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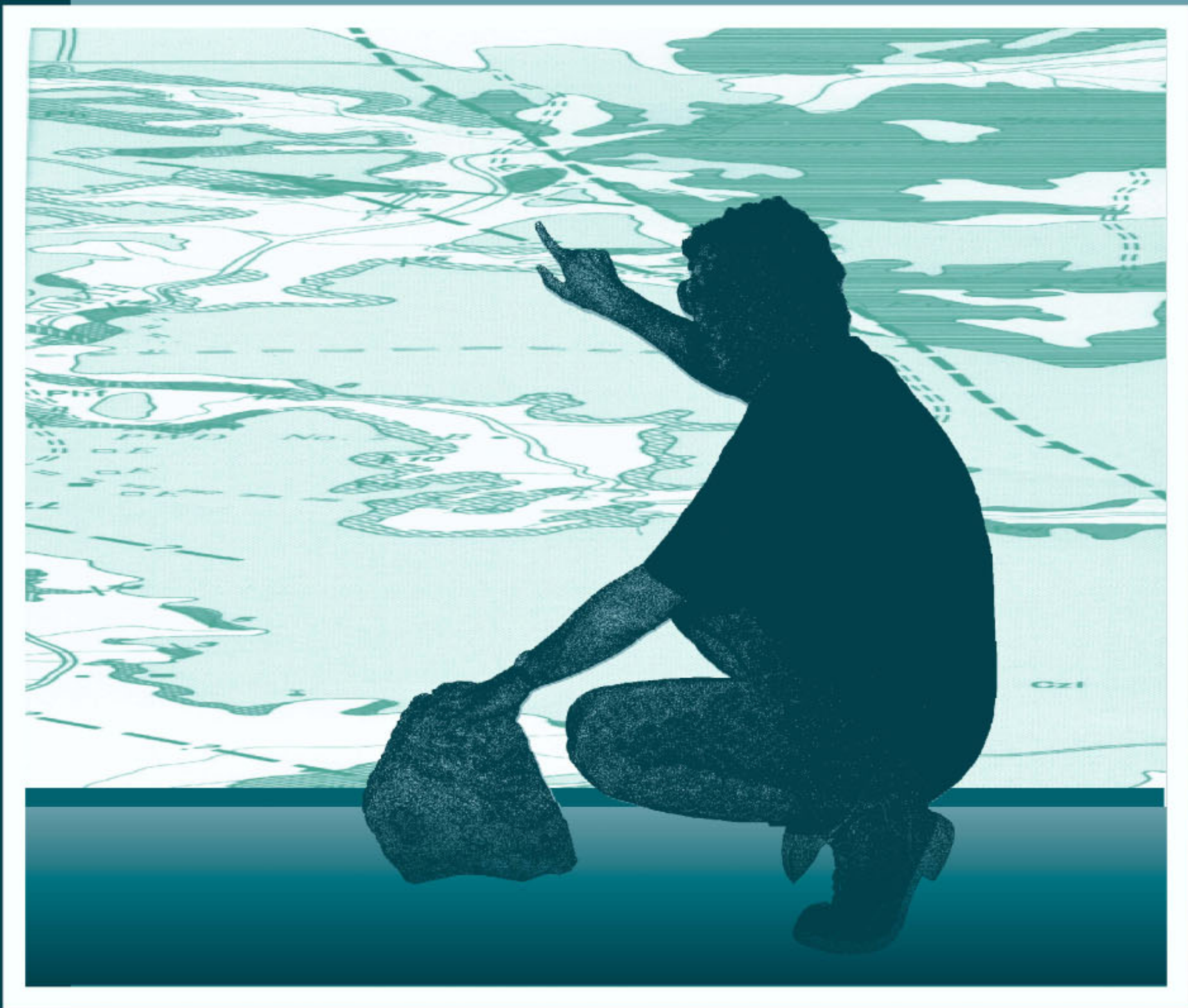
PETROLEUM SOURCE-ROCK POTENTIAL AND THERMAL HISTORY OF THE OFFICER BASIN, WESTERN AUSTRALIA

by K. A. R. Ghori



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

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DEPARTMENT OF MINERALS AND ENERGY

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Perth 1998

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Petroleum source-rock potential and thermal history of the Officer Basin, Western Australia

by

K. A. R. Ghori

Abstract

Open-file data, supplemented by new geochemical analyses from petroleum and mineral exploration drillholes, confirm the presence of good-quality, but very thin, oil source rocks in the Neoproterozoic succession of the frontier exploration region covered by the western Officer Basin in Western Australia.

Excellent oil source rocks are found in finely laminated shale and siltstone facies within an evaporitic succession penetrated in mineral corehole NJD 1 on the Kingston Shelf. Additional oil source rocks with fair oil-generating potential are identified in thin organic-rich shales of the Browne and Hussar Formations in Yowalga 3 and Kanpa 1A in the Yowalga Sub-basin. Within the northwestern Gibson Sub-basin, Neoproterozoic oil source rocks are identified in the mineral exploration drillhole LDDH 1.

On the Kingston Shelf, Neoproterozoic rocks are marginally to fully mature for oil generation. In the thick Yowalga Sub-basin, maturity ranges from immature to overmature for different Neoproterozoic formations, depending on maximum burial depth. The highest maturity was observed in the northeastern Gibson Sub-basin at Dragoon 1, where more than 2500 m of section has been removed during compressional and halokinetic uplift. Along the southern margin of the Gibson Sub-basin the Neoproterozoic section is partly within the oil-generative window, whereas in the northwestern part of the sub-basin it is mature to overmature.

Modelling indicates that the main phases of oil generation from the Neoproterozoic formations occurred during the latest Neoproterozoic, Cambrian, and Permo-Triassic. These phases occurred at different stratigraphic intervals in different parts of the basin.

The available geochemical dataset is insufficient to identify source rocks for the oil and bitumen shows in the western Officer Basin.

KEYWORDS: Officer Basin, Western Australia, Neoproterozoic, petroleum, geochemistry, source rock, potential, maturation, modelling

Introduction

This geochemical evaluation is a component of the Petroleum Exploration Initiatives program being carried out by the Geological Survey of Western Australia (GSWA). The aim of this report is to provide a regional evaluation of the source-rock potential and maturation history of the Western Australian portion of the Officer Basin (Fig. 1). The evaluation is based on open-file analytical data supplemented by new analyses of samples from petroleum and mineral exploration drillholes. This study complements the GSWA compilation of data and review of the hydrocarbon prospectivity of the Officer Basin (Perincek, 1998).

The presence of bitumen in the Neoproterozoic to Cambrian successions shows that hydrocarbon generation and migration have occurred within the basin. Yet, geochemical studies of existing data have not been able to establish the source rocks for these bitumens.

The aims of the study are firstly, to identify and characterize the source-rock intervals in the Neoproterozoic to Palaeozoic successions of the western Officer Basin, and secondly, to develop geologically plausible maturity models for existing wells by combining measured maturity values and present-day formation temperatures with burial, erosional, and thermal information. The maturity models are used to reconstruct the process of hydrocarbon generation as a function of the type and amount of kerogen, as inferred from the geochemical data. Maturity and petroleum-generation modelling were carried out using the BasinMod® UNIX Version 5.20 one-dimensional basin-modelling software package of Platte River Associates.

The geology of the Officer Basin has been described by many workers; among the most relevant papers are: Jackson and van de Graaff (1981); Karajas and Taylor (1983a,b); The Shell Company of Australia Ltd (1985); Phillips et al. (1985); Townson (1985); Iasky (1990); Walter and Gorter (1994); Williams (1994); Walter et al. (1995); and Perincek (1996). Figure 2 shows the subsurface time stratigraphy, Table 1 summarizes the formation tops, and selected geochemistry terms used in this study are defined in the Glossary (Appendix 1).

Geochemical database

Geochemical data used in this study are from open-file company reports and new analyses obtained by GSWA. A total of 1700 analyses have been carried out on more than 800 samples from 15 holes drilled for petroleum and mineral exploration. Figure 1 shows drillhole locations and Figure 3 and Table 2 summarize the type and amount of open-file and new geochemical data available for this study. Most of the analytical data were produced by Shell, Analabs, and Geotech, whereas most of the visual maturation data are from Keiraville Konsultants. Other analytical laboratories that provided results for the study area are listed in Table 2.

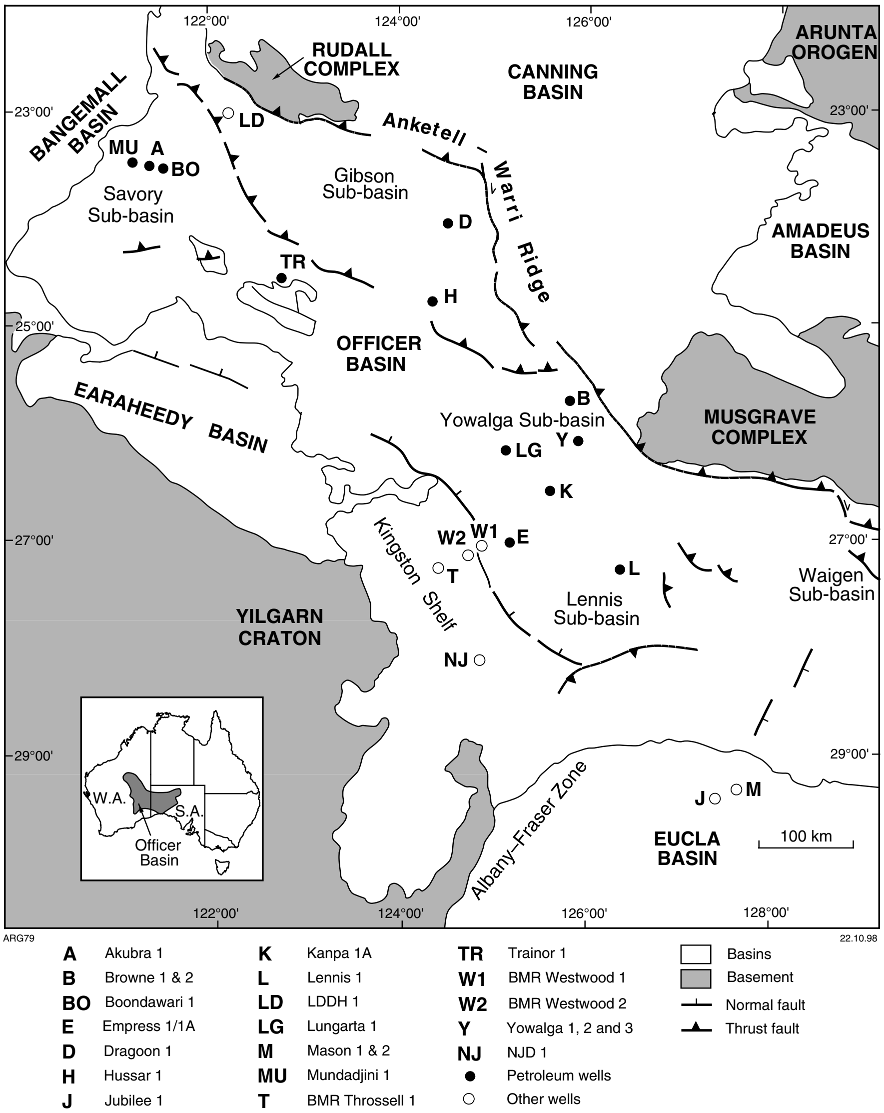

Figure 1. Regional setting and well locations of the western Officer Basin

New data for this project were obtained from 75 core samples collected from four petroleum and six mineral exploration drillholes. These samples were analysed for total organic carbon (TOC), Rock-Eval pyrolysis, pyrolysis-gas chromatography (PGC), extract-liquid chromatography (extract-LC), saturate-gas chromatography (saturate-GC), and visual maturation (%Ro). New data comprise 73 TOC, 33 Rock-Eval, one PGC, three extract-LC, three saturate-GC, and 19 visual maturation analyses. Table 3 summarizes the type and location of new geochemical data obtained for this study. New geochemical data are listed in Appendices 2 to 11 and include present-day subsurface temperatures.

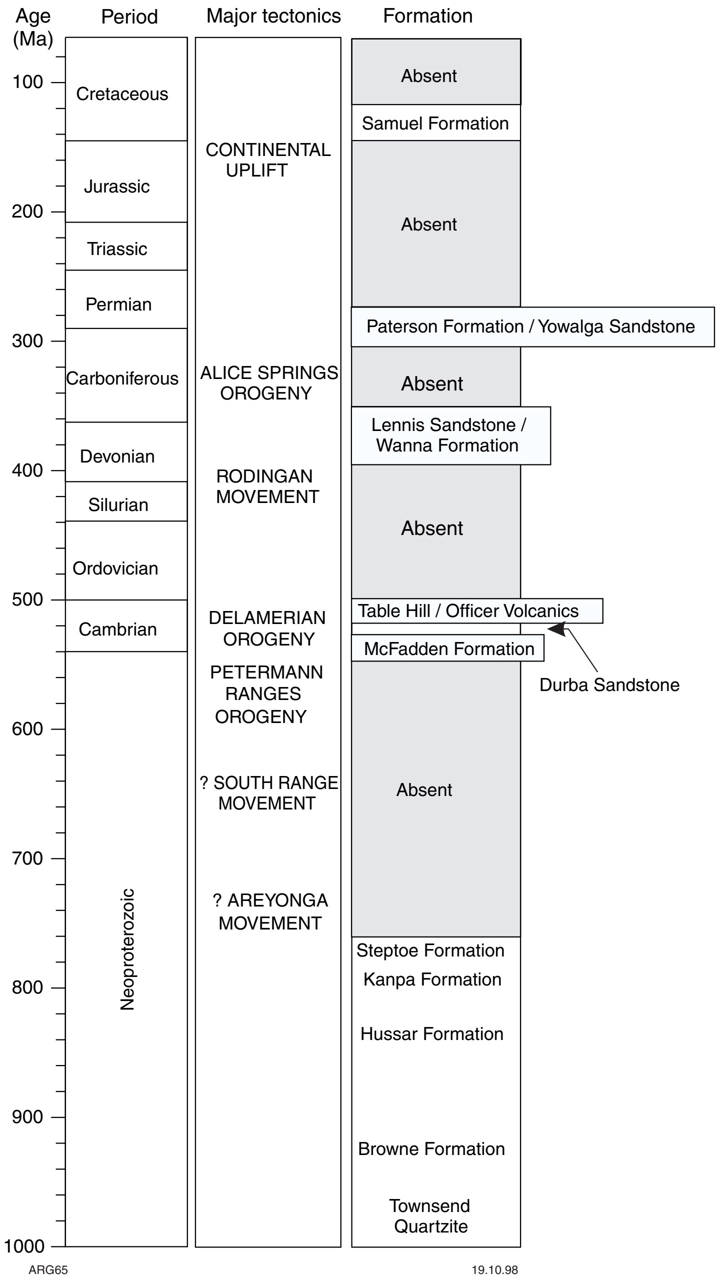

Figure 2. Subsurface time stratigraphy of the western Officer Basin

Results

Source rocks

Thin source-rock intervals with fair to very good oil-generating potential are identified in four wells: NJD 1, Kanpa 1A, Yowalga 3, and LDDH 1. The petroleum-generating potential of these source rocks was evaluated in terms of TOC versus $S_1 + S_2$ (total hydrocarbon-generating potential of rock) and is shown on Figure 4. Only those samples with more than 0.5% TOC and 1 mg/g rock $S_1 + S_2$ have been plotted.

Table 1. Formation tops used in this study from petroleum exploration wells of the western Officer Basin

Age	*Lennis Sub-basin*	*Yowalga Sub-basin*							*Gibson Sub-basin*	
Formation	*Lennis 1*	*Lungkarta 1*	*Kanpa 1A*	*Yowalga 3*	*Yowalga 1*	*Yowalga 2*	*Browne 2*	*Browne 1*	*Hussar 1*	*Dragoon 1*
Lower Cretaceous	**0**	**0**	**0**	**?**	**0**	**8**	**6**	**0**	**4**	**6**
Samuel Formation	–	0	0	–	–	–	–	–	4	6
Permo-Carboniferous	**137**	**88**	**40**	**130**	**92**	**95**	**140**	**84**	**43**	**26**
Yowalga Sandstone	–	–	–		92		140	84	–	–
Paterson Formation	137	88	40	130	–	–	–	–	43	26
Devonian	**223**	**364**	**440**	**555**	**458**	**407**	–	–	–	–
Lennis Sandstone	223	364	440	555	458	407	–	–	–	–
Cambro-Ordovician	**612**	**540**	**548**	**763**	–	**728**	–	–	**100**	–
Officer Volcanics	612	–	–	–	–	–	–	–	–	–
Table Hill Volcanics	–	540	548	763	–	728	–	–	–	–
Durba Sandstone	–	–	–	–	–	–	–	–	100	–
Cambrian	–	**704**	**657**	–	–	**846**	–	–	**465**	–
McFadden Formation	–	704	657	–	–	846	–	–	465	–
Neoproterozoic	–	**809**	**829**	**880**	–	–	**262**	**133**	**891**	**407**
Steptoe Formation	–	–	829	–	–	–	–	–	–	–
Kanpa Formation	–	809	1 301	880	–	–	–	–	891	–
Hussar Formation	–	1 196	1 817	991	–	–	–	–	1 294	–
Browne Formation	–	–	2 515	1888	–	–	262	133	1 965	407
Townsend Quartzite	–	–	3 671	–	–	–	–	–	–	–
Total depth (m)	**615**	**1 770**	**3 803**	**4 197**	**613**	**989**	**293**	**387**	**2 040**	**2 000**

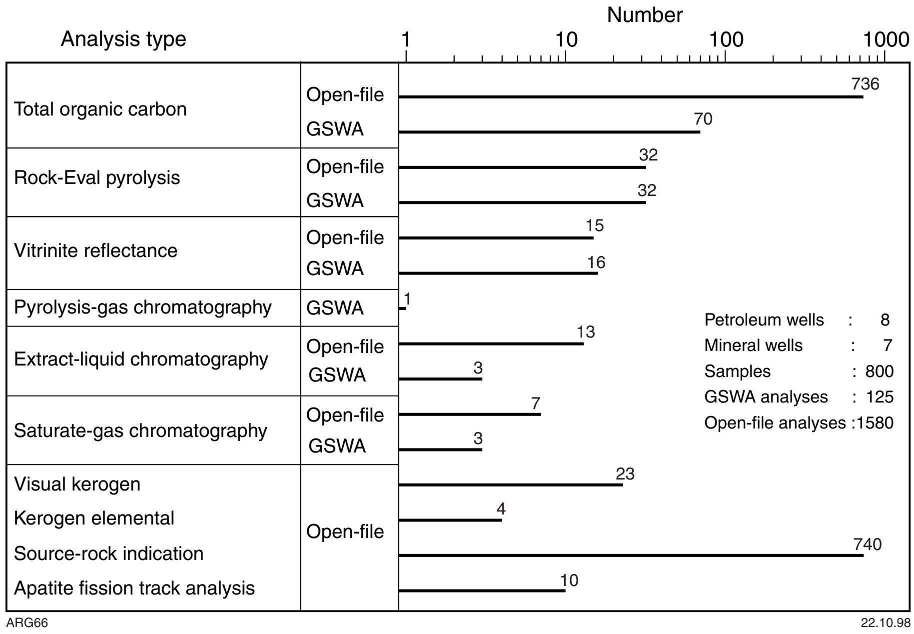

Figure 3. GSWA project and open-file geochemical database for the western Officer Basin

NJD 1

The Geological Survey of Western Australia analysed 14 cores for source-rock evaluation and one for bitumen occurrence from the Neoproterozoic to ?Mesoproterozoic successions penetrated by NJD 1 (Fig. 5), the mineral exploration drillhole drilled by Western Mining Corporation. An organic-rich sample (6.64% TOC) from 327.5 m depth, subjected to Rock-Eval pyrolysis, was found to have excellent generating potential with a potential yield of 24.2 mg/g rock. The excellent generating potential of this sample was confirmed by Rock-Eval pyrolysis on the solvent-extracted sample (Appendix 2). The same sample was also subjected to PGC, extract-LC, and saturate-GC, which confirmed the oil-generating potential (Figs 6, 7, and 8; Appendices 3 to 9). The remainder of the samples analysed were organically lean with TOC contents ranging from 0.05 to 0.25%. In NJD 1, solid bitumen was observed in cross-cutting veins in a sandstone interval between 502 and 517 m. One sample from 502.5 m was analysed and confirmed the presence of bitumen in this well (Fig. 9; Appendices 6 to 9).

Kanpa 1A

Open-file data for Kanpa 1A include analyses of 902 Neoproterozoic and Palaeozoic rock cuttings, and 16 sidewall cores undertaken by Shell; new data include analyses of eight cuttings by GSWA. The amount and type of geochemical data available are shown in Table 2.

The TOC data indicate that only eight out of 563 samples from Kanpa 1A contain more than 0.5% TOC, and analytical results for these organic-rich samples are summarized in Table 4. Of

Table 2. Type and number of geochemical analyses used in this evaluation of the western Officer Basin

Well	*Analysed by/for*	*Year*	*Interval (m) from*	*Interval (m) to*	*TOC*	*REA*	*PGC*	*Extract-LC*	*Saturate-GC*	*Organic Petrology*	*VKA*	*KEA*	*SRI-BE*	*SRI-AE*	*FTA*
Browne 1	SHELL/Shell	1979	134	355	9	–	–	–	–	–	5	–	11	–	–
	CRA	1981	216	259	2	2	–	–	–	–	–	–	–	–	–
Dragoon 1	Analab/Eagle	1982	64	2 000	73	9	–	5	5	–	–	–	–	–	–
	KK/Eagle	1983	570	1 880	–	–	–	–	–	6	–	–	–	–	–
Hussar 1	KK/Eagle	1983	990	1 824	–	–	–	–	–	9	–	–	–	–	–
	KK/GSWA	1995	860	1 822	–	–	–	–	–	3	–	–	–	–	–
	Geotech/GSWA	1995	860	1 825	7	3	–	–	–	–	–	–	–	–	–
Jubilee 1	Geotech/GSWA	1996	164	165	1	–	–	–	–	–	–	–	–	–	–
Jubilee 3	Geotech/GSWA	1996	36	–	1	–	–	–	–	–	–	–	–	–	–
Kanpa 1A	Analab/Shell	1983	630	3 571.6	530	13	–	2	2	–	–	–	–	–	–
	SHELL/Shell	1983	659	2 261	25	–	–	–	–	–	–	–	388	1	–
	Geotrack/Shell	1984	500	3 750	–	–	–	–	–	–	–	–	–	–	6
	Geotech/GSWA	1995	1 652	3 572	8	3	–	–	–	–	–	–	–	–	–
	KK/GSWA	1995	3 407	3 572	–	–	–	–	–	2	–	–	–	–	–
Lungkarta 1	Analab/Shell	1984	1 001	1 720	42	–	–	–	–	–	–	–	–	–	–
Mason 1	Amoco/CRA	1983	204	224	3	3	–	–	–	–	–	–	–	–	–
Mason 2	Amoco/CRA	1983	134	141	2	2	–	–	–	–	3	3	–	–	–
NJD 1	Geotech/GSWA	1996	203	488	11	4	1	2	2	3	–	–	–	–	–
Normandy LDDH 1	Geotech/GSWA	1996	131	697	17	11	–	1	1	3	–	–	–	–	–
Throssell 1	Geotech/GSWA	1996	62	186	6	3	–	–	–	–	–	–	–	–	–
Westwood 2	Geotech/GSWA	1996	99	101	2	–	–	–	–	–	–	–	–	–	–
Yowalga 2	SHELL/Shell	1979	286	987	15	–	–	–	–	–	6	–	19	–	–
	CRA	1981	893	989	3	3	–	–	–	–	2	1	–	–	–
	KK/GSWA	1995	894	989	3	1	–	–	–	1		–	–	–	–
Yowalga 3	SHELL/Shell	1983	890	3 287	35	–	–	–	–	–	7	–	314	7	–
	WAIT/Shell	1983	3 037	3 259	6	–	–	6	–	–	–	–	–	–	–
	Geotrack/Shell	1984	510	2 850	–	–	–	–	–	–	–	–	–	–	5
	KK/GSWA	1995	1 484	4 192	–	–	–	–	–	4	–	–	–	–	–
	Geotech/GSWA	1995	410	4 192	14	7	–	–	–	–	–	–	–	–	–
Total analyses					**815**	**64**	**1**	**16**	**10**	**31**	**23**	**4**	**732**	**8**	**11**

NOTES:
AE: After extraction
Amoco: Amoco Production Company (International)
CRA: CRA Exploration
Eagle: Eagle Corporation
FTA: Fission-track analysis
Geotech: Geotechnical Services
Geotrack: Geotrack International
KEA: Kerogen elemental analysis
KK: Keiraville Konsultants
LC: Liquid chromatography
PGC: Pyrolysis-gas chromatography
REA: Rock-Eval analysis
Shell: Shell Development Australia
SHELL: Shell Research BV, The Haque
SRI-BE: Source-rock indication before extraction
TOC: Total organic carbon
VKA: Visual kerogen analysis

Table 3. New geochemical analyses acquired by GSWA for this evaluation of the western Officer Basin

Sample number	*Well*	*Sample type*	*Depth (m) from*	*Depth (m) to*	*Depth (ft) from*	*Depth (ft) to*	*Analysis Potential*	*Analysis Maturity*	*Formation*	*Sub-basin*
1	Hussar 1	cuttings (hp)	860.0	865.0	–	–	TOC and Rock-Eval	%Ro	McFadden Formation	Gibson
2	Hussar 1	cuttings (hp)	995.0	1 000.0	–	–	TOC	–	Kanpa Formation	Gibson
3	Hussar 1	cuttings (hp)	1 640.0	–	–	–	TOC	–	Kanpa Formation	Gibson
4	Hussar 1	cuttings (hp)	1 690.0	1 695.0	–	–	TOC and Rock-Eval	%Ro	Kanpa Formation	Gibson
5	Hussar 1	core	1 822.1	–	–	–	TOC and Rock-Eval	%Ro	Hussar Formation	Gibson
6	Hussar 1	core	1 824.0	–	–	–	TOC	–	Hussar Formation	Gibson
7	Hussar 1	core	1 824.7	–	–	–	TOC	–	Hussar Formation	Gibson
8	Jubilee 1	core	164.0	165.0	–	–	TOC	–	McFadden Formation	Eucla Basin
9	Jubilee 3	core	36.0	–	–	–	TOC	–	Paterson Formation	Eucla Basin
10	Kanpa 1A	cuttings	1 652.0	1 655.0	–	–	TOC	–	Kanpa Formation	Yowalga
11	Kanpa 1A	cuttings	1 733.0	1 736.0	–	–	TOC	–	Kanpa Formation	Yowalga
12	Kanpa 1A	cuttings	1 763.0	1 769.0	–	–	TOC	–	Kanpa Formation	Yowalga
13	Kanpa 1A	cuttings (hp)	1 805.0	1 808.0	–	–	TOC	–	Kanpa Formation	Yowalga
14	Kanpa 1A	cuttings (hp)	2 243.0	2 249.0	–	–	TOC	–	Hussar Formation	Yowalga
15	Kanpa 1A	cuttings	3 407.0	3 410.0	–	–	TOC and Rock-Eval	%Ro	Browne Formation	Yowalga
16	Kanpa 1A	cuttings	3 410.0	3 413.0	–	–	TOC and Rock-Eval	–	Browne Formation	Yowalga
17	Kanpa 1A	cuttings	3 566.0	3 572.0	–	–	TOC and Rock-Eval	%Ro	Browne Formation	Yowalga
18	NJD 1	core	203.6	–	–	–	TOC	–	Neoproterozoic	Yowalga
19	NJD 1	core	252.2	–	–	–	TOC and Rock-Eval	%Ro	Neoproterozoic	Yowalga
20	NJD 1	core	277.2	–	–	–	TOC	–	Neoproterozoic	Yowalga
21	NJD 1	core	304.0	–	–	–	TOC	–	Neoproterozoic	Yowalga
22	NJD 1	core	314.5	–	–	–	TOC	–	Neoproterozoic	Yowalga
23	NJD 1	core	327.5	–	–	–	TOC, Rock-Eval, PGC, Ext.	%Ro	Neoproterozoic	Yowalga
24	NJD 1	core	336.4	–	–	–	TOC	–	?Mesoproterozoic	Yowalga
25	NJD 1	core	356.8	–	–	–	TOC	%Ro	?Mesoproterozoic	Yowalga
26	NJD 1	core	370.5	–	–	–	TOC and Rock-Eval	%Ro	?Mesoproterozoic	Yowalga
27	NJD 1	core	381.2	–	–	–	TOC	–	?Mesoproterozoic	Yowalga
28	NJD 1	core	408.5	–	–	–	TOC	%Ro	?Mesoproterozoic	Yowalga
29	NJD 1	core	434.2	–	–	–	TOC	–	?Mesoproterozoic	Yowalga
30	NJD 1	core	468.4	–	–	–	TOC	–	?Mesoproterozoic	Kingston
31	NJD 1	core	488.2	–	–	–	TOC and Rock-Eval	%Ro	?Mesoproterozoic	Kingston
32	NJD 1	core	502.5	–	–	–	Extract LC and GC	–	?Mesoproterozoic	Kingston
33	LDDH 1	core	131.3	–	–	–	TOC and Rock-Eval	–	Neoproterozoic	Gibson
34	LDDH 1	core	134.1	–	–	–	TOC and Rock-Eval	–	Neoproterozoic	Gibson
35	LDDH 1	core	165.5	–	–	–	TOC and Rock-Eval	–	Neoproterozoic	Gibson
36	LDDH 1	core	222.8	–	–	–	TOC and Rock-Eval	%Ro	Neoproterozoic	Gibson
37	LDDH 1	core	282.7	–	–	–	TOC	–	Neoproterozoic	Gibson
38	LDDH 1	core	299.5	–	–	–	TOC	–	Neoproterozoic	Gibson
39	LDDH 1	core	339.5	–	–	–	TOC	–	Neoproterozoic	Gibson
40	LDDH 1	core	386.0	–	–	–	TOC and Rock-Eval	–	Neoproterozoic	Gibson

Table 3. (continued)

Sample number	Well	Sample type	Depth (m) from	Depth (m) to	Depth (ft) from	Depth (ft) to	Analysis: Potential	Analysis: Maturity	Formation	Sub-basin
41	LDDH 1	core	447.8	–	–	–	TOC and Rock-Eval	–	Neoproterozoic	Gibson
42	LDDH 1	core	508.2	–	–	–	TOC and Rock-Eval	–	Neoproterozoic	Gibson
43	LDDH 1	core	529.6	–	–	–	TOC and Rock-Eval	%Ro	Neoproterozoic	Gibson
44	LDDH 1	core	550.6	–	–	–	TOC and Rock-Eval	–	Neoproterozoic	Gibson
45	LDDH 1	core	580.2	–	–	–	TOC	–	Neoproterozoic	Gibson
46	LDDH 1	core	608.8	–	–	–	TOC	–	Neoproterozoic	Gibson
47	LDDH 1	core	662.3	–	–	–	Extract GC		Neoproterozoic	Gibson
48	LDDH 1	core	677.6	–	–	–	TOC	–	Neoproterozoic	Gibson
49	LDDH 1	core	679.7	–	–	–	TOC and Rock-Eval	–	Neoproterozoic	Gibson
50	LDDH 1	core	697.0	–	–	–	TOC and Rock-Eval	%Ro	Neoproterozoic	Gibson
51	Throssell 1	–	62.2	–	204.00	–	TOC	–	Cainozoic	Kingston
52	Throssell 1	–	184.9	–	606.67	–	TOC and Rock-Eval	–	McFadden Formation	Kingston
53	Throssell 1	–	185.0	–	607.00	–	TOC	–	McFadden Formation	Kingston
54	Throssell 1	–	185.5	185.6	608.50	609.00	TOC	–	McFadden Formation	Kingston
55	Throssell 1	–	185.8	186.1	609.50	610.50	TOC and Rock-Eval	–	McFadden Formation	Kingston
56	Throssell 1	–	186.2	–	611.00	–	TOC	–	McFadden Formation	Kingston
57	Westwood 2	–	99.5	–	326.50	–	TOC	–	Proterozoic	Kingston
58	Westwood 2	–	101.2	–	332.00	–	TOC	–	Proterozoic	Kingston
59	Yowalga 2	core # 7	893.7	–	2 932.00	–	TOC and Rock-Eval	%Ro	McFadden Formation	Yowalga
60	Yowalga 2	core # 8	988.5	–	3 243.00	–	TOC	–	McFadden Formation	Yowalga
61	Yowalga 2	core # 8	988.8	–	3 244.00	–	TOC	–	McFadden Formation	Yowalga
62	Yowalga 3	cuttings	410.0	–	–	–	TOC	–	Paterson Formation	Yowalga
63	Yowalga 3	cuttings	947.0	953.0	–	–	TOC	–	Kanpa Formation	Yowalga
64	Yowalga 3	cuttings	1 472.0	–	–	–	TOC	–	Hussar Formation	Yowalga
65	Yowalga 3	cuttings	1 475.0	–	–	–	TOC and Rock-Eval	–	Hussar Formation	Yowalga
66	Yowalga 3	cuttings	1 478.0	–	–	–	TOC and Rock-Eval	–	Hussar Formation	Yowalga
67	Yowalga 3	cuttings	1 481.0	–	–	–	TOC and Rock-Eval	–	Hussar Formation	Yowalga
68	Yowalga 3	cuttings	1 484.0	–	–	–	TOC and Rock-Eval	%Ro	Hussar Formation	Yowalga
69	Yowalga 3	core # 1	2 386.6	–	–	–	TOC	–	Browne Formation	Yowalga
70	Yowalga 3	core # 1	2 388.4	–	–	–	TOC and Rock-Eval	%Ro	Browne Formation	Yowalga
71	Yowalga 3	cuttings	3 253.0	3 259.0	–	–	TOC and Rock-Eval	%Ro	Browne Formation	Yowalga
72	Yowalga 3	core # 2	3 277.5	–	–	–	TOC	–	Browne Formation	Yowalga
73	Yowalga 3	core # 2	3 286.4	–	–	–	TOC	–	Browne Formation	Yowalga
74	Yowalga 3	core # 3	4 187.2	–	–	–	TOC	–	Browne Formation	Yowalga
75	Yowalga 3	core # 3	4 192.0	–	–	–	TOC and Rock-Eval	%Ro	Browne Formation	Yowalga

NOTES: %Ro: Vitrinite reflectance measurements under oil immersion for evaluating source-rock maturity
Ext: extractable organic matter
hp: hand picked
PGC: pyrolysis gas chromatography
TOC : Total organic carbon

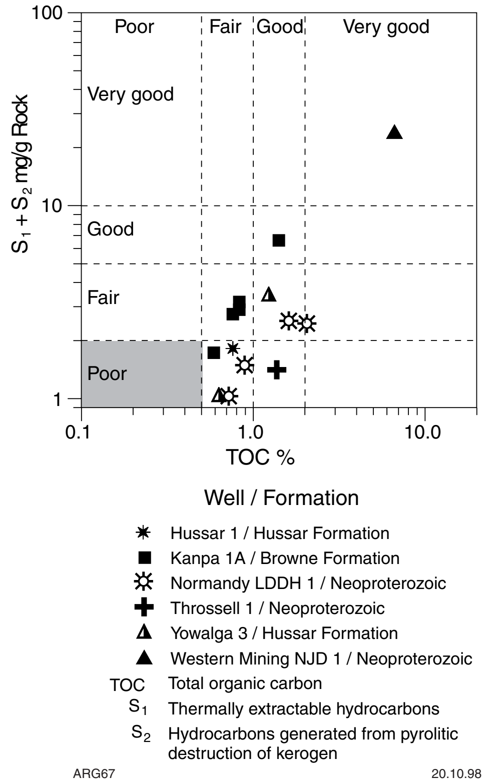

Figure 4. Petroleum-generating potential of rock samples from the western Officer Basin

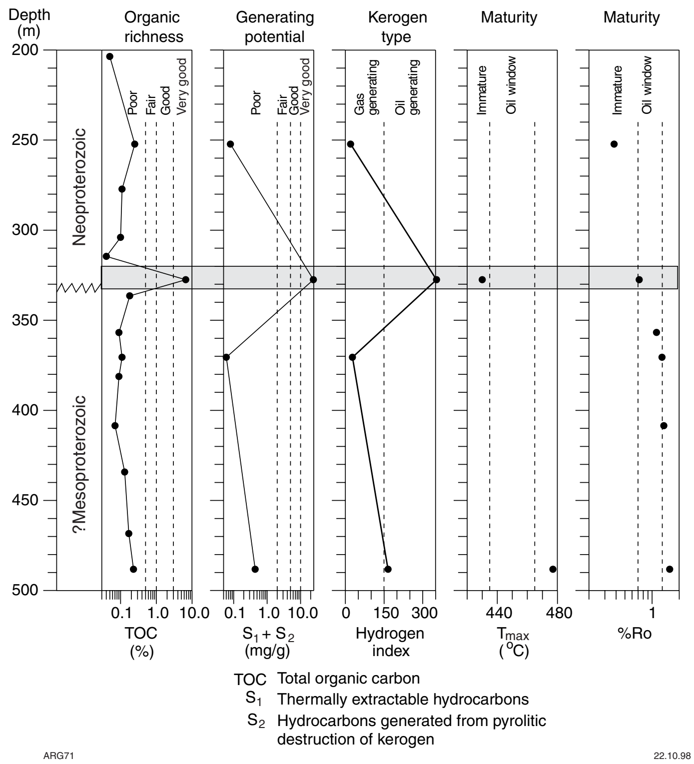

Figure 5. Petroleum source potential of rocks from NJD 1

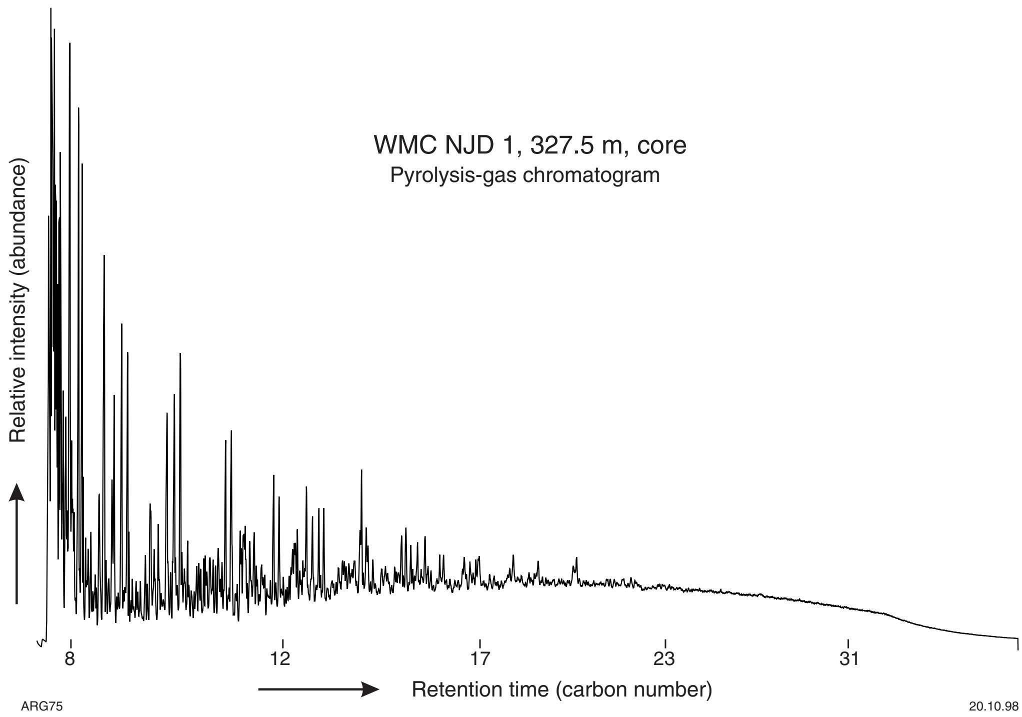

Figure 6. Pyrolysis-gas chromatogram for core from 327.5 m in NJD 1

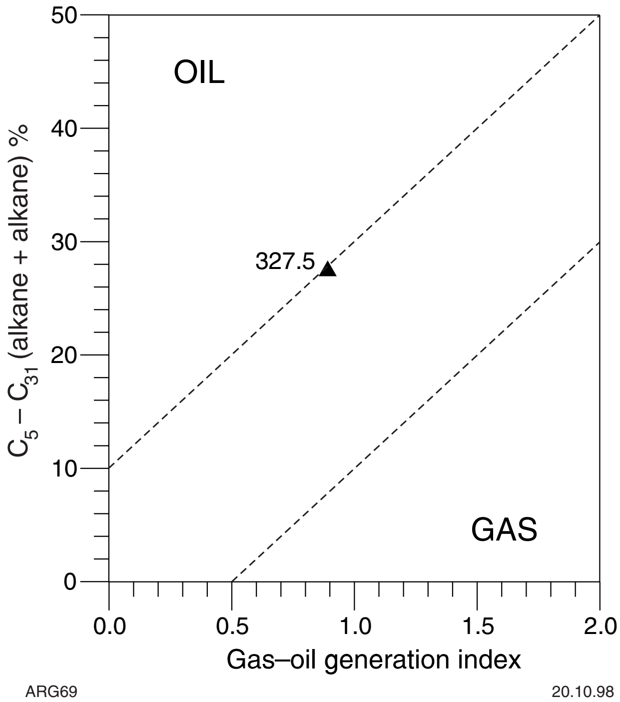

Figure 7. Kerogen typing by pyrolysis-gas chromatography for core from 327.5 m in NJD 1

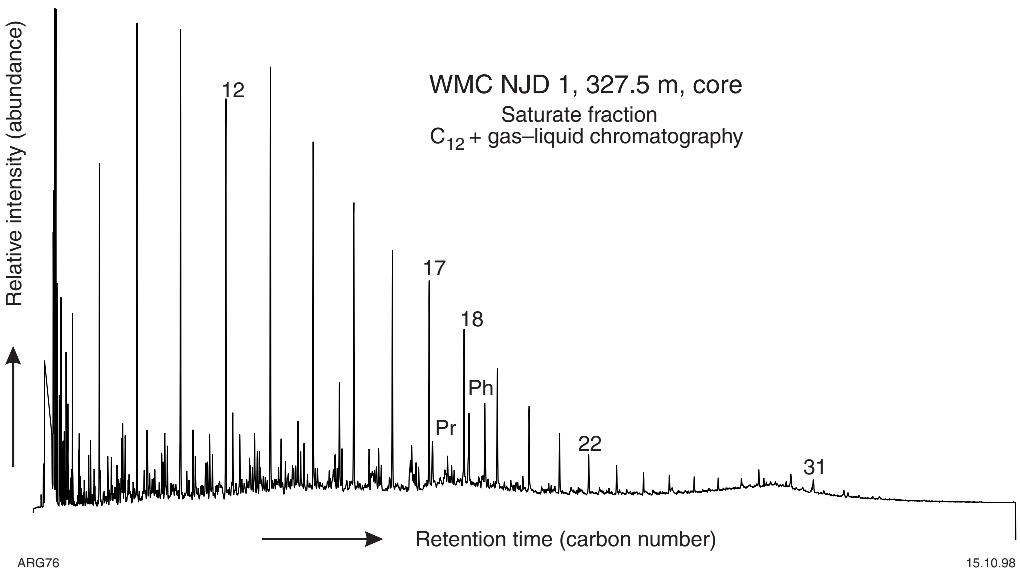

Figure 8. Chromatogram of saturate fraction for core from 327.5 m in NJD 1

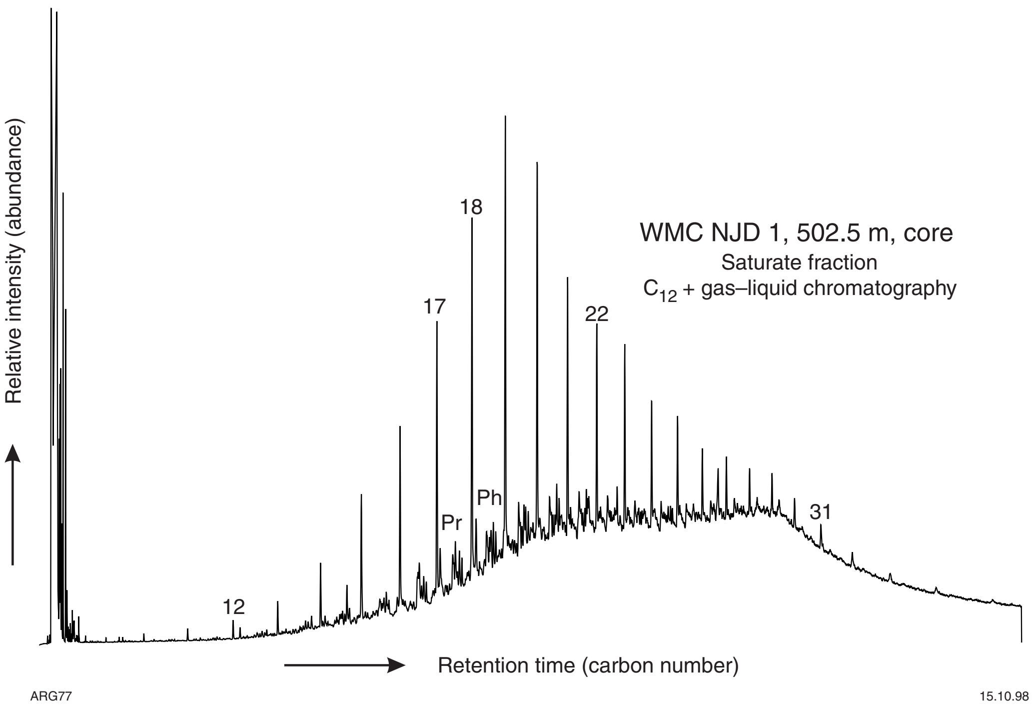

Figure 9. Chromatogram of saturate fraction for core from 502.5 m in NJD 1

Table 4. TOC and Rock-Eval data for organic-rich samples from Kanpa 1A

Depth (m)	Sample type	*TOC (%)*	*S_1 (mg/g)*	*S_2 (mg/g)*	*HI (HC mg/g TOC)*	*T_{max} (°C)*
2 771–2 774	cuttings	0.57	0.05	0.01	1	435
3 386–3 389	cuttings	0.58	0.31	0.81	140	438
3 407–3 410	cuttings	0.83	0.70	2.19	263	435
(p)3 407–3 410	cuttings	0.83	0.77	2.40	289	433
(p)3 410–3 413	cuttings	0.76	0.67	2.07	272	431
3 412.2	swc	1.41	1.78	4.83	342	436
3 431–3 434	cuttings	0.50	0.52	0.56	111	426
(p)3 566–3 572	cuttings	0.59	0.52	1.21	205	431
3 569–3 572	cuttings	0.67	0.36	0.69	10	430

NOTES: (p): analysed as a part of GSWA project
HC: hydrocarbon
HI: hydrogen index = (S_2/TOC) × 100
S_1: existing hydrocarbons
S_2: pyrolytic yield (remaining hydrocarbon potential)
swc : sidewall core
T_{max}: temperature of maximum pyrolytic yield
TOC: total organic carbon

these eight organic-rich samples only two can be classified as source rocks. A cuttings sample from 3407 to 3410 m is a fair oil source rock and one sidewall core from 3412.2 m is a good oil source rock (Fig. 10). All other samples are poor source rocks.

One cuttings sample, designated as 06:30-hour cavings (The Shell Company of Australia Ltd, 1983), was investigated by Shell for oil show. The cavings and mud samples were subjected to extract-GC to evaluate the oil show (Figs 11 and 12). The liquid extracted from the cavings sample appears to be low-maturity petroleum generated from a dominantly algal source, and does not appear to be contaminated with diesel (The Shell Company of Australia Ltd, 1983).

Yowalga 3

Open-file source-rock evaluation data for Yowalga 3 include analyses of 343 samples comprising 303 cuttings, 31 sidewall cores, and nine conventional cores from the Neoproterozoic to Cambrian section (Shell Development Australia Pty Ltd, 1981; Hermans, 1983; Green and Gleadow, 1984). An additional six cores and eight cuttings were analysed under this GSWA project (Table 2). Only 11 samples have more than 0.5% TOC and their analytical results are summarized in Table 5. The interval between 1481 and 1505 m is organic rich, with TOC values between 0.7 and 2.9%. One sample from 1484 m is a good-quality oil source rock with fair generating potential (S_1 + S_2 values of 3.5 mg/g rock). The geochemical log of Yowalga 3 indicates the presence of fair oil source rock within the Hussar Formation (Fig. 13).

LDDH 1

The Geological Survey of Western Australia analysed 17 cores from the Neoproterozoic succession penetrated in LDDH1, the mineral exploration drillhole drilled by Normandy Poseidon near Lake Disappointment (Busbridge, 1993, 1994). Of these 17 core samples 11 were organic rich,

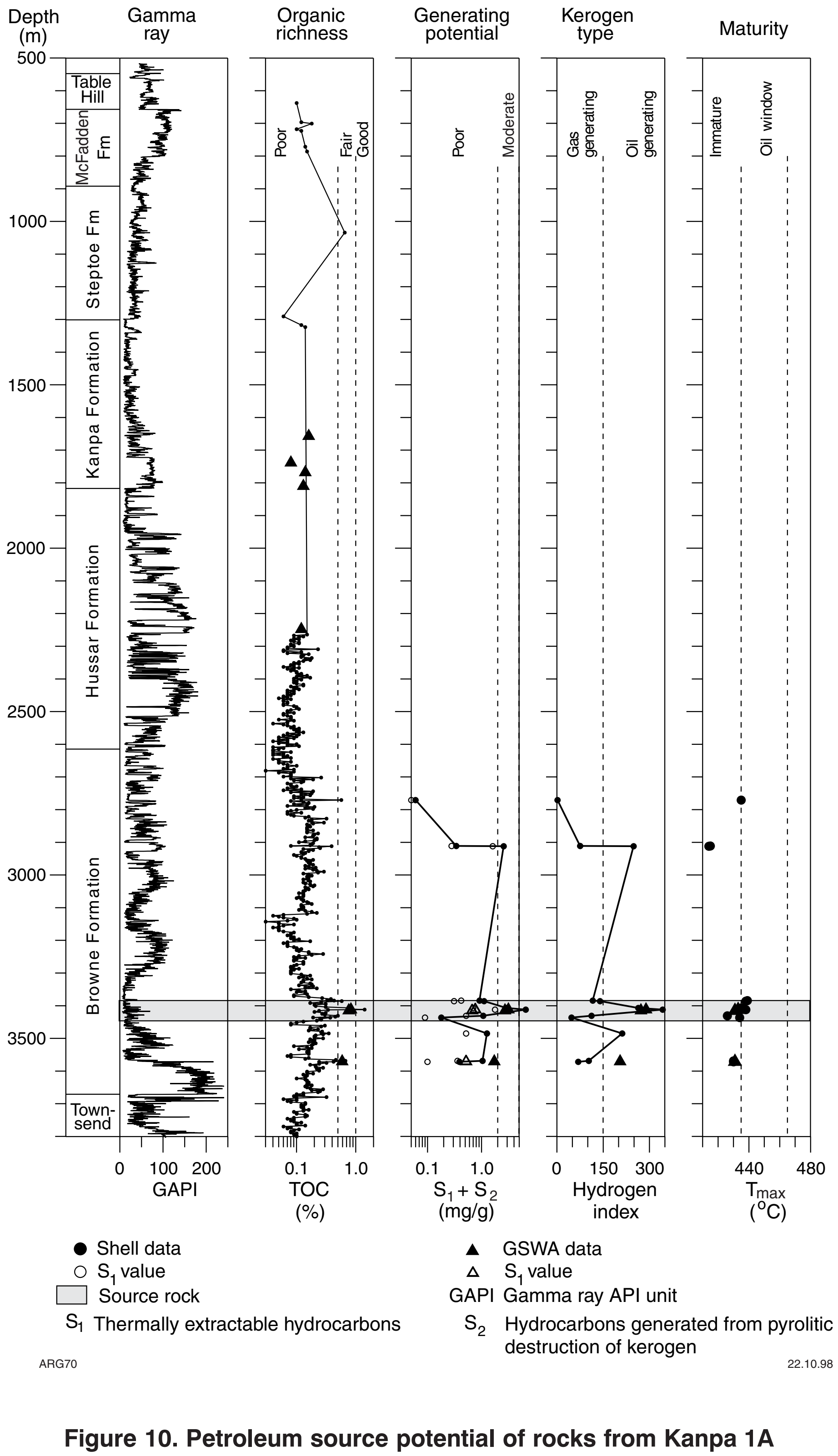

Figure 10. Petroleum source potential of rocks from Kanpa 1A

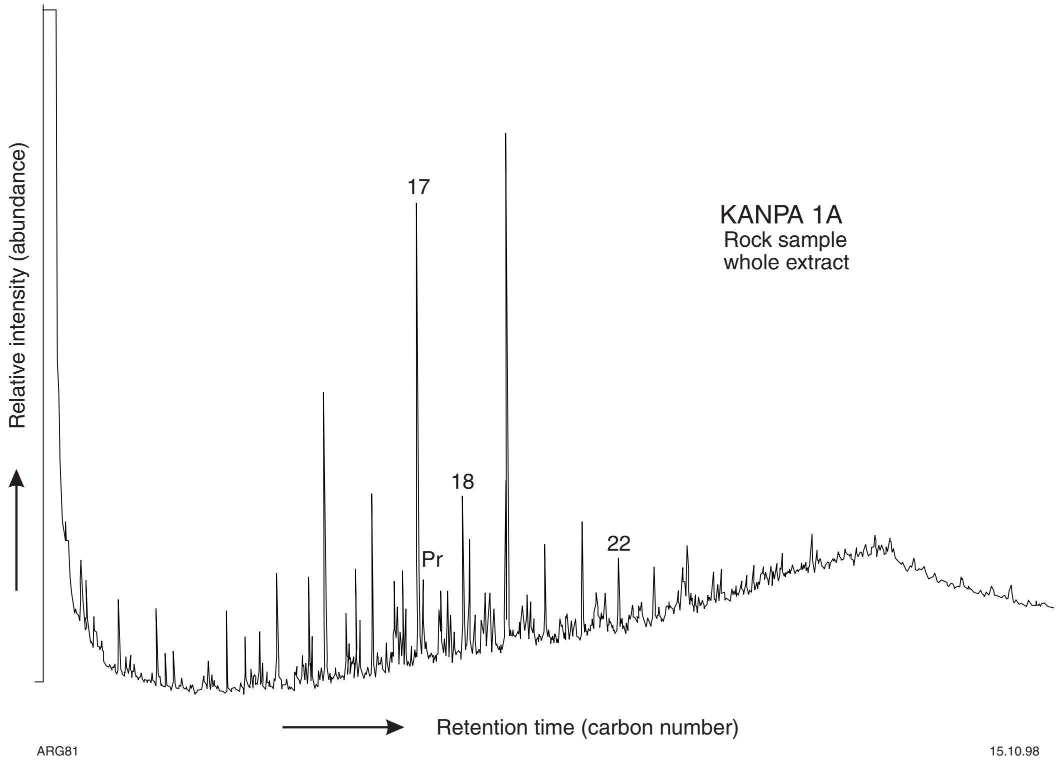

Figure 11. Chromatogram of whole extract for a cuttings sample from Kanpa 1A

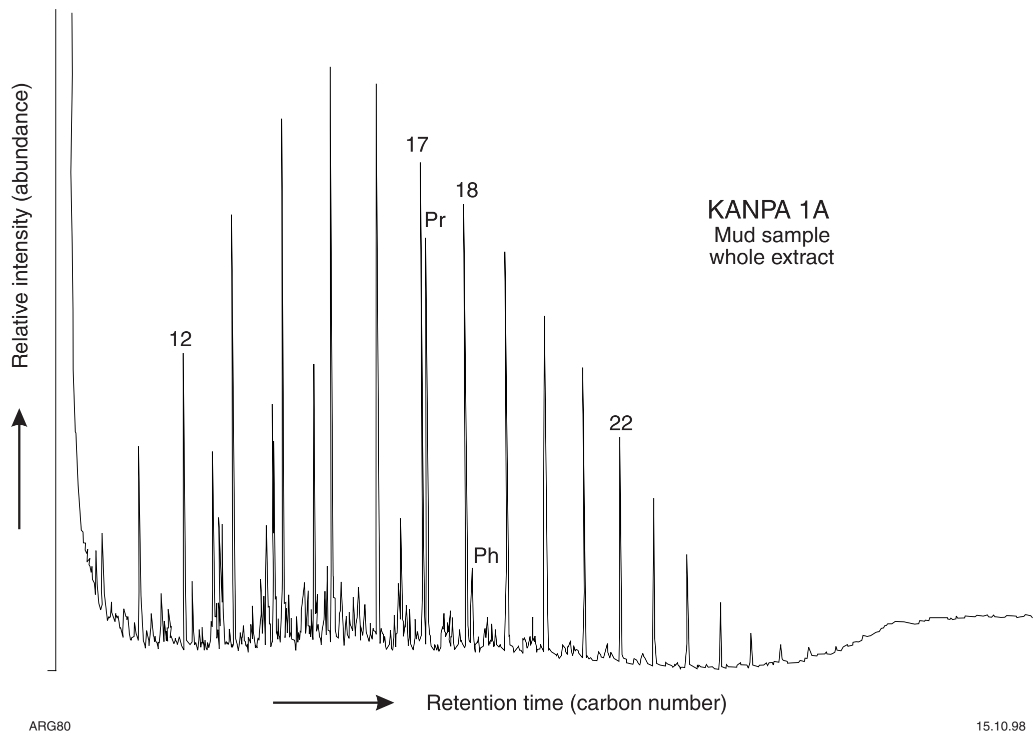

Figure 12. Chromatogram of whole extract for a mud sample from Kanpa 1A

Table 5. Summary of geochemical results for organic-rich samples from Yowalga 3

Depth (m)	*Sample type*	*SRI value*	*TOC (wt%)*	*Kerogen*
1 481	cuttings	70	1.2	sapropelic (common)
1 483	cuttings	120	1.2	sapropelic (common)
1 483.5	junkbasket	370	2.9	sapropelic (common)
1 484	junkbasket	50	0.7	–
(p)1 484	cuttings	nd	1.23	–
1 501.5	sidewall core	85	1.4	sapropelic (few)
3 194.2	sidewall core	5	0.8	–
3 217.5	sidewall core	25	0.5	–
(p)3 253–3 259	cuttings	nd	0.63	–
3 259	sidewall core	30	1.2	–
(p)4 192	core	nd	0.62	–

NOTES: (p): analysed as a part of GSWA project
nd: not determined
SRI value: source-rock index value
TOC: total organic carbon

containing over 0.5% TOC. These organic-rich samples were further analysed by Rock-Eval pyrolysis, which indicates that one sample from 222.8 m is a fair source rock. One sample from 662.3 m was subjected to gas chromatography, which confirmed the presence of bitumen in this sample (Figs 14 and 15; Appendices 2, and 6 to 9).

Other wells

No source rocks were identified in Browne 1, Dragoon 1, Hussar 1, Lungkarta 1, Mason 1 and 2, and Yowalga 2 on the basis of available TOC and Rock-Eval data. Table 2 summarizes the data available for source-rock evaluation of these wells.

Kerogen type

A hydrogen index versus T_{max} diagram is used to illustrate the kerogen type. Source-rock samples from Kanpa 1A, LDDH 1, NJD 1, and Yowalga 3 are plotted on this diagram (Fig. 16), which indicates that the kerogen in the Neoproterozoic rocks is predominantly oil and gas generating. This oil-generating character of Neoproterozoic kerogen is also confirmed by PGC analysis of an excellent source-rock sample from NJD 1 (Figs 6 and 7).

Present-day geothermal gradient

Present-day subsurface temperature data include 50 bottomhole temperatures (BHTs) recorded during wireline logging in 10 wells (Appendix 11). A graph of these recorded BHTs versus depth (Fig. 17) indicates that the temperatures recorded at depths shallower than 1500 m have widespread values and are unreliable for estimating geothermal gradients. Table 6 provides only

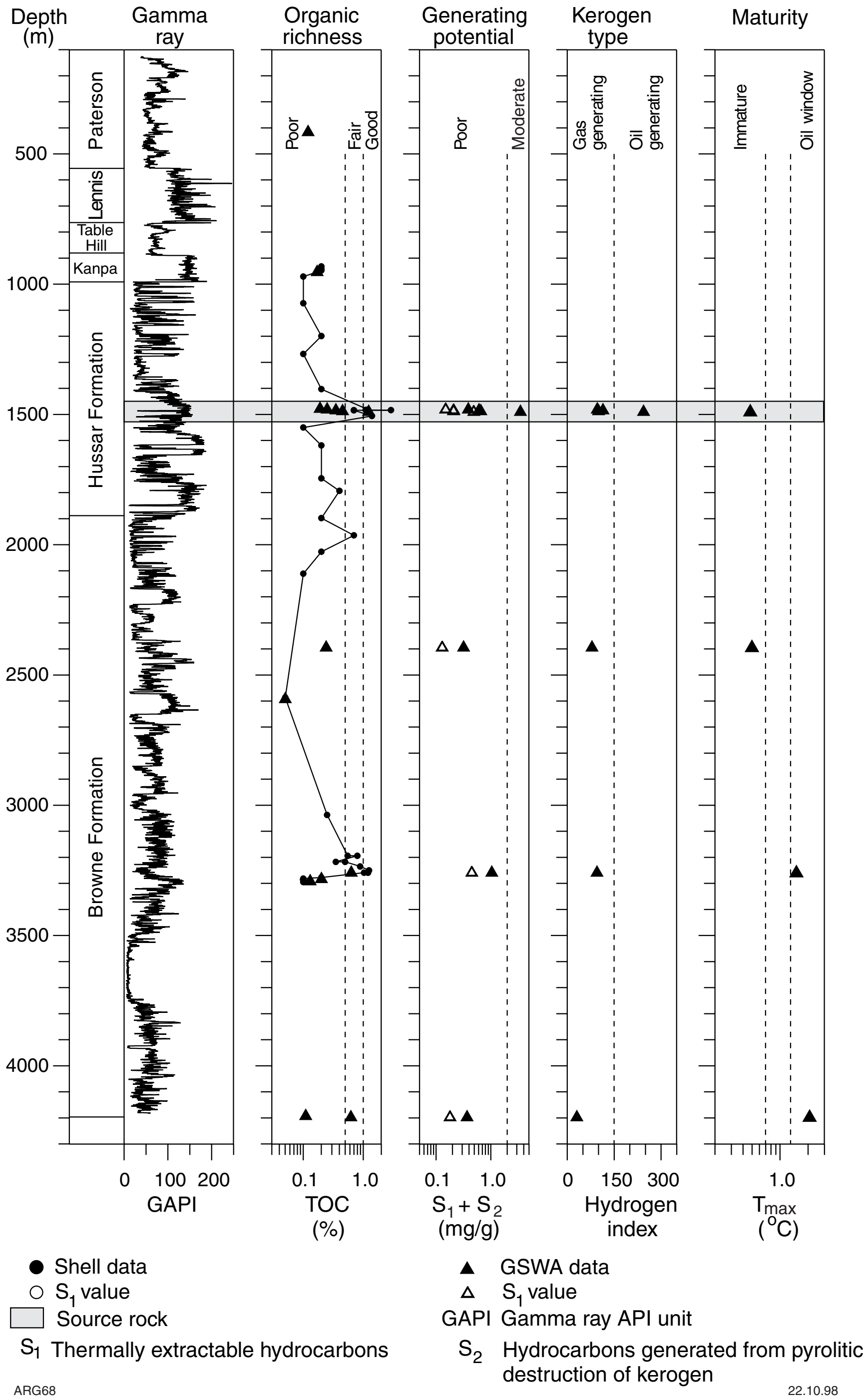

Figure 13. Petroleum source potential of rocks from Yowalga 3

the deepest recorded and estimated (Kehle, 1971; Fertl and Wickmann, 1977) BHTs for the studied wells. Geothermal gradients are calculated from the estimated BHTs using 25°C as the surface temperature. Yowalga 3 and Kanpa 1A are the deepest wells and provide reliable geothermal gradients for the Neoproterozoic Yowalga Sub-basin, with temperature gradients of 1.8°C/100 m and 1.5°C/100 m respectively. No conclusions can be reached regarding geothermal gradients in other sub-basins of the western Officer Basin from the existing dataset.

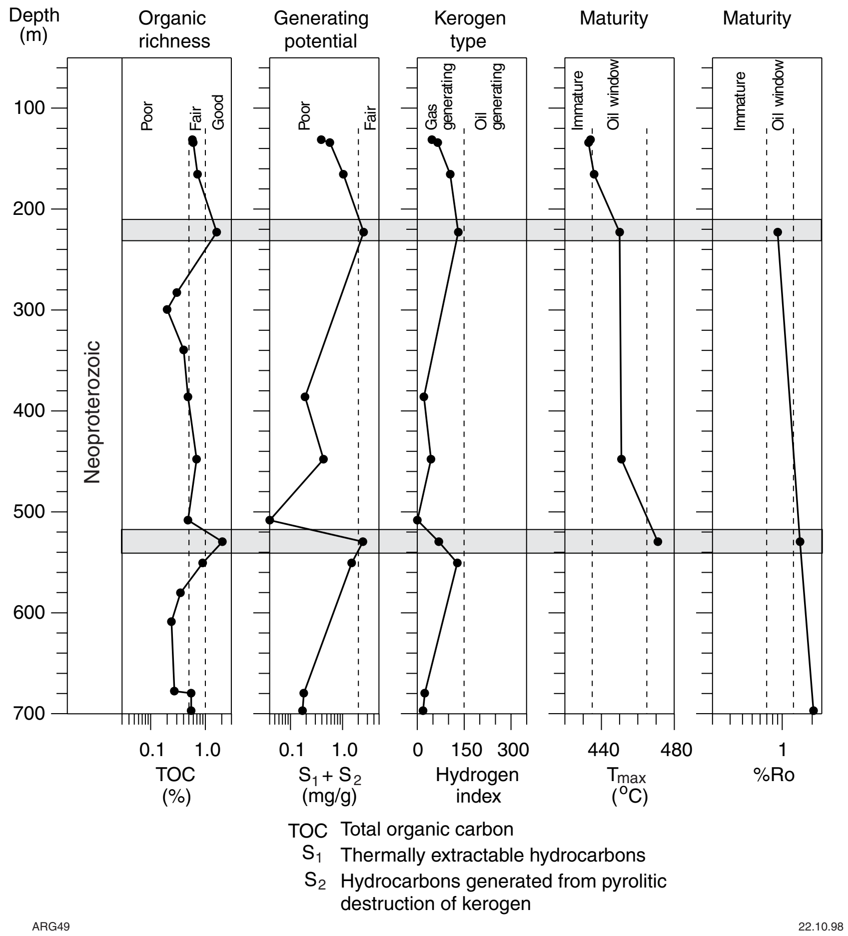

Figure 14. Petroleum source potential of rocks from Normandy LDDH 1

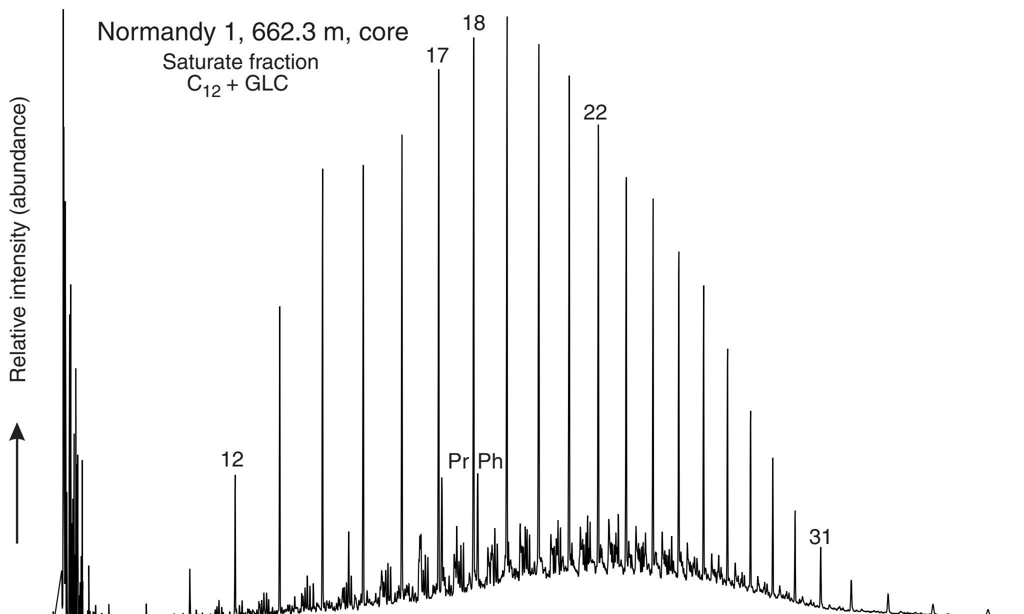

Figure 15. Chromatogram of saturate fraction for core from Normandy LDDH 1

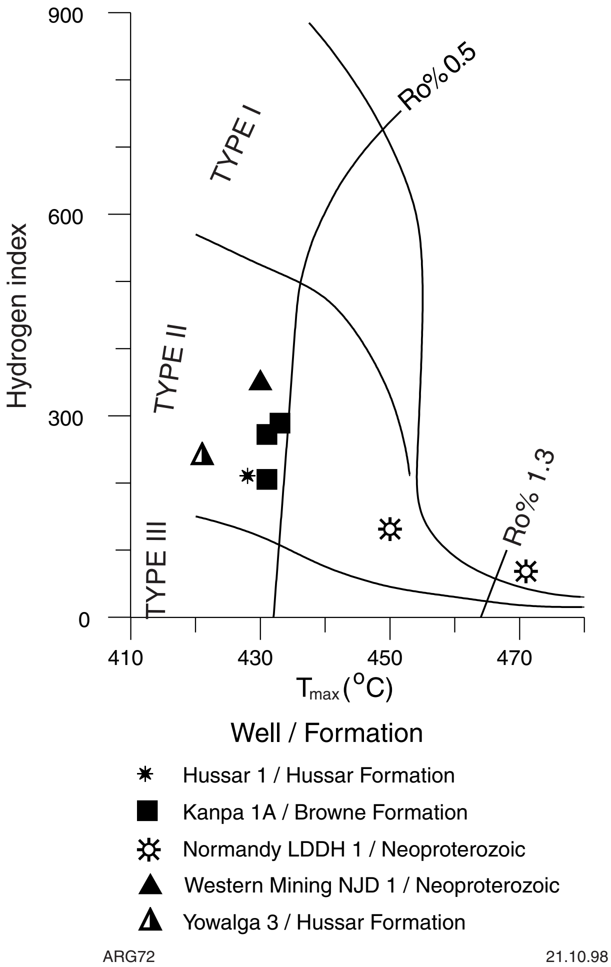

Figure 16. Rock-Eval kerogen typing of source rocks from the western Officer Basin

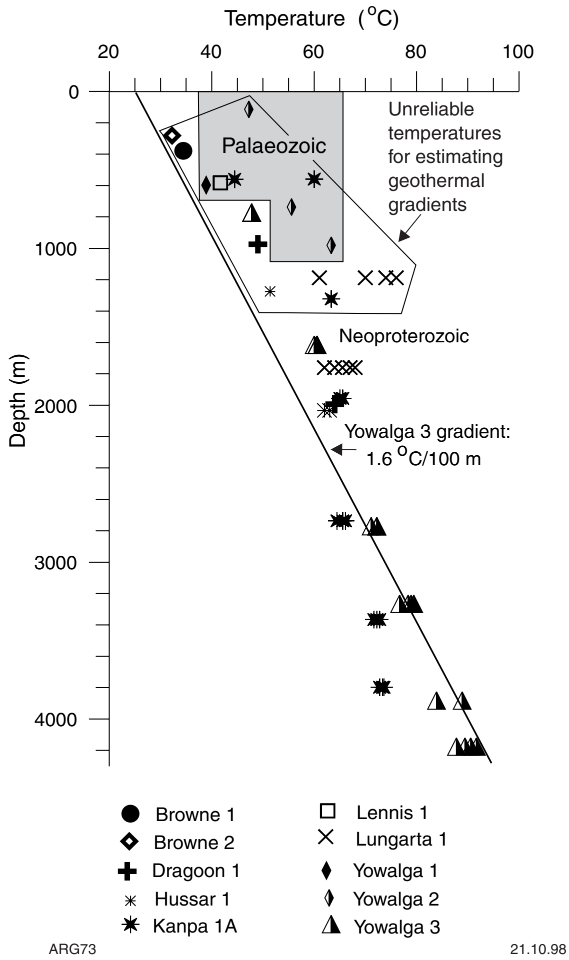

Figure 17. Recorded BHTs in ten wells from the western Officer Basin and geothermal gradient for Yowalga 3 (see Appendix 11)

Measured maturity

The parameters indicating maturity levels in the western Officer Basin include: the Rock-Eval parameters — T_{max} and production index (Appendix 2); organic petrological measurements of reflectance and fluorescence for reservoir and thucholitic (solid) bitumen and fluorescing and non-fluorescing lamalginite (Appendix 10); and apatite fission-track analyses.

Rock-Eval data

Maturity indicators include T_{max}, the temperature at which the maximum amounts of pyrolytic hydrocarbons (S_2) are generated, and production index ($PI = S_1/(S_1 + S_2)$ where S_1 is the thermally extractable hydrocarbon). The interpretation of 64 Rock-Eval analyses from the available dataset indicates that only 29 T_{max} and 20 production index values are reliable for maturity evaluation. These T_{max} and production index values are from eight wells, and plotted versus depth (Fig. 18).

Table 6. Present-day geothermal gradient in order of increasing depth for wells of the western Officer Basin

Well	*Depth rotary table (m)*	*Depth ground level (m)*	*Temperature*			
			Recorded (°C)	*Estimated (°C)*	*Surface (°C)*	*Gradient (°C/100 m)*
Browne 2	282.2	280.7	32.2	35.4	25	3.7
Browne 1	380.4	378.9	34.4	37.9	25	3.4
Lennis 1	583.7	582.2	41.7	45.8	25	3.6
Yowalga 1	598.3	596.8	38.9	42.8	25	3.0
Yowalga 2	984.8	980.8	63.3	69.7	25	4.6
Lungkarta 1	1 767.0	1 760.2	68.0	74.8	25	2.8
Dragoon 1	1 996.7	1 992.7	64.0	70.4	25	2.3
Hussar 1	2 037.5	2 033.5	63.0	69.3	25	2.2
Kanpa 1A	3 804.0	3 798.0	73.6	81.0	25	1.5
Yowalga 3	4 183.0	4 175.9	91.7	100.8	25	1.8

The plots indicate that except in Dragoon 1 and the basal parts of Yowalga 3 and NJD 1, all samples are either immature or within the oil-generative window.

Organic petrology

Maturity data from organic petrology is available for seven wells, and the new data acquired from six wells are given in Appendix 10. Data include reflectance measurements on fluorescing and non-fluorescing lamalginite, reservoir and thucholitic bitumen, and bitumen of unknown origin, as well as intensity of fluorescence. Most of the organic matter consists of alginite referred to as lamalginite. The reflectance values of lamalginite are more reliable for moderate to high maturation levels (Cook, 1995). Thucholitic bitumen that encase radioactive minerals show that its reflectance value at the outer rim is very similar to that of the coexisting vitrinite. Fluorescing lamalginite becomes non-fluorescing at higher levels of maturation, and both forms can be present in a single sample. Lamalginite and bitumen reflectance can provide maturity levels for rocks older than Devonian (Crick et al., 1988).

The reflectance values of fluorescing and non-fluorescing lamalginite and reservoir and thucholitic bitumen are plotted versus depth (Fig. 19). This plot indicates that Dragoon 1 and the basal parts of NJD 1, LDDH 1, and Yowalga 3 are overmature, whereas the remaining samples are immature or within the oil-generative window. As expected, fluorescing lamalginite has consistently low reflectance values compared to non-fluorescing lamalginite. Both the organic petrology and Rock-Eval data indicate that the oil-generative window in Kanpa 1A and Yowalga 3 (Yowalga Sub-basin) is about 1000 m deeper than in Hussar 1 (Gibson Sub-basin).

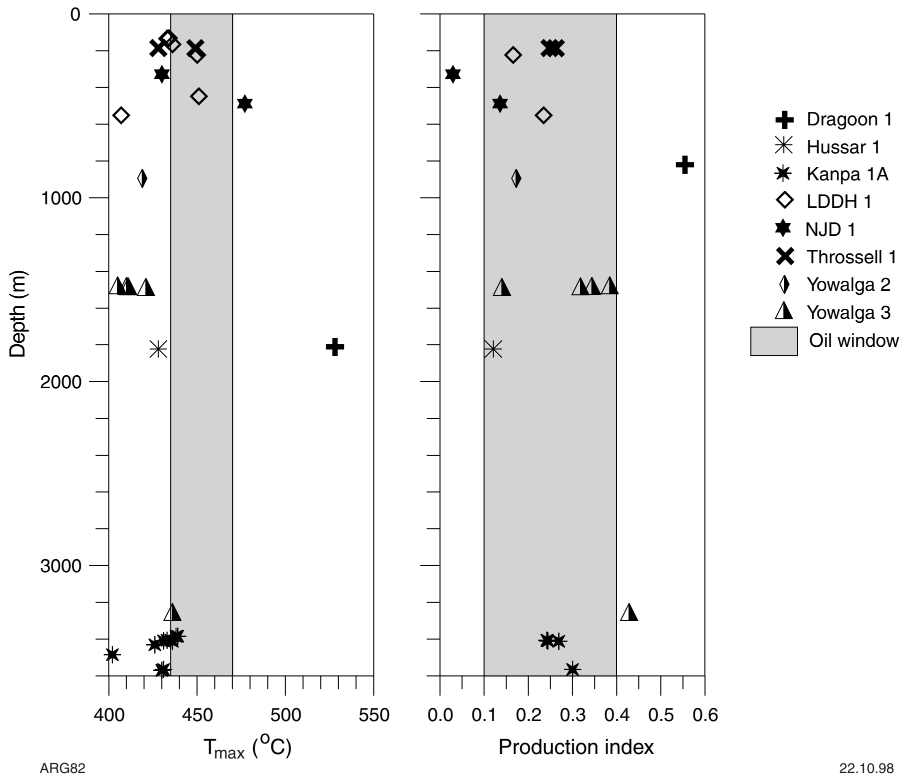

Figure 18. T_{max} and production index versus depth plots for the western Officer Basin

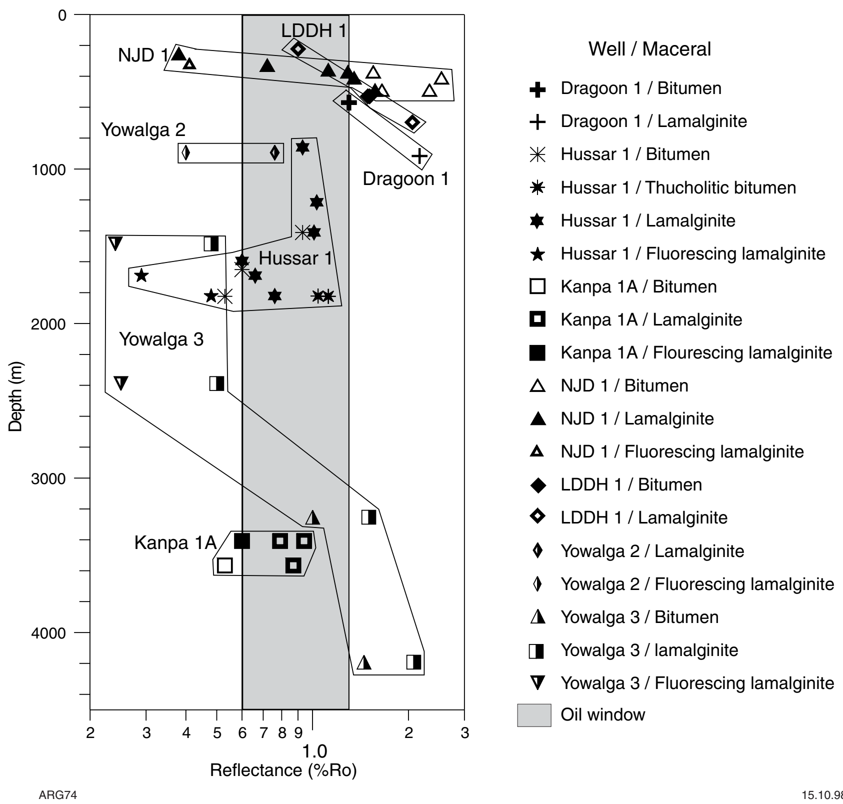

Figure 19. Equivalent %Ro versus depth plot for the western Officer Basin

Apatite fission-track analysis

The fission-track age is largely a function of track annealing in response to increasing temperature between 70 and 120°C, whereas track length reflects the style of cooling. Apatite fission-track analysis is therefore useful in understanding the geothermal history of the host rocks. Green and Gleadow (1984) provided fission-track data and interpretation for 10 cuttings samples from Kanpa 1A (5 samples) and Yowalga 3 (5 samples). They suggested that most of the Neoproterozoic section in Kanpa 1A and Yowalga 3 may have been mature to overmature relatively early in the history of the basin. This interpretation implies that in these areas the maximum palaeodepths were reached before the major uplift and erosion during the Petermann Ranges Orogeny, which was the first major erosional event for the Neoproterozoic succession.

Simulated maturity and petroleum generation

Dragoon 1, Hussar 1, Kanpa 1A, and Yowalga 3 are the deepest wells in the western Officer Basin and contain most of the available subsurface data for maturity and hydrocarbon-generation modelling. Maturity and hydrocarbon-generation modelling results are presented as plots of maturity calibration, burial and oil window, kerogen transformation ratio, and rate of generation.

Maturity calibration plots

These plots compare measured with calculated temperatures and measured with calculated maturity. Figures 20 to 23 illustrate maturity calibration in Dragoon 1, Hussar 1, Kanpa 1A, and Yowalga 3 respectively. The models have been constrained by the equivalent vitrinite reflectance of organic matter, T_{max} from Rock-Eval, and maturity information from apatite fission-track analysis. In maturity modelling, transient heat flows, thermal conductivities, and erosional histories were used to constrain the models.

Estimates of local erosion at each well location were made from seismic and geological information. Erosion estimates, along with thermal conductivities and maturity data, were used to constrain palaeoheat flows and present-day heat flows in the maturity modelling. The amount of erosion (in metres) and present-day heat flow required for the best fit of the models to the measured data are summarized in Table 7.

The Rock-Eval parameter T_{max} and organic petrology data for samples from NJD 1, LDDH 1, and Yowalga 2 indicate that the Neoproterozoic succession is immature to mostly mature. Basin modelling of these wells was not undertaken due to structural complexity and insufficient data.

Burial and oil-window plots

The oil window displayed in the burial history plots has been divided into three zones to indicate the levels of kerogen conversion to petroleum. These zones correspond to an early generation phase (10–25%), a main phase (25–65%), and a late phase (65–90%) of kerogen transformation to petroleum. A vitrinite reflectance value of 0.65% has been adopted for the onset of the oil window.

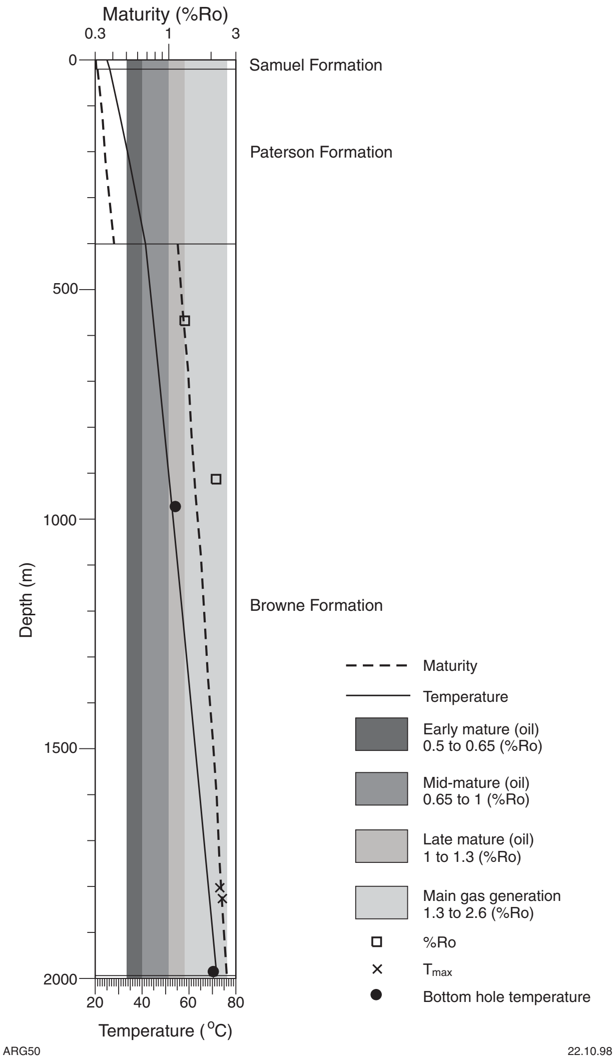

Figure 20. Comparison of measured and calculated maturity in Dragoon 1

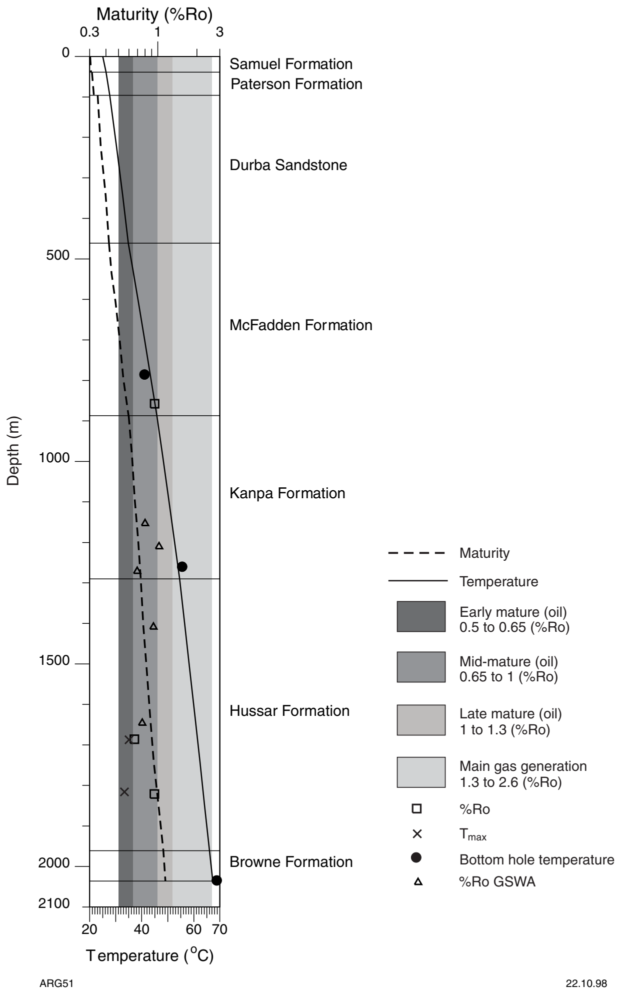

Figure 21. Comparison of measured and calculated maturity in Hussar 1

This is based on the kerogen type estimated from geochemical data: 10% type I kerogen, 70% type II kerogen, and 20% type III kerogen. Figures 24 to 27 show the burial curve and oil window for Dragoon 1, Hussar 1, Kanpa 1A, and Yowalga 3 respectively.

In Hussar 1 and Kanpa 1A, the Browne Formation and parts of the Hussar Formation are within the oil window, whereas the Kanpa Formation and younger rocks are immature for oil generation. In Yowalga 3, the Browne Formation is partly immature to fully mature, whereas the basal section is overmature. In Dragoon 1, the Neoproterozoic (Browne Formation) is overmature for oil generation. Figure 28 illustrates thermal maturity (%Ro) from Kanpa 1A in the south to Dragoon 1 in the north.

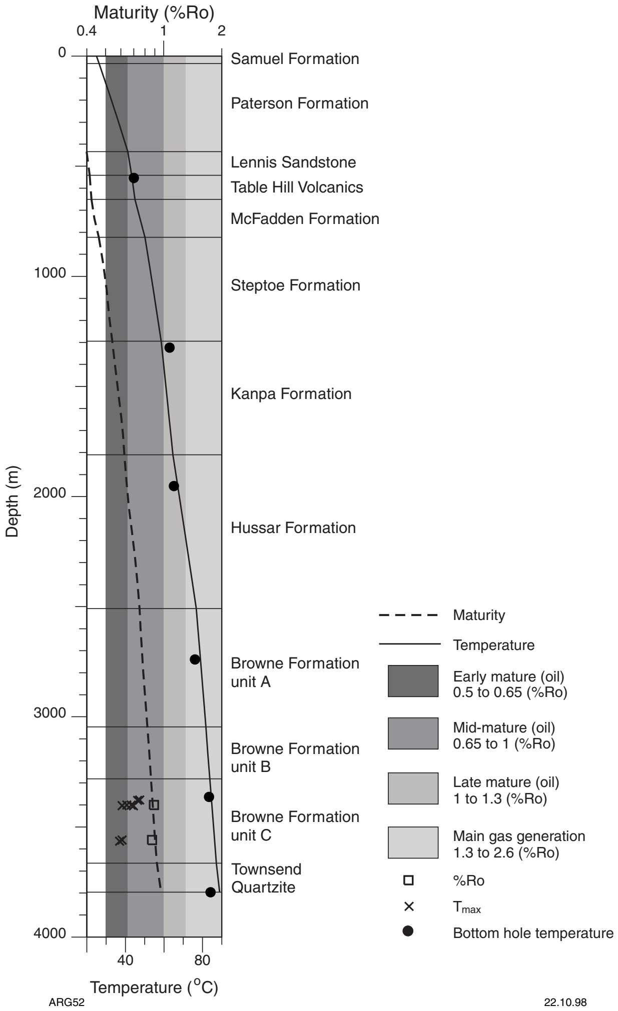

Figure 22. Comparison of measured and calculated maturity in Kanpa 1A

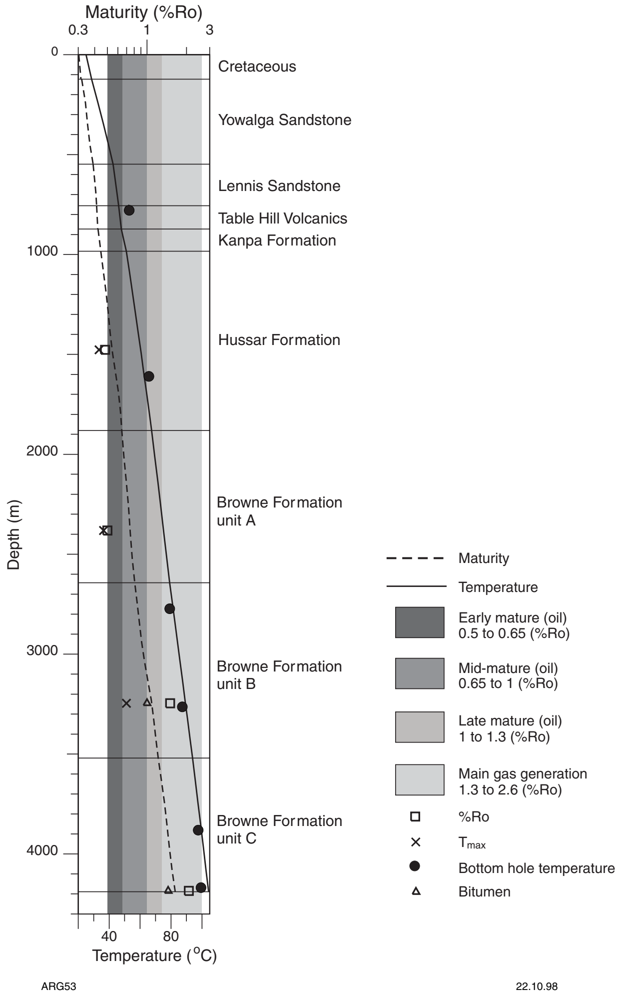

Figure 23. Comparison of measured and calculated maturity in Yowalga 3

Table 7. Estimated erosion and heat flow required to match the measured maturity

Tectonic event	*Age*	*Dragoon 1 (m)*	*Hussar 1 (m)*	*Kanpa 1A (m)*	*Yowalga 3 (m)*
Continental uplift	Jurassic	~50	~50	~50	~50
Alice Springs Orogeny	300 to 330 Ma	330	330	220	220
Rodingan Movement	400 to 500 Ma	~50	~50	~50	~50
Delamerian Orogeny	520 to 525 Ma	~360	620	170	73
Petermann Ranges Orogeny	550 to 625 Ma	1 850	740	150	550
Present-day heat flow (mW/m^2)		71.9	42	39.3	38.5

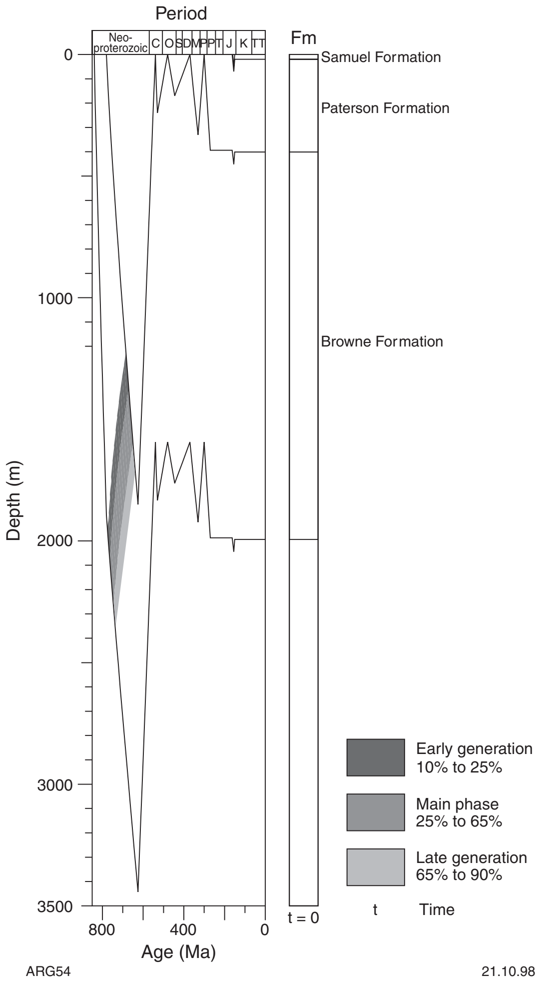

Figure 24. Burial and oil-window plot for Dragoon 1

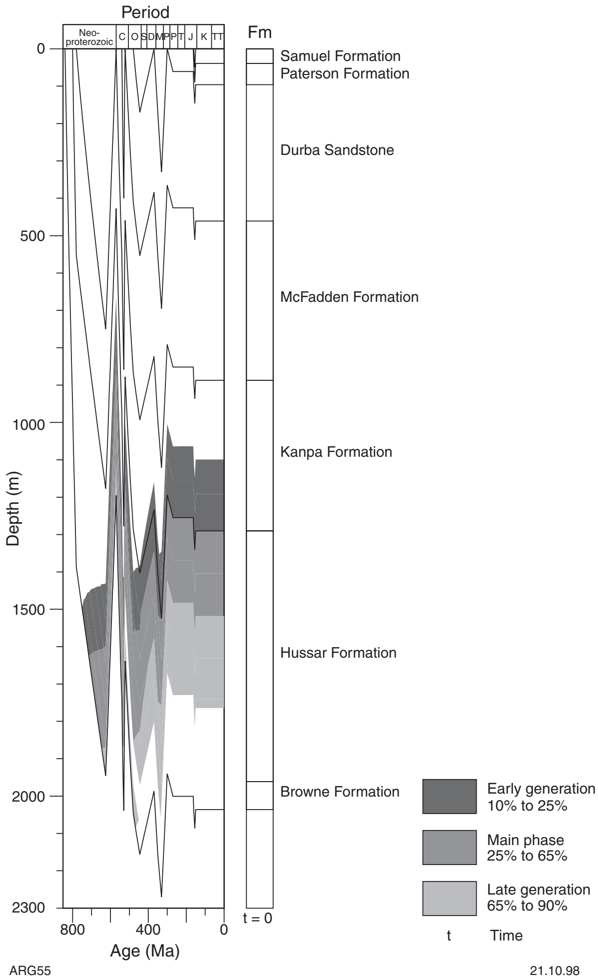

Figure 25. Burial and oil-window plot for Hussar 1

Kerogen transformation ratio and rate of generation plots

The time of petroleum generation is a function of kerogen conversion to petroleum over a period of time. The generation time is illustrated as plots of kerogen transformation ratio and rate of generation versus time. Figures 29 to 34 show the transformation ratio and rate of generation for the Neoproterozoic sections in Hussar 1, Kanpa 1A, and Yowalga 3. These plots suggest that most of the Neoproterozoic succession progressively passed through the oil window from the latest part of the Neoproterozoic to the Permo-Triassic, depending on stratigraphic position, maximum depth of burial, and structural history.

Discussion

The petroleum prospectivity of Proterozoic successions is well established worldwide. The oldest indigenous dry gas was encountered within the Palaeoproterozoic succession (2500–1600 Ma) on

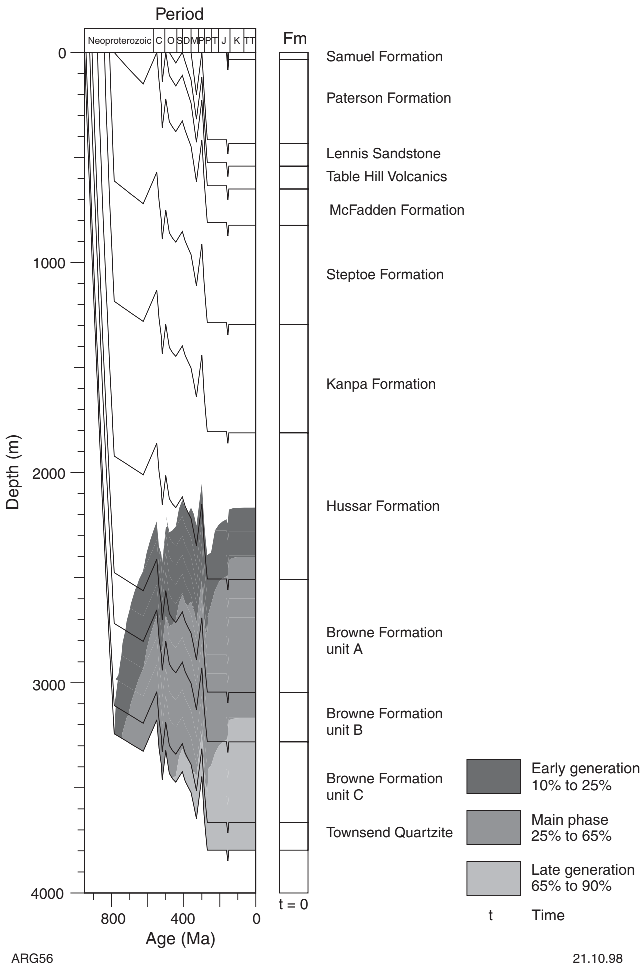

Figure 26. Burial and oil-window plot for Kanpa 1A

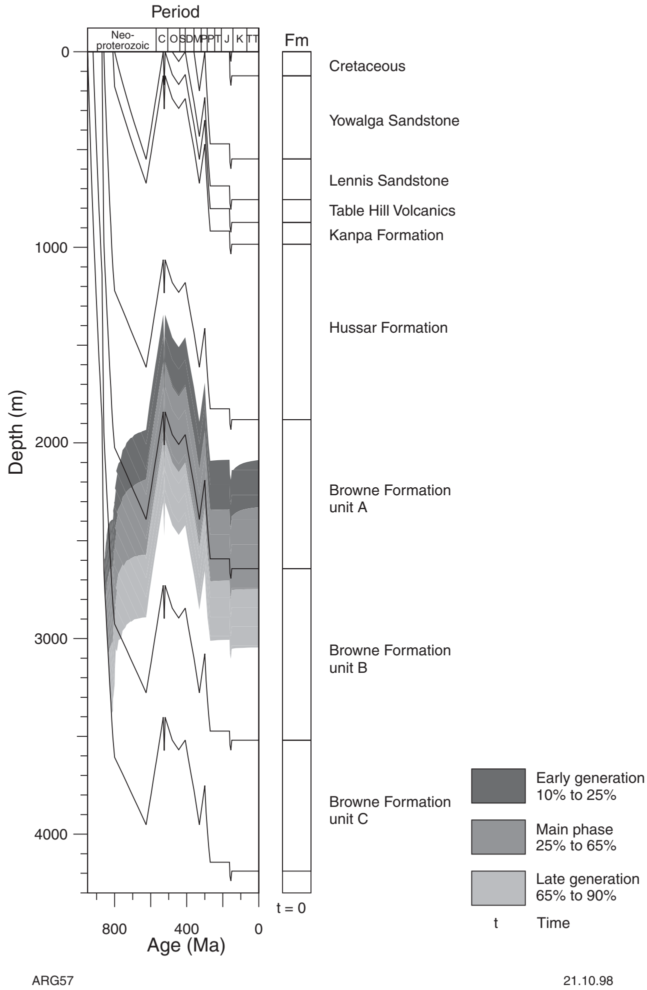

Figure 27. Burial and oil-window plot for Yowalga 3

the Kola Peninsula in Russia, and in the McArthur Group in northern Australia (Jackson et al., 1988; Summons et al., 1988; McKirdy and Imbus, 1992). The world's oldest proven oil source rock is from the Mesoproterozoic Roper Group (1600–1000 Ma) in the McArthur Basin in northern Australia (Taylor et al., 1994). The world's oldest petroleum in proven commercial accumulations is in Neoproterozoic successions (1000–540 Ma) in Siberia (Kontorovich et al., 1990), Oman (de la Grandville, 1982), and China (Mo et al., 1984).

Source potential

Good-quality, thin, oil source beds with excellent generating potential are identified within the Neoproterozoic section of the mineral exploration drillhole NJD 1 (Figs 1, 4, 5, 6, 7, and 16), where bleeding oil was reported.

Good-quality, thin, oil source rocks with fair generating potential are identified within the Neoproterozoic Browne Formation in Kanpa 1A and the Hussar Formation in Yowalga 3 in the

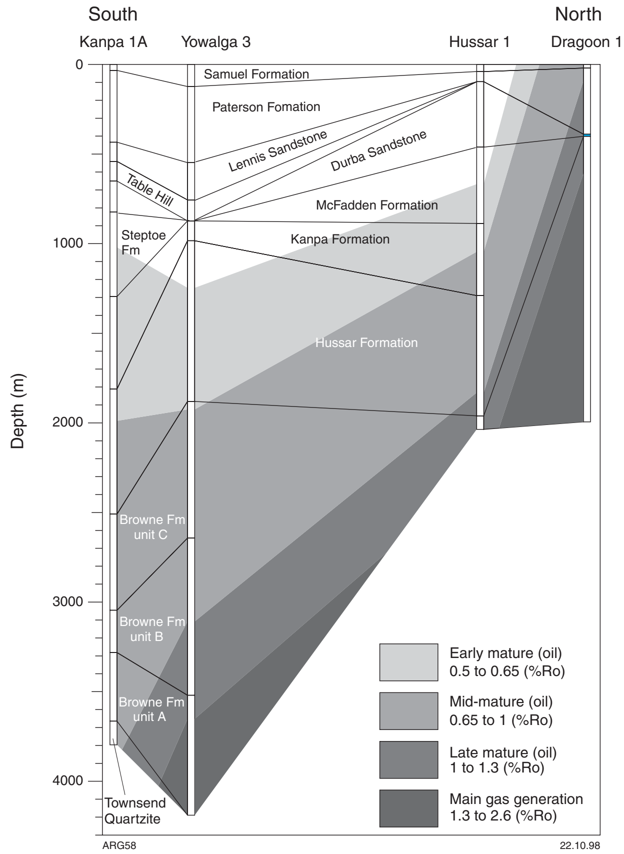

Figure 28. **Maturity (%Ro) from Kanpa 1A in the south to Dragoon 1 in the north**

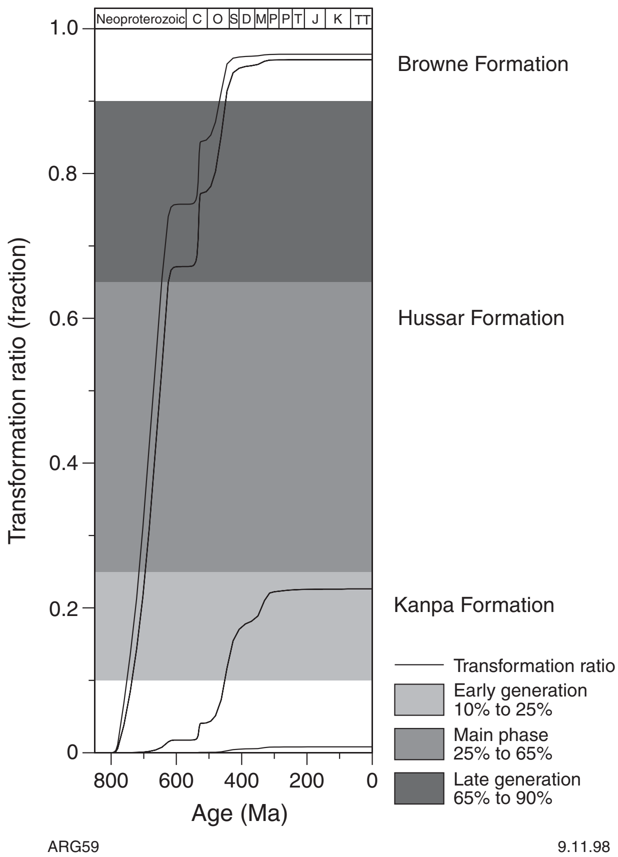

Figure 29. **Kerogen transformation ratio plot for Hussar 1**

Yowalga Sub-basin (Figs 4, 10, 13, and 16). No source rocks were identified in Browne 1 and 2 and Lungkarta 1, whereas Yowalga 1 and 2 (Fig. 1) did not penetrate Neoproterozoic rocks (Table 1).

Good-quality, thin, oil source rocks with fair generating potential are also identified within the Neoproterozoic succession penetrated in LDDH 1 (Figs 4, 14, and 16), which is near the northwestern margin of the Gibson Sub-basin. LDDH 1 was drilled to a total depth of 701 m and penetrated well-laminated dolomitic and calcareous shales with commonly higher TOC content (average 0.64%) than samples from the Yowalga Sub-basin. However, only one sample from 222.8 m has fair source potential. No source rocks were identified in Hussar 1 (Fig. 4) or Dragoon 1.

Samples from NJD 1, Kanpa 1A, Yowalga 3, and LDDH 1 suggest that good-quality, but thin, oil source rocks exist in the western Officer Basin. However, sparse well coverage across the Officer Basin precludes a complete assessment of the source-rock potential for the Neoproterozoic successions. Additional stratigraphic wells are needed to further define the source potential in the sub-basins of the Officer Basin.

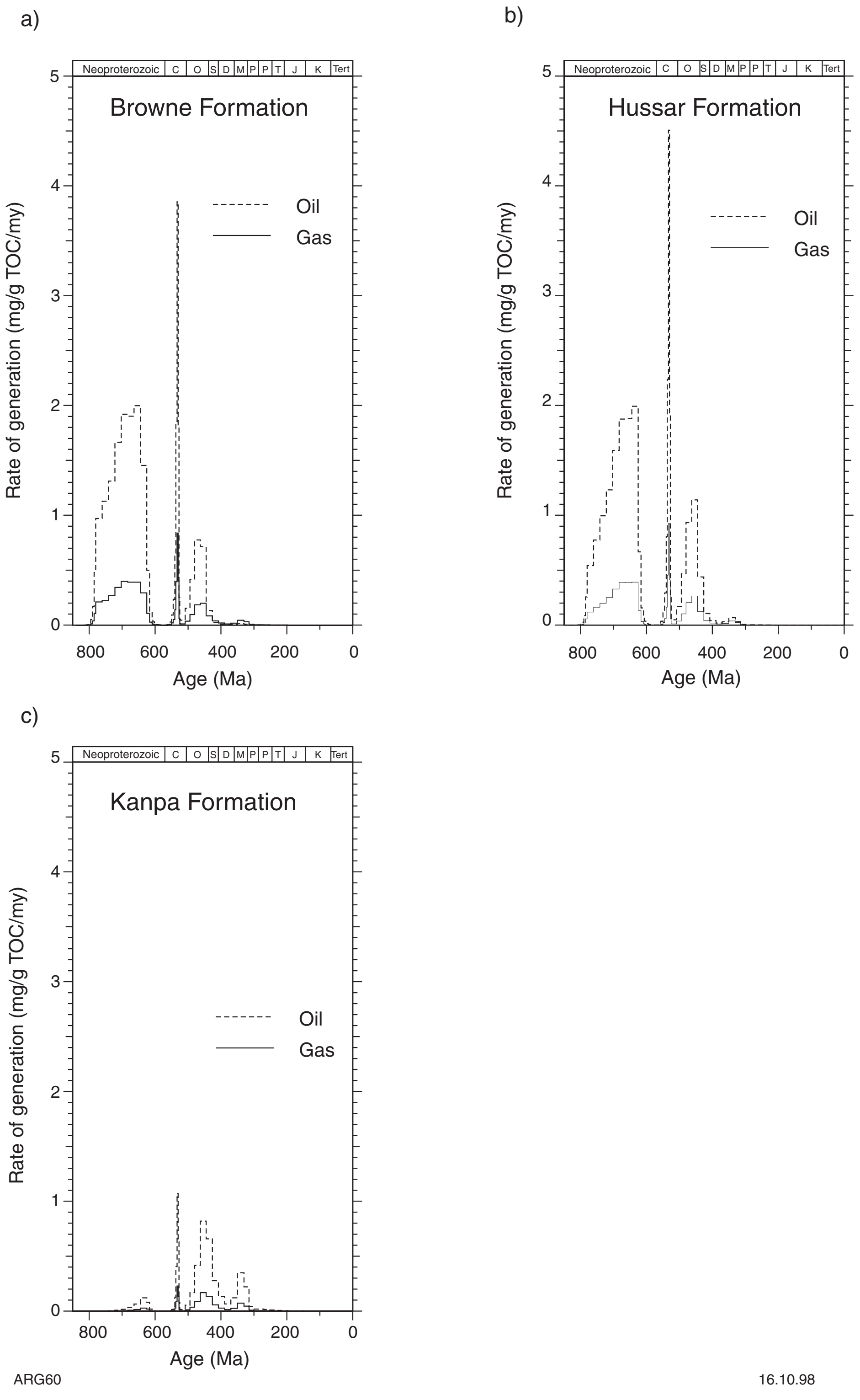

Figure 30. Rate of oil and gas generation plots for Hussar 1

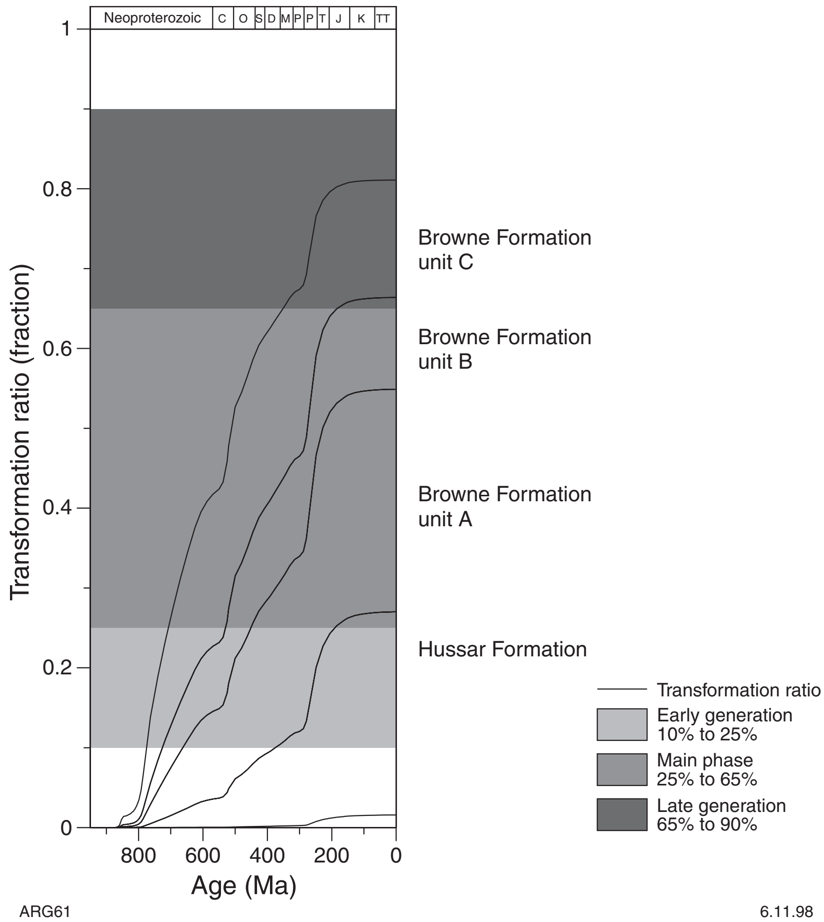

Figure 31. Kerogen transformation ratio plot for Kanpa 1A

Source maturity

Production index, T_{max}, equivalent %Ro data, and maturity modelling suggest that most of the Neoproterozoic section is within the oil window, except in Dragoon 1 and the basal parts of Yowalga 3, NJD 1, and LDDH 1.

On the Kingston Shelf, the excellent oil source beds lie within the oil-generative window in NJD 1 (Figs 18 and 19). These source beds were identified within the Neoproterozoic succession at 327.5 m by GSWA (Fig. 5) and from 328.5 to 329 m by Shell (Clark, 1983). In NJD 1, the interval down to about 330 m is marginally mature to mature for oil generation, whereas the interval from 330 m to the total depth of 517 m is mature to mostly overmature. The section below 330 m was interpreted as Mesoproterozoic by Shell. Oil shows were reported in NJD 1 and bitumen veins are present between 502 and 517 m, but no geochemical and depth information are available (Western Mining Corporation Ltd, 1981). The high reflectance values of bitumen indicate an overmature section (Fig. 19). In this part of the Officer Basin, the Neoproterozoic is comparatively thin (about 230 m thick in NJD 1) and at shallow depths (about 100 m depth in

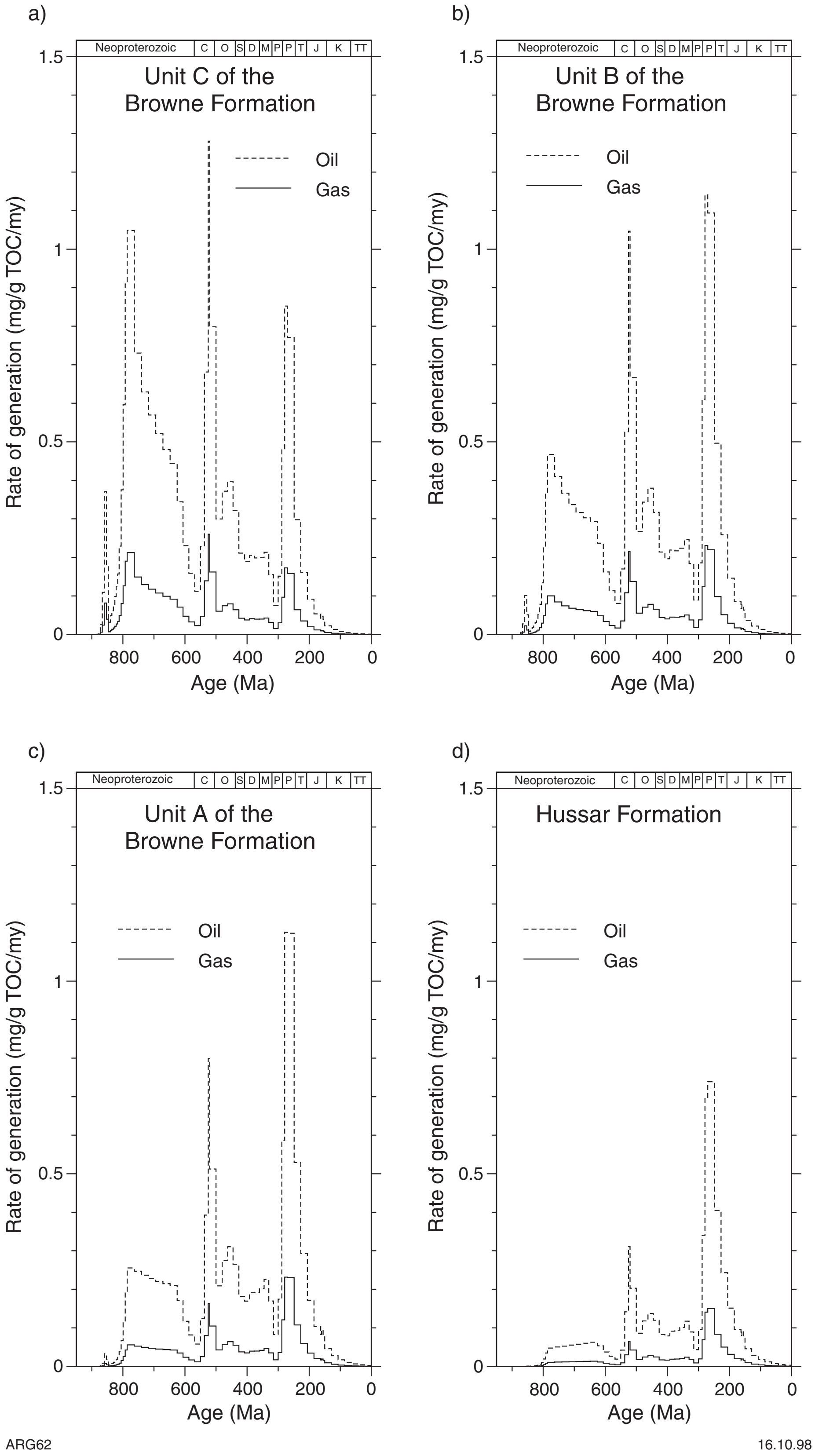

Figure 32. Rate of oil and gas generation plots for Kanpa 1A

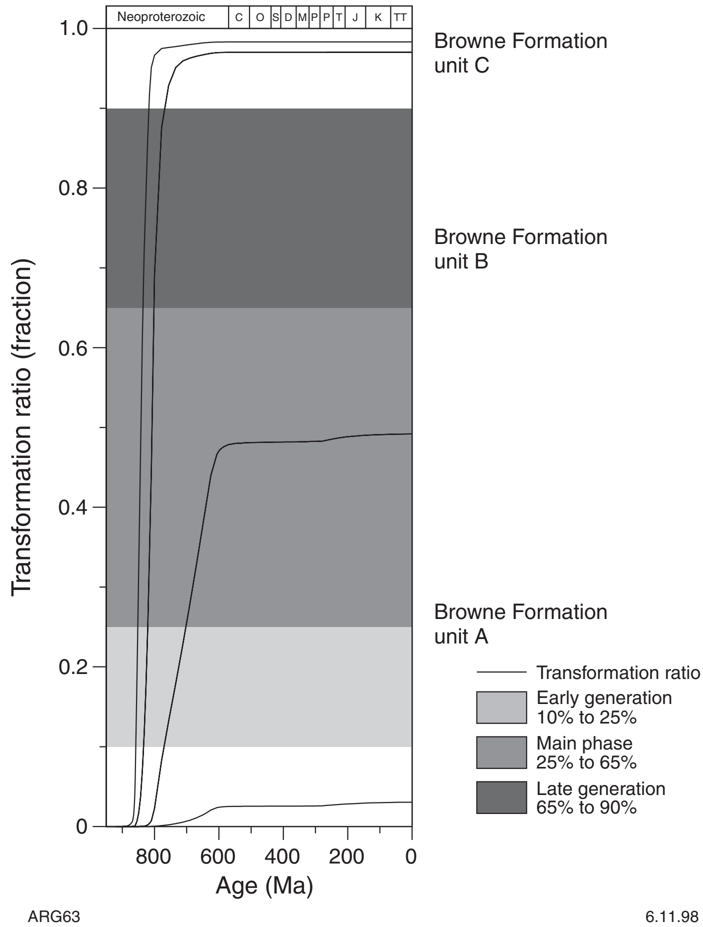

Figure 33. Kerogen transformation ratio plot for Yowalga 3

NJD 1). However, it is marginally to fully mature for oil generation. No other geochemical information is presently available for this part of the western Officer Basin.

In the deep Yowalga Sub-basin, the Neoproterozoic section is very thick (2974 m in Kanpa 1A and more than 3316 m in Yowalga 3). The Neoproterozoic section ranges from immature to overmature due to variation in maximum burial depth at different locations.

In Kanpa 1A the section below 2100 m is presently within the oil-generative window (Fig. 26), indicating that the upper part of the Browne Formation is within the main phase of oil generation, and the lower part is at the late stage of oil generation, whereas the lower part of the Hussar Formation is within the early stage of oil generation. The immature section of the Neoproterozoic succession in Kanpa 1A includes the upper part of the Hussar Formation, and the Kanpa and Steptoe Formations. The oil source rock identified in this well lies within unit C of the Browne Formation and is presently within the late stage of oil generation.

In Yowalga 3, the interval between 2200 and 3200 m is within the oil-generative window (Fig. 27), the central part of the Browne Formation is within the oil window, and the lower part is

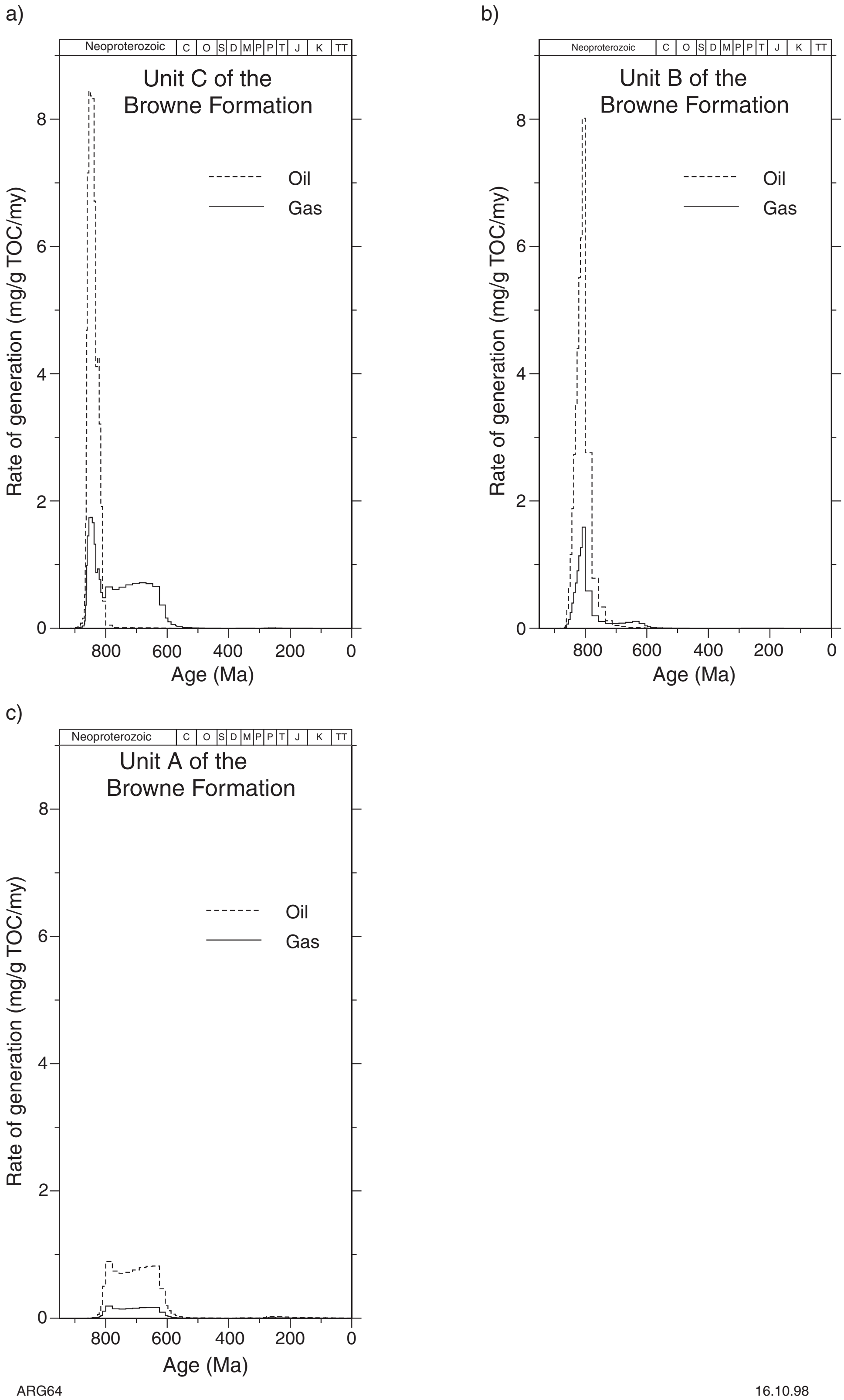

Figure 34. Rate of oil and gas generation plots for the Browne Formation in Yowalga 3

Table 8. Source rocks recognized in western Officer Basin wells

Location	*Well*	*Formation/age*	*Organic richness*	*Generating potential*	*Kerogen type*
Kingston Shelf	NJD 1 (WMC)	Neoproterozoic	excellent	excellent	oil
Yowalga Sub-basin	Kanpa 1A	Browne Formation	fair	fair	oil
	Yowalga 3	Hussar Formation	good	fair	oil
Gibson Sub-basin	LDDH 1 (Normandy)	Neoproterozoic	good	fair	oil

NOTES: Normandy: Normandy Poseidon Ltd
WMC: Western Mining Corporation Ltd

within the gas window. The immature section of the Neoproterozoic succession includes the upper part of the Browne Formation, and the Hussar and Kanpa Formations. The oil source rock at 1484 m within the Hussar Formation in Yowalga 3 is immature for oil generation.

In the Gibson Sub-basin, the maturity of the Neoproterozoic section varies geographically. In Hussar 1 near the southern margin, the section between 1100 and 1900 m is within the oil-generative window (Fig. 25). The Hussar and Kanpa Formations are partly within the oil window and the Browne Formation is within the gas window. In this well, one sample from 1822.1 m with marginal generating potential (0.76% TOC and $S_1 + S_2 = 1.6$ mg/g rock) lies within the late stage of oil generation. In the northeastern portion of the sub-basin at Dragoon 1, the top of the Neoproterozoic section is at 403 m and is overmature for oil generation (Fig. 24). The maturity data from LDDH 1 suggest that the Neoproterozoic section is mature to overmature along the northwestern margin of the Gibson Sub-basin. In LDDH 1, one sample classified as a fair source rock from 222.8 m is within the late stage of oil generation (Figs 18 and 19).

The existing information suggests that thermal maturity within the Neoproterozoic succession of the western Officer Basin increases from the Kingston Shelf in the southwest to the northeastern Gibson Sub-basin. This hypothesis is consistent with the structural deformation level that is much higher along the northern margin of the basin (Phillips et al., 1985; Townson, 1985).

The equivalent %Ro and Rock-Eval maturity data for samples from different present-day depths indicate a similar level of maturation in wells studied (Figs 18 and 19). The similar present-day level of maturation observed at significantly different depths from different locations suggests that the maximum palaeoburial depth of the Neoproterozoic succession was uniform across the western Officer Basin, varying only with palaeotopography. The source-rock maturity (%Ro) across the Yowalga and Gibson Sub-basins is shown in Figure 28.

Timing of oil and gas generation

Kerogen kinetics is used to simulate the timing of oil and gas generation in Hussar 1, Kanpa 1A, and Yowalga 3. It is assumed that rocks are organic rich (1% TOC) and contain oil-generating kerogen (10% type I, 70% type II, and 20% type III).

In Hussar 1, the Hussar Formation is presently within the oil window. The Hussar Formation progressively passed through the oil window and experienced three phases of oil generation with the peak rate occurring in the Cambrian. The underlying Browne Formation is within the gas window and the overlying Kanpa Formation is partly mature (Figs 29 and 30).

In Kanpa 1A, the Browne Formation is within the oil window. The Browne Formation has experienced three phases of oil generation — the first during the Neoproterozoic, the second during the Cambrian, and the third during the Permo-Triassic. The peak rate of oil generation occurred during the Cambrian in the lower section, in unit C of the Browne Formation, whereas in the upper section, in unit A, the peak rate occurred during the Permo-Triassic (Figs 31 and 32). In Kanpa 1A, the basal section of the Hussar Formation is at an early stage of oil generation.

In Yowalga 3, units B and C in the Browne Formation are presently within the oil-generative window with peak oil generation occurring during the Neoproterozoic. The basal section in unit C of the Browne Formation is currently within the gas window (Figs 33 and 34).

Three phases of oil generation are predicted for the western Officer Basin by modelling the maturation and oil-generation histories. These phases occurred during the Neoproterozoic, Cambrian, and Permo-Triassic. The phases of peak generation vary both stratigraphically and geographically.

Conclusions

This geochemical evaluation of the frontier western Officer Basin indicates the presence of good-quality, but very thin, oil source rocks in the Neoproterozoic succession.

The best source-rock potential exists in finely laminated shale and siltstone within evaporitic successions on the Kingston Shelf, where the Neoproterozoic section is up to 200 m thick (in NJD 1). The organic-rich shale between 327 and 329 m is rated as an excellent oil source rock. This organic-rich shale has only been identified in NJD 1, where the TOC content is 6.64% and the potential yield is 24.17 mg/g rock. Thin organic-rich shales identified in the Yowalga and Gibson Sub-basins have only fair oil-generating potential.

The sources of minor oil and numerous bitumen shows found throughout the western Officer Basin have not yet been identified. Either the sources for these shows have not yet been penetrated, or they are too thin to have been recognized by standard oilfield practise.

The maturity of the Neoproterozoic succession ranges from immature to overmature. However, most of the Neoproterozoic succession presently lies within the oil-generative window in all studied wells except Dragoon 1.

Basin modelling of Hussar 1, Kanpa 1A, and Yowalga 3 indicate that the main phases of oil generation occurred during the Neoproterozoic, Cambrian, and Permo-Triassic. The peak rate of maturation and maximum petroleum generation occurred at different times in different parts of the basin. In the deeper parts of the basin (Yowalga 3), the rate of oil generation peaked during the Neoproterozoic, at least within the basal Browne Formation. In shallower parts of the basin (Kanpa 1A), the generation rate peaked during the Cambrian in the basal section of the Browne Formation, and during the Permo-Triassic in the upper section of the Browne Formation. In areas where source rocks are currently within the oil window, petroleum generation and expulsion may have been accelerated during periods of higher heat flow, such as during the Alice Springs Orogeny (Carboniferous) or continental uplift (Jurassic).

The vast area covered by the western Officer Basin is still largely unexplored. This geochemical study is unable to identify effective source-rock units and the source for oil shows in the basin from the available dataset; however, it has verified the presence of thin, good-quality source units in the Neoproterozoic succession.

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Appendix 1

Glossary of terms

Geochemistry terms, mainly compiled from Miles (1989), Peters and Moldowan (1993), and Cook (1995), with reference to usage in this study:

alkane (paraffins): Carbon and hydrogen compounds with single bonds. Bonds may form straight chain (normal), branched chain or cyclic chain (naphthenes) hydrocarbons. These compounds are saturated hydrocarbons. The simplest alkane is methane (CH_4), then ethane (C_2H_6), propane (C_3H_8), and so on. They are part of the lipid fraction of organic matter and can range from 5 to 80% in crude oils. Alkanes are analysed by pyrolysis-gas chromatography to evaluate the oil-generating potential of kerogen.

alkene (olefine): Carbon and hydrogen compounds with carbon–carbon double bonds. They may have normal, branched or cyclic structures. These compounds are unsaturated hydrocarbons. The simplest alkenes are ethene (C_2H_4) and propene (C_3H_6). Normally, alkenes are not present in crude oils but they undergo saturation during diagenesis to form alkanes of crude oils. Alkenes can be produced by rapid heating, as during laboratory pyrolysis. They are analysed by pyrolysis-gas chromatography to evaluate the oil-generating potential of kerogen.

apatite fission-track analysis (AFTA): An analytical technique developed for palaeotemperature analysis. AFTA is unique in estimating maximum palaeotemperatures attained in a sedimentary basin and their variation through time. The fission-track age is largely a function of track annealing in response to increasing temperature (i.e. 70 to 120°C), whereas their length reflects the style of cooling. Therefore, the pattern of ages and distributions of their lengths reflect the geothermal history of their host rocks.

chromatogram: Peaks versus time graph of separated components by chromatography. A single peak on the chromatogram may represent more than one compound. A chromatogram of the whole or saturate fraction is used for screening and correlating oils and rock extracts by comparing ratios of peak to height or peak to area.

extract: Oil and oil-like products extracted from rocks by organic solvent, either by ultrasonic or soxhlet method. Extracts are examined for their quantity, bulk composition, carbon isotopic ratios, and biomarkers by liquid and gas chromatography and mass spectrometry. These analyses are used for source-rock evaluation and oil to source correlation.

gas chromatography (saturate-GC): An analytical technique to separate mixtures of compounds in crude oils and extracts, especially for the saturate fraction, by capillary column chromatography. These analyses are used for evaluating the type of crude oils, source rocks, and oil to source correlation.

hydrogen index (HI): A Rock-Eval parameter defined as $(S_2/TOC) \times 100$ and measured in units of mg HC/g TOC. The Hydrogen Index is a measure of hydrogen richness in kerogen and has a direct relationship with elemental hydrogen to carbon ratios. The index is used to define the type of kerogen and approximate level of maturation.

lamalginite: Lamalginite is organic matter of algal origin and is part of the exinite maceral group. Morphologically the organic matter are remains of unicellular or colonial algae. In pre-Devonian rocks where vascular land plants are absent, vitrinite-like macerals are mainly derived from the polysaccharide component of the algal cells. These vitrinite-like macerals are used to derive equivalent vitrinite reflectance values for thermal maturity evaluation.

liquid chromatography (extract-LC): An analytical technique to subdivide crude oils and extracts into saturate, aromatic, polar, or NSO (nitrogen, sulfur, and oxygen compounds) fractions, either by high-performance liquid chromatography (HPLC), thin layer chromatography (TLC), or column chromatography. These analyses are used for typing crude oils and evaluating source rocks.

oxygen index (OI): A Rock-Eval parameter defined as (S_3/TOC) × 100 and measured in mg CO_2/g TOC. The OI is the measure of oxygen richness in kerogen and has a direct relationship with elemental oxygen to carbon ratios. The index is used in conjunction with HI to define the type of kerogen and approximate level of maturation. The OI derived from Rock-Eval pyrolysis of carbonate rocks is considered unreliable because there is a possibility of contamination from inorganic carbon.

potential yield (PY): A Rock-Eval parameter defined as $S_1 + S_2$, which is the total amount of already generated and potential hydrocarbons produced during pyrolysis. Values may be reported in ppm, mg/g, kg/tonne, or barrels/acre ft. This parameter is used to evaluate the hydrocarbon-generating potential of a source rock.

production index (PI): A Rock-Eval parameter defined as $S_1/(S_1+S_2)$, which is the ratio of already generated hydrocarbons to potential hydrocarbons generated during pyrolysis. The PI is useful in describing thermal maturity of source rocks or indicating contamination because the presence of migrated oil affects the ratio. Also called 'transformation ratio'.

pyrolysis-gas chromatography (PGC): An analytical technique to examine the pyrolysis product by gas chromatography (GC). The chemical composition of pyrolysate (S_2) from Rock-Eval is examined to define the type of kerogen. The evaluation of the type of kerogen is more accurate by the PGC technique than by Rock-Eval pyrolysis.

Rock-Eval pyrolysis: A commercially available anhydrous pyrolysis instrument used as a rapid 'screening' tool in evaluating the quantity, quality, and thermal maturity of rock samples. The pyrolysis is done in two steps. Firstly, there is an initial volatilization of already generated hydrocarbons in rocks during heating up to 300°C, which produces the P_1 peak area of S_1. In the second step, the kerogen is converted to hydrocarbons by increasing the sample temperature to 550°C. This produces the P_2 peak area of S_2. Carbon dioxide produced during the pyrolysis up to a temperature of 390°C is collected, which produces the P_3 peak area of S_3. Parameters PY, HI, OI, and PI are calculated from Rock-Eval derived values for S_1, S_2, and S_3, and TOC.

S_1: A Rock-Eval parameter; a measure of already generated hydrocarbons in nature and expressed as mg/g rock.

S_2: A Rock-Eval parameter; a measure of the remaining hydrocarbon potential of rock and expressed as mg/g rock.

S_3: A Rock-Eval parameter, which is a measure of the carbon dioxide released during pyrolysis up to 390°C and expressed as mg/g rock. This is proportional to oxygen present in the kerogen and may be unreliable in carbonate rocks because there is a possibility of contamination from inorganic carbon.

thucholitic bitumen: Solid bitumens that are polymerized hydrocarbons encasing radioactive minerals (thucholities). The reflectance at the rim of thucholites is very similar to that of the coexisting vitrinite and used for assessing thermal maturity of rocks.

T_{max}: A Rock-Eval maturity parameter based on temperature at which the maximum amount of pyrolysate (S_2) is generated from the kerogen.

TOC: The quantity of total organic carbon expressed as weight percent of the rock.

transformation ratio (TR): Ratio of generated hydrocarbons (S_1) to the genetic potential ($S_1 + S_2$), defined as ($S_1 + HC_{expelled} / S_{20}$) × 100 as a unitless percentage; where S_{20} represents the original S_2 value. This term is also related to the production index and the ratio of extract to total organic carbon.

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Appendix 2

TOC and Rock-Eval pyrolysis data for samples from the western Officer Basin

Well	*Depth (m)*		*Sample type*	*TOC*	T_{max}	S_1	S_2	S_3	$S_1 + S_2$	*PI*	*HI*	*OI*
	from	*to*		*(wt%)*	*(°C)*							
Hussar 1	860.0	865.0	cuttings (hp)	0.28	345	1.22	0.21	0.69	1.43	0.85	75	246
Hussar 1	995.0	1 000.0	cuttings (hp)	0.14	–	–	–	–	–	–	–	–
Hussar 1	1 640.0	–	cuttings (hp)	0.16	–	–	–	–	–	–	–	–
Hussar 1	1 690.0	1 695.0	cuttings (hp)	0.35	430	0.13	0.15	0.35	0.28	0.46	43	100
Hussar 1	1 822.1	–	core	0.76	428	0.22	1.60	0.09	1.82	0.12	211	12
Hussar 1	1 824.0	–	core	0.07	–	–	–	–	–	–	–	–
Hussar 1	1 824.7	–	core	0.15	–	–	–	–	–	–	–	–
Jubilee 1	164.0	165.0	core	0.02	–	–	–	–	–	–	–	–
Jubilee 3	36.0	–	core	0.13	–	–	–	–	–	–	–	–
Kanpa 1A	1 652.0	1 655.0	cuttings	0.16	–	–	–	–	–	–	–	–
Kanpa 1A	1 733.0	1 736.0	cuttings	0.08	–	–	–	–	–	–	–	–
Kanpa 1A	1 763.0	1 769.0	cuttings	0.14	–	–	–	–	–	–	–	–
Kanpa 1A	1 805.0	1 808.0	cuttings (hp)	0.13	–	–	–	–	–	–	–	–
Kanpa 1A	2 243.0	2 249.0	cuttings (hp)	0.12	–	–	–	–	–	–	–	–
Kanpa 1A	3 407.0	3 410.0	cuttings	0.83	433	0.77	2.40	1.58	3.17	0.24	289	190
Kanpa 1A	3 410.0	3 413.0	cuttings	0.75	–	–	–	–	–	–	–	–
Kanpa 1A	3 410.0	3 413.0	cuttings	0.76	431	0.67	2.07	1.34	2.74	0.24	272	176
Kanpa 1A	3 566.0	3 572.0	cuttings	0.59	431	0.52	1.21	4.13	1.73	0.30	205	700
NJD 1	203.6	–	core	0.05	–	–	–	–	–	–	–	–
NJD 1	252.2	–	core	0.25	–	0.03	0.05	0.55	0.08	0.38	20	220
NJD 1	277.2	–	core	0.11	–	–	–	–	–	–	–	–
NJD 1	304.0	–	core	0.10	–	–	–	–	–	–	–	–
NJD 1	314.5	–	core	0.04	–	–	–	–	–	–	–	–
NJD 1	327.5	–	core	6.64	430	0.7	23.47	1.04	24.17	0.03	353	16
NJD 1	336.4	–	core	0.18	–	–	–	–	–	–	–	–
NJD 1	381.2	–	core	0.09	–	–	–	–	–	–	–	–
NJD 1	434.2	–	core	0.13	–	–	–	–	–	–	–	–
NJD 1	468.4	–	core	0.17	–	–	–	–	–	–	–	–
NJD 1	488.2	–	core	0.23	477	0.06	0.38	0.3	0.44	0.14	165	130
LDDH 1	131.3	–	core	0.58	434	0.12	0.27	0.27	0.39	0.31	47	47
LDDH 1	134.1	–	core	0.60	433	0.18	0.39	0.71	0.57	0.32	65	118
LDDH 1	165.5	–	core	0.72	436	0.27	0.76	0.42	1.03	0.26	106	58
LDDH 1	222.8	–	core	1.61	450	0.42	2.11	0.32	2.53	0.17	131	20
LDDH 1	282.7	–	core	0.30	–	–	–	–	–	–	–	–
LDDH 1	299.5	–	core	0.20	–	–	–	–	–	–	–	–
LDDH 1	339.5	–	core	0.40	–	–	–	–	–	–	–	–
LDDH 1	386.0	–	core	0.48	–	0.09	0.10	0.19	0.19	0.47	21	40
LDDH 1	447.8	–	core	0.69	451	0.13	0.30	0.58	0.43	0.30	43	84
LDDH 1	508.2	–	core	0.48	–	0.04	0.00	0.70	0.04	1.00	0	146
LDDH 1	529.6	–	core	2.05	471	1.05	1.40	0.07	2.45	0.43	68	3
LDDH 1	550.6	–	core	0.89	407	0.35	1.14	0.08	1.49	0.23	128	9
LDDH 1	580.2	–	core	0.35	–	–	–	–	–	–	–	–
LDDH 1	608.8	–	core	0.24	–	–	–	–	–	–	–	–
LDDH 1	677.6	–	core	0.27	–	–	–	–	–	–	–	–
LDDH 1	679.7	–	core	0.55	–	0.05	0.13	0.34	0.18	0.28	24	62
LDDH 1	697.0	–	core	0.55	–	0.07	0.1	0.29	0.17	0.41	18	53
Throssell 1	62.2	–	core	0.04	–	–	–	–	–	–	–	–
Throssell 1	184.9	–	core	1.37	428	0.35	1.06	0.31	1.41	0.25	77	23
Throssell 1	185.0	–	core	0.10	–	–	–	–	–	–	–	–
Throssell 1	185.5	185.6	core	0.10	–	–	–	–	–	–	–	–
Throssell 1	185.8	186.1	core	0.63	449	0.16	0.45	0.07	0.61	0.26	71	11
Throssell 1	186.2	–	core	0.36	–	0.12	0.24	0.13	0.36	0.33	67	36
Westwood 2	99.5	–	core	0.02	–	–	–	–	–	–	–	–
Westwood 2	101.2	–	core	0.02	–	–	–	–	–	–	–	–
Yowalga 2	893.7	–	core	0.39	419	0.14	0.67	0.22	0.81	0.17	172	56
Yowalga 2	988.5	–	core	0.09	–	–	–	–	–	–	–	–
Yowalga 2	988.8	–	core	0.18	–	–	–	–	–	–	–	–
Yowalga 3	410.0	–	cuttings	0.12	–	–	–	–	–	–	–	–
Yowalga 3	1 481.0	–	cuttings	0.45	411	0.21	0.45	0.33	0.66	0.32	100	73
Yowalga 3	1 484.0	–	cuttings	1.23	421	0.49	3.00	0.47	3.49	0.14	244	38
Yowalga 3	2 388.4	–	core	0.24	423	0.13	0.19	4.42	0.32	0.41	79	1 842
Yowalga 3	2 386.6	–	core	0.05	–	–	–	–	–	–	–	–
Yowalga 3	3 253.0	3 259.0	cuttings (hp)	0.63	436	0.45	0.60	0.46	1.05	0.43	95	73
Yowalga 3	3 277.5	–	core	0.20	–	–	–	–	–	–	–	–
Yowalga 3	3 286.4	–	core	0.13	–	–	–	–	–	–	–	–
Yowalga 3	4 187.2	–	core	0.11	–	–	–	–	–	–	–	–
Yowalga 3	4 192.0	–	core	0.62	345	0.18	0.19	1.39	0.37	0.49	31	224

NOTES:
hp: hand picked
HI: hydrogen index
OI: oxygen index
PI: production index

S_1: existing hydrocarbons (HC)
S_2: pyrolytic yield (HC)
S_3: organic carbon dioxide

$S_1 + S_2$: potential yield
T_{max}: temperature of maximum pyrolytic yield (S_2)
TOC: total organic carbon

Appendix 3

Pyrolysis-gas chromatography data for a core sample from 327.5 m depth from NJD 1: alkane and alkene component

Carbon number	*Alkane* *A*	*B*	*C*	*Alkene* *A*	*B*	*C*	*Alkane + Alkene* *A*	*B*	*C*	*Alkane/Alkene*
1	–	–	–	–	–	–	–	–	–	–
2	–	–	–	–	–	–	–	–	–	–
3	–	–	–	–	–	–	–	–	–	–
4	–	–	–	–	–	–	–	–	–	–
5	3.350	0.786	0.118	6.157	1.445	0.218	9.507	2.231	0.336	0.54
6	2.431	0.571	0.086	2.508	0.589	0.089	4.939	1.159	0.175	0.97
7	1.841	0.432	0.065	1.756	0.412	0.062	3.597	0.844	0.127	1.05
8	1.179	0.277	0.042	1.462	0.343	0.052	2.641	0.620	0.093	0.81
9	0.762	0.179	0.027	0.907	0.213	0.032	1.669	0.392	0.059	0.84
10	0.861	0.202	0.030	0.720	0.169	0.025	1.581	0.371	0.056	1.20
11	0.583	0.137	0.021	0.539	0.127	0.019	1.122	0.263	0.040	1.08
12	0.316	0.074	0.011	0.449	0.105	0.016	0.765	0.180	0.027	0.70
13	0.281	0.066	0.010	0.287	0.067	0.010	0.568	0.133	0.020	0.98
14	0.263	0.062	0.009	0.342	0.080	0.012	0.605	0.142	0.021	0.77
15	0.201	0.047	0.007	0.159	0.037	0.006	0.360	0.084	0.013	1.26
16	0.090	0.021	0.003	0.043	0.010	0.002	0.133	0.031	0.005	2.09
17	0	0	0	0	0	0	0	0	0	–
18	0	0	0	0	0	0	0	0	0	–
19	0	0	0	0	0	0	0	0	0	–
20	0	0	0	0	0	0	0	0	0	–
21	0	0	0	0	0	0	0	0	0	–
22	0	0	0	0	0	0	0	0	0	–
23	0	0	0	0	0	0	0	0	0	–
24	0	0	0	0	0	0	0	0	0	–
25	0	0	0	0	0	0	0	0	0	–
26	0	0	0	0	0	0	0	0	0	–
27	0	0	0	0	0	0	0	0	0	–
28	0	0	0	0	0	0	0	0	0	–
29	0	0	0	0	0	0	0	0	0	–
30	0	0	0	0	0	0	0	0	0	–
31	0	0	0	0	0	0	0	0	0	–

NOTES: A: % of resolved compounds in S_2
B: mg/g rock (Rock-Eval)
C: (mg/g rock) / TOC
TOC: total organic carbon

Appendix 4

Pyrolysis-gas chromatography data for a core sample from 327.5 m depth from NJD 1: aromatic and phenolic component

Key	*Compound type*	*Value*		
		A	*B*	*C*
aromatic	Benzene	1.518	0.356	0.054
aromatic	Toluene	2.345	0.550	0.083
aromatic	Ethylbenzene	0.546	0.128	0.019
aromatic	m- + p-xylene	1.369	0.321	0.048
aromatic	Styrene	0.495	0.116	0.017
aromatic	o-xylene	0.626	0.147	0.022
phenolic	Phenol	0.775	0.182	0.027
phenolic	o-cresol	0	0	0
phenolic	m- + p-cresol	0	0	0
phenolic	C_2 phenol	0	0	0
phenolic	C_2 phenol	0	0	0

NOTES: A: % of resolved compounds in S_2; B: mg/g Rock (Rock-Eval); C: (mg/g Rock) / TOC; TOC: total organic carbon; S_2: pyrolytic yield

Appendix 5

Pyrolysis-gas chromatography data for a core sample from 327.5 m depth from NJD 1: parameter summary

Parameter	*A*	*B*	*C*	*D*
C_1–C_4 abundance (all compounds)	16.45	3.86	0.58	–
C_5–C_8 abundance (all resolved compounds)	55.49	13.02	1.96	–
C_5–C_8 abundance (alkanes + alkenes)	20.68	4.85	0.73	–
C_9–C_{14} abundance (all resolved compounds)	25.35	5.95	0.90	–
C_9–C_{14} abundance (alkanes + alkenes)	6.31	1.48	0.22	–
C_{15}–C_{31} abundance (all resolved compounds)	2.71	0.64	0.10	–
C_{15}–C_{31} abundance (alkanes + alkenes)	0.49	0.12	0.02	–
C_9–C_{31} abundance (all resolved compounds)	28.06	6.59	0.99	–
C_9–C_{31} abundance (alkanes + alkenes)	6.80	1.60	0.24	–
C_5–C_{31} abundance (all resolved compounds)	83.54	19.61	2.95	–
C_5–C_{31} abundance (alkanes + alkenes)	27.49	6.45	0.97	–
C_5–C_{31} alkane abundance	12.16	2.85	0.43	–
C_5–C_{31} alkene abundance	15.33	3.60	0.54	–
C_5–C_8 alkane / alkene	–	–	–	0.74
C_9–C_{14} alkane / alkene	–	–	–	0.95
C_{15}–C_{31} alkane / alkene	–	–	–	1.44
C_5–C_{31} alkane / alkene	–	–	–	0.79
(C_1–C_5) / C_{6+}	–	–	–	0.89
R (m + p-xylene)/n-octene	–	–	–	0.94

NOTES: A: % of resolved compounds in S_2; B: mg/g rock (Rock-Eval); C: (mg/g rock) / TOC; D : ratio; TOC: total organic carbon; S_2: pyrolytic yield

Appendix 6

Extract-liquid chromatography data for core samples from the western Officer Basin: concentrations

Well	*Depth (m)*	*Rock extracted (g)*	*Total extract (ppm)*	*Loss on column (ppm)*	*Hydrocarbons (HC) Saturates (ppm)*	*Hydrocarbons (HC) Aromatics (ppm)*	*Total HC (ppm)*	*Non-HCs NSOs (ppm)*	*Total non-HC (ppm)*
NJD 1	327.5	14.3	964.4	48.9	223.6	286.5	510.1	405.3	405.3
	502.5	34.9	3 301.8	521.0	1 291.3	572.0	1 863.3	917.5	917.5
LDDH 1	662.3	70.2	31.3	–	–	–	–	–	–

NOTES; NSOs: nitrogen, sulfur, and oxygen compounds

Appendix 7

Extract-liquid chromatography data for core samples from the western Officer Basin: composition

Well	*Depth (m)*	*Extractable organic matter (EOM) Saturates (%)*	*Aromatics (%)*	*HC's (%)*	*NSOs (%)*	*Non-HCs (%)*	*TOC (%)*	*EOM (mg)/ TOC (g)*	*Sat. (mg)/ TOC (g)*	*Arom./ Sat.*
NJD 1	327.5	24.4	31.3	55.7	44.3	44.3	6.6	14.5	3.4	1.3
	502.5	46.4	20.6	67.0	33.0	33.0	–	–	–	–
LDDH 1	662.3	–	–	–	–	–	–	–	–	–

NOTES: Arom.: aromatics
HC: hydrocarbon
NSOs: nitrogen, sulfur, and oxygen compounds
Sat.: saturates
TOC: total organic carbon

Appendix 8

Saturate-gas chromatography data for core samples from the western Officer Basin: alkane composition

Well	*Depth (m)*	*Pristane/ Phytane*	*Pristane/ n-C_{17}*	*Phytane/ n-C_{18}*	*CPI (1)*	*CPI (2)*	*$(C_{21} + C_{22})/(C_{28} + C_{29})$*
NJD 1	327.5	0.65	0.32	0.58	1.13	1.06	4.41
	502.5	1.22	0.24	0.14	1.23	1.22	4.43
LDDH 1	662.3	1.03	0.26	0.24	1.03	1.02	3.25

NOTES: CPI: carbon preference index

$$\text{CPI (1)} = \frac{(C_{23} + C_{25} + C_{27} + C_{29})\ \text{wt\%} + (C_{25} + C_{27} + C_{29} + C_{31})\ \text{wt\%}}{2 \times (C_{25} + C_{26} + C_{28} + C_{30})\ \text{wt\%}}$$

$$\text{CPI (2)} = \frac{(C_{23} + C_{25} + C_{27})\ \text{wt\%} + (C_{25} + C_{27} + C_{29})\ \text{wt\%}}{2 \times (C_{24} + C_{26} + C_{28})\ \text{wt\%}}$$

Appendix 9

Saturate-gas chromatography data for core samples from the western Officer Basin: n-alkane distributions

Well	*Depth (m)*	$n\text{-}C_{12}$	$n\text{-}C_{13}$	$n\text{-}C_{14}$	$n\text{-}C_{15}$	$n\text{-}C_{16}$	$n\text{-}C_{17}$	$i\text{-}C_{19}$	$n\text{-}C_{18}$	$i\text{-}C_{20}$	$n\text{-}C_{19}$	$n\text{-}C_{20}$	$n\text{-}C_{21}$	$n\text{-}C_{22}$	$n\text{-}C_{23}$	$n\text{-}C_{24}$	$n\text{-}C_{25}$	$n\text{-}C_{26}$	$n\text{-}C_{27}$	$n\text{-}C_{28}$	$n\text{-}C_{29}$	$n\text{-}C_{30}$	$n\text{-}C_{31}$
NJD 1	327.5	13.8	14.7	12.9	10.5	8.8	7.9	2.5	6.6	3.8	5.0	3.7	2.3	1.7	1.1	0.9	1.0	0.7	0.5	0.5	0.4	0.2	0.3
	502.5	0.4	0.8	1.9	3.9	6.7	8.7	2.1	11.7	1.7	15.2	11.0	7.4	6.7	5.3	3.8	3.7	2.1	1.8	1.5	1.7	1.0	0.8
LDDH 1	662.3	1.7	3.8	5.5	6.0	6.5	7.4	1.9	7.8	1.9	8.0	7.9	7.1	6.4	5.7	4.9	4.3	3.8	3.1	2.3	1.9	1.2	1.0

NOTES: n: normal
i: iso

Appendix 10

Organic petrology (reflectance) data for the western Officer Basin

Well	*Sample type*	*Top depth (m)*	*Bottom depth (m)*	*Maceral*	*Vit refl Mean*	*Vit refl SD*	*Vit refl Min*	*Vit refl Max*	*No. of readings*	*Comments*
Hussar 1	DC	860.00	865.00	Lamalginite	0.93	0.136	0.69	1.06	5	Rare lamalginite, yellow to orange. (Claystone > siltstone > sandstone. Dispersed organic matter (DOM) rare, lamalginite > ?vitrinite. Liptinite and ?vitrinite rare, inertinite absent. Lamalginite most common as small acritarch-like entities but one larger orange-fluorescing spore-like palynomorph is present. ?Vitrinite is as small irregular bodies, possibly having affinities with bitumen. Characteristics of some of the deeper samples indicate that these bitumens similar to thucholites in character but no thucholitic structures could be found. Rare oil drops, but they may be within an artificial composite. Some larger fluorescing bodies are probably degraded walnut-mud additive. Common iron oxides, both diffuse and as lenses within silt grains. Abundant iron sulfides; optical properties suggest most are marcasite rather than pyrite)
Hussar 1	DC	1 690.00	1 695.00	Lamalginite	0.66	0.075	0.55	0.74	6	Sparse lamalginite, yellowish orange to dull orange or non-fluorescing. (Carbonate > calcareous claystone > siltstone > sandstone. DOM sparse, lamalginite only. Rare isolated palynomorphs and more abundant lamellae. Some show fluorescence and are lamalginite. Morphologically similar material also present but does not show fluorescence and has reflectances from 0.55 to 0.74%. Vitrinite and inertinite absent. Siltstones largely red beds; iron oxides common. Common pyrite)
				Fluor-Lamalginite	0.29	–	0.25	0.33	2	
Hussar 1	CC	1 822.10	–	Thucholitic bitumen	1.04	0.176	0.85	1.25	19	Rare lamalginite, yellow to dull orange, or non-fluorescing. (Siltstone, calcareous, DOM common, lamalginite > bitumen. Liptinite common, bitumen sparse. Liptinite rarely as isolated brightly fluorescing palynomorphs, more commonly as weakly or non-fluorescing lamellae. Lamalginite shows strong positive alteration on standing with dull orange changing to bright yellow after about 90 minutes. Non-fluorescing lamalginite has higher reflectance than the fluorescing type. Bitumen is either clearly thucholitic in origin, related to zircons, or probably thucholitic in origin. As far as possible, reflectances were measured on rims of bitumens but the reflectance has a core to rim gradient. Sparse oil drops and irregular masses interstitial to grains, yellowish orange in fluorescence. Mineral fluorescence patchy, orange to weak orange. Common pyrite)
				Lamalginite						
				Fluor-Lamalginite	0.76	–	0.58	0.87	11	
					0.48	–	0.47	0.48	2	
Kanpa 1A	DC	3 407.00	–	Liptinite	0.94	0.71	0.93	0.95	?2	Rare lamalginite, yellow to dull orange. (Claystone > carbonate > siltstone. DOM rare, lamalginite > ?bitumen. Liptinite rare, ?bitumen rare. Liptinite is present as isolated palynomorphs. Bitumen may be thucholitic in origin but has indefinite form. Mineral fluorescence patchy, moderate orange or absent. Some grains may be artificial composites. Iron oxides common. Common pyrite)
				Lamalginite	0.79	–	–	–	?1	
				Fluor-Lamalginite	0.60	–	–	–	?1	
Kanpa 1A	CC	3 566.00	–	Lamalginite	0.87	0.113	–	–	?1	No fluorescing liptinite present. (Carbonate > siltstone > sandstone. Organic matter abundant, reservoir bitumens > ?non-fluorescing
				Reservoir-bitumens	0.53	–	0.37	0.71	24	

Appendix 10 (continued)

Well	*Sample type*	*Top depth (m)*	*Bottom depth (m)*	*Maceral*	*Vit refl Mean*	*Vit refl SD*	*Vit refl Min*	*Vit refl Max*	*No. of readings*	*Comments*
Kanpa 1A	CC	3 566.00	–	Reservoir-bitumens	0.53	–	0.37	0.71	24	lamalginite. Much of the organic matter is undoubtedly reservoir bitumens. This is intimately mixed with material that has the form of lamalginite. It is possible that the bitumens were generated from lamalginite and impregnated the lamalginite as it became altered. The two populations could not be separated morphologically in many cases and reflectances appear to overlap. Oil drops, yellow, abundant, interstitial within carbonates. Mineral fluorescence patchy, moderate to weak orange. Iron oxides rare. Pyrite sparse)
LDDH 1	CC	222.80	–	Lamalginite	0.90	0.064	0.80	1.03	21	Rare non-fluorescing lamalginite. (Carbonate > claystone > ?siltstone. DOM rare, lamalginite only. Lamalginite is present as small lenses and does not fluoresce. Common small bright-orange specks in fluorescence mode, possibly oil droplets but too small to assign confidently as oil. Mineral fluorescence pervasive, weak dull-orange but absent where pyrite and diffuse organic matter present. Pyrite abundant)
LDDH 1	CC	529.60	–	?Lamalginite Bitumen	1.51 1.49	0.123 –	1.49 1.29	1.55 1.78	?3 25	Rare ?non-fluorescing lamalginite. (Evaporites > carbonate > claystone. DOM rare, lamalginite only, most of the organic matter is bitumen and bitumen coke. Bitumen shows strong bireflectance and some fields show mosaic structure. Mosaic ranges from fine mosaic to possible flow mosaic. Common oil, orange, occluded within carbonate, apparently not in equilibrium with the bitumen. Mineral fluorescence pervasive, moderate to bright orange. Pyrite common)
LDDH 1	CC	697.00	–	?Lamalginite	2.06	0.117	1.90	2.18	3	Rare non-fluorescing ?lamalginite. (Claystone > siltstone. DOM rare, lamalginite only. The ?lamalginite is present as small indeterminate masses and does not fluoresce. Mineral fluorescence pervasive, weak dull-orange, but rapid alteration to moderate greenish orange within about 2 seconds of irradiation. Pyrite common)
NJD 1	CC	252.20	–	?Lamalginite indeterminate	0.38 1.40	0.450 –	– 1.26	– 1.50	1 3	Fluorescing liptinite absent. (Silty, argillaceous carbonate. DOM rare, lamalginite > indeterminate higher reflecting component. Diffuse alginite-related organic matter ubiquitous but has not taken a polish and reflectance cannot be measured. The diffuse component does not fluoresce and is associated with dark laminae in fluorescence mode. Mineral fluorescence patchy, moderate orange to absent. Iron oxides common. Pyrite common)
NJD 1	CC	*252.20	–	Lamalginite	0.66	0.111	0.47	0.90	26	Sample was expected to be a demineralized organic-matter concentrate but actually comprises small particles of organic-rich calcareous siltstone. The organic matter content is about 8% and comprises non-fluorescing lamalginite. Weak mineral fluorescence, dull orange or brown. Iron oxides common. Pyrite common
NJD 1	CC	327.50	–	Lamalginite Fluor-Lamalginite	0.72 0.41	0.112 –	0.71 0.26	0.73 0.52	3 26	Abundant lamalginite, orange to very dull orange. (Argillaceous carbonate. DOM abundant, lamalginite > possible bitumens. Lamalginite present as composite lamellae, with weakly fluorescing forms dominant. Some lamalginite is non-reflecting and shows

Appendix 10 (continued)

Well	*Sample type*	*Top depth (m)*	*Bottom depth (m)*	*Maceral*	*Vit refl Mean*	*Vit refl SD*	*Vit refl Min*	*Vit refl Max*	*No. of readings*	*Comments*
NJD1	CC	327.50	–	Fluor-Lamalginite	0.41	–	0.26	0.52	26	stronger fluorescence. Mineral fluorescence patchy moderate-orange to absent. Pyrite sparse)
NJD 1	CC	*327.50	–	Lamalginite Fluor-Lamalginite	0.45 0.22	0.087 –	0.37 0.20	0.52 0.24	25 3	Sample expected to be a demineralized organic-matter concentrate but comprises small particles of organic-rich calcareous siltstone. Organic matter content of individual grains ranges from absent to about 25% and is about 8% overall. It comprises dominant non-fluorescing but low-reflectance lamalginite and less commonly, lower reflecting, fluorescing lamalginite. Weak mineral fluorescence, dull orange or brown. Iron oxides common. Pyrite common
NJD 1	CC	356.76	–	?Lamalginite	1.12	0.120	0.94	1.18	?2	Fluorescing liptinite absent. (Silty, micaceous claystone. DOM rare, ?lamalginite > possible bitumen coke. Small fragments of presumed lamalginite are non-fluorescing and moderately highly reflecting. A particle of coke may represent bitumen coke and has a reflectance of 1.92% and shows medium-size mosaic. Mineral fluorescence weak dull-brown to absent. Iron oxides sparse. Pyrite common)
NJD 1	CC	370.50	–	?Lamalginite ?Bitumen	1.29 1.55	0.166 –	1.02 1.41	1.53 1.89	10 7	Sparse fluorescing lamalginite, yellow to yellowish orange, rare non-fluorescing. (Siltstone, sandy. DOM sparse, ?lamalginite > probable bitumen. Fluorescing lamalginite sparse, non-fluorescing lamalginite rare and bitumen rare. Most of the sample contains high-reflecting entities identified as probable lamalginite and bitumens within a matrix that shows essentially no mineral fluorescence. However, a small number of lenses contain strongly fluorescing lamalginite similar to that found in some other horizons within NJD 1. The fluorescing and non-fluorescing entities do not appear to represent an equilibrium assemblage. The sample had to be crushed to improve impregnation but the fluorescing lamalginite does not appear to be a contaminant. Mineral fluorescence mostly weak dull-brown or absent, rare strong orange. Pyrite abundant)
NJD 1	CC	408.50	–	?Lamalginite Indeterminate	1.35 2.54	– –	– –	– –	?1 1	Fluorescing liptinite absent. (Claystone > siltstone, calcareous and sideritic. DOM rare, ?lamalginite > indeterminate organic matter, which could be a bitumen but does not show any of the forms typically shown by bitumens. Mineral fluorescence largely uniform, weak dull-brown or absent, rare dull-orange patches. Iron oxides sparse. Pyrite common)
NJD 1	CC	488.20	–	Lamalginite ?Bitumen ?Bitumen	1.57 1.65 2.33	0.156 – –	1.28 1.49 2.31	1.78 1.89 2.37	24 4 2	Sparse lamalginite, non-fluorescing. (Siltstone. DOM sparse, lamalginite only. Liptinite sparse, non-fluorescing lamalginite as small lenses. ?Bitumen is present as small equidimensional masses, and some show incipient coke structure. Two bitumens were distinguished on the basis of reflectance. Mineral fluorescence pervasive, weak dull orange. Pyrite abundant)
NJD 1	CC	*488.20	–	Population 1 Population 2	1.63 0.75	0.372 –	1.38 0.65	1.75 0.97	22 5	Sample expected to be a demineralized organic matter concentrate but comprises small particles of organic-rich calcareous siltstone. Organic matter content of individual grains ranges from sparse to about 85%

Appendix 10 (continued)

Well	*Sample type*	*Top depth (m)*	*Bottom depth (m)*	*Maceral*	*Vit refl Mean*	*Vit refl SD*	*Vit refl Min*	*Vit refl Max*	*No. of readings*	*Comments*
NJD 1	CC	*488.20	–	Population 2	0.75	–	0.65	0.97	5	and is about 75% overall. It comprises a matrix of indeterminate origin and reflectance (<0.6% but probably >0.3%), elongate lenses of non-fluorescing but low-reflectance lamalginite, more-abundant similar lenses of more-strongly reflecting lamalginite, and equidimensional grains that are referable to bitumen. The bitumen and higher reflectance lamalginite reflectances overlap and are reported as Population 1. Rare thucholitic bitumen shows a rim reflectance of 0.84%. Weak mineral fluorescence, dull orange or brown. Pyrite abundant
Yowalga 2	CC	893.70	–	Lamalginite	0.76	0.104	0.62	0.87	3	Sparse lamalginite, yellow to dull orange, sparse non-fluorescing lamalginite. (Siltstone. DOM common, liptinite only. Liptinite common. The lamalginite is present as sparse isolated palynomorphs and more common lamellar lenses. The lamellae range from dull-orange fluorescing to non-fluorescing. Estimation of the abundance of lamalginite is difficult because a high proportion shows no, or weak, fluorescence and much of it is too diffuse to take a polish. Mineral fluorescence patchy, moderate orange or absent. Pyrite common)
				Fluor-Lamalginite	0.40	–	0.29	0.51	3	
Yowalga 3	DC	1 484.00	–	Lamalginite	0.48	0.078	0.38	0.57	3	Abundant lamalginite, yellow to orange, rare non-fluorescing. (Claystone, calcareous > siltstone > sandstone. DOM abundant, liptinite only. Liptinite abundant. Lamalginite is present mainly as extensive lamellae, with typically yellow and less commonly orange fluorescence. Non-fluorescing liptinite is rare. The mode of occurrence of the lamalginite is similar to that in the Green River Formation and the McArthur Basin. The intensity of the fluorescence intensity from I_{546} = 1.2 to I_{546} = 1.8. Oil drops, yellow, sparse, disseminated within siltstones. Mineral fluorescence pervasive, strong orange. Pyrite common)
	DC	1 484.00	–	Fluor-Lamalginite	0.24	–	0.11	0.36	12	
Yowalga 3	CC	2 388.40	–	Lamalginite	0.50	–	–	–	1	Sparse lamalginite, yellowish orange to orange, rare non-fluorescing. (Claystone, calcareous, silty. DOM sparse, liptinite only. Liptinite sparse. Lamalginite is present as isolated palynomorphs and medium-length lamellae. Fluorescence is much less intense than for 1484 m. Non-fluorescing liptinite is rare. Oil drops, yellow, rare, disseminated. Mineral fluorescence patchy, strong orange or absent. Pyrite common)
				Fluor-Lamalginite	0.25	–	–	–	1	
Yowalga 3	DC	3 253.00	3 259.00	Lamalginite	1.50	0.146	1.31	1.65	6	Rare lamalginite, bright yellow, but probably only in cavings. (Siltstone > claystone > carbonate > sandstone. DOM rare, liptinite >> reservoir bitumens. Liptinite rare, ?reservoir bitumens rare. Lamalginite present as small irregular and probably residual masses that show distinct anisotropy. They and bitumens present in argillaceous limestone that contains numerous dark streaks that are probably where lamalginite was present before oil generation occurred. Fluorescing lamalginite confined to a few grains and considered to represent cavings. Mineral fluorescence patchy, orange to weak orange. Pyrite abundant)
				Reservoir-bitumens	1.00	–	0.86	1.21	6	

Appendix 10 (continued)

Well	*Sample type*	*Top depth (m)*	*Bottom depth (m)*	*Maceral*	*Vit refl Mean*	*Vit refl SD*	*Vit refl Min*	*Vit refl Max*	*No. of readings*	*Comments*
Yowalga 3	CC	4 192.00	–	Lamalginite	2.08	0.172	1.78	2.35	19	Fluorescing liptinite absent. (Claystone silty with carbonate lenses. DOM common to abundant. Liptinite >> bitumens. Liptinite common to abundant, ?bitumens rare. Lamalginite has taken a poor polish and abundance is difficult to assess. Bireflectance distinct but weak for the level of reflectance found. Lamalginite probably residual after lamalginite and within lacositic layers. Mineral fluorescence patchy, moderate orange to dull orange. Pyrite abundant)
				Reservoir-?Bitumens	1.45	–	1.41	1.49	2	

NOTES: CC: Conventional core
DC: Ditch cuttings
DOM: Dispersed organic matter
Max: maximum
Min: minimum
SD: Standard deviation
Vit refl: vitrinite reflectance

NJD 1 samples marked * are from palynological organic-matter concentrates. The samples appear to have been concentrated by physical rather than chemical means. However, it is possible that the optical properties of the components have been altered by the preparation processes. The organic-matter concentrates and whole-rock data are similar but do not correspond exactly. The non-fluorescing lamalginite population seen in the organic-matter concentrate from 252.2 m was not found in the whole-rock sample. Conversely, the small non-fluorescing lamalginite population found in the whole-rock sample from 327.5 m was not present in the organic-matter concentrate. The lower reflecting population in the organic-matter concentrate from 488.2 m was not found in the whole-rock sample. The reflectance of the lower population does not appear to be consistent with that of the higher population and the two high-reflecting populations gave similar means for the two types of samples. The bitumen reflectances are also similar to the higher value. Some of the optical properties are consistent with the presence of contact alteration effects within the NJD 1 section.

Appendix 11

Temperature data for petroleum exploration wells from the western Officer Basin

Well	*RT (m)*	*GL (m)*	*Temperature (°C) Recorded*	*Estimated*	*Surface*	*Gradient (°C/100 m)*	*TSC*	*Date*
Browne 1	380.4	378.9	34.4	37.9	25	3.4	–	14/09/65
Browne 1	282.2	280.7	32.2	35.4	25	3.7	–	19/10/65
Dragoon 1	977.4	973.4	49.0	53.9	25	3.0	6.0	27/08/82
Dragoon 1	1 996.7	1 992.7	64.0	70.4	25	2.3	10.5	15/09/82
Hussar 1	1 266.5	1 262.5	51.0	56.1	25	2.5	4.5	3/11/82
Hussar 1	2 037.5	2 033.5	62.0	68.2	25	2.1	6.5	2/12/82
Hussar 1	2 037.5	2 033.5	63.0	69.3	25	2.2	11.0	2/12/82
Kanpa 1A	565.5	559.5	44.4	48.9	25	4.3	6.0	11/01/82
Kanpa 1A	565.5	559.5	60.0	66.0	25	7.3	5.0	16/12/82
Kanpa 1A	1 325.0	1 319.0	63.3	69.7	25	3.4	7.5	27/02/83
Kanpa 1A	1 961.8	1 955.8	65.0	71.5	25	2.4	6.0	30/03/83
Kanpa 1A	1 961.8	1 955.8	65.5	72.1	25	2.4	9.3	26/02/83
Kanpa 1A	2 743.0	2 737.0	64.4	70.9	25	1.7	6.5	30/04/83
Kanpa 1A	2 743.0	2 737.0	65.5	72.1	25	1.7	11.7	30/04/83
Kanpa 1A	2 743.0	2 737.0	66.1	72.7	25	1.7	16.8	30/04/83
Kanpa 1A	3 371.5	3 365.5	71.7	78.8	25	1.6	3.8	20/05/83
Kanpa 1A	3 371.5	3 365.5	72.2	79.4	25	1.6	11.3	20/05/83
Kanpa 1A	3 371.5	3 365.5	72.8	80.0	25	1.6	19.8	20/05/83
Kanpa 1A	3 804.0	3 798.0	72.8	80.0	25	1.4	6.5	21/06/83
Kanpa 1A	3 804.0	3 798.0	73.3	80.7	25	1.5	15.3	21/06/83
Kanpa 1A	3 804.0	3 798.0	73.6	81.0	25	1.5	18.5	21/06/83
Lennis 1	583.7	582.2	41.7	45.8	25	3.6	–	7/09/65
Lungkarta 1	1 194.5	1 187.7	61.0	67.1	25	3.5	5.3	28/10/84
Lungkarta 1	1 194.5	1 187.7	70.0	77.0	25	4.4	9.7	29/10/84
Lungkarta 1	1 194.5	1 187.7	74.0	81.4	25	4.7	13.8	29/10/84
Lungkarta 1	1 194.5	1 187.7	76.0	83.6	25	4.9	17.0	29/10/84
Lungkarta 1	1 767.0	1 760.2	62.0	68.2	25	2.5	3.8	11/11/84
Lungkarta 1	1 767.0	1 760.2	64.0	70.4	25	2.6	8.5	11/11/84
Lungkarta 1	1 767.0	1 760.2	65.5	72.1	25	2.7	12.0	12/11/84
Lungkarta 1	1 767.0	1 760.2	67.0	73.7	25	2.8	14.0	12/11/84
Lungkarta 1	1 767.0	1 760.2	68.0	74.8	25	2.8	20.0	13/11/84
Yowalga 1	598.3	596.8	38.9	42.8	25	3.0	–	26/09/65
Yowalga 2	118.6	114.5	47.2	51.9	25	(a)23.5	–	3/02/66
Yowalga 2	741.0	736.9	55.6	61.1	25	4.9	–	3/10/66
Yowalga 2	984.8	980.8	63.3	69.7	25	4.6	–	23/03/66
Yowalga 3	778.8	771.7	47.8	52.6	25	3.6	4.0	25/08/80
Yowalga 3	1 621.0	1 613.9	60.0	66.0	25	2.5	6.0	23/09/80
Yowalga 3	1 621.0	1 613.9	60.5	66.6	25	2.6	8.5	23/09/80
Yowalga 3	2 777.0	2 769.9	71.1	78.2	25	1.9	5.3	25/10/80
Yowalga 3	2 777.0	2 769.9	72.2	79.4	25	2.0	13.5	26/10/80
Yowalga 3	3 272.5	3 265.4	76.7	84.3	25	1.8	7.0	17/11/80
Yowalga 3	3 272.5	3 265.4	78.3	86.2	25	1.9	11.0	18/11/80
Yowalga 3	3 272.5	3 265.4	78.9	86.8	25	1.9	13.5	18/11/80
Yowalga 3	3 272.5	3 265.4	79.4	87.4	25	1.9	17.0	18/11/80
Yowalga 3	3 889.0	3 881.9	83.9	92.3	25	1.7	9.0	14/12/80
Yowalga 3	3 889.0	3 881.9	88.9	97.8	25	1.9	16.0	14/12/80
Yowalga 3	4 183.0	4 175.9	87.8	96.5	25	1.7	9.0	1/07/81
Yowalga 3	4 183.0	4 175.9	89.4	98.4	25	1.8	13.0	1/07/81
Yowalga 3	4 183.0	4 175.9	90.5	99.6	25	1.8	18.0	1/07/81
Yowalga 3	4 183.0	4 175.9	91.7	100.8	25	1.8	21.0	1/07/81

NOTES: The source of all data is the well log
RT: Rotary table
(a) spurious recording
TSC: time since mud circulation
GL: Ground level