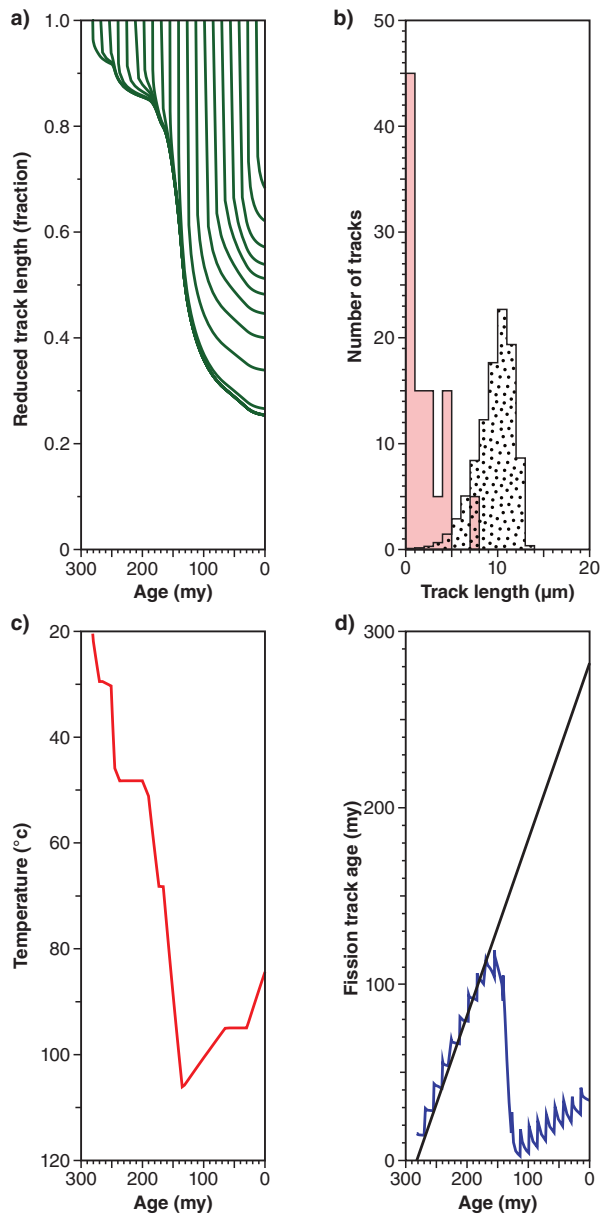
Appendix 4.2. Plot of basic apatite fission track data of the Cattamarra Coal Measures (1050 m) sample from Arranoo South 1

Arranoo South 1

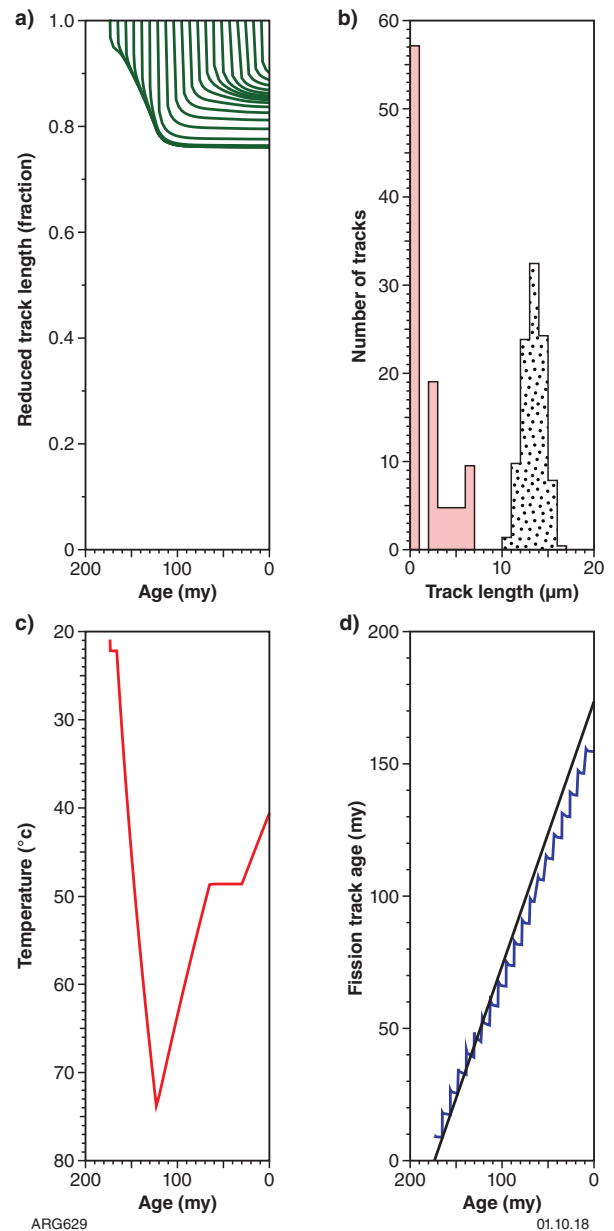
Appendix 4.3. Plot of basic apatite fission track data of the Cattamarra Coal Measures (1285 m) sample from Arranoo South 1

Arranoo South 1

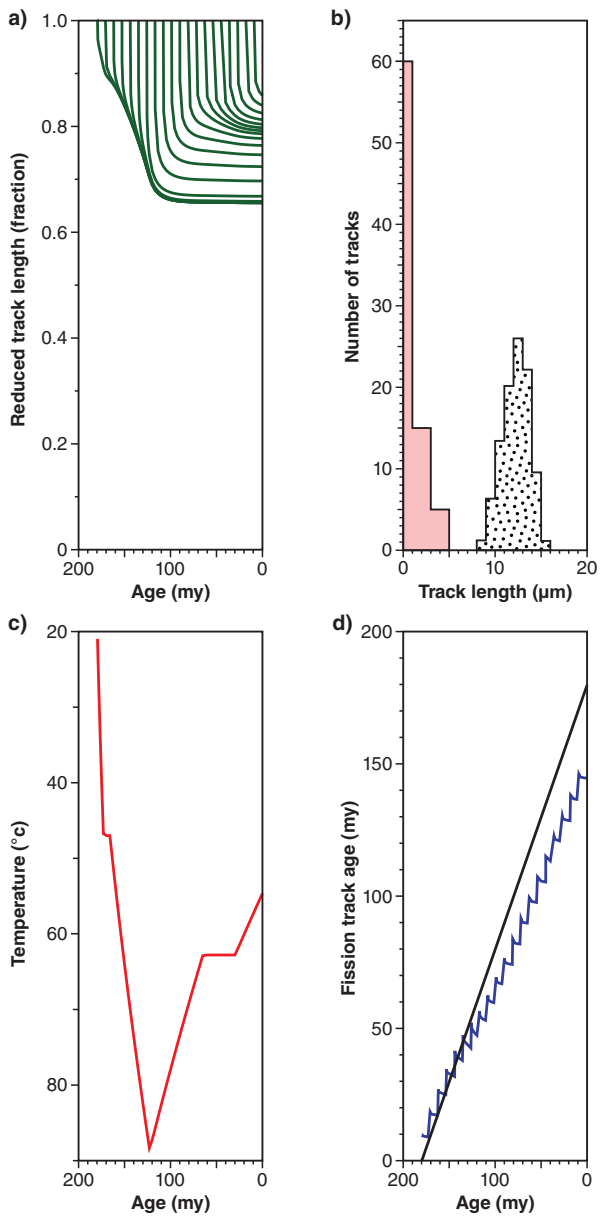
Appendix 4.4. Plot of basic apatite fission track data of the Wagina Sandstone (1635 m) sample from Arranoo South 1

Arranoo South 1

Appendix 4.5. Plot of basic apatite fission track data of the Irwin River Coal Measures (1748 m) sample from Arranoo South 1

Cataby 1

Appendix 4.6. Plot of basic apatite fission track data of the Cattamarra Coal Measures (700 m) sample from Cataby 1

Cataby 1

ARG630

Durango apatite fission track
sample depth = 1150 m

Measured track
length

Measured mean = 1.30 μm
Standard deviation = 1.17 μm

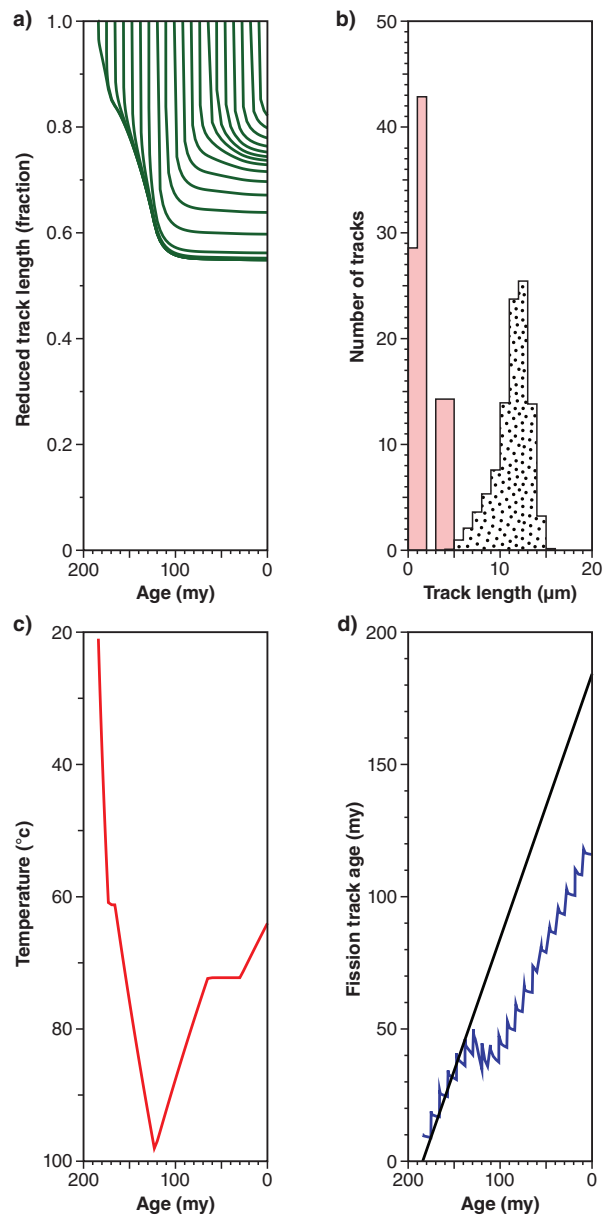
Calculated track
length

Calculated mean = 12.24 μm
Standard deviation = 1.46 μm

— Reduced length
— Temperature
— Fission track age

01.10.18

Appendix 4.7. Plot of basic apatite fission track data of the Cattamarra Coal Measures (1150 m) sample from Cataby 1

Cataby 1

ARG631

Durango apatite fission track
sample depth = 1460 m

Measured track
length

Measured mean = 1.93 μm
Standard deviation = 1.40 μm

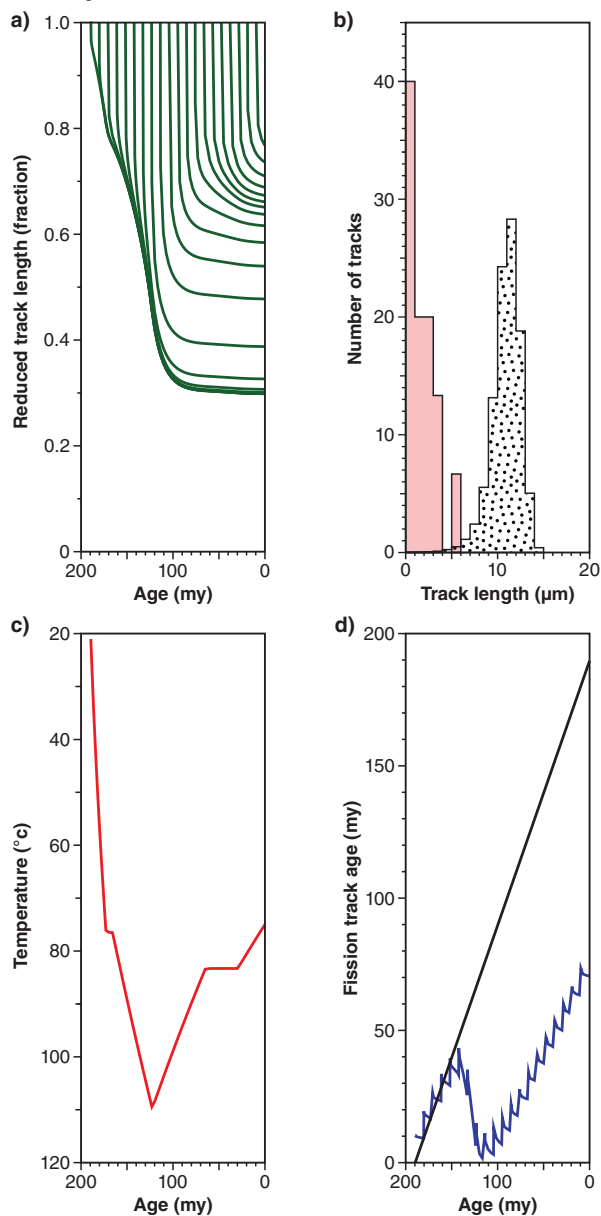
Calculated track
length

Calculated mean = 11.37 μm
Standard deviation = 1.88 μm

— Reduced length
— Temperature
— Fission track age

01.10.18

Appendix 4.8. Plot of basic apatite fission track data of the Cattamarra Coal Measures (1460 m) sample from Cataby 1

Cataby 1

ARG632

Durango apatite fission track
sample depth = 1830 m

Measured track
length

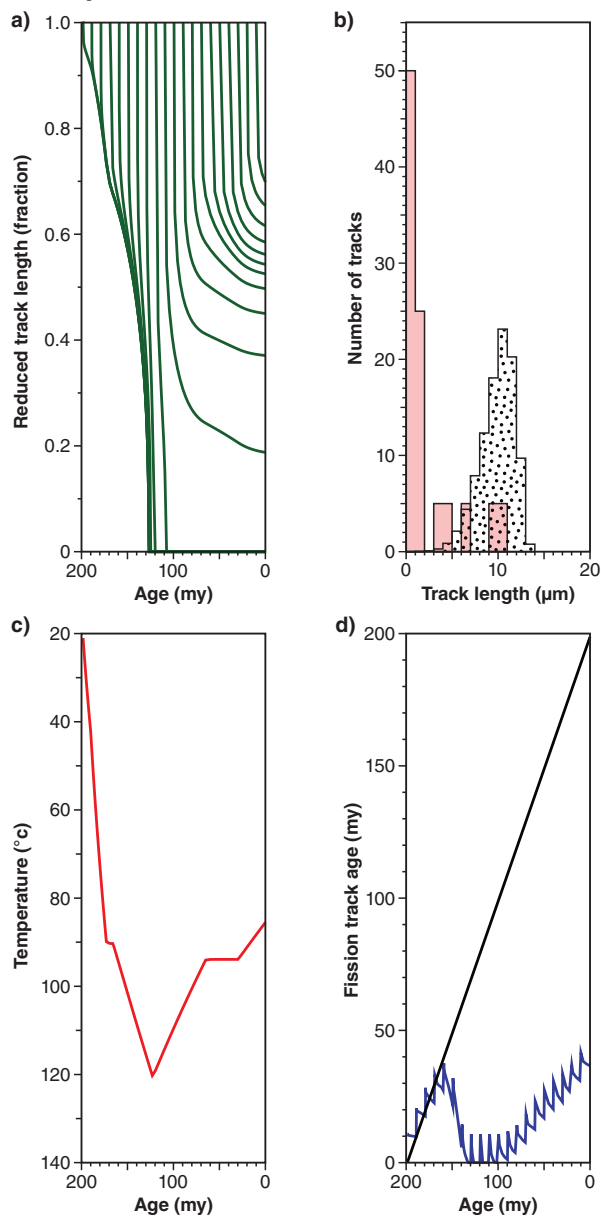
Measured mean = 1.83 μm
Standard deviation = 1.45 μm

Calculated track
length

Calculated mean = 10.91 μm
Standard deviation = 1.58 μm

— Reduced length
— Temperature
— Fission track age

Appendix 4.9. Plot of basic apatite fission track data of the Cattamarra Coal Measures (1830 m) sample from Cataby 1

Cataby 1

ARG633

Durango apatite fission track
sample depth = 2225 m

Measured track
length

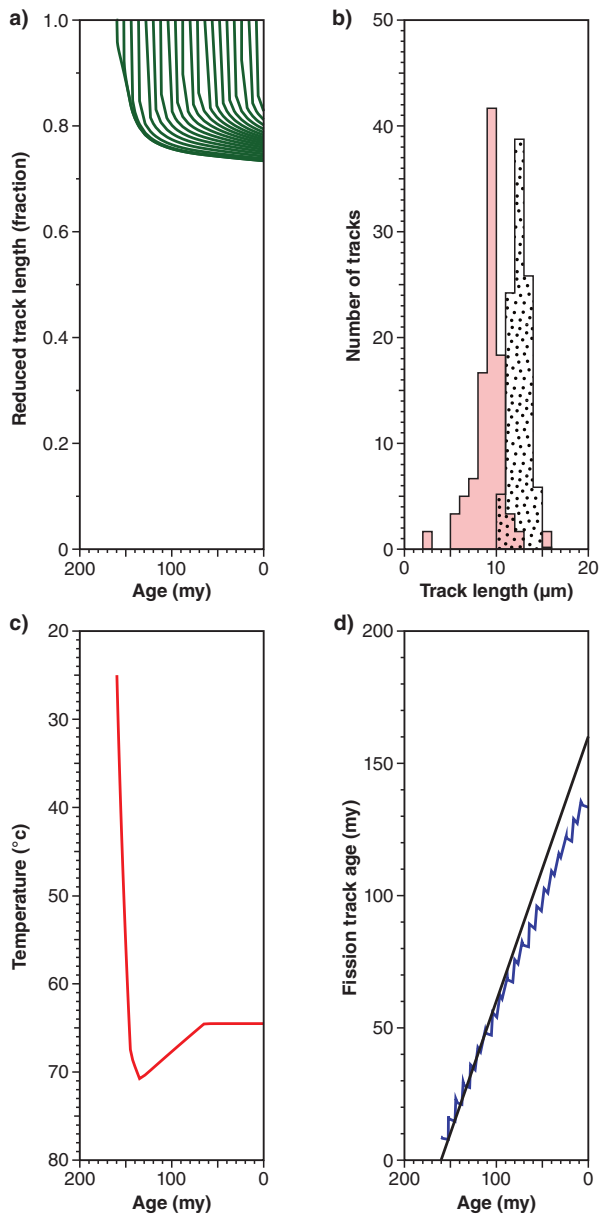
Measured mean = 2.35 μm
Standard deviation = 2.99 μm

Calculated track
length

Calculated mean = 9.89 μm
Standard deviation = 1.86 μm

— Reduced length
— Temperature
— Fission track age

Appendix 4.10. Plot of basic apatite fission track data of the Cattamarra Coal Measures (2225 m) sample from Cataby 1

Erregulla Area

ARG634

Durango apatite fission track
sample depth = 1475 m



Measured track
length

Measured mean = 9.20 μm
Standard deviation = 1.79 μm



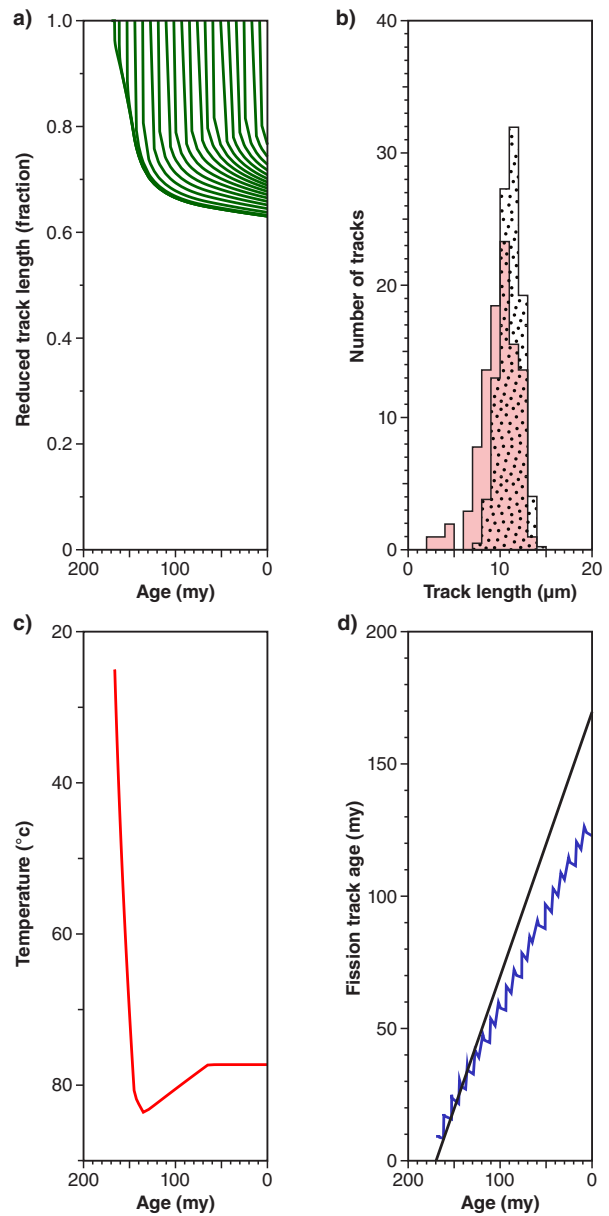
Calculated track
length

Calculated mean = 12.53 μm
Standard deviation = 0.98 μm

— Reduced length
— Temperature
— Fission track age

01.10.18

Appendix 4.11. Plot of basic apatite fission track data of the Yarragadee Formation (1475 m) sample from West Erregulla 1

Erregulla Area

ARG635

Durango apatite fission track
sample depth = 2025 m



Measured track
length

Measured mean = 9.89 μm
Standard deviation = 2.03 μm



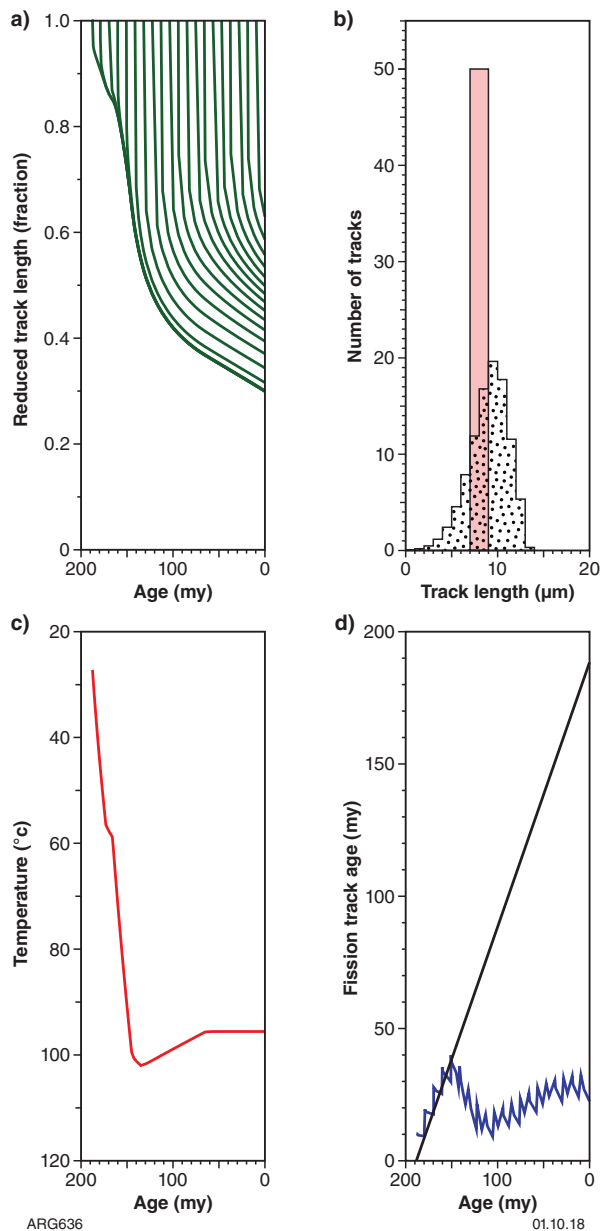
Calculated track
length

Calculated mean = 11.11 μm
Standard deviation = 1.20 μm

— Reduced length
— Temperature
— Fission track age

10.10.18

Appendix 4.12. Plot of basic apatite fission track data of the Yarragadee Formation (2025 m) sample from West Erregulla 1

Erregulla Area

Durango apatite fission track sample depth = 2748 m

Measured track length

Measured mean = 8.00 μm

Standard deviation = 0.50 μm

Calculated track length

Calculated mean = 9.01 μm

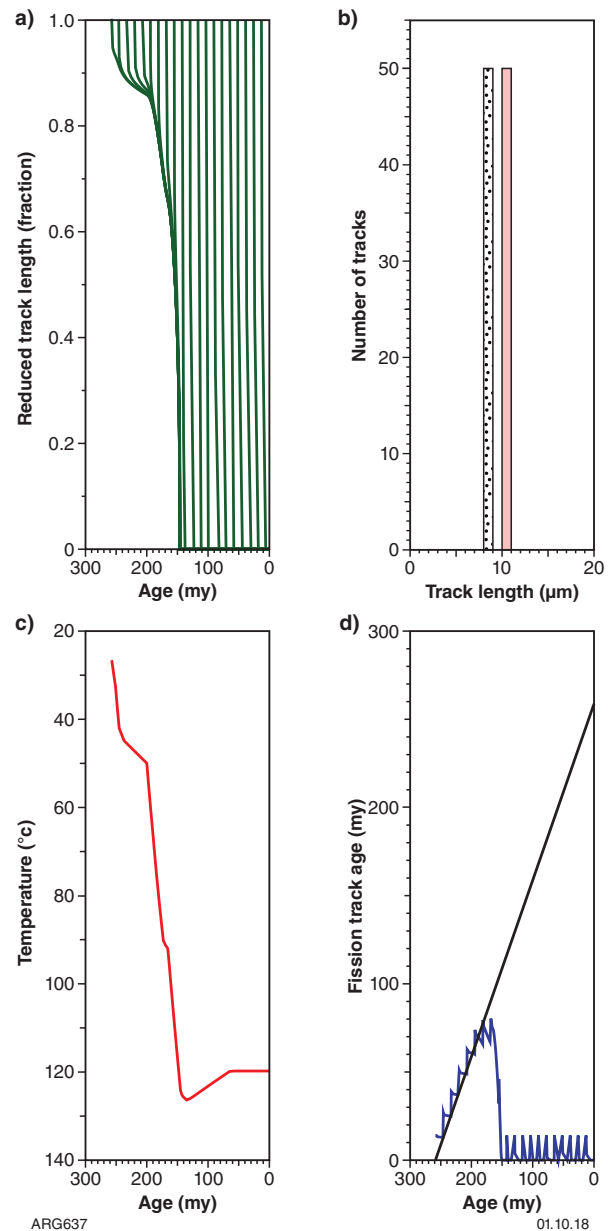
Standard deviation = 2.11 μm

— Reduced length

— Temperature

— Fission track age

Appendix 4.13. Plot of basic apatite fission track data of the Eneabba Formation (2748 m) sample from West Erregulla 1

Erregulla Area

Durango apatite fission track sample depth = 3990 m

Measured track length

Measured mean = 9.50 μm

Standard deviation = 1.00 μm

Calculated track length

Calculated mean = 0.00 μm

Standard deviation = 0.00 μm

— Reduced length

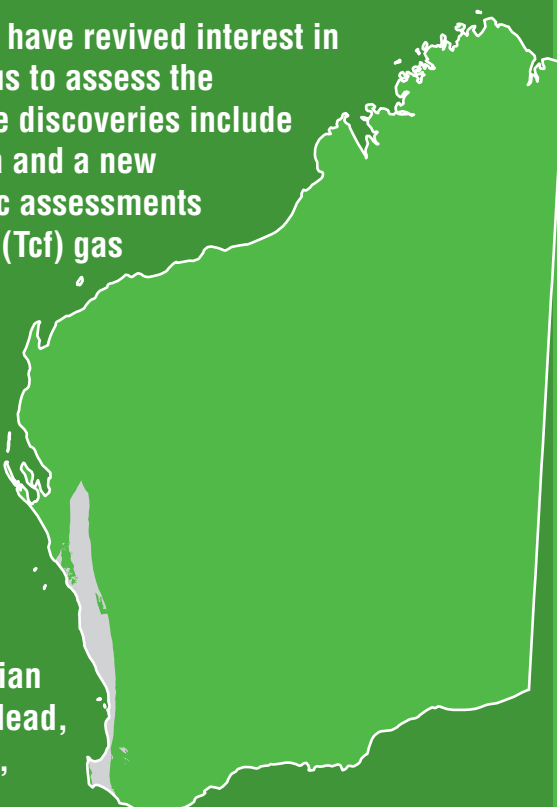
— Temperature

— Fission track age

Appendix 4.14. Plot of basic apatite fission track data of the Wagina Sandstone (3999 m) sample from West Erregulla 1

Recent discoveries in the northern Perth Basin have revived interest in petroleum exploration and supplied the impetus to assess the hydrocarbon source rocks within the basin. The discoveries include a new Permian gas/condensate play at Waitsia and a new Triassic shale play in Arrowsmith 2. Volumetric assessments have estimated that up to 25 trillion cubic feet (Tcf) gas and up to 8 Tcf gas with 500 million barrels oil/condensate could be present within the Permian and the Triassic sedimentary successions respectively.

Interpretation and modelling of the petroleum geochemistry, organic petrology, apatite fission track analysis, heat flow, subsurface temperature, and other exploration data from the onshore Perth Basin indicate that the condensate from Whicher Range 1 has a Permian source; oil and gas/condensate from the Cliff Head, Dongara, Eremia, Hovea, Jingemia, Mondarra, Mount Horner, North Erregulla, Woodada, and Yardarino fields are derived from Triassic source rocks; oil and gas/condensate from Gingin 1 and Walyering 1 and 2 are from a Jurassic source; and the oil from Gage Roads 1 is sourced from a Jurassic–Cretaceous source. Modelling of 60 wells with TOC and Rock-Eval data indicates variations in the timing of petroleum generation and accumulation across the basin.



Further details of geological products and maps produced by the Geological Survey of Western Australia are available from:

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