A summary of Rock-Eval data for the Bonnet Plume Basin, Yukon: Implications for a previously unrecognized oil play

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ABSTRACT

Previous studies based on regional geology, sediment type and stratigraphic thickness, concluded that the Bonnet Plume Basin in northeastern Yukon has gas potential, but insignificant oil potential. However, these studies were not based on samples collected from within the basin. For this study, in total, 226 rock samples collected from outcrop and drill core throughout the Bonnet Plume Basin were analyzed by Rock-Eval 6 programmed pyrolysis and combustion to assess the petroleum source-rock potential of the strata. The results indicate that the Road River Formation (Cambrian to Devonian) has no source rock potential, but the Bonnet Plume Formation (Cretaceous to Tertiary) has gas and perhaps oil potential. Potential oil generation in the Bonnet Plume Formation is attributed to the occurrence of liptinite-bearing coal and previously unrecognized, siliceous, oil shale. A hydrocarbon-rich tar associated with a naturally burning coal seam was also discovered in the Bonnet Plume Formation.

RÉSUMÉ

Des études antérieures fondées sur la géologie régionale, le type de sédiment et l'épaisseur des couches stratigraphiques ont conclu que le bassin de Bonnet Plume dans le nord est du Yukon a un potentiel gazier, mais un potentiel pétrolier négligeable. Ces études n'étaient toutefois pas fondées sur des échantillons prélevés à l'intérieur du bassin. Nous avons analysé 226 échantillons de roche prélevés dans des affleurements ou des carottes de forage dans l'ensemble du bassin de Bonnet Plume à l'aide d'une pyrolyse et d'une combustion Rock-Eval 6 programmées dans le but d'évaluer le potentiel pétrolier de la roche mère de ces strate. Les résultats indiquent que la Formation de Road River (Cambrien-Dévonien) n'a aucun potentiel comme roche mère, mais que la Formation de Bonnet Plume (Crétacé-Tertiaire) a un potentiel gazier et possiblement pétrolier. La production de pétrole potentielle dans la Formation de Bonnet Plume est attribuée à la présence de charbon contenant de la liptinite et d'un shale bitumineux siliceux auparavant inconnu. Un goudron riche en hydrocarbures associé à un filon de charbon à combustion naturelle a également été découvert dans la Formation de Bonnet Plume.

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INTRODUCTION

The Bonnet Plume Basin is one of eight oil and gas basins identified in Yukon (Fig. 1). As a 'frontier' basin, no oil or gas wells have been drilled and no seismic surveys have been attempted, although an east-west gravity profile was completed across the basin in the late 1970s (Sobczak and Long, 1980). The Bonnet Plume Basin has long been recognized for the occurrence of thick lignite coal seams (*i.e.*, up to 17 m, Cameron and Beaton, 2000), including one that is naturally burning (de Sainville, 1898). In addition, Paleozoic strata are thought to be petroliferous, with 'tar' described as oozing from outcrops in several places (Camsell, 1906). Extensive coal exploration, including detailed geologic mapping, trenching and drilling, was undertaken in the late 1970s to early 1980s, resulting in the discovery of the largest coal resource in the Yukon: an estimated 2800 megatonnes (Cameron and Beaton, 2000). Link *et al*. (1989) reported total organic carbon (TOC) values up to 9.6% (*i.e.*, an excellent petroleum source rock) and Type I kerogen (*i.e.*, oil-prone) and Type II kerogen (*i.e.*, oil- and gas-prone) in Paleozoic strata from wells north of the basin. However, based on regional geology, sediment type and stratigraphic thickness, Hannigan (2000) concluded that the Bonnet Plume Basin has gas potential, but insignificant oil potential. Specifically, lower Plaeozoic clastic and carbonate strata are thought to be potential source rocks, as are Cretaceous clastic strata (Hannigan, 2000). The median estimate for the total gas potential in the Bonnet Plume Basin is 896 Bcf of in-place gas, and the extensive coal deposits indicate that it has significant coalbed methane potential as well (Hannigan, 2000). Nevertheless, Hannigan's (2000) report was not based on samples collected from within the basin. The present study reports the results from Rock-Eval 6 analyses of outcrop and drill core samples collected throughout the Bonnet Plume Basin in order to assess the petroleum source-rock potential of the strata.

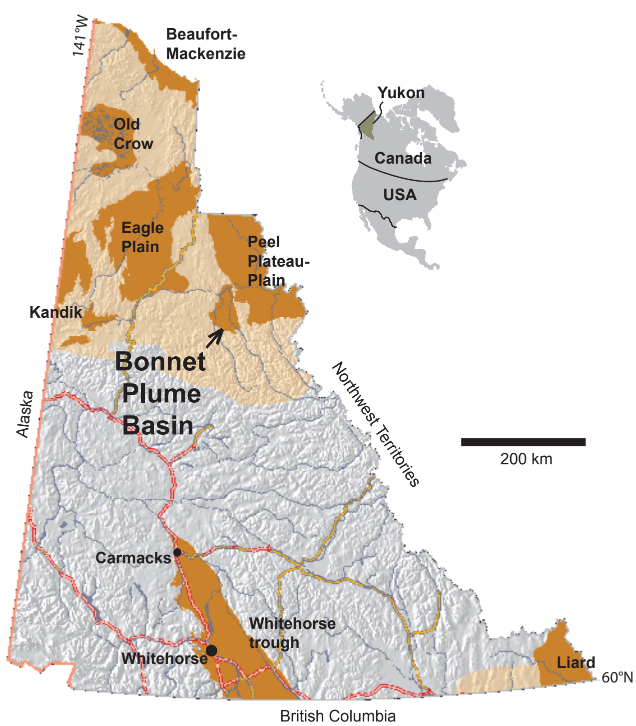

Figure 1. *Petroleum basins in Yukon (from Oil and Gas Branch, Yukon Government, 2007).*

GEOLOGIC SETTING

The Bonnet Plume Basin (Fig. 2) is a physiographic and structural depression near the eastern margin of the Frontal Belt of the Cordilleran Orogen in northeastern Yukon (Norris and Hopkins, 1977; Hannigan, 2000). It formed in early Late Cretaceous time by down-dropping Paleozoic strata along regional faults, and contains up to 7500 m of clastic and carbonate sediments ranging from Precambrian to Tertiary in age (Mountjoy, 1967; Norris and Hopkins, 1977; Hannigan, 2000). The oldest strata are Precambrian metasedimentary rocks of the Wernecke Supergroup. This is overlain unconformably by a thick Paleozoic succession of marine limestone and mudstone, including Illtyd, Slats Creek, Taiga, Rabbit Kettle, Bouvette, Canol, Imperial and Road River formations (Norris and Hopkins, 1977; Hannigan, 2000). The Bonnet Plume Formation unconformably overlies the Paleozoic sedimentary rocks, and is informally subdivided into the lower Bonnet Plume Formation and the upper Bonnet Plume Formation (Mountjoy, 1967). The lower Bonnet Plume Formation (Middle to Late Albian) is up to 1500 m thick, and consists of interbedded conglomerate, sandstone, mudstone and bituminous coal deposited in a marginal marine to fluvial environment (Rouse and Srivastava, 1972; Norris and Hopkins, 1977; Long, 1978; Nichols and Sweet., 1993). The upper Bonnet Plume Formation (Maastrichtian to Paleocene) is up to 400 m thick, and consists of fluvial sandstone, mudstone and lignite (Rouse and Srivastava, 1972; Norris and Hopkins, 1977; Long, 1978; Nichols and Sweet 1993). Long (1986) suggested that lower Bonnet Plume coals were deposited in fan-marginal and lowland-moor settings, whereas upper Bonnet Plume Formation coals were deposited in a lowland-moor environment. Only the Road River Formation (Cambrian to Devonian) and Bonnet Plume

Formation (Cretaceous to Tertiary) crop out in the Bonnet Plume Basin.

METHODS

A total of 226 samples were collected from outcrop and drill core throughout the Bonnet Plume Basin. Source rock quantity, quality and thermal maturation level were determined by Rock-Eval 6 programmed pyrolysis and combustion using standard techniques by the Geological Survey of Canada in Calgary, Alberta. Technical details of the Rock-Eval apparatus, procedures and applications are available in Espitalie *et al*. (1985), Peters (1986), Peters and Casa (1994), Tyson (1995), Lafargue *et al*. (1998), Behar *et al*. (2001) and Fowler *et al*. (2005), whereas a less technical summary is provided by Lowey and Long (2006). Table 1 provides definitions for commonly used Rock-Eval parameters and presents a summary of guidelines for interpreting source rock quantity, quality and maturation using Rock-Eval.

RESULTS

ROAD RIVER FORMATION

With regards to source rock quantity, TOC ranges from 0.35 to 2.30% (Appendix 1) with a mean of 1.25%, indicating a poor to good source rock; S_1 ranges from 0

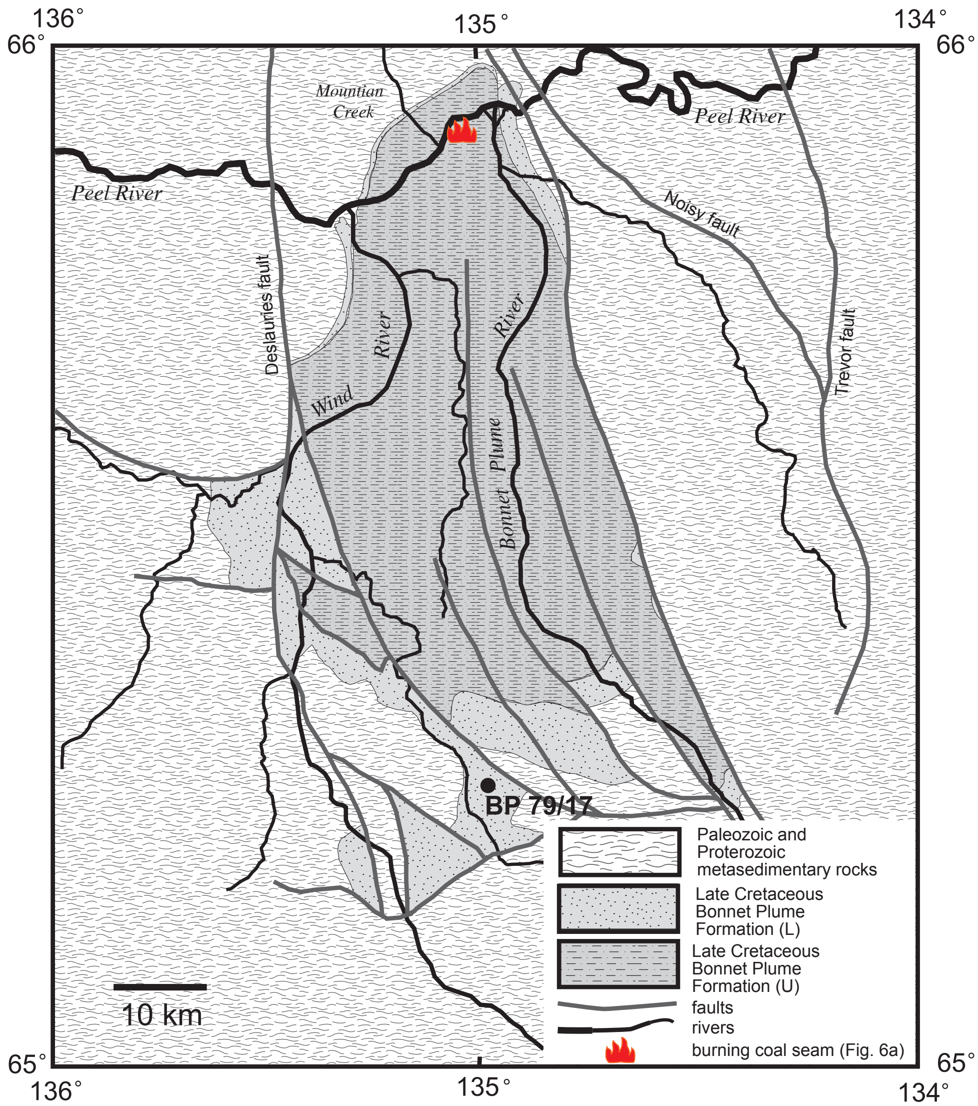

Figure 2. *Geologic setting of the Bonnet Plume Basin, Yukon. Flame symbol indicates location of naturally burning coal seam (modified from Long, 1978; and Norris, 1982).*

to 0.71 mg HC/g rock with a mean of 0.128 mg HC/g rock, indicating a poor to fair source rock; and S_2 ranges from 0.01 to 0.16 mg HC/g rock with a mean of 0.04 mg HC/g rock, indicating a poor source rock. With regards to source rock quality, HI ranges from 1.00 to 140.00 mg HC/g TOC with a mean of 3.33 mg HC/g TOC indicating no hydrocarbons to gas are present; and the S_2/S_3 ratio ranges from 0.01 to 0.31 with a mean of 0.17, indicating no hydrocarbons are present. Based on the S_2 *vs*. TOC plot (Fig. 3a) and the HI *vs*. T_{max} plot (Fig. 3b), only Type III, or gas-prone is present. With regards to source rock thermal maturation, T_{max} ranges from 288 to 542°C with a mean of 352°C, indicating the rock ranges from thermally immature to postmature with respect to oil generation (Fig. 3b). Note that due to low S_2 values (*i.e*., values of S_2 <0.2 mg HC/g rock), subsequent Rock-Eval parameters are considered unreliable (Peters, 1986). Hence, Figure 3 should be interpreted with caution.

Table 1. *Guidelines for interpreting source rock quantity, quality and maturation, and commonly used Rock-Eval parameters. From Epstein et al. (1977), Espitalie et al. (1985), Peters (1986), Traverse (1988), Peters and Cassa (1994) and Fowler et al. (2005).*

QUANTITY	[1]TOC (wt. %)	[2]S_1 (mg HC/g rock)	[3]S_2 (mg HC/g rock)	
Poor	<0.5	<0.5	<2.5	
Fair	0.5-1	0.5-1	2.5-5	
Good	1-2	1-2	5-10	
Very good	2-4	2-4	10-20	
Excellent	>4	>4	>20	
QUALITY	**[4]HI (mg HC/g TOC)**	**[5]S_2/S_3**	**[6]Kerogen Type**	
None	<50	<1	IV	
Gas	50-200	1-5	III	
Gas and oil	200-300	5-10	II/III	
Oil	300-600	10-15	II	
Oil	>600	>15	I	
MATURATION	**[7]Ro (%)**	**[8]Tmax (°C)**	**[9]CAI**	**[10]TAI**
Immature	0.2-0.6	<435	<1.0	1.5-2.6
Early	0.6-0.65	435-445	1.0-2.0	2.6-2.6
Mature				
Peak	0.65-0.9	445-450	2.0-3.0	2.7-2.9
Late	0.9-1.35	450-470	3.0-4.0	2.9-3.3
Postmature	>1.35	>470	>4.0	>3.3

[1]TOC=total organic carbon
[2]S_1=hydrocarbons thermally distilled from sample ('free hydrocarbons')
[3]S_2=hydrocarbons generated by pyrolytic degradation of kerogen in sample ('potential hydrocarbons')
[4]HI=Hydrogen Index=(S_2x100/TOC)
[5]S_2/S_3=(pyrolyzed hydrocarbons/carbon dioxide generated during pyrolysis)
[6]Kerogen Type IV~ reworked-oxidized organic matter ('dead carbon')
III~ terrestrial plants
II/III~ marine organic matter/terrestrial plants
I~ lacustrine and marine algae
[7]Ro=random vitrinite reflectance
[8]T_{max}=Rock-Eval oven temperature at which the maximum amount of S_2 is generated
[9]CAI=conodont alteration index
[10]TAI=spore and pollen thermal alteration index
Also, the Oxygen Index [OI=(S_3x100/TOC)] is used in HI *vs*. OI plots to assess kerogen type.

LOWER BONNET PLUME FORMATION

With regards to source rock quantity, TOC ranges from 0.14 to 62.79% (Appendix 2) with a mean of 4.77%, indicating a poor to excellent source rock; S_1 ranges from 0 to 0.82 mg HC/g rock with a mean of 0.10 mg HC/g rock, indicating a poor source rock; and S_2 ranges from 0.02 to 36.92 mg HC/g rock with a mean of 4.77 mg HC/g rock, indicating a poor to excellent source rock. With regards to source rock quality, HI ranges from 10.00 to 409.00 mg HC/g TOC with a mean of 83.64 mg HC/g TOC indicating no hydrocarbons to oil are present; and the S_2/S_3 ratio ranges from 0.02 to 15.50 with a mean of 1.91, indicating no hydrocarbons to oil are present. Based on the S_2 *vs*. TOC plot (Fig. 4a) and the HI *vs*. T_{max} plot (Fig. 4b), Type III, or gas-prone kerogen and Type II, or gas- and oil-prone kerogen is present. With regards to source rock thermal maturation, T_{max} ranges from 402° to 471°C with a mean of 435°C, indicating the rock ranges from thermally immature to postmature with respect to oil generation (Fig. 4b).

UPPER BONNET PLUME FORMATION

With regards to source rock quantity, TOC ranges from 0.01 to 58.74% (Appendix 3) with a mean of 14.96%, indicating a poor to excellent source rock; S_1 ranges from 0 to 12.44 mg HC/g rock with a mean of 1.24 mg HC/g rock, indicating a poor to excellent source rock; and S_2 ranges from 0 to 116.66 mg HC/g rock with a mean of 23.39 mg HC/g rock, indicating a poor to excellent source rock. With regards to source rock quality, HI ranges from 0 to 414.00 mg HC/g TOC with a mean of 97.45 mg HC/g TOC indicating no hydrocarbons to oil is present; and the

S_2/S_3 ratio ranges from 0 to 11.31 with a mean of 1.39, indicating no hydrocarbons to oil is present. Based on the S_2 *vs.* TOC plot (Fig. 5a) and the HI *vs.* T_{max} plot (Fig. 5b), Type III, or gas-prone kerogen and Type II, or gas- and oil-prone kerogen is present. With regards to source rock thermal maturation, T_{max} ranges from 274 to 608°C with a mean of 426°C, indicating the rock ranges from thermally immature to postmature-mature with respect to oil generation (Fig. 4b).

Also associated with the upper Bonnet Plume Formation is a naturally burning coal (Fig. 6a). It occurs on the right limit of the Peel River opposite Mountain Creek (Fig. 2), and has been burning for over 100 years (de Sainville, 1898). Associated with the burning coal is a previously unrecognized tar (Fig. 6b). When fresh, the tar is black, vitreous, hot to touch and has a distinct chemical odour. Although Rock-Eval analysis has not been completed, the tar contains 42.8% resins and asphaltenes (hydrocarbon-like compounds containing mainly sulphur, nitrogen and oxygen), 24.5% aromatic hydrocarbons and 7.7% saturated hydrocarbons (K. Osadetz, writ. comm., 2008). The tar is physically and chemically similar to tar derived from the pyrolysis of coal and oil shale (Cane, 1976; Meyers, 1982).

DISCUSSION AND CONCLUSIONS

The Road River Formation contains small to moderate amounts of TOC, negligible to small amounts of S_1 and small amounts of S_2, indicating that overall, it is a poor source rock. HI values and the S_2/S_3 ratio suggest that only gas would be present. The majority of the T_{max}

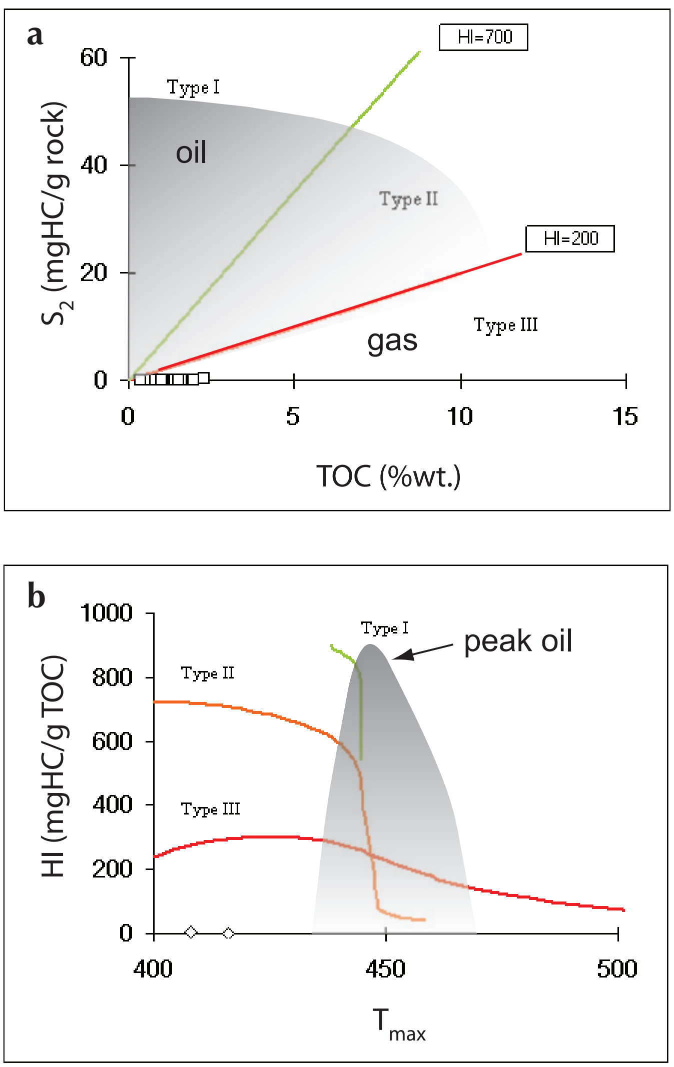

Figure 3. (a) *S_2 vs. TOC plot, Road River Formation.* ***(b)*** *HI vs. T_{MAX} plot, Road River Formation.*

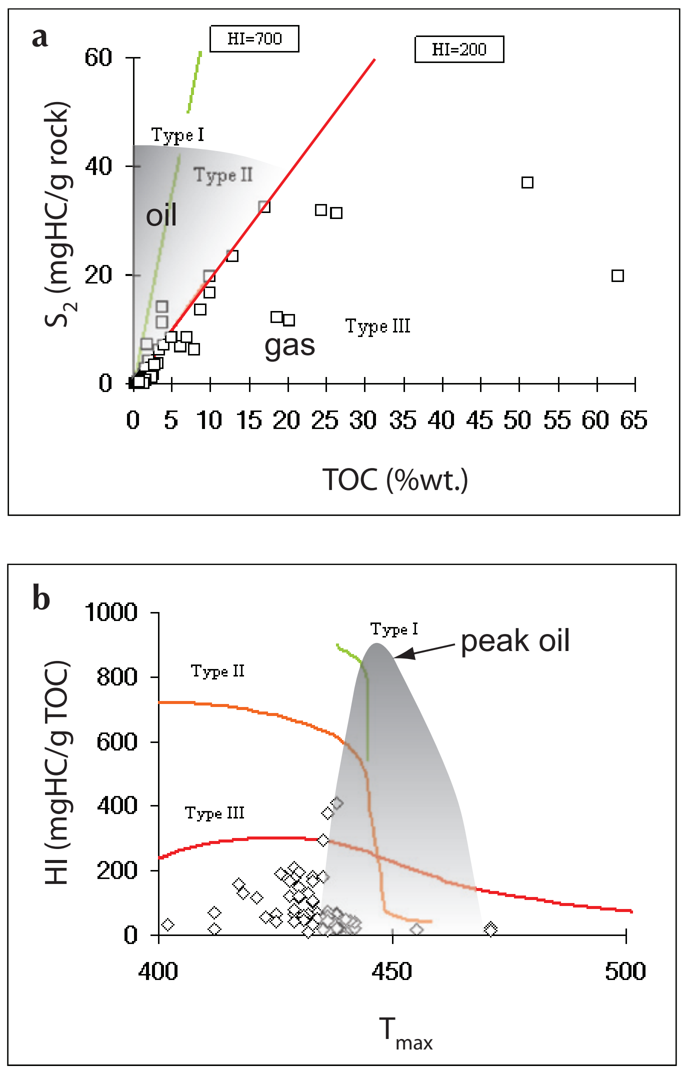

Figure 4. (a) *S_2 vs. TOC plot, lower Bonnet Plume Formation.* ***(b)*** *HI vs. T_{MAX}, lower Bonnet Plume Formation.*

values are probably unreliable due to the low S_2 values, and so the thermal maturity of the strata within the basin is uncertain. However, based on vitrinite reflectance and the conodont alteration index, Link and Bustin (1989) determined that the Road River Formation north of the Bonnet Plume Basin is postmature and that thermal maturity increases southwards. In addition, Link *et al.* (1989) concluded that the Road River Formation currently has poor source-rock potential, but probably generated oil in Devonian to Carboniferous time.

The lower Bonnet Plume Formation contains small to large amounts of TOC (note that coal is defined as greater than 50% by weight carbonaceous material, Neuendorf *et al.*, 2005), small to moderate amounts of S_1, and small to large amounts of S_2, indicating that overall, it is an excellent source rock. HI values, the S_2/S_3 ratio and the S_2 *vs.* TOC and the HI *vs.* T_{max} plots suggest that gas and possibly oil are present. The presence of Type II kerogen (*i.e.*, organic matter of marine origin that is oil- and gas-prone) is supported by the occurrence of dinoflagellate cysts (Nichols and Sweet, 1993), which indicate the lower Bonnet Plume Formation is, in part, marginal marine in origin. The T_{max} values indicate the rock is mainly thermally immature to early mature with respect to oil generation. According to Cameron and Beaton (2000), maximum random vitrinite reflectance values (Ro_{max}) for the lower Bonnet Plume range from 0.55 to 0.65, whereas D.G.F. Long (writ. comm., 2002) states that the average Ro_{max} value is 0.47. In general, the vitrinite reflectance values agree with the maturation level determined by Rock-Eval analysis. Also, coal rank in the

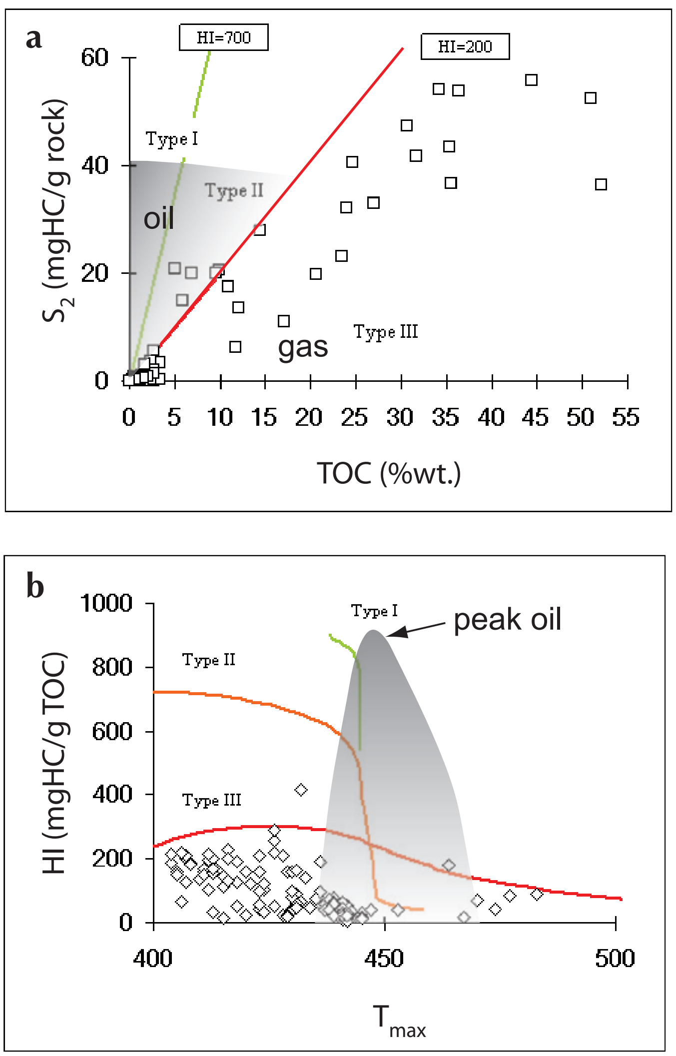

Figure 5. (a) *S_2 vs. TOC plot, upper Bonnet Plume Formation.* ***(b)*** *HI vs. T_{MAX}, upper Bonnet Plume Formation.*

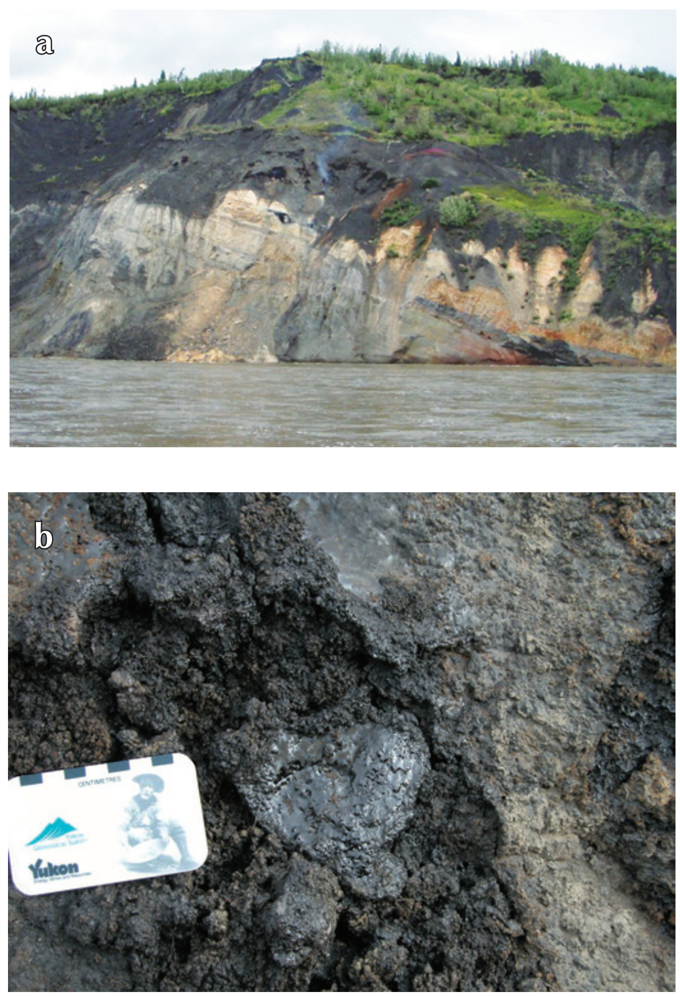

Figure 6. (a) *Naturally burning coal seam, upper Bonnet Plume Formation, Peel River, Yukon. Note associated tar (dark black patches).* ***(b)*** *Close-up of hydrocarbon-rich tar associated with the burning coal seam (scale is 7 cm long).*

lower Bonnet Plume Formation is sub-bituminous A to high volatile C bituminous (Long, 1986; Cameron and Beaton, 2000), corresponding to the beginning half of the oil window (Fowler *et al*., 2005). Economic accumulations of petroleum are thought to occur if coal rank is less than, or equal to, high-volatile bituminous (Stack *et al*., 1982). In addition, oil generation is marginally supported by the composition of the coal, which contains up to 9.7% liptinite (D.G.F. Long, writ. comm., 2002). According to Peters and Cassa (1994), 15 to 20% liptinite is required for coal to generate oil.

The upper Bonnet Plume Formation contains small to large amounts of TOC, negligible to large amounts of S_1 and negligible to large amounts of S_2, indicating that overall, it is an excellent source rock. HI values, the S_2/S_3 ratio, the S_2 *vs*. TOC and the HI *vs*. T_{max} plots suggest that gas and possibly oil are present. The T_{max} values indicate the rock is mainly thermally immature to early mature with respect to oil generation. According to D.G.F. Long (writ. comm., 2002), the average Ro_{max} values for the upper Bonnet Plume is 0.31**,** in general agreement with the maturation level determined by Rock-Eval analysis. Also, coal rank in the upper Bonnet Plume Formation is lignite (Cameron and Beaton, 2000), corresponding to pre-oil window conditions (Fowler *et al*., 2005). However, oil generation is supported by the composition of lignite, which contains up to 19% liptinite (D.G.F. Long, writ. comm., 2002), and the previously unrecognized tar.

Potential oil generation in the Bonnet Plume Formation is attributed to the occurrence of liptinite-bearing coal and previously unrecognized oil shale. Numerous studies have shown that coal provides the source for commercial oil accumulations in several sedimentary basins (Hendrix *et al*., 1995, and references therein). Oil-prone coal is not only characterized by high HI and S_2 values, but also high S_1 values: that is, it is thermally mature with respect to oil generation (Tissot and Welte, 1984). As an example, sample W1-79 from the upper Bonnet Plume Formation (Appendix 3) displays characteristics similar to oil-prone coal with HI=203, S_2=104.68 mg HC/g rock and S_1=6.35 mg HC/g rock. Note that Peters (1986) cautioned that Rock-Eval analysis tends to overestimate the liquid-hydrocarbon generative potential of coal. Several rock samples from the Bonnet Plume Formation are also similar to siliceous oil shale (*i.e*., clay minerals are predominant), rather than carbonate-rich oil shale (Duncan, 1976; Yen and Chilingar, 1976). Oil shale is characterized by high TOC and S_2 values, but low S_1 values: that is, it is thermally immature with respect to oil generation (Hunt**,** 1996). As an example, sample BP 79/17-201.2 from the lower Bonnet Plume Formation (Appendix 2) displays characteristics similar to oil shale with TOC=16.99%, S_2=32.28 mg HC/g rock and S_1=0.74 mg HC/g rock. In conclusion, the Bonnet Plume Formation is gas-prone and possibly oil-prone. Additional field and laboratory work is planned to follow-up on this previously unrecognized oil play.

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APPENDIX 1

Results of Rock-Eval analysis, Road River Formation

Sample	Qty	T_{max}	S_1	S_2	S_3	PI	S_2/S_3	PC(%)	TOC(%)	HI	OI
GL07-20A	70.3	408	0.01	0.02	0.37	0.46	0.26	0.01	0.35	6	106
GL07-21A	50.1	330	0.05	0.04	0.19	0.55	0.26	0.02	1.98	2	10
GL07-22A	70.3	312	0.01	0.01	0.33	0.46	0.26	0.02	1.55	1	21
GL07-23A	70.6	416	0.00	0.01	0.67	0.28	0.26	0.02	0.81	1	83
GL07-24A	70.1	328	0.01	0.01	0.26	0.34	0.26	0.01	0.70	1	37
GL08-34A	70.8	301	0.12	0.03	0.35	0.82	0.09	0.03	1.59	2	22
GL08-35A	70.4	341	0.02	0.02	0.95	0.52	0.02	0.03	0.88	2	108
GL08-36A	70.3	309	0.11	0.06	0.41	0.64	0.15	0.03	1.42	4	29
GL08-37A	50.3	291	0.71	0.16	0.55	0.81	0.29	0.10	2.30	7	24
GL08-37B	70.0	298	0.08	0.04	0.21	0.67	0.19	0.02	1.05	4	20
GL08-38A	50.4	525	0.01	0.01	0.91	0.66	0.01	0.04	1.35	1	67
GL08-39A	70.5	288	0.25	0.05	0.44	0.83	0.11	0.04	1.42	4	31
GL08-40A	70.6	296	0.45	0.08	0.26	0.85	0.31	0.05	0.81	10	32
GL08-41A	69.9	299	0.08	0.03	0.27	0.74	0.11	0.02	1.50	2	18
GL08-59A	70.6	542	0.01	0.03	1.43	0.14	0.02	0.05	1.02	3	140

APPENDIX 2

Results of Rock-Eval analysis, lower Bonnet Plume Formation

Depth (metres)	Sample	Qty	T_{max}	S_1	S_2	S_3	PI	S_2/S_3	PC (%)	TOC (%)	HI	OI	Coal (c)
	GL08-58A	10.6	412	0.79	36.92	30.61	0.02	1.21	5.71	51.13	72	60	c
40.2	BP 79/17	70.5	417	0.33	13.60	5.58	0.02	2.44	1.51	8.65	157	65	
41.8	BP 79/17	25.9	421	0.75	31.14	15.47	0.02	2.01	3.73	26.37	118	59	
42.3	BP 79/17	50.5	418	0.82	31.82	14.33	0.03	2.22	3.67	24.43	130	59	
44.0	BP 79/17	69.6	425	0.21	12.14	11.77	0.02	1.03	1.83	18.53	66	64	
45.0	BP 79/17	70.4	439	0.01	0.20	1.84	0.03	0.11	0.08	0.68	29	271	
47.0	BP 79/17	70.0	433	0.05	2.29	1.25	0.02	1.83	0.27	2.24	102	56	
48.5	BP 79/17	70.6	436	0.46	14.09	1.09	0.03	12.93	1.29	3.73	378	29	
49.5	BP 79/17	70.9	430	0.06	2.43	1.09	0.02	2.23	0.27	1.99	122	55	
50.9	BP 79/17	70.5	439	0.01	0.43	1.21	0.02	0.36	0.08	0.99	43	122	
52.5	BP 79/17	70.8	438	0.03	1.04	0.55	0.03	1.89	0.12	1.50	69	37	
54.0	BP 79/17	71.0	437	0.02	0.77	1.40	0.02	0.55	0.12	1.34	57	104	
55.6	BP 79/17	70.8	437	0.02	0.55	1.59	0.03	0.35	0.11	1.39	40	114	
57.0	BP 79/17	70.5	438	0.02	0.70	0.40	0.03	1.75	0.09	1.04	67	38	
58.5	BP 79/17	70.2	440	0.01	0.15	1.18	0.06	0.13	0.05	0.58	26	203	
59.5	BP 79/17	70.8	438	0.01	0.17	1.16	0.03	0.15	0.06	0.70	24	166	
61.0	BP 79/17	70.2	438	0.01	0.19	1.19	0.04	0.16	0.06	0.55	35	216	

APPENDIX 2, CONTINUED

Depth (metres)	Sample	Qty	T_{max}	S_1	S_2	S_3	PI	S_2/S_3	PC (%)	TOC (%)	HI	OI	Coal (c)
62.0	BP 79/17	70.6	435	0.01	0.24	0.85	0.02	0.28	0.05	0.82	29	104	
63.8	BP 79/17	70.8	439	0.01	0.56	2.14	0.02	0.26	0.12	1.19	47	180	
66.2	BP 79/17	71.0	434	0.03	1.18	1.65	0.02	0.72	0.17	1.67	71	99	
68.5	BP 79/17	70.2	425	0.01	0.36	6.49	0.02	0.06	0.30	0.91	40	713	
69.6	BP 79/17	70.1	436	0.02	0.82	0.50	0.03	1.64	0.10	1.07	77	47	
71.0	BP 79/17	70.8	436	0.01	0.42	0.33	0.03	1.27	0.06	0.70	60	47	
73.8	BP 79/17	70.3	438	0.01	0.15	1.34	0.07	0.11	0.06	0.55	27	244	
75.4	BP 79/17	70.9	412	0.00	0.04	1.70	0.08	0.02	0.06	0.22	18	773	
76.7	BP 79/17	70.4	471	0.01	0.05	0.23	0.12	0.22	0.02	0.23	22	100	
87.8	BP 79/17	70.4	430	0.10	3.69	1.27	0.03	2.91	0.41	3.15	117	40	
88.6	BP 79/17	70.2	427	0.35	23.52	4.23	0.01	5.56	2.31	12.90	182	33	
90.5	BP 79/17	70.9	441	0.01	0.14	1.52	0.09	0.09	0.06	0.56	25	271	
93.6	BP 79/17	70.5	438	0.01	0.11	1.23	0.04	0.09	0.06	0.54	20	228	
94.5	BP 79/17	70.2	442	0.00	0.14	0.45	0.03	0.31	0.03	0.58	24	78	
110.0	BP 79/17	70.3	430	0.07	2.91	0.79	0.02	3.68	0.30	1.97	148	40	
111.0	BP 79/17	70.3	434	0.01	0.63	2.01	0.02	0.31	0.12	1.26	50	160	
112.5	BP 79/17	70.2	437	0.01	0.66	1.54	0.02	0.43	0.11	1.27	52	121	
121.5	BP 79/17	70.1	442	0.01	0.45	1.47	0.02	0.31	0.09	1.04	43	141	
128.7	BP 79/17	70.1	440	0.01	0.31	1.64	0.03	0.19	0.08	0.75	41	219	
130.3	BP 79/17	70.8	437	0.01	0.61	1.62	0.02	0.38	0.11	1.20	51	135	
131.0	BP 79/17	70.2	435	0.27	11.21	1.33	0.02	8.43	1.05	3.81	294	35	
134.0	BP 79/17	70.8	435	0.02	0.55	0.68	0.03	0.81	0.08	1.00	55	68	
135.7	BP 79/17	70.8	429	0.10	4.14	0.58	0.02	7.14	0.39	1.96	211	30	
137.0	BP 79/17	70.1	437	0.01	0.41	1.00	0.02	0.41	0.07	0.93	44	108	
141.5	BP 79/17	70.8	432	0.03	1.77	0.44	0.02	4.02	0.18	1.37	129	32	
143.5	BP 79/17	70.3	441	0.01	0.63	2.22	0.02	0.28	0.13	1.36	46	163	
144.5	BP 79/17	70.8	435	0.01	0.65	1.45	0.02	0.45	0.11	1.22	53	119	
156.5	BP 79/17	70.7	433	0.22	6.13	1.64	0.03	3.74	0.64	3.36	182	49	
159.1	BP 79/17	70.6	429	0.05	1.69	2.78	0.03	0.61	0.27	2.56	66	109	
161.5	BP 79/17	70.5	436	0.01	0.39	0.39	0.03	1.00	0.05	0.66	59	59	
163.0	BP 79/17	70.6	435	0.01	0.52	3.14	0.02	0.17	0.15	1.14	46	275	
164.5	BP 79/17	70.0	438	0.20	7.44	0.48	0.03	15.50	0.67	1.82	409	26	
165.5	BP 79/17	10.5	402	0.11	19.82	17.34	0.01	1.14	3.67	62.79	32	28	c
169.3	BP 79/17	70.8	435	0.05	2.71	0.52	0.02	5.21	0.27	1.50	181	35	
170.7	BP 79/17	20.5	430	0.24	19.76	2.81	0.01	7.03	1.89	9.96	198	28	
173.0	BP 79/17	70.5	440	0.02	0.61	0.41	0.03	1.49	0.08	1.21	50	34	
174.4	BP 79/17	70.7	436	0.00	0.03	1.38	0.08	0.02	0.05	0.25	12	552	
180.5	BP 79/17	70.9	429	0.14	6.95	1.77	0.02	3.93	0.71	3.89	179	46	
182.0	BP 79/17	70.8	471	0.00	0.02	0.26	0.15	0.08	0.02	0.14	14	186	
190.8	BP 79/17	70.2	433	0.10	6.67	2.27	0.02	2.94	0.72	6.19	108	37	
192.3	BP 79/17	70.5	433	0.29	16.61	3.10	0.02	5.36	1.63	9.84	169	32	
194.9	BP 79/17	70.4	455	0.01	0.08	0.45	0.09	0.18	0.03	0.38	21	118	
197.3	BP 79/17	70.6	428	0.05	3.35	1.23	0.01	2.72	0.38	2.74	122	45	
201.2	BP 79/17	50.4	426	0.74	32.28	6.57	0.02	4.91	3.23	16.99	190	39	
208.7	BP 79/17	70.5	435	0.01	0.72	2.30	0.02	0.31	0.14	1.36	53	169	
208.5	BP 79/17	70.5	436	0.02	0.64	1.61	0.03	0.40	0.12	1.39	46	116	
220.2	BP 79/17	70.1	432	0.01	0.51	0.46	0.02	1.11	0.07	1.14	45	40	
224.2	BP 79/17	70.8	432	0.01	0.84	0.50	0.02	1.68	0.11	1.30	65	38	
311.5	BP 79/17	70.5	429	0.05	6.28	3.93	0.01	1.60	0.77	7.83	80	50	
313.5	BP 79/17	70.3	428	0.14	8.37	2.04	0.02	4.10	0.85	5.04	166	40	
316.5	BP 79/17	70.1	423	0.23	11.64	7.78	0.02	1.50	1.69	20.21	58	38	
317.4	BP 79/17	70.5	435	0.00	0.13	0.41	0.02	0.32	0.03	0.61	21	67	
327.8	BP 79/17	70.5	431	0.02	1.12	0.62	0.02	1.81	0.14	1.77	63	35	
335.5	BP 79/17	70.7	434	0.01	0.39	0.35	0.03	1.11	0.06	0.77	51	45	

APPENDIX 2, CONTINUED

Depth (metres)	Sample	Qty	T_{max}	S_1	S_2	S_3	PI	S_2/S_3	PC (%)	TOC (%)	HI	OI	Coal (c)
337.0	BP 79/17	70.3	431	0.01	0.76	0.59	0.02	1.29	0.11	1.61	47	37	
338.2	BP 79/17	70.3	433	0.01	0.23	0.64	0.05	0.36	0.05	0.66	35	97	
347.4	BP 79/17	70.6	431	0.02	1.09	1.94	0.02	0.56	0.18	2.32	47	84	
349.8	BP 79/17	70.7	429	0.02	0.69	2.85	0.02	0.24	0.21	1.61	43	177	
356.4	BP 79/17	70.1	432	0.00	0.14	0.75	0.03	0.19	0.06	1.41	10	53	
358.2	BP 79/17	70.0	430	0.14	8.34	1.82	0.02	4.58	0.84	6.94	120	26	
359.5	BP 79/17	70.5	438	0.01	0.18	0.45	0.03	0.40	0.04	0.73	25	62	

APPENDIX 3

Results of Rock-Eval analysis, upper Bonnet Plume Formation

Sample	Qty	T_{max}	S_1	S_2	S_3	PI	S_2/S_3	PC(%)	TOC (%)	HI	OI	coal (c)
W4-9	70.4	445	0.04	0.22	0.86	0.14	0.26	0.05	0.72	31	119	
W4-11	70.8	474	0.03	0.12	0.25	0.19	0.48	0.02	0.30	40	83	
W4-12	10.2	378	0.50	36.37	26.74	0.01	1.36	5.20	52.16	70	51	c
W4-15	70.4	432	0.13	1.49	2.33	0.08	0.64	0.25	2.21	67	105	
W4-34	70.3	444	0.02	0.29	8.93	0.06	0.03	0.49	1.30	22	687	
W4-37	70.9	453	0.08	0.39	0.60	0.17	0.65	0.07	0.92	42	65	
W4-41	70.3	423	0.07	0.55	1.66	0.11	0.33	0.15	1.37	40	121	
W4-42	70.1	415	1.23	13.47	14.57	0.08	0.92	2.06	12.00	112	121	
W4-43	10.3	412	12.44	85.46	35.10	0.13	2.43	10.41	50.18	170	70	
W4-44	10.3	396	7.19	91.35	39.78	0.07	2.30	11.11	58.74	156	68	c
W4-45	10.3	414	4.65	68.16	31.63	0.06	2.15	8.03	41.86	163	76	c
W4-46	10.3	404	4.19	90.33	32.83	0.04	2.75	10.11	48.45	186	68	c
W4-47	10.5	405	3.71	54.08	27.34	0.06	1.98	6.63	34.22	158	80	c
W4-48	20.8	405	2.74	53.77	26.98	0.05	1.99	6.58	36.38	148	74	c
W4-49	70.1	410	1.96	32.17	20.53	0.06	1.57	4.11	24.02	134	85	c
W4-50	70.3	418	2.01	27.76	11.06	0.07	2.51	3.14	14.50	191	76	c
W4-51	10.4	408	4.41	80.91	34.94	0.05	2.32	9.24	42.77	189	82	c
W4-52	10.2	413	4.49	77.35	29.91	0.05	2.59	8.58	43.82	177	68	c
W4-53	70.6	420	0.04	0.17	1.01	0.18	0.17	0.06	0.71	24	142	
W4-61	70.6	428	0.02	0.15	0.60	0.13	0.25	0.04	0.62	24	97	
W1-14	10.5	418	1.77	60.78	36.23	0.03	1.68	7.23	48.19	126	75	
W1-17	10.7	415	1.13	72.66	36.33	0.02	2.00	8.25	50.97	143	71	c
W1-481m	70.4	436	0.01	0.50	0.36	0.02	1.39	0.06	0.68	74	53	
W1-23	70.6	439	0.08	1.12	1.38	0.07	0.81	0.15	1.39	81	99	
W1-31	70.8	477	0.08	0.54	0.57	0.13	0.95	0.08	0.65	83	88	
W1-32	70.3	426	0.11	6.12	13.30	0.02	0.46	1.19	11.68	52	114	
W1-33	20.5	430	0.55	19.76	20.68	0.03	0.96	2.78	20.61	96	100	c
W1-34	70.5	447	0.04	0.36	0.78	0.11	0.46	0.06	0.85	42	92	
W1-36	70.3	470	0.12	0.67	0.88	0.15	0.76	0.10	0.98	68	90	
W1-45	70.7	441	0.02	0.27	0.71	0.07	0.38	0.06	0.99	27	72	
W1-46	70.4	464	0.20	0.78	0.49	0.20	1.59	0.12	0.43	181	114	
W1-51	70.5	426	0.34	5.70	1.53	0.06	3.73	0.57	2.60	219	59	
W1-61	10.0	412	1.53	36.68	27.89	0.04	1.32	5.00	35.49	103	79	c
W1-62	70.1	483	0.12	0.97	1.66	0.11	0.58	0.18	1.11	87	150	
W1-63	10.2	416	2.39	41.58	22.31	0.05	1.86	5.08	31.61	132	71	c
W1-64	10.6	416	5.29	83.06	23.85	0.06	3.48	8.75	36.27	229	66	c
W1-65	10.2	411	4.33	70.51	29.79	0.06	2.37	7.97	44.03	160	68	c
W1-66	10.4	411	4.74	68.23	31.28	0.06	2.18	7.85	40.38	169	77	c
W1-67	10.5	407	3.64	55.91	37.12	0.06	1.51	7.20	44.46	126	83	c

APPENDIX 3, CONTINUED

Sample	Qty	T_{max}	S_1	S_2	S_3	PI	S_2/S_3	PC(%)	TOC (%)	HI	OI	coal (c)
W1-68	10.5	411	3.14	66.02	34.21	0.05	1.93	7.67	43.92	150	78	c
W1-69	50.1	423	1.62	20.69	6.31	0.07	3.28	2.20	9.92	209	64	
W1-76	10.3	412	3.77	92.11	42.47	0.04	2.17	10.23	46.91	196	91	c
W1-77	20.4	413	3.00	47.35	23.41	0.06	2.02	5.56	30.61	155	76	c
W1-78	10.7	413	4.22	97.14	38.93	0.04	2.50	10.59	48.17	202	81	c
W1-79	10.6	407	6.35	104.68	37.93	0.06	2.76	11.26	51.53	203	74	c
W1-80	10.6	408	3.59	93.44	41.67	0.04	2.24	10.40	51.74	181	81	c
W1-81	10.1	390	3.68	74.03	38.35	0.05	1.93	8.91	50.24	147	76	c
W1-82	10.4	413	3.46	75.56	32.77	0.04	2.31	8.41	37.93	199	86	c
W1-83	10.3	396	2.23	69.95	49.61	0.03	1.41	9.18	56.51	124	88	c
W1-84	10.3	407	5.12	114.29	40.61	0.04	2.81	12.47	54.01	212	75	c
W1-85	10.6	413	4.60	83.19	34.82	0.05	2.39	9.42	48.82	170	71	c
W1-87	10.7	388	2.22	75.82	41.74	0.03	1.82	9.25	56.54	134	74	c
W1-88	10.5	404	5.22	116.66	40.18	0.04	2.90	12.40	54.19	215	74	c
W1-89	20.5	412	4.25	64.88	20.08	0.06	3.23	6.92	29.85	217	67	c
W1-90	10.7	387	1.83	52.47	44.19	0.03	1.19	7.46	50.91	103	87	c
W1-91	10.2	406	3.96	105.97	35.42	0.04	2.99	11.12	47.88	221	74	c
W1-94	70.8	424	0.05	0.59	1.04	0.08	0.57	0.09	0.56	105	186	
W1-95	70.4	430	0.02	0.18	0.46	0.11	0.39	0.04	0.41	44	112	
W2-3	70.2	416	0.03	0.08	0.30	0.26	0.27	0.02	0.04	200	750	
W2-5	70.4	435	0.01	0.02	0.65	0.38	0.03	0.02	0.03	67	2167	
W2-15	25.7	421	0.90	43.36	24.21	0.02	1.79	5.17	35.31	123	69	
W2-17	70.8	431	0.11	1.80	2.07	0.06	0.87	0.24	1.99	90	104	
W2-20	25.1	423	0.66	22.97	17.83	0.03	1.29	3.05	23.44	98	76	
W2-21	20.3	420	1.70	71.64	28.28	0.02	2.53	7.88	45.23	158	63	
W2-25	70.6	432	0.65	20.93	1.85	0.03	11.31	1.92	5.05	414	37	
W2-26	70.3	436	0.03	0.26	0.60	0.10	0.43	0.04	0.44	59	136	
W2-27	70.0	434	0.02	0.26	1.74	0.06	0.15	0.07	0.55	47	316	
W2-28	70.7	406	0.61	11.07	23.04	0.05	0.48	2.23	17.12	65	135	
W2-29	70.6	437	0.03	0.65	0.77	0.04	0.84	0.09	1.03	63	75	
W2-30	70.7	431	0.03	0.24	0.99	0.13	0.24	0.06	0.39	62	254	
W2-31	50.7	429	0.53	17.40	7.16	0.03	2.43	1.91	10.89	160	66	
W2-32	70.5	437	0.02	0.51	4.30	0.04	0.12	0.18	1.17	44	368	
W2-33	70.6	442	0.03	0.28	0.64	0.10	0.44	0.05	0.48	58	133	
W2-37	70.3	441	0.10	0.47	0.41	0.18	1.15	0.07	0.71	66	58	
W2-49	70.4	440	0.07	0.84	1.51	0.08	0.56	0.14	1.61	52	94	
W2-50	10.7	423	1.21	69.47	27.57	0.02	2.52	7.58	43.90	158	63	c
GL07-25A	70.4	339	0.01	0.03	0.15	0.20	0.20	0.01	0.01	300	1500	
GL07-26A	70.7	415	0.01	0.13	0.43	0.08	0.30	0.04	0.79	16	54	
GL07-26B	70.5	441	0.01	0.11	1.25	0.11	0.09	0.06	1.09	10	115	
GL07-26C	70.7	413	0.05	0.55	1.74	0.08	0.32	0.15	1.55	35	112	
GL07-26F	10.4	375	8.46	97.27	17.36	0.08	5.60	10.60	56.86	171	31	
GL08-21A	70.4	430	0.01	0.15	1.58	0.03	0.09	0.07	0.41	37	385	
GL08-22A	69.9	430	0.02	0.54	0.40	0.03	1.35	0.07	0.68	79	59	
GL08-23A	70.4	426	1.65	14.92	2.33	0.10	6.40	1.54	5.80	257	40	
GL08-24A	70.6	436	0.02	0.95	0.41	0.02	2.32	0.10	0.96	99	43	
GL08-25A	70.3	438	0.01	0.97	0.56	0.01	1.73	0.11	1.26	77	44	c
GL08-26A	70.0	430	0.07	3.27	1.72	0.02	1.90	0.38	3.37	97	51	
GL08-26B	70.3	439	0.01	0.67	0.37	0.01	1.81	0.08	1.02	66	36	
GL08-27A	69.9	428	1.08	20.00	7.07	0.05	2.83	2.19	9.53	210	74	
GL08-28A	70.5	442	0.01	0.07	0.73	0.07	0.10	0.03	2.68	3	27	
GL08-29A	70.3	441	0.01	0.61	0.35	0.02	1.74	0.07	1.24	49	28	
GL08-30A	50.4	304	0.71	0.36	0.57	0.66	0.63	0.11	3.30	11	17	

APPENDIX 3, CONTINUED

Sample	Qty	T_{max}	S_1	S_2	S_3	PI	S_2/S_3	PC(%)	TOC (%)	HI	OI	coal (c)
GL08-32A	71.0	396	0.01	0.01	0.15	0.43	0.07	0.01	1.42	1	11	
GL08-33A	70.6	424	0.00	0.01	0.18	0.26	0.06	0.01	0.03	33	600	
GL08-33B	70.8	608	0.01	0.02	0.24	0.26	0.08	0.01	0.04	50	600	
GL08-34A	70.8	301	0.12	0.03	0.35	0.82	0.09	0.03	1.59	2	22	
GL08-35A	70.4	341	0.02	0.02	0.95	0.52	0.02	0.03	0.88	2	108	
GL08-36A	70.3	309	0.11	0.06	0.41	0.64	0.15	0.03	1.42	4	29	
GL08-37A	50.3	291	0.71	0.16	0.55	0.81	0.29	0.10	2.30	7	24	
GL08-37B	70.0	298	0.08	0.04	0.21	0.67	0.19	0.02	1.05	4	20	
GL08-38A	50.4	525	0.01	0.01	0.91	0.66	0.01	0.04	1.35	1	67	
GL08-39A	70.5	288	0.25	0.05	0.44	0.83	0.11	0.04	1.42	4	31	
GL08-40A	70.6	296	0.45	0.08	0.26	0.85	0.31	0.05	0.81	10	32	
GL08-41A	69.9	299	0.08	0.03	0.27	0.74	0.11	0.02	1.50	2	18	
GL08-42A	70.8	439	0.02	0.80	1.98	0.02	0.40	0.13	1.30	62	152	
GL08-44A	70.3	433	0.05	2.58	0.76	0.02	3.39	0.26	1.84	140	41	
GL08-44B	70.5	440	0.01	0.24	0.63	0.02	0.38	0.05	0.95	25	66	
GL08-44C	70.7	441	0.01	0.31	0.67	0.02	0.46	0.05	0.97	32	69	
GL08-44D	70.9	443	0.01	0.35	1.94	0.01	0.18	0.09	1.09	32	178	
GL08-44E	70.5	447	0.01	0.48	0.59	0.02	0.81	0.07	1.16	41	51	
GL08-44F	70.6	423	0.01	0.05	0.31	0.12	0.16	0.02	0.09	56	344	
GL08-44G	70.9	467	0.00	0.03	0.45	0.07	0.07	0.02	0.16	19	281	
GL08-44H	70.2	445	0.01	0.06	0.40	0.18	0.15	0.03	0.33	18	121	
GL08-45A	70.6	430	0.07	3.68	0.88	0.02	4.18	0.36	2.32	159	38	
GL08-45B	70.0	443	0.01	0.41	0.48	0.02	0.85	0.06	1.08	38	44	
GL08-46A	70.1	439	0.01	0.28	0.46	0.04	0.61	0.05	0.93	30	49	
GL08-46B	70.2	435	0.03	1.99	1.84	0.01	1.08	0.28	2.66	75	69	
GL08-46C	70.4	442	0.01	0.09	0.31	0.06	0.29	0.02	0.33	27	94	
GL08-46D	70.6	445	0.00	0.02	0.39	0.04	0.05	0.02	0.16	12	244	
GL08-46E	70.3	429	0.01	0.12	0.47	0.10	0.26	0.04	0.51	24	92	
GL08-47A	70.4	442	0.00	0.20	0.65	0.02	0.31	0.04	0.64	31	102	
GL08-51B	70.3	418	0.61	1.37	0.88	0.31	1.56	0.22	2.68	51	33	
GL08-53A	70.4	438	0.04	0.78	0.86	0.05	0.91	0.13	1.94	40	44	
GL08-54A	50.7	424	1.55	33.09	18.54	0.04	1.78	4.04	27.06	122	69	
GL08-54B	70.6	431	0.02	0.67	1.20	0.02	0.56	0.12	1.46	46	82	
GL08-54C	70.1	426	0.76	20.02	3.75	0.04	5.34	1.94	6.93	289	54	
GL08-55A	70.8	441	0.00	0.15	0.30	0.03	0.50	0.03	0.68	22	44	
GL08-55B	70.6	442	0.00	0.05	0.17	0.07	0.29	0.01	0.22	23	77	
GL08-55C	70.6	429	0.01	0.13	0.54	0.05	0.24	0.04	0.70	19	77	c
GL08-56A	70.0	436	0.07	3.04	0.80	0.02	3.80	0.30	1.60	190	50	
GL08-56B	50.1	431	1.52	40.67	15.14	0.04	2.69	4.41	24.61	165	62	c
GL08-56C	70.2	439	0.00	0.16	0.60	0.03	0.27	0.04	0.69	23	87	
GL08-57A	70.4	274	0.00	0.00	0.26	1.00	0.00	0.01	0.01	0	2600	