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Jurassic coal in Western Australia and its depositional environment

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Abstract: The Jurassic coal in Western Australia is represented by the Cattamarra Coal Measures of the Cockleshell Gully Formation, located in the Hill River area. The area occupies the Hill River Shelf of North Perth Basin, situated approximately 225 km north of Perth. Six drill core samples from the coal measures comprising coal seams G 1 to G 6 were examined for lithotype and maceral analyses. The coal measures subcrop in a half-graben, bounded by the Lesueur-Peron Fault in the west, and the Warradarge Fault in the east.

Predominantly, the coal comprises banded, dull banded, and dull lithotypes, with minor bright, bright banded, and fusainous types, or is regarded as clarain and durain, with minor amounts of vitrain and fusain. Tiny specks of pyrite are present in the coal. Maceral analysis reveals that the coal is rich in vitrinite and inertinite, whilst the exinite and mineral matter are minor in content. The vitrinite, composed mainly of telocollinite and desmocollinite, varies from 41.6% to 73.0%. Meanwhile, the inertinite having a range from 10.4% to 24.8%, is dominated by semifusinite, fusinite, and inertodetrinite. The exinite group content which is relatively low with 6.2%–20.4% in range, is represented by sporinite, cutinite, alginite, and resinite. The mineral matter, dominated by clay and pyrite ranges from 2.8% to 35.6%. The microlithotypes analyses show that the vitrite plus clarite content varies between 42.5% to 64.8%, intermediates from 25.4% to 50.7%, whilst inertite plus durite content is relatively low, ranging from 4.8% to 18.5%.

Based on lithotype, maceral, and microlithotype analyses, the depositional environment of the coal is interpreted as a telmatic wet forest swamp of a brackish to upper-lower delta plain environment. Furthermore, trace element distribution, especially Boron content in the coal supports the presence of a marine influence during peat deposition in the mire. Thereby, the environment of coal deposition is postulated to be an upper to lower delta type.

INTRODUCTION

The coal samples for this study were obtained from the bore holes drilled in the Gairdner Range of Hill River Coalfield, situated 225 km north of Perth, Western Australia (Fig. 1). The Gairdner Range occupies the geomorphological unit known as the Arrowsmith Region (Playford *et al.*, 1976). The western boundary of the Arrowsmith Region is delineated by the Gingin Scarp, whilst the eastern limit of the region is marked by the Dandaragan Scarp.

The aim of the study was to establish the petrographic composition of Jurassic coal in Western Australia, represented by the Hill River coal, in order to interpret the depositional environment of the coal precursor. The petrographic composition comprises maceral, microlithotype, and mineral matter contents. Additional data, namely trace element analysis was used to support the depositional environment interpretation.

Geological setting

The area of Hill River Coalfield occupies the Hill River Shelf of the North Perth Basin, shown in Figure 2. This shelf is located at the western flank of the Dandaragan Trough and the area is bounded by the Lesueur-Peron Faults in the west and the Warradarge Fault in the east (Kristensen, 1989).

The rock sequences, ranging in age from Late Triassic to Late Jurassic, outcrops in the area (Table 1). The Lesueur Sandstone of Middle to Late Triassic in age, comprising coarse- to very coarse-grained feldspathic and kaolinitic sandstone, and conglomerate with minor siltstone is the oldest sequence in the area. It is overlain conformably by the Early Jurassic Eneabba Formation, characterised by the predominance of interbedded

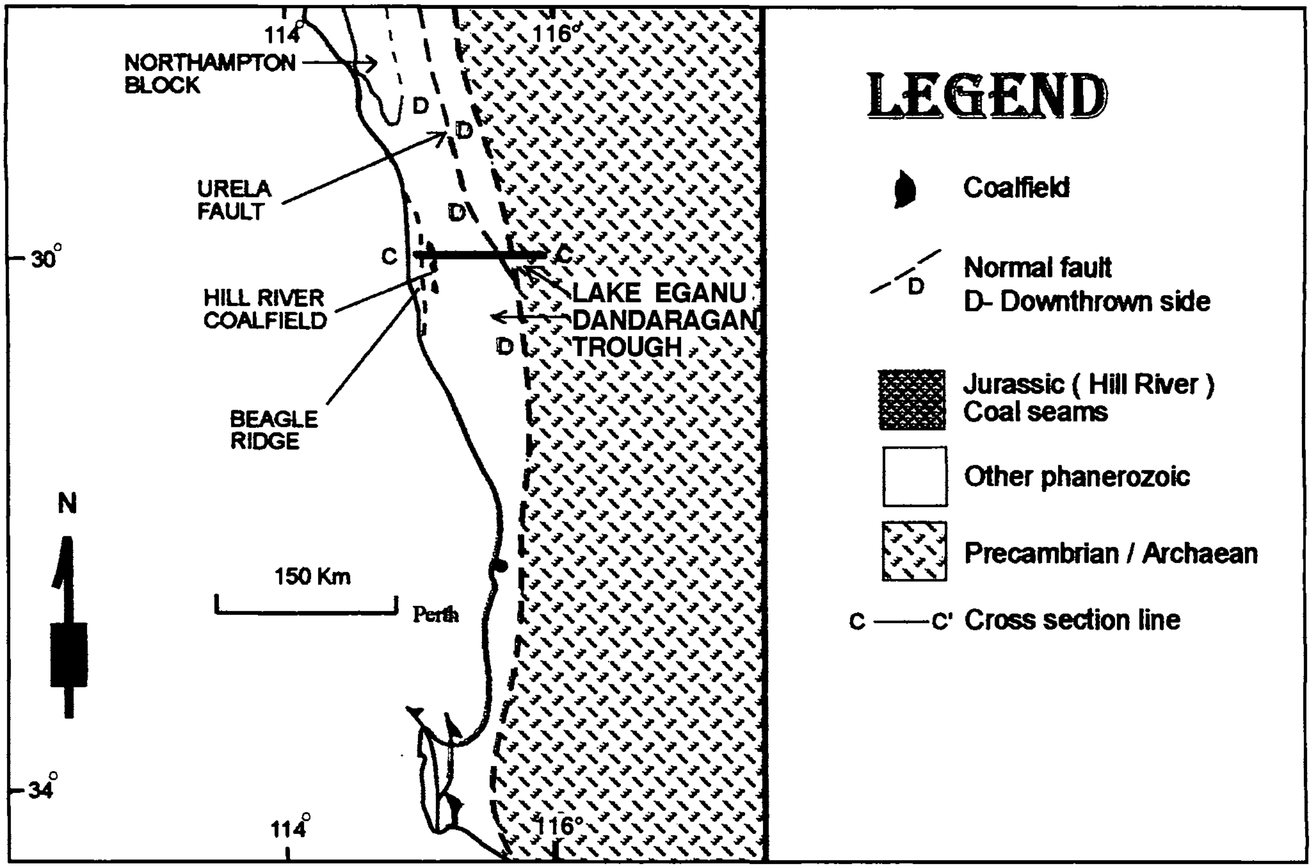


Figure 1. Locality map of Hill River Coalfield (modified from Playford *et al.*, 1976).

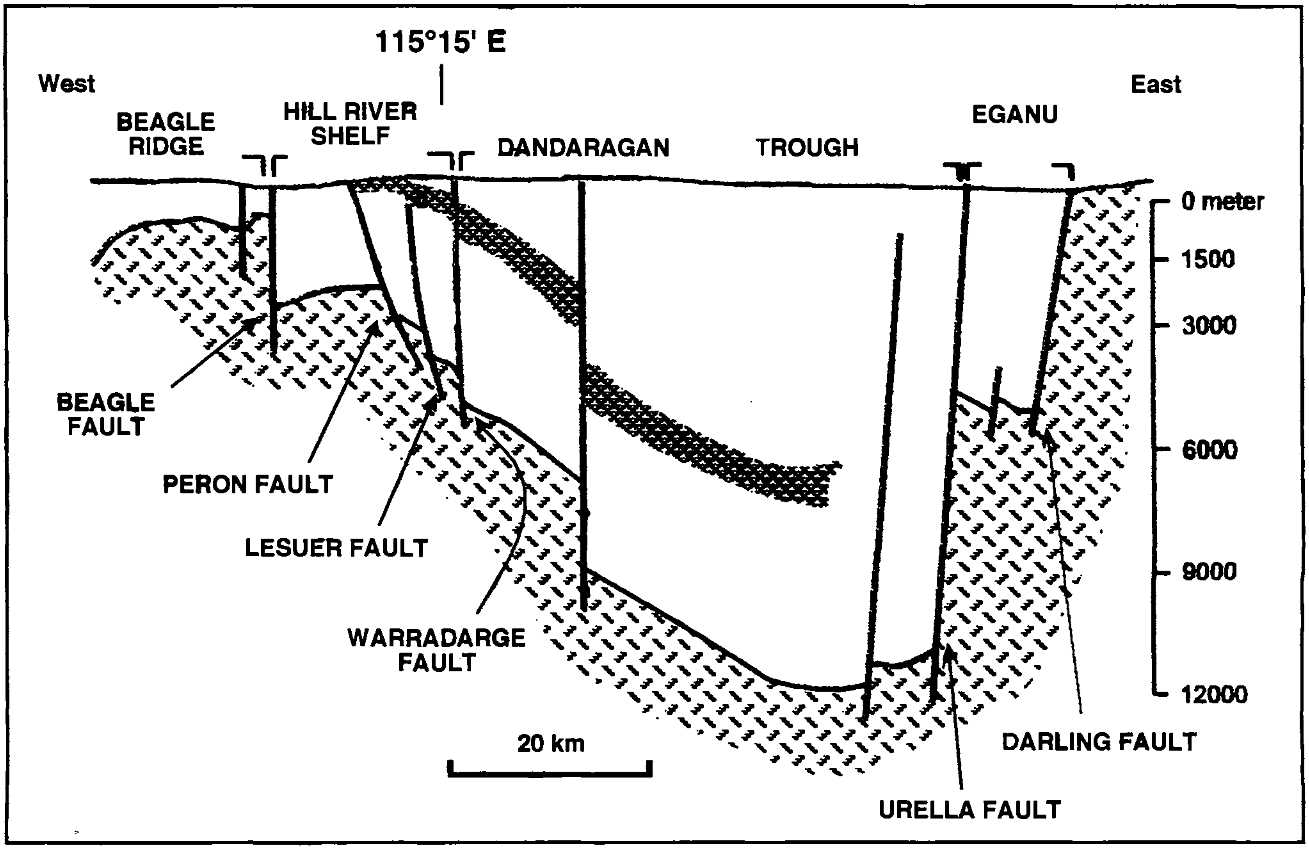


Figure 2. Structural setting and cross-section of Hill River area (modified from Playford *et al.*, 1976).

Table 1. Triassic-Late Jurassic stratigraphy of Hill River Coalfield (Kristensen, 1989).

AGE	EXISTING NOMENCLATURE		CRAE NOMENCLATURE	
Late Jurassic	Yarragadee Formation		Mt. Peron Sandstone	
Middle Jurassic	Cadda Formation			
Early Jurassic	Cockleshell Gully Formation	Cattamarra Coal Measures (Member)	Cattamarra Group	**Hill River Coal Measures** Bitter Pool Claystone
		Eneabba Member	Eneabba Formation	
Middle - Late Triassic	Lesueur Sandstone		Lesueur Sandstone	

mottled and multicoloured claystone. The Eneabba Formation underlies conformably the Bitter Pool Claystone of Early Jurassic age, consisting of claystone.

The Bitter Pool Claystone underlies conformably the Hill River Coal Measures comprising cyclic sequences of sandstones, fining-upwards into mudstone and coal. The sand/shale ratio gradually increases towards the base. The unit is dominated by fine-grained sandstone with some zones of marine and brackish-water microfossils and shell beds (Sappal and Islam, 1992). Rip-up clasts of underlying coal and mudstone are commonly recognised within the sandstone. The 5 to 6 sub-seams of the coal seam G occupy the upper part of the formation, and have a cumulative thickness of 8.50 m.

The Hill River Coal Measures are overlain by the Late Jurassic Mt. Peron Sandstone, which has less favourable condition of peat formation. According to the CRAE Nomenclature given in Table 1, the Bitter Pool Claystones and the Hill River Coal Measures are grouped into the Cattamarra Coal Measures.

Structure

The conspicuous folds in the Hill River Shelf are associated with faults (Fig. 2). The Cockleshell Gully Anticline present in the Hill River area, is highly faulted and composed of a series of blocks, which step down to the east. The highly distorted dome-like structure is present, which is flanked by two faults with displacements exceeding 1,000 m.

The area is bounded from the west to the east by the normal fault, namely the Beagle, the Lesueur-Peron and the Warradarge Faults, respectively.

PETROGRAPHY

Lithotype, maceral, microlithotype, and mineral matter analyses were established on cored samples from the drill holes CPCH 1, CPCH 37, CPCH 39, CPCH 47, CPCH 57 and CPCH 60.

Macroscopically, the coal is dominated by banded, dull banded and dull lithotypes, with minor bright, bright banded and fusainous types. In accordance with Warbrooke (1981), the dull lithotype indicates an open water condition, whilst the brighter type is deposited in a wet swamp area.

The petrographic analyses were carried out to establish variability within the G 1–G 5/6 coal seams. Maceral analyses in terms of vitrinite, exinite, and inertinite of the five to six sub-seams from those six drill cores are presented in Tables 2 and 3. The table also shows data of vitrinite reflectance and mineral matter distribution in the individual sub-seams of the drill cores. Moreover, microlithotype composition of the individual sub-seams is given in Table 4.

Maceral analysis

The dominant maceral groups are vitrinite and inertinite, while the exinite and mineral matter are of minor contents, as shown in Tables 2 and 3. The vitrinite content ranges between 41.60% to 73.00%, and comprises vitrinite A (telocollinite and telinite) and vitrinite B (desmocollinite, corpocollinite, and vitrodetrinite). The maceral group of vitrinite, classified medium to high proportions, is dominated by telocollinite and desmocollinite. The telocollinite was derived from xylem and cortex tissues, and thus originated from wood producing plants. Other macerals of vitrinite group, those are desmocollinite and corpocollinote represent a thoroughly decomposed and gelified attritus from a variety of source materials. The relatively high vitrinite content in most of the sub-seams the coal, indicates that a reasonable degree of preservation of decayed plant material occurred, and vitrinite could be used as a measure of petrographic indices to interpret a peat depositional environment.

Inertinite maceral group consisting mainly of semifusinite, fusinite, and inertodetrinite, with minor macrinite, and rare sclerotinite and micrinite ranges from 10.40% to 24.80%. Furthermore, semifusinite dominates over other inertinite macerals, and it is generally associated with vitrinite and fusinite. Inertodetrinite representing the second highest proportion of the inertinite group, is present particularly in association with desmocollinite. Micrinite occurs as traces, associated especially with vitrinite in the coal.

Exinite group varies from 7.20% to 20.80%. In order of decreasing proportions, it is represented by sporinite, alginite, cutinite, liptodetrinite, and resinite. The sporinite, cutinite, and alginite predominate, whilst resinite and liptodetrinite are present in minor amounts. Thin walled-sporinite (tenuisporinite) is the dominant component within the exinite in the Hill River coal. Cutinite is often recognised in association with varieties of vitrinite B especially with corpocollinite, and also with resinite.

Mineral matter

The predominant recognisable mineral matter in the coal are the syngenetic and diagenetic types, intergrown intimately with macerals. The minor amount is epigenetic type, coarsely intergrown and associated with cleats or fractures, coating or infillings in the maceral groups. The mineral matter distribution is given in Tables 2 and 3.

The most prominent mineral, recognised in the coal is clay. The clay minerals occur as pellets or bands among macerals, and also as cell cavity infillings in telinite, fusinite, and cleat infillings. The amount of the clay mineral varies from 1.00% to 27.00% in the coal. The highest content of the minerals occupies the lowest sub-seam of the coal (G 5/6).

The syngenetic pyrite present as framboids, and cell fillings in macerals. Tiny specks, granules and framboids of pyrite are often recognised in vitrinite, particularly in desmocollinite and telocollinite macerals. The epigenetic pyrite comprises isolated bodies, and cleat and fracture infillings in the coal. The pyrite ranges between 1.00% and 7.20%. Similar to the clay mineral content, the lowest sub-seam (G 5/6) of each core contains the highest pyrite content.

Silica occurs as single or group of rounded to elongated bodies. In addition, carbonates occur as cell wall infillings in fusinite and also as replacement in vitrinite. Both minerals are present rarely.

Microlithotype analysis

Vitrite and duroclarite are the major microlithotypes occurring in the Hill River coal (Table 4), and their contents range between 25.20% and 45.50%, and 13.20% to 37.80%, respectively. These are followed by inertite ranging between 3.80% and 12.80%, clarite from 2.40% to 13.80%, and vitrinertite with a range of 3.40% to 13.20%. The subordinate microlithotypes are liptite, durite, vitrinertoliptite and clarodurite which occur within the range of 0.10% to 3.0%. The carbominerites predominantly comprise carbargilite and carbopyrite. Range of carbargilite content is between 4.30% and 27.80%, while carbopyrite shows a value of around 0.40% to 8.60%. Carbankerite and carbosilicate display a nearly similar amount, which range from 0.10% to 0.60%.

Most of the sub-seams are dominated by the microlithotypes vitrite + clarite with amounts of more than 50%. In general, sub-seams containing high trimacerite content, also have a high inertinite content.

Table 2. Maceral, mineral matter, and vitrinite reflectance analyses of CPCH 1, 37, and 39, Hill River coal.

MACERAL	CPCH 1						CPCH 37					CPCH 39					
	G 1	G 2	G 3	G 4	G 5	G 6	G 1	G 2	G 3	G 4	G5/6	G 1	G 2	G 3	G 4	G 5	G 6
Telinite	0.6	1.0	0.4	0.2	0.2	0.4	0.0	1.0	1.6	0.8	1.0	0.6	1.2	2.2	0.8	1.8	0.2
Telocollinite	29.2	35.5	33.0	25.6	29.2	19.6	34.0	37.8	36.2	38.4	30.0	23.8	34.0	37.6	42.2	33.0	28.0
Vitrinite-A	29.8	36.5	33.4	25.8	29.4	20.0	34.0	38.8	37.8	39.2	31.0	24.4	35.2	39.8	43.0	34.8	28.2
Desmocollinite	22.3	20.3	24.0	23.8	22.4	18.6	24.6	23.2	19.4	23.8	23.0	31.2	30.2	26.4	28.8	24.6	23.0
Corpocollinite	8.6	5.0	5.4	2.6	3.6	6.2	3.4	2.1	6.0	1.2	1.0	3.0	0.4	1.0	1.2	1.0	0.6
Vitrodetrinite	0.3	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
Vitrinite-B	31.8	25.4	29.6	26.4	26.0	24.8	28.2	25.4	25.4	25.0	24.0	34.4	30.6	27.4	30.0	25.6	23.6
VITRINITE	61.0	61.9	63.0	52.2	55.4	44.8	62.2	64.2	63.2	64.2	55.0	58.8	65.8	67.2	73.0	60.4	51.8
Sporinite	5.3	5.6	8.3	8.6	7.0	5.6	5.8	4.6	5.5	4.6	2.8	6.1	6.4	8.4	8.8	5.8	4.2
Cutinite	2.0	0.9	1.1	1.4	2.2	1.0	1.0	0.4	2.1	1.0	1.2	1.5	0.6	0.6	1.4	0.8	1.8
Resinite	1.0	0.6	0.7	1.0	0.6	0.2	1.0	0.4	0.6	0.2	0.2	0.4	0.0	0.4	0.2	0.6	0.2
Alginite	4.1	4.6	3.4	8.0	5.6	8.2	1.4	1.4	0.6	0.6	2.0	1.0	0.2	0.6	0.2	1.4	1.2
Liptodetrinite	0.4	0.1	0.3	1.8	0.6	0.8	0.2	0.0	1.2	0.4	0.4	1.0	0.0	0.2	0.8	0.6	0.2
EXINITE	12.8	11.8	13.8	20.8	16.0	15.8	9.4	6.8	10.0	6.8	6.6	10.0	7.2	10.2	11.4	8.2	7.6
Semifusinite	10.8	8.9	6.3	8.2	5.4	5.0	9.2	7.6	6.6	6.4	7.6	9.0	10.4	6.4	4.4	5.8	11.6
Fusinite	2.5	2.3	1.9	1.2	1.6	1.0	2.0	2.4	4.4	1.6	1.4	3.4	2.4	2.2	0.8	1.8	4.2
Sclerotinite	0.1	0.1	0.2	0.0	0.2	0.4	0.4	0.4	0.0	0.2	0.4	0.4	0.0	0.0	0.0	0.4	0.2
Macrinite	3.1	3.8	2.1	3.0	1.4	4.0	2.2	1.2	1.4	1.2	1.4	1.8	1.6	1.0	1.0	1.0	1.0
Micrinite	0.2	0.5	0.6	0.2	0.4	0.0	0.2	0.6	1.4	0.0	0.4	0.2	0.2	0.0	0.0	0.2	0.0
Inertodetrinite	5.0	6.2	4.6	6.0	6.4	5.0	7.0	11.0	7.6	4.8	6.4	10.0	7.0	8.0	4.2	5.0	6.2
INERTINITE	21.7	21.8	15.7	18.6	15.4	15.4	21.0	23.2	21.4	14.2	17.6	24.8	21.6	17.6	10.4	14.2	23.2
Clay	3.1	2.2	5.8	3.6	9.0	17.6	4.8	2.4	2.2	8.4	14.2	4.0	2.0	2.2	1.0	15.2	10.4
Pyrite	1.2	2.3	1.5	4.6	4.0	6.0	1.8	1.8	2.2	5.2	3.8	1.0	1.6	1.8	3.2	1.2	5.2
Carbonate	0.0	Trace	0.0	0.0	0.0	0.4	0.2	1.4	1.0	0.8	2.8	1.4	1.6	1.0	1.0	0.8	1.8
Quartz	0.2	Trace	0.2	0.2	0.2	0.0	0.6	0.2	0.0	0.4	0.0	0.0	0.2	0.0	0.0	0.0	0.0
MIN. MATTER	4.5	4.5	7.5	8.4	13.2	24.0	7.4	5.8	5.4	14.8	20.8	6.4	5.4	5.0	5.2	17.2	17.4
RO max.	0.47	0.49	0.50	0.50	0.50	0.48	0.46	0.47	0.45	0.46	0.49	0.48	0.47	0.44	0.49	0.44	0.43

Table 3. Maceral, mineral matter and vitrinite reflectance analyses of CPCH 47, 57, and 60, Hill River coal.

MACERAL	CPCH 47					CPCH 57					CPCH 60				
	G 1	G 2	G 3	G 4	G 5	G 1	G 2	G 3	G 4	G 5	G 1	G 2	G 3	G 4	G 5
Telinite	0.6	1.0	0.4	2.6	2.4	0.4	0.4	0.4	0.0	0.0	0.0	0.0	0.2	0.2	0.0
Telocollinite	33.4	36.0	39.8	36.8	23.8	31.4	35.8	30.4	32.2	16.6	32.2	32.2	31.6	33.8	15.4
Vitrinite A	34.0	37.0	40.2	39.4	26.2	31.8	36.2	30.8	32.2	16.6	32.2	32.4	31.8	34.0	15.4
Desmocollinite	24.6	28.8	21.0	24.0	26.0	27.6	23.0	24.4	30.8	29.6	30.6	34.4	27.6	30.6	23.8
Corpocollinite	2.0	1.4	3.2	4.0	1.6	3.8	2.2	2.0	2.6	1.0	2.2	2.4	7.2	3.0	2.4
Vitrodetrinite	0.2	0.0	0.6	0.2	0.0	0.2	0.2	0.2	0.0	0.0	0.2	0.2	0.4	0.0	0.0
Vitrinite B	26.8	30.2	24.8	28.2	27.6	31.6	25.4	26.6	33.4	30.6	33.0	37.0	35.2	33.6	26.2
VITRINITE	60.8	67.6	65.0	67.6	53.8	63.4	61.6	57.4	65.6	47.2	65.2	69.4	67.0	67.6	41.6
Sporinite	5.7	4.8	5.0	5.8	5.2	5.6	5.0	7.4	6.7	4.6	3.8	4.0	4.6	4.6	1.8
Cutinite	0.6	0.4	1.8	1.4	1.0	2.1	1.9	2.1	2.7	1.8	2.0	2.0	4.6	3.0	2.0
Resinite	0.6	0.6	0.6	0.0	0.2	0.4	0.6	0.6	0.4	0.4	0.0	0.0	0.6	0.6	0.0
Alginite	1.5	0.4	0.4	0.6	1.8	1.7	2.3	1.5	1.2	3.2	1.4	1.8	0.6	0.6	1.4
Liptodetrinite	0.0	0.0	0.0	0.6	0.4	0.6	0.0	0.0	0.2	3.8	0.8	0.0	0.2	0.0	3.4
EXINITE	8.4	6.2	7.8	8.4	8.6	10.4	9.8	11.6	11.2	13.8	8.0	7.8	10.6	8.8	8.6
Semifusinite	11.0	8.6	9.8	6.8	7.4	9.8	12.8	7.2	6.8	8.0	7.6	7.4	7.8	5.6	6.6
Fusinite	3.8	3.0	3.0	3.4	3.0	2.8	2.8	5.0	3.6	4.6	3.6	2.0	3.6	4.6	3.0
Sclerotinite	0.0	0.0	0.0	0.2	0.0	0.0	0.2	0.0	0.0	0.4	0.0	0.4	0.0	0.2	0.6
Macrinite	0.8	1.6	1.6	1.0	0.6	0.8	1.2	1.6	1.2	1.4	0.8	0.8	1.2	0.4	0.2
Micrinite	0.2	0.0	0.6	0.6	0.4	0.4	0.8	0.6	0.2	0.0	0.2	0.2	0.2	0.2	0.0
Inertodetrinite	8.6	7.6	6.0	5.4	7.0	8.2	7.0	5.2	4.6	5.0	7.2	9.2	4.0	5.4	3.8
INERTINITE	24.4	20.8	21.0	17.4	18.4	22.0	24.8	23.6	15.4	19.4	19.4	20.0	16.8	16.4	14.2
Clay	2.6	1.8	3.6	2.0	12.8	2.0	1.0	3.2	5.2	12.6	3.0	1.0	1.8	1.0	27.0
Pyrite	2.4	2.4	1.8	3.4	5.8	1.2	1.6	2.8	1.4	4.8	2.2	1.2	2.4	5.6	7.2
Carbonate	1.4	1.2	0.8	1.2	0.6	1.0	1.2	1.4	1.2	2.0	2.2	0.6	1.4	1.2	3.6
Quartz	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	Trace	Trace	0.0	Trace
MIN. MATTER	6.4	5.4	6.2	6.6	19.2	4.2	3.8	7.4	7.8	19.6	7.4	2.8	5.6	7.2	35.6
RO max.	0.44	0.46	0.44	0.46	0.48	0.48	0.49	0.49	0.49	0.48	0.49	0.51	0.5	0.49	0.48

Table 4. Microlithotype Analysis of Hill River Coal.

CORE	Sub-Seam	Vitrite	Liptite	Inertite	Clarite	Durite	Vitrinertite	Duroclarite	Vitrinertoliptite	Clarodurite	Carbopyrite	Carbargillite	Carbominerite
CPCH 1	G 1	35.6	0.5	6.2	12.9	0.3	8.9	24.2	0.1	0.0	0.9	9.2	10.4
	G 2	45.5	0.1	9.4	3.8	0.2	8.4	25.7	0.4	1.0	0.9	4.3	5.5
	G 3	39.6	0.0	4.9	3.3	0.2	8.4	33.6	1.1	3.0	1.4	4.3	5.9
	G 4	25.2	0.2	4.2	13.8	1.2	3.4	37.8	2.6	1.8	3.0	6.8	9.8
	G 5	39.0	0.0	5.2	8.4	0.0	10.6	22.4	0.4	0.6	6.6	6.8	13.4
	G 6	36.4	0.0	10.0	2.8	0.4	5.2	13.4	0.4	1.6	8.6	21.2	29.8
CPCH 37	G 1	36.8	0.0	9.0	8.8	0.8	8.4	23.0	2.2	2.0	2.6	6.0	9.0
	G 2	42.2	0.6	12.2	5.4	0.0	6.2	22.6	0.4	1.4	1.2	7.4	9.0
	G 3	44.0	0.4	8.8	7.8	0.4	6.2	23.6	1.0	1.4	1.2	5.0	6.4
	G 4	34.4	0.4	3.8	13.2	0.2	5.4	26.2	0.2	1.2	3.8	11.0	16.2
	G 5	38.4	0.2	9.4	2.6	0.4	10.0	16.4	0.0	0.4	5.2	17.0	22.2
CPCH 39	G 1	31.4	0.2	12.8	6.8	2.0	8.6	24.6	1.4	2.2	0.4	9.6	10.0
	G 2	42.0	0.2	7.6	9.0	0.4	8.6	20.8	0.4	1.4	1.4	7.6	9.6
	G 3	35.6	1.0	11.0	3.8	1.4	6.8	29.2	2.0	0.4	2.4	6.0	8.8
	G 4	42.8	0.2	5.6	11.6	0.8	7.8	20.4	0.4	0.8	3.2	6.4	9.8
	G 5	34.2	0.4	4.6	5.4	0.2	6.4	24.8	1.2	0.4	1.6	20.6	22.4
	G 6	35.6	0.0	12.6	5.4	0.2	6.8	15.6	0.4	1.2	3.0	19.2	22.2
CPCH 47	G 1	45.2	0.4	12.0	3.2	0.2	11.4	13.2	0.8	1.0	2.8	9.4	12.6
	G 2	44.0	0.4	12.6	4.0	0.0	8.2	18.0	1.2	2.4	2.4	6.4	9.2
	G 3	43.2	0.0	12.8	5.2	0.2	10.4	17.0	0.6	1.2	3.0	6.4	9.4
	G 4	42.2	0.6	6.8	9.4	0.0	6.4	18.0	2.4	1.8	6.4	5.8	12.6
	G 5	35.4	0.0	8.8	5.8	0.0	7.0	15.6	1.0	1.6	6.6	18.2	24.8
CPCH 57	G 1	35.8	0.0	13.8	2.4	0.6	12.8	18.4	0.4	2.0	0.6	12.0	14.0
	G 2	44.2	0.2	9.0	4.0	0.0	13.2	20.2	0.4	2.6	1.4	4.6	6.2
	G 3	44.2	0.2	16.2	5.4	0.4	6.6	16.4	0.8	0.0	1.2	7.6	9.8
	G 4	45.0	0.0	8.0	9.6	0.0	5.8	14.6	0.6	0.4	4.6	10.8	15.8
	G 5	29.2	0.4	10.0	5.4	0.2	5.2	13.8	0.6	1.2	5.2	27.8	33.6
CPCH 60	G 1	42.6	0.2	12.8	3.4	0.6	6.0	14.8	1.2	1.2	3.4	13.4	16.8
	G 2	44.2	0.4	11.8	3.6	0.2	9.2	13.2	0.8	1.2	4.0	11.4	15.4
	G 3	40.2	0.0	13.2	5.4	0.2	7.8	15.8	0.8	1.4	3.8	11.2	15.0
	G 4	38.0	0.6	9.2	10.2	0.2	8.6	16.8	0.4	2.2	4.2	9.4	13.6
	G 5	29.0	0.2	12.2	6.8	0.4	6.4	14.2	0.0	0.2	4.0	26.6	30.6

Rank variation

33 samples from six drill cores were determined in terms of vitrinite reflectance measurements. The results of measurements are given in Tables 2 and 3. Mean maximum reflectance value of the coal varies between 0.46% and 0.54%. The variation of mean reflectance values of vitrinite indicates that a coalification stage of the coal occurred at sub-bituminous level, based on the Australian rank values, corresponding to the sub-bituminous A and B rank of the ASTM classification, or metalignitous type of Pareek's (1987).

GEOCHEMISTRY

The geochemistry of the Jurassic coal of Hill River area is focused on trace element analysis. Trace elements for the coal from the individual sub-seams were analysed by ANALABS. Data on the trace elements of coal are presented in Table 5 and discussed in this section.

Trace elements

Trace elements in coal have geological significance, and they are important from the viewpoint of the depositional environment and seam correlation (Casagrande *et al.*, 1977, 1980; Casagrande, 1987). Swaine (1971) considered that diagnostic trace elements in coal may be helpful in ascertaining the presence of marine influence during peat deposition, particularly the concentration of boron (B). Rimmer and Davis (1988) suggested that the trace elements distribution within coal, was expected to indicate variations in depositional environment of the peat swamp, transport and alteration of inorganic matter within the swamp, as well as coalification.

The concentration of the trace elements in the coal varies greatly as from 0.30 ppm to 3140 ppm, whilst boron concentration is present between 37.0 and 409.0 ppm.

DEPOSITIONAL ENVIRONMENT

Petrographic analyses of the sub-seams in terms of macerals and microlithotypes, supported by trace elements analysis are used to establish the depositional environment of the coal (Cohen *et al.*, 1984; Davies and Raymond, 1983; Graese *et al.*, 1992; Hunt, 1982; Hunt and Hobday, 1984; Marchioni and Kalkreuth, 1991). Additionally, the presence of marine microplanktons (Sappal and Islam, 1991, 1992), is also used to interpret the depositional environment of the Hill River coal.

The maceral data of the coal are plotted on facies diagrams of Diessel (1982, 1986 and 1992), whereas, microlithotype data are plotted on ternary facies diagrams of Smyth (1979), and Hacquebard and Donaldson (1969 *in* Marchioni 1980).

Depositional environment and the macerals

The maceral compositions obtained from the sub-seams G 1 to G 5/6 of six drill holes are plotted onto the D-T-F ternary diagrams as illustrated in Figure 3. All sub-seams analysed are localised close together in the wet forest moor of mainly telmatic to limno-telmatic environments. A shift to an accumulation in somewhat limno-telmatic zone is present. The (T + F)/D ratios of the sub-seams range mostly between 2.5 and 4.5, which indicate high input of woody tissues in the coal. The T/F ratios have values from 1.8 to 5 and reflect the wet condition of coal environment. The high value of T/F also indicates that the coal has high gelification and moisture levels with low "dispersed" maceral content (D), and this suggests a moderate influence of circulating water which influenced the coal mire. The depositional environment for the coal is interpreted dominantly as being wet to very wet forest moor condition with relatively low detrital input.

In order to assess the type of prevailing moor during deposition of the coal precursor, variations in maceral content throughout the sub-seams of drill holes CPCH 1, 37, 39, 47, 57, and 60 are illustrated in Figure 4 by using Tissue Preservation and Gelification Indices (TPI and GI) (Diessel, 1986 and 1992). Using diagnostic maceral composition, a TPI is plotted against GI, to establish a correlation between depositional environment of coal formation and the coal facies indicators.

The TPI is a measure of the predominance of material with remnant cellular structure over that without cellular structure, and is expressed as the following formula:

$$\text{TPI} = \frac{\text{telinite} + \text{telocollinite} + \text{semifusinite} + \text{fusinite}}{\text{desmocollinite} + \text{corpocollinite} + \text{inertodetrinite} + \text{macrinite}}$$

The GI is a measure of the persistence of wet conditions and is formulated as:

$$\text{GI} = \frac{\text{vitrinite} + \text{macrinite}}{\text{semifusinite} + \text{fusinite} + \text{inertodetrinite}}$$

A decrease in the GI indicates an increase in oxidation, so that the GI is an inverted oxidation index.

On this TPI-GI diagram sub-seams are located almost close together, and this is an evidence of a stable swamp phase. The coal facies diagram indicates that the Hill River coal mostly falls within telmatic wet forest swamp with minor limno-

Table 5. Trace element analysis of selected Hill River coals.

CORE	SUB-SEAM	B (ppm)	OTHER TRACE ELEMENTS		
			0–10 ppm	10–100 ppm	100–1,000 ppm
CPCH 1	G 1	163.0	As, Cd, U	Be, Co, Ni, Ga, Y, Mo, Pb, Th	B, V, Cr, Mn, Cu, Zn, Sr, Zr
	G 2	406.0	Be, As, Cd, U	Co, Ni, Zn, Ga, Y, Mo, Pb, Th	B, V, Cr, Mn, Cu, Sr, Zr
	G 3	409.0	Be, As, Mo, Cd, U	Co, Ni, Zn, Ga, Y, Pb, Th	B, V, Cr, Cu, Sr, Zr
	G 4	244.0	Be, Mo, Cd, U	Co, Ni, Ga, As, Y, Pb, Th	B, V, Cr, Mn, Cu, Zn, Sr, Zr
	G 5/6	196.0	Mo, Cd, U	Be, Co, Ga, As, Y, Cd, Th	B, V, Cr, Mn, Ni, Cu, Zn, Sr, Zr
CPCH 39	G 1	60.0	As, Mo, Cd, U	Be, B, Co, Ga, Y, Pb, Th	V, Cr, Mn, Ni, Cu, Zn, Sr, Zr
	G 2	128.0	Be, As, Mo, Cd, U	Co, Ni, Zn, Ga, Y, Pb, Th	B, V, Cr, Mn, Cu, Sr, Zr
	G 3	147.0	As, Mo, Cd, U	Be, Co, Ni, Ga, Pb, Th	B, V, Cr, Mn, Cu, Zn, Sr, Y, Zr
	G 4	141.0	Mo, Cd, U	Be, Co, Ga, As, Y, Pb, Th	B, V, Cr, Mn, Ni, Cu, Zn, Sr, Zr
	G 5	85.0	As, Mo, Cd, U	Be, B, Co, Ni, Zn, Ga, Y, Pb, Th	V, Cr. Mn, Cu, Sr, Zr
CPCH 57	G 1	38.0	Be, As, Mo, Cd, U	B, Co, Ni, Zn, Ga, Sr, Y, Pb, Th	V, Cr, Cu, Sr
	G 2	47.0	Be, As, Mo, Cd, U	B, Co, Ni, Zn, Ga, Y, Pb, Th	V, Cr, Cu, Sr, Zr, Pb
	G 3	52.0	Mo, Cd, U	Be, B, Co, Ni, Ga, As, Y, Pb, Th	V, Cr, Cu, Zn, Sr, Zr
	G 4	53.0	Mo, Cd, U	Be, B, Co, Ni, Ga, As, Y, Pb, Th	V, Cr, Cu, Mn, Zn, Sr, Zr
	G 5	37.0	Mo, Cd, U	Be, B, Co, Ni, Zn, Ga, As, Y, Pb, Th	V, Cr, Mn, Cu, Sr, Zr

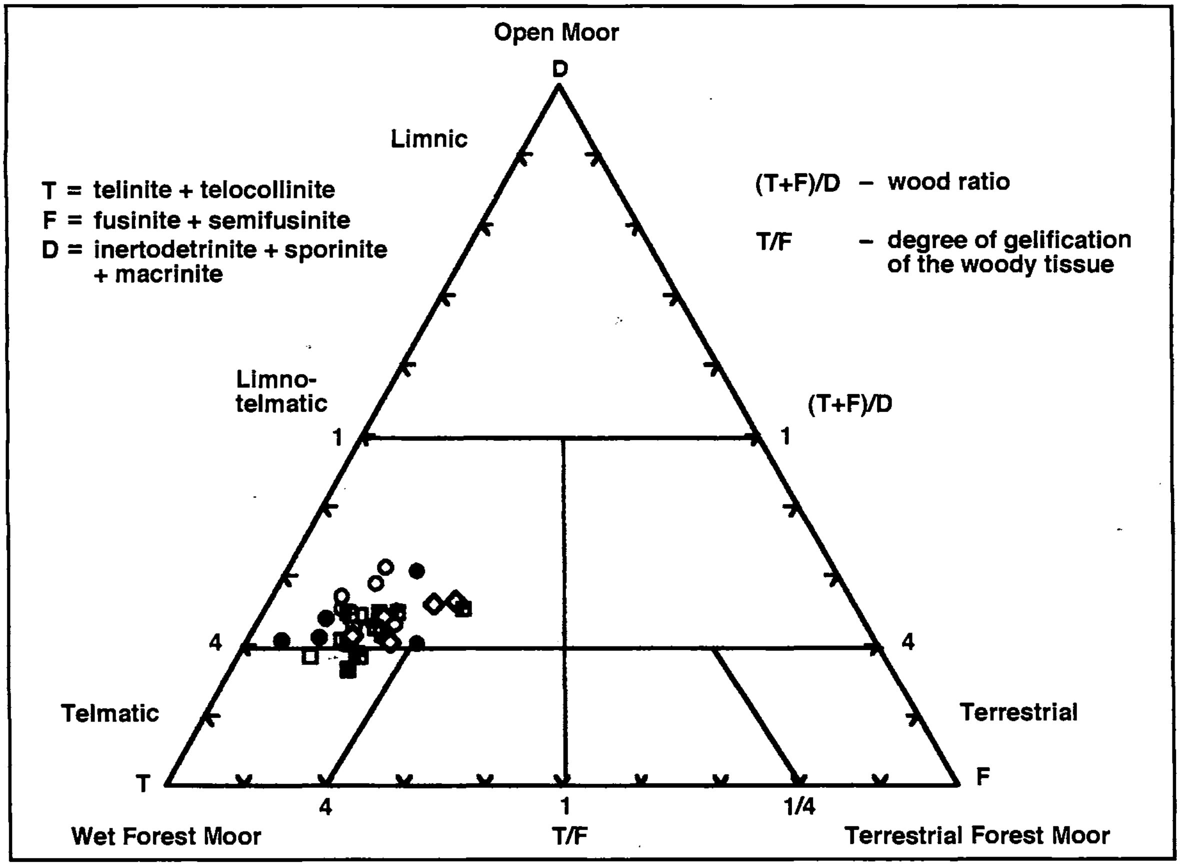


Figure 3. Facies diagram of Hill River coal (after scheme of Diessel, 1982).

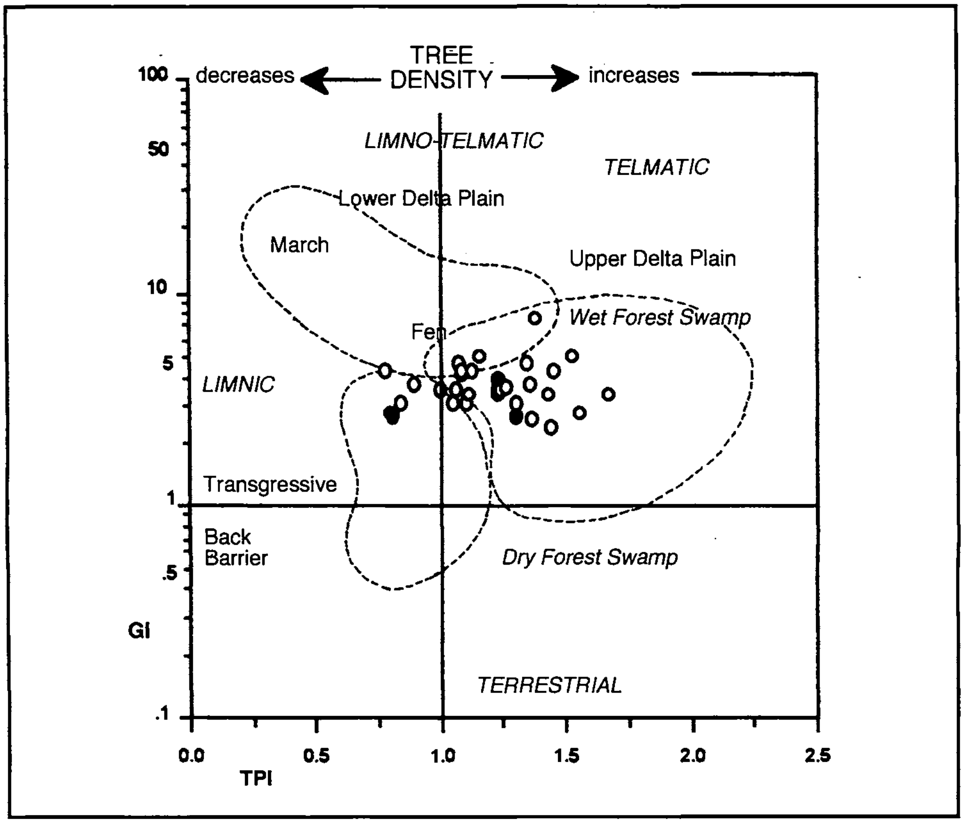


Figure 4. Facies diagram of Hill River coal (after scheme of Diessel, 1986 and 1992).

telmatic fen environments. It represents an intermittently to permanently flooded area of coal deposition. One sub-seam plots in the zone of lower delta plain, two sub-seams are in a transitional zone between upper delta and lower delta plains, whilst four sub-seams are present within a transgressive back-barrier area. The rest of the sub-seams fall in the zone of upper delta plain. The wide TPI plot ranging within 0.77 to 1.67 interval, is indicative of somewhat more frequent clastic influx during peat accumulation, and favoured preservation of structured vitrinite precursor (Kalkreuth *et al.*, 1991). It also suggests a presence of cyclic development of plant communities with variables tissues in the mire (Akande *et al.*, 1992). This low value of TPI may indicate that a substantial degree of transportation processes took place in the coal precursor swamp prior to the final deposition of peat (Kalkreuth and Leckie, 1989). It also reflects a predominant occurrence of shrubs and grass in coal precursor environment. Frequent clastic input during peat accumulation was probably present, indicated by the wide range of the TPI value. The GI values, varying from 2.40 to 7.80, do not show wide fluctuation, and this indicates that all the sub-seams of the coal developed in a wet area of the depositional environment. The highest GI value (7.80) shown by one sub-seam coinciding with the highest vitrinite content and the lowest inertinite content, indicates the wettest condition of the coal. It also represents a low level of aerobic decomposition with rapid organic matter accumulation (Lamberson *et al.*, 1991). On the basis of the variation of GI and TPI values, the coal accumulated in forested peatland from weakly to relatively strongly decomposed woody tissues, under conditions of slow to moderate subsidence in a telmatic and/or limno-telmatic setting, and mild to strong humification and strong gelification of plant tissues occurred in the coal mire.

Microlithotype composition of coal from drill holes CPCH 1, 37, 39, 47, 57, and 60 is plotted on B, C, and A + D ternary diagram of Marchioni (1980) (Fig. 5). The data mainly fall in the telmatic forest moor zone with transition zone to reed moor, as evident by the relatively higher content of vitrinite-rich clarite (clarite-V), vitrite, cutinite-rich clarite (cuticloclarite), and vitrinite-rich vitrinertite (vitrinertite-V) in the coal related to alternating high and low ground water table conditions. However, a decrease of vitrinite-rich clarite and vitrite with increasing sporinite-rich clarite (sporoclarite) occurs in the sub-seams located in reed moor zone.

The microlithotypes of the coal samples from the six drill holes are plotted on the ternary diagram of Smyth (1979) as illustrated in Figure 6. The microlithotypes of the coal mainly fall in area C, with two sub-seams in area B, whilst one sub-seam lies within a transition zone between C to D areas. On the basis of microlithotype interpretation, the coal mainly accumulated in a brackish environment with sediment influx from a fluvial system (Smyth, 1984, 1989; Struckmeyer and Felton, 1990; Styan and Bustin, 1983a, 1983b; Teichmüller, 1982; Teichmüller and Teichmüller, 1979). Occurrence of alginite in coal is also indicative of intermittent brackish conditions. However, one sub-seam is located in the transition area of the brackish zone and upper delta plain, whilst the other sub-seams are related to fluvial systems with a high sediment influx.

Concentration of certain trace elements in coal, especially boron, is helpful as an indicator of the depositional environment of coal precursor. Swaine (1971, 1982) and Lyons *et al.* (1989) considered that coal having a boron content of 40.0–120.0 ppm tends to indicate brackish water coal, whilst a boron content varying from 120.0 ppm to 450.0 ppm in coal represents a marine-influenced environment. On the basis of boron concentration present between 37.0 and 409.0 ppm, the Hill River coal is postulated to have accumulated in brackish to marine-influenced environments.

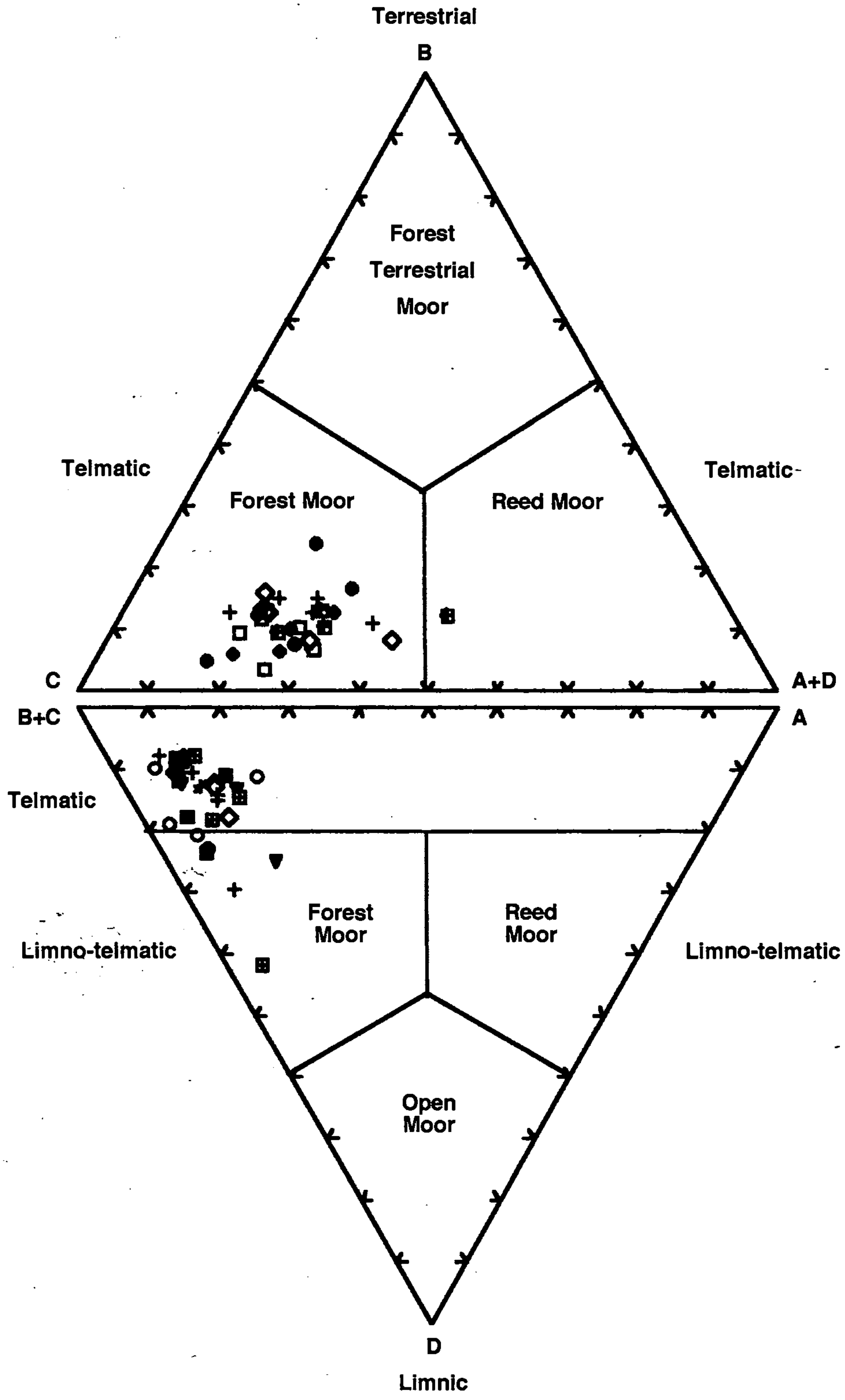
The palynological studies on the selected coal (CPCH 1) and its associated sediments carried out by Sappal and Islam (1991, 1992), showing the presence of acanthomorphs and sphaeromorphs acritarchs in the coal measures support the interpretation that the coal was deposited in a brackish environment.

In summary, the depositional environment of the Hill River coal, based on macerals, microlithotypes, and trace element contents, is postulated to be a telmatic wet forest swamp of upper to lower delta plain, influenced by marine incursion, possibly in a regressive phase of a marine transgression.

CONCLUSIONS

Petrographic and trace element examinations reveal that the Hill River coal is characterised by:

- Predominance of a moderate to high vitrinite content. It is present in all sub-seams in the six drill cores. Its content is moderate to high. Thus the coal can be regarded as a vitrinite-rich coal. The lack of telinite indicates a slow burial and high pH of swamp water (Rimmer and Davis, 1988). The vitrinite A content is higher than vitrinite B in the coal.
- Low values of inertinite contents, which reflect that a low degree of decomposition of peat and low degree of oxidation in the coal occurred.



A = Sporoclarite + Duroclarite + Vitrinertoliptite
B = Vitrinertite (I) + Inertite
C = Clarite (V) + Vitrite + Cuticloclarite + Vitrineritite (V)
D = Clarodurite + Durite + Carbominerite

Figure 5. Facies diagram of Hill River coal (after scheme of Hacquebard and Donaldson, 1969, *in* Marchioni, 1980).

The inertinite macerals are the result of an *in-situ* oxidation process, while inertodetrinite may also have been subjected to transportation from other areas of the mire.

- Medium to high exinite content. The association of cutinite with varieties of vitrinite B especially with corpocollinite, suggest a leaf source for the peat. The abundance of resinite-rich leaf remains observed in the coal, may indicate shrubby vegetation occurred.
- The vitrite plus clarite content, more than 50% in general, and it shows an occurrence of forest in the area. Moreover, it indicates that an increased level of standing water and water table, with concomitant change in floral type and preservation of organic accumulation from oxidation processes occurred in the mire.
- A sub-bituminous stage (Australian), sub-bituminous stage A-B (USA-ASTM), or metalignitous coal type (Pareek's, 1987), based on reflectance measurement.
- The boron content of the coal, varying from 37.0 to 409.0 ppm.

Moreover, on the basis of the variation of GI and TPI values, the coal accumulated in forested peatland from weakly to relatively strongly decomposed woody tissues, under conditions of slow to moderate subsidence in a telmatic and/or limno-telmatic setting, and mild to strong humification and strong gelification of plant tissues occurred in the coal mire. In conclusion, the depositional environment of the Hill River coal, based on macerals, microlithotypes, and trace elements, is postulated to be an upper to lower delta plain, influenced by marine incursion, possibly in a regressive phase of a marine transgression.

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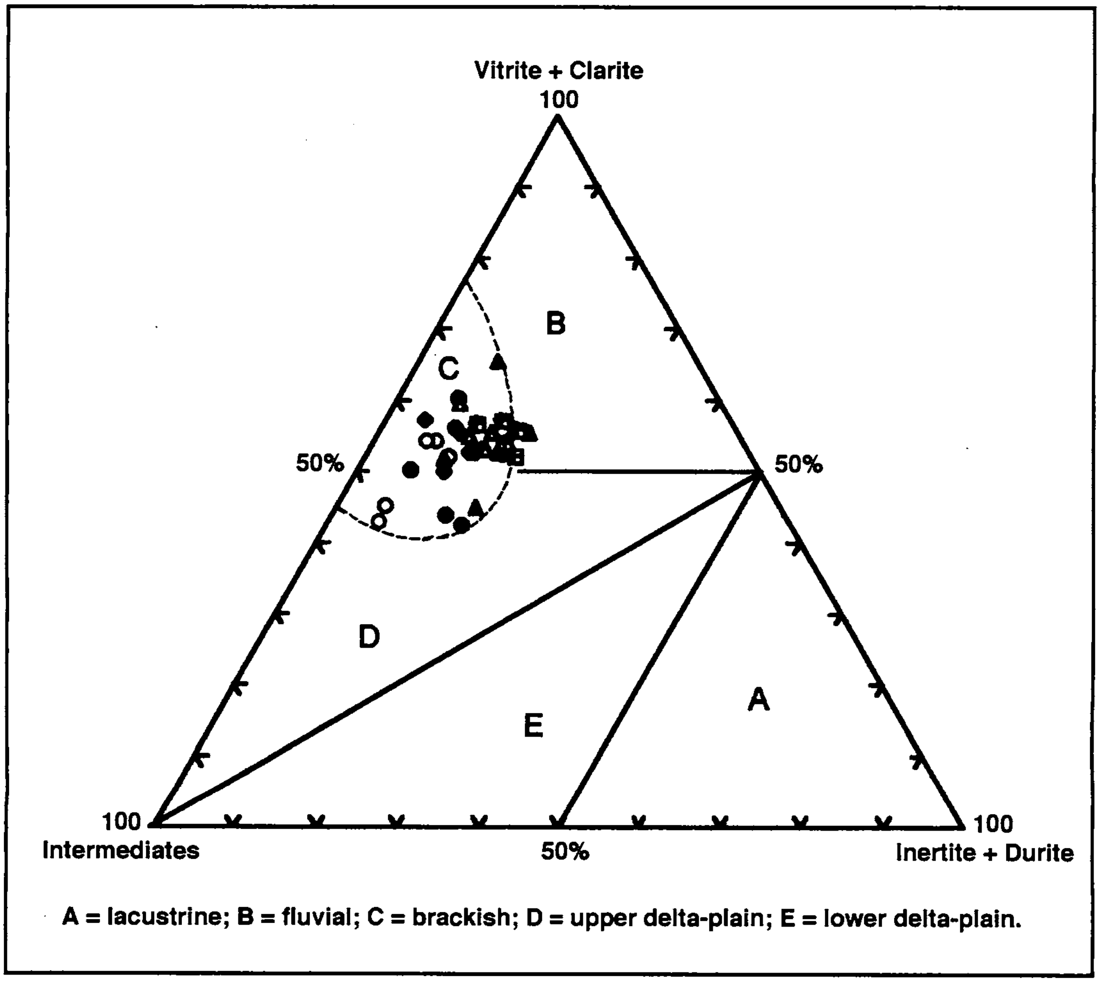

Figure 6. Ternary diagram of depositional environment of Hill River coal (after scheme of Smyth, 1979).

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