High-quality oil-prone source rocks within carbonates of the Silurian Dirk Hartog Group, Gascoyne Platform, Western Australia

by K. A. R. Ghori[1]

Abstract

Geochemical evaluation of core samples from the Silurian Dirk Hartog Group indicates that thin oil-prone shaly to micritic source beds are interbedded within carbonate facies of the Upper Silurian Coburn Formation. These laminated organic-rich source beds are recognized only in those wells in which the Dirk Hartog Group has been fully drilled. Such source beds have fair to excellent hydrocarbon-generating potential and are rich in oil-prone kerogen. Excellent source beds in drillhole Yaringa East 1 (deepening) have an organic richness of up to 7.43% total organic carbon, potential yield (S_1+ S_2) of up to 38.1 mg/g, and hydrogen index of up to 505. Good source beds are also recognized in Coburn 1 and GSWA Woodleigh 2A. Detailed geochemical analyses confirm that oil-prone organic facies are of high quality and were deposited in reducing environments. In Coburn 1, GSWA Woodleigh 2A, and Yaringa East 1 (deepening), the maturity of these source beds ranges from immature to within the early oil-generative window. To the northwest, the Silurian section is more mature as it is buried more deeply, and it is within the peak oil-generative window in Quobba 1 and Pendock 1. For those wells the available geochemical data are based on cuttings and side-wall cores, implying that good oil-source beds may have been missed because continuous core was not available.

KEYWORDS: Petroleum, source rock, geochemistry, Silurian, Dirk Hartog Group, Gascoyne Platform, Western Australia.

Introduction

Many petroleum systems throughout the world were charged by Silurian source beds (Klemme and Ulmishek, 1991), from both siliciclastic- and carbonate-dominated successions. For clastic-dominated rocks, the best examples are organic-rich graptolitic shales of the Lower Silurian succession in north Africa (Boote et al., 1998) and the Middle East (Alsharhan and Nairn, 1997). In the Palaeozoic basins of north Africa, these source beds are considered to have generated 80–90% of the more than 46 billion barrels of oil discovered. An example of source beds in a Silurian carbonate-dominated succession is within Niagaran reefs of the Michigan Basin (North America). The source beds are laminated inter-reef deposits, and are considered to be the primary source rock for oil in the Niagaran reefs, even though they are characterized by relatively low organic richness, of typically 0.3 – 0.6% total organic carbon (TOC; Gardner and Bray, 1984).

This paper documents Silurian source beds within carbonate-dominated rocks of the Southern Carnarvon Basin in Western Australia. The succession is known only from the Gascoyne Platform, where shaly to micritic source beds have excellent to fair hydrocarbon-generating potential, with maturity ranging from immature to within the early oil-generative window.

The stratigraphy, distribution, and lithology of the Silurian Dirk Hartog Group has been discussed in many papers, the most significant of which are Hocking et al. (1987), Gorter et al. (1994), Mory et al. (1998), Mory and Yasin (1998), and Yasin and Mory (1999). The group spans the entire Silurian period, and has been divided into the Ajana, Yaringa, and Coburn Formations (in ascending order; Mory et al., 1998). Lithologically, the group is dominated by shallow-marine dolomitic lithofacies, with evaporitic anhydrite and halite facies and minor siliciclastic lithofacies. These facies probably extended over most of the Gascoyne Platform during the Silurian. They are best studied in the fully cored intervals drilled in GBH 2 by CRA Exploration in 1980, ND 001 and 002 by BHP in 1993, Coburn 1 by Knight Industries in 1997, Woodleigh 2A by the Geological Survey of Western Australia (GSWA) in 1999, and Yaringa East 1 (deepening) by Britannia Gold NL in 2000 (Fig. 1). Other wells in the region contain only short cored intervals, so the

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remainder of these sections can be evaluated only from cuttings and side-wall cores.

Source-rock evaluation

Petroleum source rocks within the Silurian Dirk Hartog Group are here evaluated from 179 TOC, 51 Rock-Eval pyrolysis, eight pyrolysis gas-chromatography (PGC), 11 extract gas-chromatography and mass-spectrometry (GC-MS), and 26 organic petrology analyses of cuttings and core samples. Figure 1 shows the locations of wells from which the Dirk Hartog Group was sampled and analysed, as well as the depth range of the group. Table 1 lists analytical data for TOC and Rock-Eval pyrolysis of core samples having more than 0.5% TOC and 1.0 mg/g pyrolysate yield.

Source-rock richness

Organic richness and pyrolysate yields (S_2) from Rock-Eval pyrolysis are used to identify source rocks.

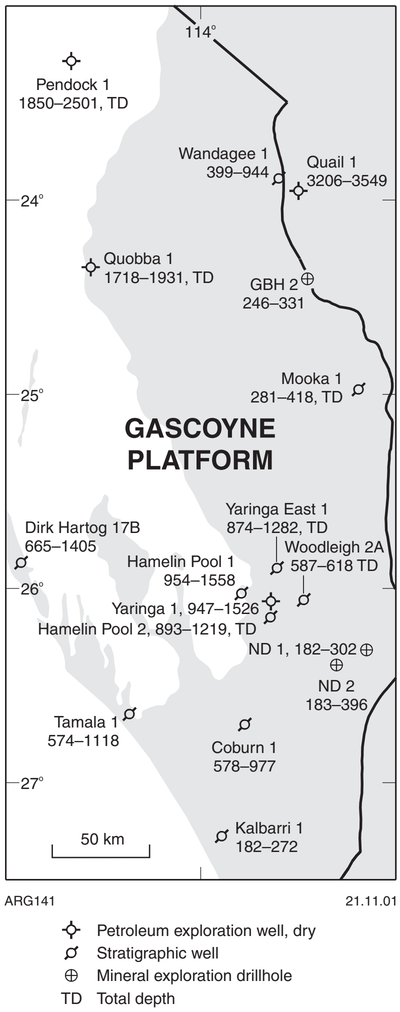

Figure 1. Well locations and depths in metres at which the Dirk Hartog Group was intersected. Shaded area represents land.

Samples with a TOC range of 0.5 to 1.0% and a S_2 yield of 1–5 mg/g of rock are classified as having fair source potential; 1.0 – 2.0% TOC and 5–10 mg/g S_2 as good; 2.0 – 4.0% TOC and 10–20 mg/g S_2 as very good; and more than 4.0% TOC and over 20 mg/g S_2 as excellent (Baskin, 1997). Figure 2a shows the samples with fair to excellent hydrocarbon-generating potential.

The Rock-Eval parameter hydrogen index (HI) is related directly to the atomic hydrogen to carbon ratio (H/C) and indicates the hydrogen-richness of kerogen or organic facies of rocks, whereas T_{max} is a maturity indicator that represents the temperature at which the maximum amount of S_2 hydrocarbons is generated. These parameters (HI and T_{max}) show that the source rocks are rich in oil-prone organic facies of type II kerogen and are immature to early mature (Fig. 2b).

Source-rock quality

Detailed geochemical analyses, including PGC and GC-MS, supplement TOC and Rock-Eval pyrolysis in evaluating source-rock quality, which increases with hydrogen-richness of source-rock organic facies.

Table 1. Total organic carbon (TOC) and Rock-Eval pyrolysis data for core samples having more than 0.5% TOC and 1.0 mg/g pyrolysate yield

Well	*Depth (m)*	*TOC (%)*	*T_{max} (°C)*	*S_1*	*S_2*	*S_3*	*S_1+S_2*	*PI*	*HI*	*OI*	*%Ro*	*Mi*	*Ma*	*R*	*M*
BHP ND 001	191.9	0.70	411	0.16	1.23	0.21	1.39	0.12	176	30	–	–	–	–	–
Coburn 1	606.2	1.23	426	0.86	4.23	0.67	5.09	0.17	344	54	–	–	–	–	–
Coburn 1	623.9	2.06	424	0.86	5.43	0.08	6.29	0.14	264	4	0.65	0.42	0.92	18	Tb
Coburn 1	633.5	0.51	427	0.29	1.36	1.59	1.65	0.18	267	312	–	–	–	–	–
Coburn 1	839.4	0.53	429	0.19	1.05	1.19	1.24	0.15	198	225	–	–	–	–	–
Coburn 1	853.2	0.59	433	0.26	1.30	1.03	1.56	0.17	220	175	–	–	–	–	–
Mooka 1	339.0	0.61	414	0.09	1.25	0.38	1.34	0.07	205	62	0.53	0.45	0.65	5	Dv
Yaringa East 1	967.7	0.67	436	0.31	2.84	0.36	3.15	0.10	424	54	–	–	–	–	–
Yaringa East 1	973.6	1.27	432	0.71	4.98	0.78	5.69	0.12	392	61	–	–	–	–	–
Yaringa East 1	976.2	7.43	428	4.97	33.11	0.40	38.08	0.13	446	5	0.61	0.47	0.82	10	Tb
Yaringa East 1	980.9	0.66	428	0.18	1.64	1.02	1.82	0.10	248	155	–	–	–	–	–
Yaringa East 1	1 066.1	0.69	429	0.31	1.92	0.14	2.23	0.14	278	20	–	–	–	–	–
Yaringa East 1	1 161.0	2.02	424	1.35	5.79	1.42	7.14	0.19	287	70	0.62	–	–	1	Tb
Yaringa East 1	1 185.6	0.62	430	0.30	1.93	1.73	2.23	0.13	311	279	–	–	–	–	–
Yaringa East 1	1 201.6	1.10	433	0.62	5.55	1.25	6.17	0.10	505	114	–	–	–	–	–
Yaringa East 1	1 242.5	0.83	427	0.91	3.13	0.83	4.04	0.23	377	100	–	–	–	–	–
Woodleigh 2A	591.5	1.49	436	0.12	3.82	0.68	3.94	0.03	256	46	–	–	–	–	–
Woodleigh 2A	592.4	2.24	431	0.23	8.22	0.83	8.45	0.03	367	37	0.50	0.40	0.58	28	Dv

NOTES: Dv = detrovitrinite
HI = hydrogen index
M = maceral
Ma = maximum reflectance
Mi = minimum reflectance
OI = oxygen index
PI = production index
R = number of readings
%Ro = mean reflectance
S_1 = existing hydrocarbons (HC)
S_2 = pyrolytic yield (HC)
S_3 = organic carbon dioxide
S_1 + S_2 = potential yield
Tb = thucholitic bitumen
T_{max} = temperature of maximum pyrolytic yield (S_2)
TOC = total organic carbon

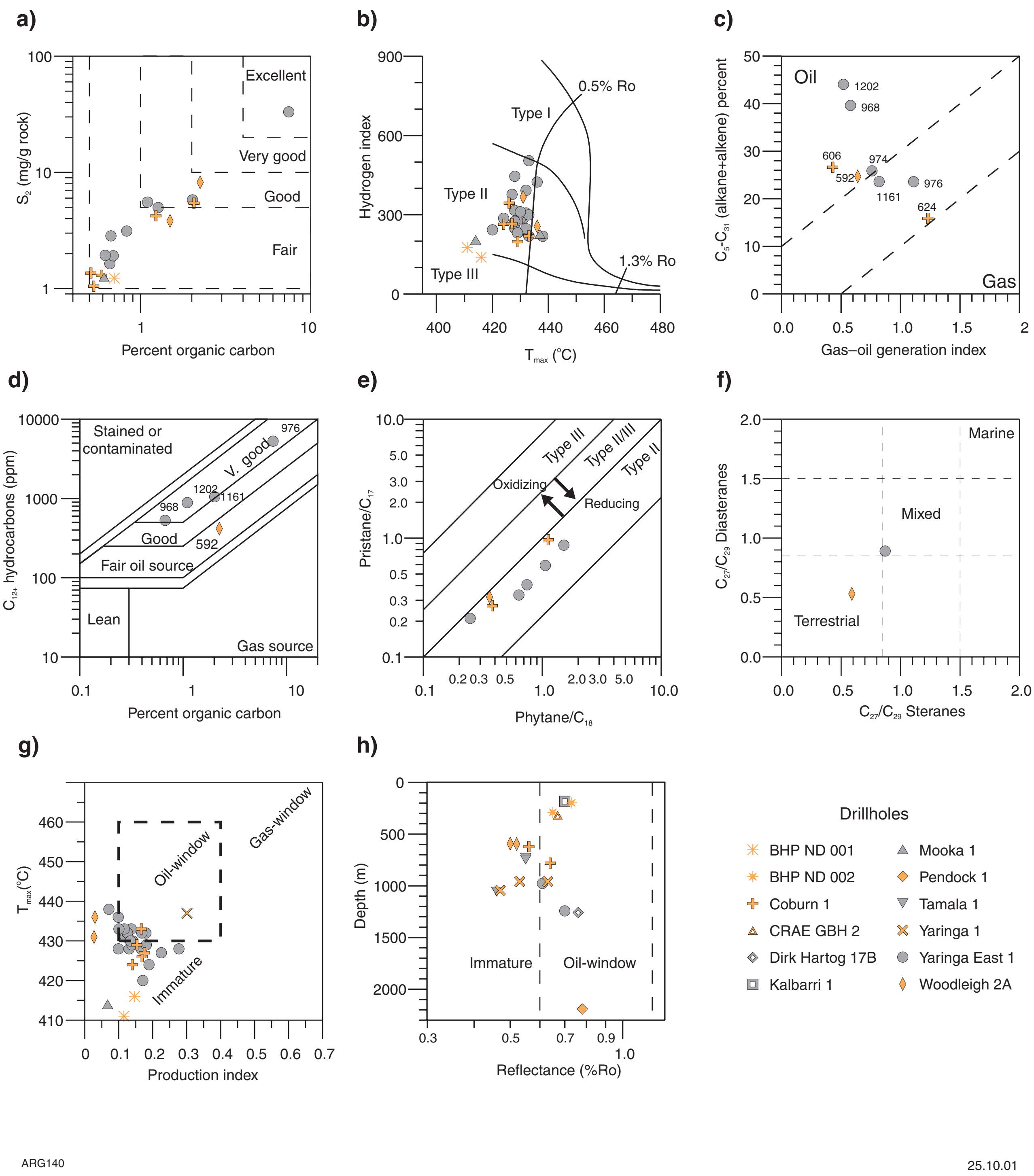

Figure 2. Geochemical interpretative diagrams for the Dirk Hartog Group: a) petroleum-generating potential; b) Rock-Eval kerogen typing; c) pyrolysis gas-chromatography kerogen typing; d) source-rock rating as a function of C_{12+} hydrocarbon yields versus organic richness; e) kerogen type and depositional environment from gas-chromatography biomarkers; f) organic matter type from gas chromatography – mass spectrometry biomarkers; g) maturity from Rock-Eval; h) maturity from organic petrology

Pyrolysis gas-chromatography

Pyrolysis gas-chromatography provides a detailed molecular characterization of kerogen to evaluate its oil- versus gas-generating potential (Larter, 1985). The type and amount of liquid hydrocarbons yielded, and the calculated PGC parameters of gas–oil generation index (GOGI; C_1–C_5/C_{6+}) and C_5–C_{31} saturated (alkanes) and unsaturated (alkenes) hydrocarbons (Fig. 2c), confirm that these source rocks are rich in oil-prone kerogen as indicated by Rock-Eval pyrolysis.

Gas chromatography – mass spectrometry

Extract concentration, composition, and the distribution of biomarker alkanes can be used to evaluate source richness, quality, maturity, and environment of deposition. However, caution is required in interpretation because these parameters also depend on maturity and the organic facies present (Peters and Moldowan, 1993). The Gascoyne Platform samples have a high yield of heavy hydrocarbons (C_{12+}) as a function of their organic richness and maturity, and are rated as fair to very good oil-prone source rocks (Fig. 2d). The organic-rich sample (2.24% TOC) from 592.4 m in GSWA Woodleigh 2A is rated as a fair source rock because it is the least mature among the analysed samples, and thus has the lowest heavy hydrocarbons (C_{12+}) yield as a function of its low maturity.

Biomarkers identified by GC and GC–MS of the saturated hydrocarbons are indicators of organic facies, depositional environment, thermal maturation, and biodegradation, and also can be used for source-rock characterization. For the Dirk Hartog Group, GC biomarker parameters include pristane to phytane values of 0.80 – 1.33, pristane to n-C_{17} of 0.21 – 0.97, and phytane to n-C_{18} of 0.25 – 1.52. These parameters indicate that the oil-prone organic facies were deposited in a reducing environment. Low pristane to phytane ratios in source rocks typically indicate reducing conditions as observed in the group, whereas the pristane/n-C_{17} and phytane/n-C_{18} values indicate oil-prone organic facies with type II kerogen (Fig. 2e). The GC–MS biomarkers for samples from GSWA Woodleigh 2A and Yaringa East 1 (deepening) indicate that the organic matter is terrestrial and mixed terrestrial to marine, respectively (Fig. 2f).

Source-rock maturity

Rock-Eval and organic petrology data indicate that maturation ranges from immature to within the early oil-generative window (Fig. 2g,h). The maturity of the Dirk Hartog Group increases northward, probably due to increasingly deeper burial; it was intersected at 182 m in the southernmost well (Kalbarri 1) and at 1850 m in the northernmost well (Pendock 1; Fig. 1). The source beds in Yaringa East 1 (deepening), for example, are more deeply buried compared to source beds in Coburn 1 and Woodleigh 2A, and are noticeably more mature (Table 1).

Discussion

Excellent to good oil-prone source rocks identified in the Dirk Hartog Group, although thin, are significant in evaluating the prospectivity of the region. The carbonate succession contains fine-grained, laminated to banded, shaly to micritic, organic-rich source beds up to a metre thick. In comparison, shaly beds within the more clastic parts of the Dirk Hartog Group are poor in organic matter. To date, Silurian source beds in the region have been recognized only in fully cored wells, because identification of source rocks is more difficult in carbonate-dominated facies than in clastic-dominated facies. The organic-rich beds indicate euxinic conditions during deposition, either through restricted water circulation or by vertical stratification of the water column. Globally, there are many effective source rocks in carbonate-dominated facies of Silurian and Devonian age (Palacas, 1984; Gardner and Bray, 1984; Powell, 1984). Previous GSWA studies have also documented the deposition of thin but excellent source beds within the carbonate-dominated facies of the Devonian Gneudna Formation from GSWA Gneudna 1 and Barrabiddy 1A (Ghori, 1998, 1999).

The recognition of excellent to good oil-prone source beds within carbonate-dominated rather than clastic-dominated facies should influence exploration strategies within the region as well as directing future source-rock studies to such facies.

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