DISPARATE HYDROCARBON GENERATION POTENTIAL AND MATURATION PROFILES OF PAKAWAU GROUP SOURCE COALS: IMPLICATIONS FOR TARANAKI BASIN EXPLORATION

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Abstract

Past geochemical analyses of Taranaki Basin hydrocarbons suggest source rock (coals) are variable in chemical character and are primarily of mixed terrestrial/paralic/marine origin. Most of these analyses have focused on the oil-source relationship without regard to the source coal depositional environment. Using Pakawau Group coals, this study focuses first on depositional environment and then source coal quality and maturity properties corresponding to depositional environment. Two coal facies are clearly identified on the basis of petrography, proximate analysis, and Rock-Eval analysis. Sedimentary structures and palynology show the two facies correspond with two different depositional environments; (i) floodplain and (ii) estuarine/paralic.

According to Rock-Eval data, the paralic coals yield about twice as much hydrocarbon (30 wgt%) as the floodplain coals (17 wgt%), despite having similar liptinite proportions. Furthermore, vitrinite (telocollinite) reflectance of the paralic coal samples, which outcrop less than 2 m apart, ranges from 0.38 to 0.52% Ro. This reflectance range is attributed to perhydrous vitrinite (hydrogen-rich vitrinite) which depresses vitrinite reflectance. Consequently, in the case of paralic coals, vitrinite reflectance is not a reliable indicator of burial history.

Given the same burial history, the paralic coals have the potential to mature earlier than floodplain coals. The significance is that kitchens containing paralic coals are shallower. Hydrocarbon-source analysis that shows a possible paralic or marine source rock contribution may be due to a contribution from paralic coals and not necessarily a 'true' marine source rock. Future geochemical work associated with oil-source and maturation studies must recognise that Taranaki Basin coals do not have a unique hydrocarbon generation potential and maturation profile. Classifying potential source samples (and corresponding geochemical data) according to depositional environment provides the best hope to elucidate the so-called "mixed terrestrial/paralic/marine" Taranaki Basin source rock.

Introduction

Previous work has shown that Taranaki Basin hydrocarbons are sourced from Late Cretaceous to Eocene terrestrial/paralic sequences. More specifically, it has been demonstrated that Pakawau Group and Kapuni Group coals are probably the primary source rocks for these hydrocarbons (e.g. Thompson 1982, Cook 1987, Czochanska et al. 1988, Hirner & Lyon 1989, Hirner & Robinson 1989, Frankenberger et al. 1990, Johnston et al. 1990).

On the basis of biomarkers, Czochanska et al. (1988) divide the oils and condensate into two broad families that reflect source coal floral composition. Hydrocarbons found along the Taranaki Fault were sourced from coals dominated by angiosperms, probably Eocene coals of the Kapuni Group. Whereas the source coals for the oils and condensate in the southern region of Taranaki (Maui wells and Moki-1) are dominated by the presence of gymnosperms with a "significant marine derived component" (p. 134), probably Late Cretaceous Pakawau Group coals (figure 1A).

The same two families are recognised by Frankenberger et al. (1990) on the basis of trace element distributions. Furthermore, Hirner & Lyon (1989) and Hirner & Robinson (1989) essentially recognise the same families using stable (sulphur & carbon) isotopes. But Hirner & Robinson (1989) separately classifies the Moturoa field into its own family. Apparently the sulphur isotopes from the Moturoa field indicate a wholly freshwater source coal. In contrast, sulphur isotopes from the other two families can be derived from bacterial reduction of marine sulphate in a closed system (i.e. the supply of marine water was limited). Hirner & Robinson (1989) suggest the source coal developed in "(partly) closed (lagoonal?) basins or in areas with a correspondingly increased sedimentation rate" (p.125). High or moderate sedimentation rates, however, are incompatible with environments in which peat accumulates. With respect to some assumptions, Hirner & Robinson (1989) were able to identify potential source coal types while ruling other coal types out.

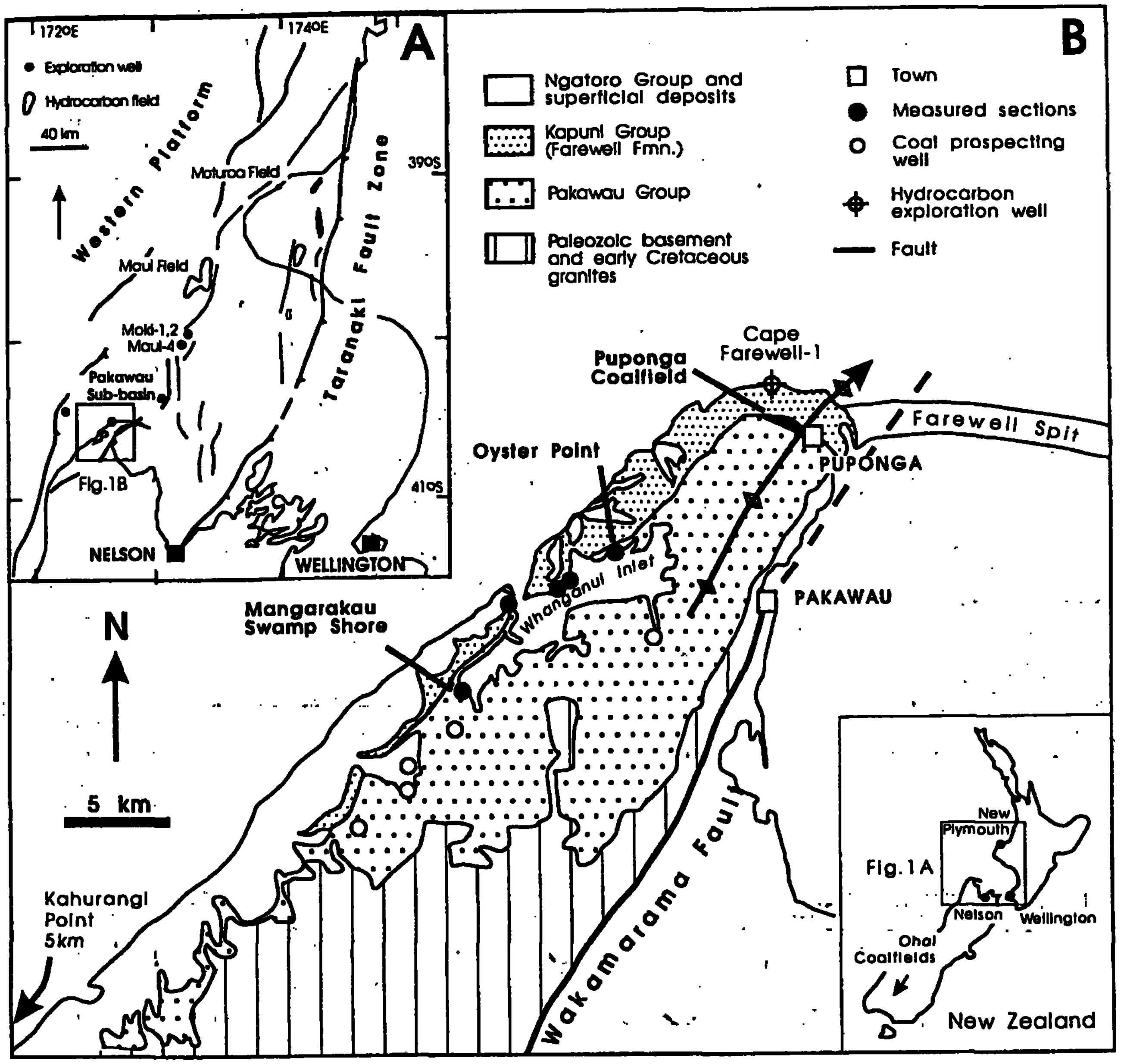

Fig. 1. Location map. A) Map of Taranaki Basin, bounded by the Taranaki Fault Zone and the Western Platform, showing features referred to in the text. All (unlabelled) exploration wells that penetrate the Pakawau Sub-basin are shown (modified after Pilaar and Wakefield 1984). B) Onshore simplified geological map (after Bishop, 1971).

The presently available geochemical data indicates Taranaki Basin hydrocarbons were probably derived from at least two distinct source coal types, possibly three. One of the important general signals coming from the geochemical work is the complexity of the Taranaki Basin oil-source system which suggests source coals are variable in chemical character. It is therefore possible that hydrocarbon generation potential and maturation characteristics of the source coals are also variable.

Indeed, Newman & Newman (1982) proposed that coals derived from different environmental settings may have different hydrocarbon generation potential and maturation characteristics. Subsequent work lends credence to this early work (e.g. Suggate 1990, Newman et al. 1992). On the basis of this work, aberrations in geochemical oil-source and maturation analyses may be explained by variations in peat depositional environment. It is therefore appropriate, in the context of the Taranaki Basin oil-source system, to focus some studies on local mire development (i.e. development of peat accumulation ecosystems), distribution, and coal characteristics.

For the first time, this paper presents an integration of depositional peat environments with geochemical data pertaining to Taranaki Basin coals. The coals come from the Late Cretaceous–early Tertiary Puponga Coal Measures Member (Puponga CMM, Pakawau Group) that outcrops in the Pakawau Sub-basin, northwest Nelson (figure 1). The Pakawau Sub-basin (ca.5000km^2) is the southernmost (and an analog) of several similar half-grabens that underlie the greater Taranaki Basin (Thrasher 1990). The objectives of this study include: elucidating the mire depositional environment, assessment of the petroleum source rock potential of the coals, and analysis of the coal thermal maturity characteristics

Terminology

Sometimes the oil and coal disciplines use different terminology for similar concepts and similar terminology for different concepts. Furthermore, some terms are common usage in one discipline yet rarely used in the other. Therefore, for this paper, it is necessary that the terms 'coal type', 'rank' and 'maturity' are clearly defined to enhance clarity.

Coal type

Coal type refers to the organic constituents (i.e. macerals) of coal, and is quantified according to the maceral groups: vitrinite (derived from woody tissue), liptinite (primarily derived from algae, resins, pollens, spores, cutin etc.), and inertinite (oxidised inert plant tissue), and their submaceral components (Stach, 1975). Newman et al. (1992) broaden this definition to include "any compositional feature or variation of the organic substance which cannot be attributed to burial history" (p. 337). This paper uses 'coal type' in the latter sense.

Variations in coal type are attributable to climate, floral assemblage, peat oxygenation and acidity, nutrient supply, rates of subsidence (Stach, 1975), and marine or fresh water influence (Newman & Newman 1982). In particular, this means that the same vegetation falling into, for example, environments of contrasting oxygenation may result in quite different coal types.

Rank and maturity

Coal rank is the degree of coalification (or metamorphism) and has, according to Suggate (1974), two components: (i) thermal effects on coal chemistry and (ii) pressure effects that reduce moisture. Coal rank is generally assessed on the basis of specific energy (for low rank coals) and volatile matter or fixed carbon (for high rank coals), but has been correlated with numerous other parameters (e.g. vitrinite reflectance). Isorank samples have the same coalification, i.e. burial history.

Maturity is a function of both rank and coal (or source rock) type characteristics (Suggate 1959, 1974, 1990, 1993, Suggate & Lowery 1982, Newman et al. 1992). Consequently, two different coal types undergoing the same burial history (i.e. isorank) may have different maturities. The corollary is that the maturity of different coal types may be the same if they are subjected to different burial histories. Thus, it is important to note that rank is not synonymous with maturity.

Geological and stratigraphic setting

Sediments deposited in the fault-bounded Pakawau Sub-basin (figure 1A) unconformably overlie basement of metamorphosed Paleozoic sedimentary and volcanic rocks, granites, diorites, and schists (Bishop, 1971; Nathan et al., 1986). The Pakawau sediments comprise conglomerates, sandstones, siltstones, mudstones and thin coals (generally < 1 m thickness). The basal sediments are lithic, becoming more quartzose (Titheridge, 1977) and feldspathic (Wizevich, 1992) upsection, eventually passing into the widespread calcareous sediments and limestones of the Taranaki Basin proper (Ngatoro Group, Palmer 1985). The stratigraphic nomenclature used for Pakawau sub-basin sediments in the vicinity of Whanganui Inlet is illustrated in figure 2.

Bal (1992, in press) measured five stratigraphic sections (totalling 223 m) of the Puponga CMM and parts of the under- and overlying units along the western shore of the Whanganui Inlet, northwest Nelson (figure 1B). Detailed lithofacies analysis combined with qualitative coal petrology and palynology identified two contrasting depositional systems; (i) a progradational sequence of estuarine and upper-delta floodplain deposits and (ii) overlying alluvial

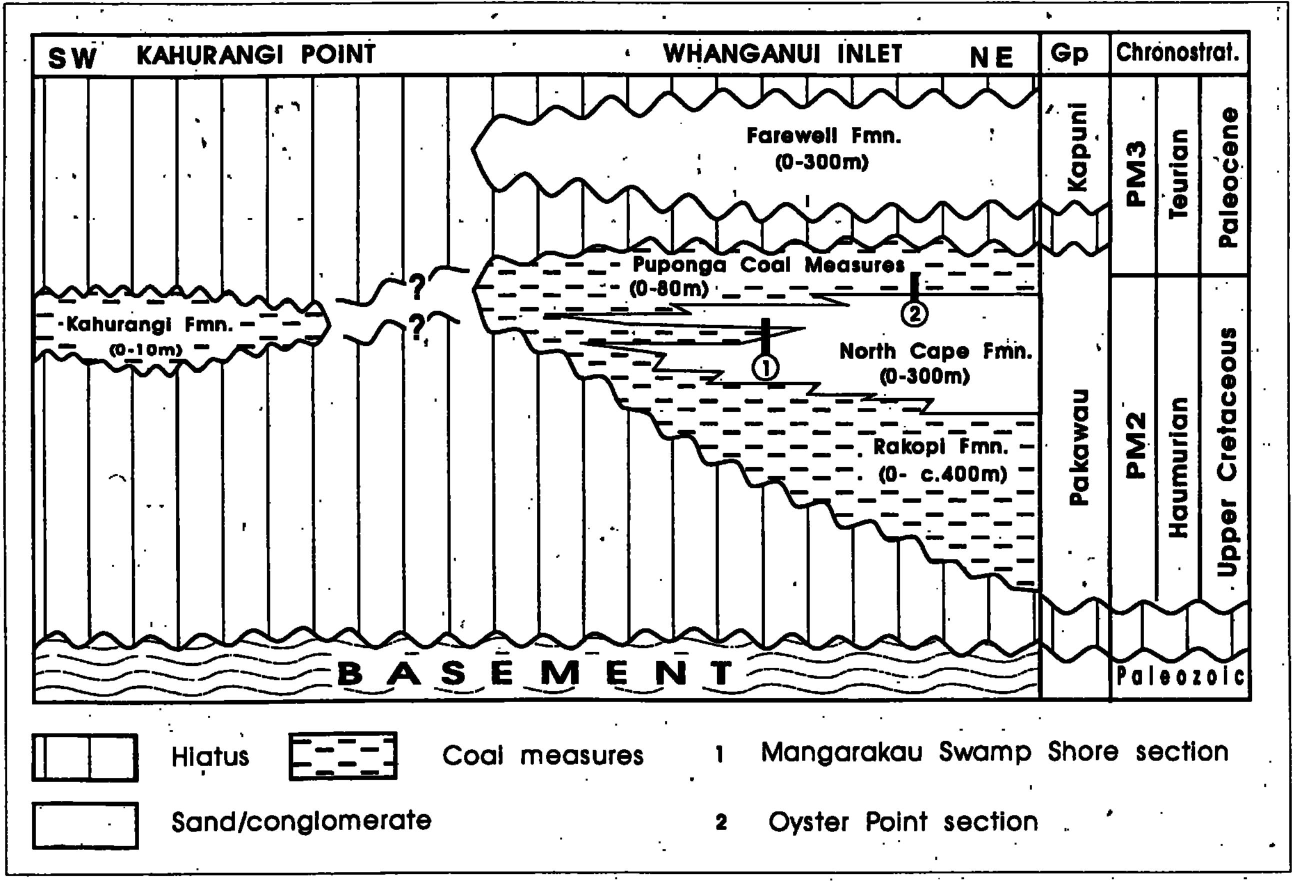

Fig. 2. Chronostratigraphy of Whanganui Inlet area and schematic position of Mangarakau Swamp Shore and Oyster Point measured sections.

sediments deposited by coarse-grained braided (or possibly meandering) rivers with associated floodplain sediments. The lower Teurian surface separating the two depositional systems may mark a sequence boundary that separates the Pakawau Group from the Kapuni Group (Fig. 2; Bal 1994).

This paper concerns Pakawau Group (Puponga CMM) coals from the progradational sequence comprising the following subenvironments: high energy subtidal channels, high-flow regime sub- to inter-tidal sand shoals or flats, intertidal mixed sand/mud and mud flats, salt marsh; paralic and floodplain mires, fluvial crevasse channels and levees, and open/closed bays (figure 3).

The Mangarakau Swamp Shore section (figure 1B and figure 4) is representative of paralic deposits in which coal seams have a low percentage thickness (3%) but relatively high frequency (20%) of beds. Coal outcrops are either fresh or display minimal weathering. Seams range in thickness from 4 cm to 27 cm and average 10 cm. Individual seams are of uniform thickness and are continuous in outcrop (at least 10 m). The presence of rootlets shows that the coals are autochthonous. These coals generally have sharp upper and lower contacts with carbonaceous mudstones (salt marsh deposits) or tidal flat deposits that contain dinoflagellates indicative of marine deposition.

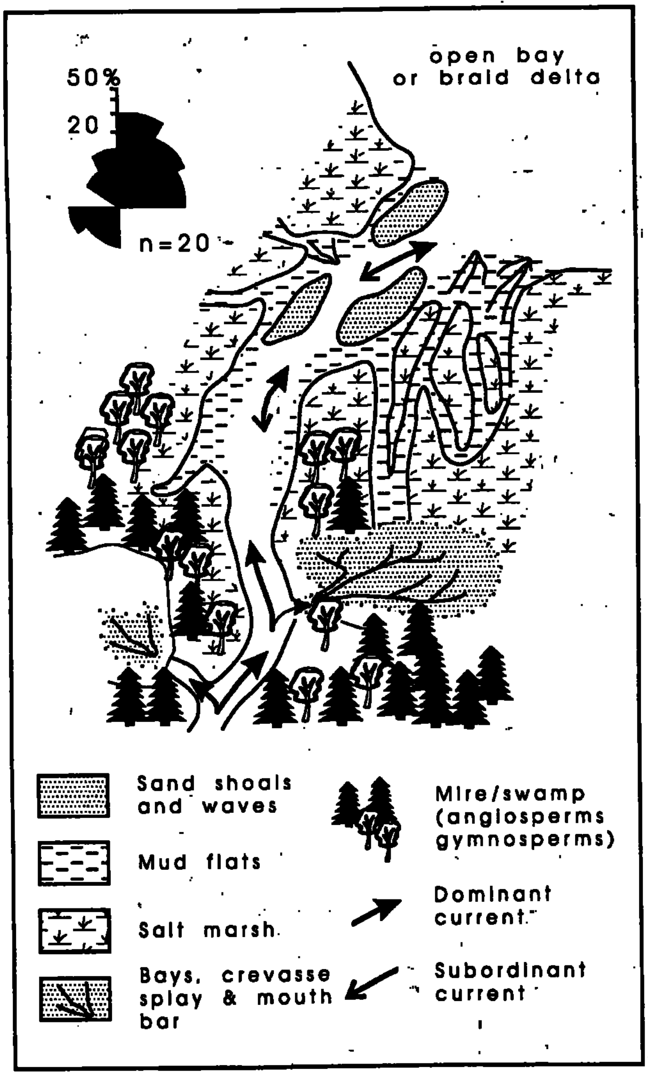

Fig. 3. Paleogeographic reconstruction, on the basis of the sedimentology and coal analysis, of the upper North Cape Formation and associated Puponga Coal Measures Member (after Bal, in press).

The Oyster Point section (figure 1B and figure 4) is representative of fluvial, floodplain and bay fill deposits developed on the upper delta plain (i.e. beyond the reach of the tidal rise). As with the paralic deposits, the floodplain coal seams have a low percentage thickness (3%) but relatively high frequency (16%) of beds. Coal outcrops have a fresh appearance. In general, the seams associated with fluvial deposits are sometimes thicker than those observed in the Mangarakau section, ranging from 4 cm to 52 cm, but the average thickness is about the same (10 cm). Seams less than 10 cm are not very continuous and are frequently cut out by overlying channelled sand deposits. In contrast, thicker seams are able to be traced for at least 20 m (limit of outcrop). These thicker beds resist erosion by channels, as indicated by occasional sharp undulating contact with an overlying sand- or gravel-filled channel. Underlying beds usually show rootlets that range from subtle features through to large coalified roots (up to 6 cm in diameter). Coal seams are usually under- and overlain by grey mudstones or brown carbonaceous mudstones.

The Puponga Coalfield (figure 1B) is the lateral equivalent of the coal measures on the northwestern shores of Whanganui Inlet. Here, the Puponga CMM is not well-exposed. The best exposures are limited to the entrances of old mine shafts in which coals show minimal weathering. Seams are generally described as thin. Maximum thicknesses of between 1.0–2.4 m were worked in the mine (Suggate, 1956). Due to the lack of outcrop, there has been no detailed lithofacies analysis on the Puponga CMM in this area. Broadly, the coals are associated with fine sandstones, mudstones, and thin beds of conglomerate. On the basis of association with muds, silts, and gravels, Wells (1984) suggested that the peats developed on the floodplain and locally between fans.

Methods

Seven coal samples were selected for analyses on the basis of perceived low ash content and the degree of weathering (minimal weathering is desirable). On a visual basis, all samples had minimal to no weathering effects. Analyses could not be applied to all samples due to time and cost constraints, and samples were therefore prioritised to maximise sample variability as perceived by a visual inspection and qualitative petrographic analyses. Analyses included: palynology, maceral composition, proximate analysis, specific energy, Rock-Eval, sulphur contents, and vitrinite reflectance.

Palynological analysis was undertaken at the University of Canterbury following methodology outlined in Warnes (1993). Petrographic descriptions of coal blocks were also undertaken at University of Canterbury following usual international procedures under both white and ultra-violet light. Polished and etched surfaces were appraised (cf. Moore & Ferm 1992), polished surfaces were point counted. Vitrinite reflectance was carried out according to standard procedures (ISO, 1984) at the University of Canterbury, except between 50 and 100 readings were taken depending on the variance of measurements. Bireflectance was minimal to nonexistent, therefore Ro random rather than Ro max was measured. Reflectance was measured on the submaceral telocollinite (cf. Toxopeus, 1983). Routine coal analyses, comprising proximate, specific energy, and sulphur content were carried out by Coal Research Association New Zealand. Rock-Eval analysis was done by Geotechnical Services Pty. Ltd. (Perth).

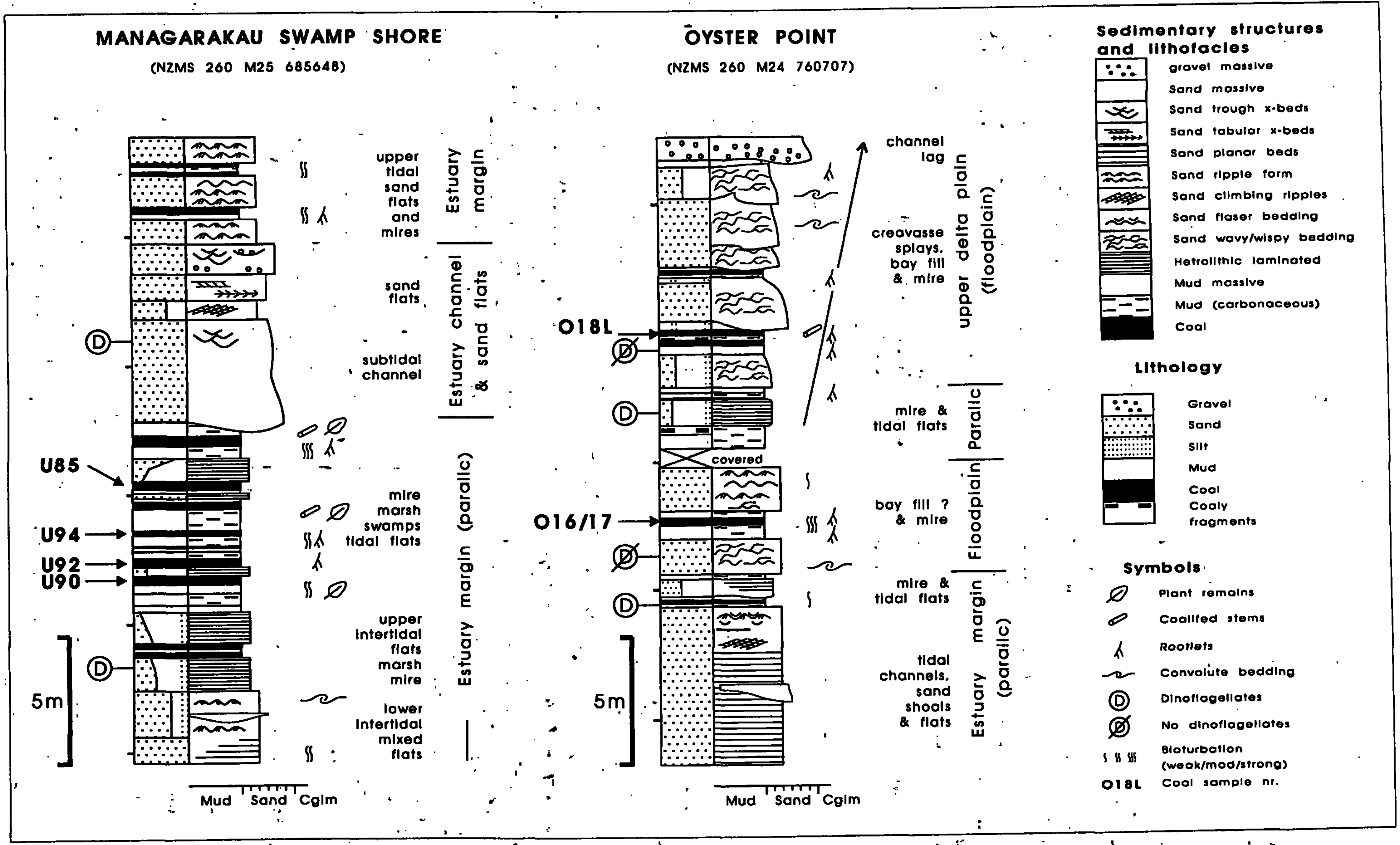

Fig. 4. Sampled sections in Whanganui Inlet are representative of paralic and fluvial environments (after Bal, in press).

Table 1. Normalised results of analyses. All values are in weight percent, except for maceral and palynomorphs, which are reported as number percent.

Locality:		Puponga Mine	Oyster Point		Mangarakau Swamp Shore			
	sample nr.	PM1	O16/17	O18lwr	U85	U90	U92	U94
PAL	Angiosperms	13	21	-	-	28	29	-
	Gymnosperms	30	72	-	-	50	53	-
	Pteridophyta	55	7	-	-	22	18	-
VIT	telocollinite	27.8	19.8	28.0	48.5	52.4	39.5	46.3
	desmocollinite	38.5	25.5	27.4	15.5	19.8	23.5	13.3
	vitrodetrinite	20.0	41.3	33.4	25.3	15.4	24.6	31.3
LIPT	sporinite	tr	tr	0.2	tr	tr	1.0	2.0
	cutinite	3.3	5.3	2.2	3.5	4.5	4.0	2.3
	resinite	0.3	0.8	2.8	4.5	3.8	tr	2.3
	liptodet rinite	4.5	4.0	3.4	2.5	3.0	1.8	2.8
	suberinite	2.0	tr	2.2	-	1.3	-	-
INE	semifusinite	3.0	2.8	0.2	0.3	-	5.8	-
	sclerotinite	0.8	0.5	0.2	-	-	-	-
	fusinite	tr	-	-	-	-	-	-
SUMMARY	vitrinite	86.8	86.6	88.8	89.3	87.6	87.6	90.9
	liptinite	10.1	10.1	10.8	10.5	12.6	6.8	9.4
	inertinite	3.8	3.6	0.4	0.3	-	5.8	-
	TPI	0.5	0.3	0.5	1.2	1.5	0.8	1.0
	framboidal pyrite	-	-	-	tr	abund	tr	tr
	total minerals	0.3	3.2	7.9	7.0	9.1	0.3	22.2
vitrin. refelc. (Ro_{rand})		0.57	0.51	0.52	-	0.43	0.38	0.52
total sulphur		0.4	0.6	0.4	1.2	6.0	3.2	0.7
PROX	moisture	8.2	9.8	7.3	5.3	4.2	4.9	4.4
	ash	11.0	9.7	25.7	27.8	26.0	6.3	45.0
	volatile matter[1]	37.2	44.1	44.8	47.8	49.5	50.3	44.4
	fixed carbon	51.8	55.6	29.5	24.4	24.5	43.4	10.6
	specific energy[2]		31.0				33.7	
ROCK EVAL	temp max (°C)	431	430	429	-	421	420	425
	S1(mgHC/g rock)	1.28	1.66	2.02	-	2.64	6.86	1.70
	S2(mgHC/g rock)	107	95	104	-	148	216	106
	S3(mgHC/g rock)	9.80	21.66	16.66	-	5.19	10.39	4.7
	S1+S2	108	96	106	-	150	223	108
	Production Index (S1/(S2+S2))	0.01	0.02	0.02	-	0.02	0.03	0.02
	hydrogen index ($mgHC/gC_{org}$)	159	162	162	-	290	310	327
	oxygen index ($mgCO_2/gC_{org}$)	15	37	26	-	10	15	14
	total organic carbon	67	59	65	-	51	70	32

[1] Volatile matter (VM) %dmmSf=100(VM-0.1ash-0.5sulphur)/100-1.1ash-sulphur

[2] *specific energy (SpE) MJ/kg dmmSf=100(SpE-0.095*sulphur)/100-1.1*ash-sulphur*

all parameters to dry basis first (calculations after Newman & Newman 1982)

Results

The results are summarised in table 1. Figure 5 illustrates the relationship between Rock-Eval, proximate, and elemental analyses.

Palynology

All coal samples are dated as Haumurian (Maastrichtian). In general, the palynomorphs are relatively well preserved, translucent, and have light-yellow to brown colours. Three main groups, Angiospermae, Gymnospermae (dominated by podocarps), and Pteridophytae (ferns and club mosses) are recognised (table 2 and figure 6). The two paralic samples show consistent palynomorph assemblages that differ from the floodplain flora. However, the Puponga floodplain assemblage is dramatically different from both the paralic and Oyster Point palynomorph assemblage.

Petrographic analyses

In terms of the three main maceral groups, vitrinite, liptinite and inertinite, there is little variation between samples. All samples have a high proportion of vitrinite (87-91%; table 1) with liptinites (7–13%) making up most of the balance.

There is, however, a marked variation in vitrinite submaceral proportions (figure 7). These include the plant tissues

Table 2. Palynomorph counts expressed as a percentage of total counts per sample.

sample nr	U92	U90	O16/17	PM1
UCP nr	1260	1238	1239	1261
total counts	307	256	252	385
Angiosperms	%	%	%	%
Caryophyllidites polyoratus				0.5
Gambierina rudata				0.3
Liliacidites variegatus	1.0	5.9	1.6	
L. intermedius	1.3	0.4		
L. sp				1.0
Monosulcites granulatus	0.7	0.4		
M. sp. a			0.8	2.1
M. sp. b		3.9		
M. cf. *minima*	6.8	2.3	0.8	
Nothofagidites kaitangata	0.7		0.4	
Polycolpites cf. *pseudomoides*	0.3	1.6		
P. clavatus				0.3
Proteacidites subpalisadus	1.0			
P. scabaratus			2.0	
P. parvus			0.4	
Quadraplanus brossus		0.8		
Rhiopites sp.		0.4		1.0
Tetrad (sp. unknown)			4.0	
Tricolpites gillii	0.3		1.6	
T. granulatus		0.4		
T. pachyexinus	1.3	0.8	0.4	
T. reticulatus	4.2	1.2	2.8	3.1
T. sp	1.3	4.3	3.2	
T. sp. *F*	2.9	2.0		2.3
T. sp. *G*	0.7	1.6		0.5
T. striatus				0.3
T. lilliei	6.5	2.0	2.8	0.8
Tricolporites sp.				0.8
Triorites fragilis	0.3			0.5
T. minor			0.4	0.5
Gymnosperms				
Araucariacites sp.	0.3	2.3	2.0	
Dacrydium praecupressinoides	0.7	1.2		2.9
Microcachryidites antarcticus	10.7	8.6	7.5	2.6
Podocarpidites marwickii	6.5	1.2	0.4	1.0
P. sp.	6.8	3.9	1.6	8.8
P. ellipticus	14.0	19.5	3.2	10.6
P. cf. *ellipticus*			0.8	
Phyllocladidites mawsonii	12.1	12.9	25.8	4.7
P. paleogencus	1.0		2.0	
Trichotomosulcites subgranulatus	0.7	0.4	29.0	
Pteridophytes				
Baculatisporites sp.	0.3			
Cyathidites minor	5.9	6.3	0.8	13.2
Gleicheniidites cf. *circinidites*		3.9		12.2
Lycopodiumsporites sp.			0.4	
indeterminate sp.			1.6	1.6
Laevigatosporites major	0.7	1.2	2.0	1.6
L. ovatus	9.4	4.7		8.1
Osmundacidites wellmanii	0.3			1.0
Peromonolites bowenii	0.3		0.8	2.6
Polypodiites sp.		0.4		
Stereisporites antiquasporites	0.3	0.4	1.2	2.1
Trilites fragilis				0.3
T. morleyi		1.2		
T. verrucatus	0.7	3.5		11.9
T. sp.				0.8
T. cf. *tuberculiformis*		0.8		

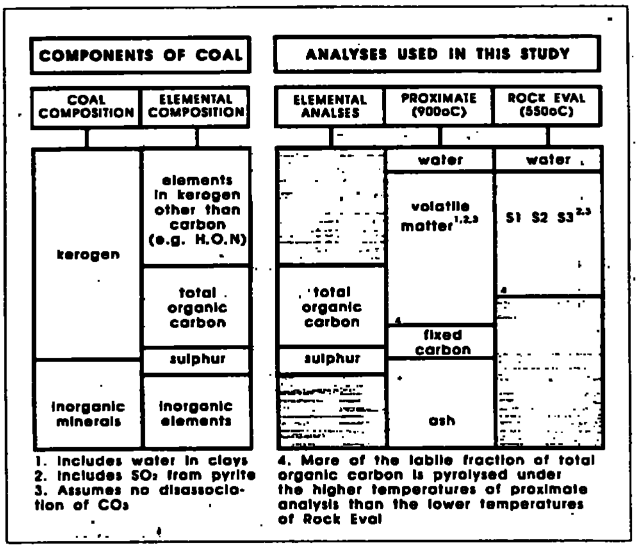

Fig. 5. Schematic relationship between components of coal, elemental analyses and different pyrolysis techniques used in this study. Both proximate and Rock-Eval are anhydrous pyrolysis techniques. In the coal industry, proximate analysis is the standard method used to assess coal quality and rank. In the oil industry, Rock-Eval is used for assessing source rock quality and maturity. Correlation between volatiles determined by Rock-Eval (i.e yield S1+S2) and volatiles determined by proximate analyses show a good, but not one-to-one, correlation (see Newman, this volume).

telocollinite (a structured framework submaceral, comprising stems, roots, and leaves), desmocollinite (a matrix submaceral comprising structureless vitrinite) and vitrodetrinite (a structured matrix submaceral comprising vitrinitic plant parts smaller than 10 µm across the short axis). The paralic samples have the highest proportion of telocollinite. In contrast the floodplain samples are dominated by desmocollinite and vitrodetrinite.

Liptinites fluoresce with a strong bright yellow corresponding to spores, cutin, or resins or a dark brown/gold (usually resin). Sporinite is often flattened and cutin may be folded back on itself resulting in a convoluted pattern. Cutinite (derived from cuticles of leaf epiderms and twigs) is usually thickest (1–2 µm and up to 5 µm) in the paralic samples. Generally, there is a low proportion of inertinites (oxidised macerals; 0–6%).

There is a marked difference in texture between the paralic and floodplain samples (figure 8). This difference reflects tissue preservation which is quantified by determining the ratio of preserved tissue to poorly preserved tissue; the tissue preservation index or TPI (Diessel 1985, Lamberson et al. 1991).

$$\text{TPI} = \frac{\text{telocollinite}}{\text{desmocollinite} + \text{vitrodetrinite}}$$

High TPI values (c. > 1.0) indicate excellent preservation of plant tissues. In general, all samples have relatively well-preserved tissues. However, the paralic coals are characterised by significantly higher TPIs than the floodplain coals (table 1).

Vitrinite reflectance measurements come from well-defined normal populations (the widest 99% confidence interval for the mean is ± 0.014%). The mean reflectance of each sample ranges from 0.38 to 0.57% (figure 9).

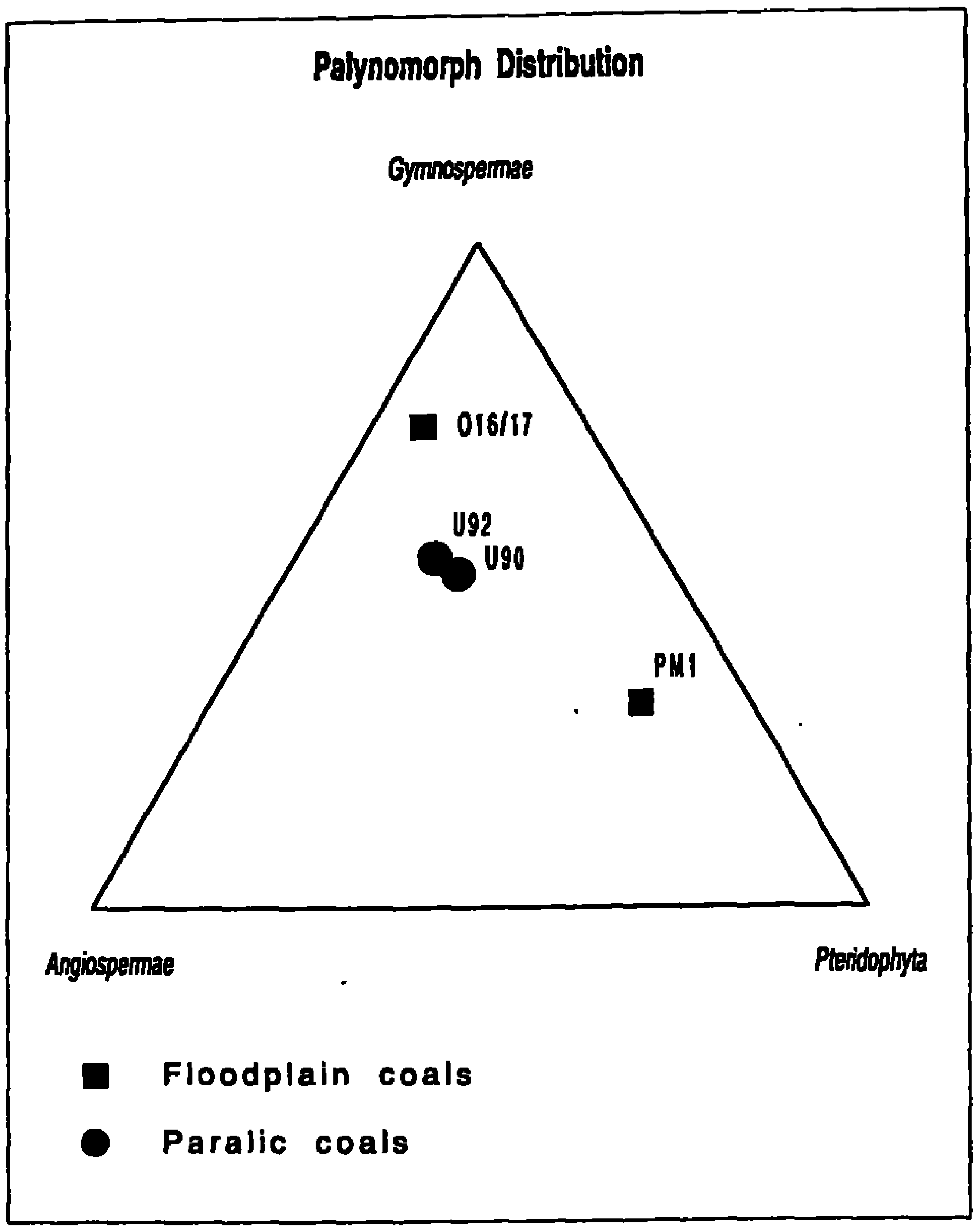

Fig. 6. Palynomorph ternary diagram. Samples from the paralic setting come from closely spaced seams in the same section. Floodplain samples O16/17 (Oyster Point) and PM1 (Puponga Mine) are c.10 km apart. The wide variation in floodplain palynomorph proportions may reflect different floodplain environments.

Minerals (quartz, clay, framboidal pyrite and discrete pyrite crystals) were also counted. The presence of well-developed and striking framboidal pyrite was exclusively identified in the paralic samples (figure 8D), although other pyrite forms occur in all samples.

Proximate analyses, specific energy, and sulphur content

All samples have a relatively high proportion of ash (6–45%) i.e. mineral content. Except for sample U94, the volatile matter (on a dry matter mineral and sulphur free basis; dmmSf) is appreciably higher in the paralic samples when compared with the floodplain samples. Specific energy was determined for two samples selected on the basis of different lithofacies and on low ash contents. The paralic sample produced the higher specific energy value, consistent with its higher volatile matter. Sulphur contents are variable ranging from 0.4 to 6.0% but, the floodplain samples are consistently characterised by low sulphur contents (0.4–0.6%; table 1).

Rock-Eval pyrolysis and total organic carbon content

Peters (1986) and Langford & Blanc-Vallron (1990) provide critical comment on Rock-Eval parameter interpretation. The low S1 values and the production index, a measure of free hydrocarbons in the sample, indicate all samples are immature. The paralic samples have a considerably higher hydrocarbon yield and hydrogen index compared with the floodplain samples (table 1). Total organic carbon contents are variable.

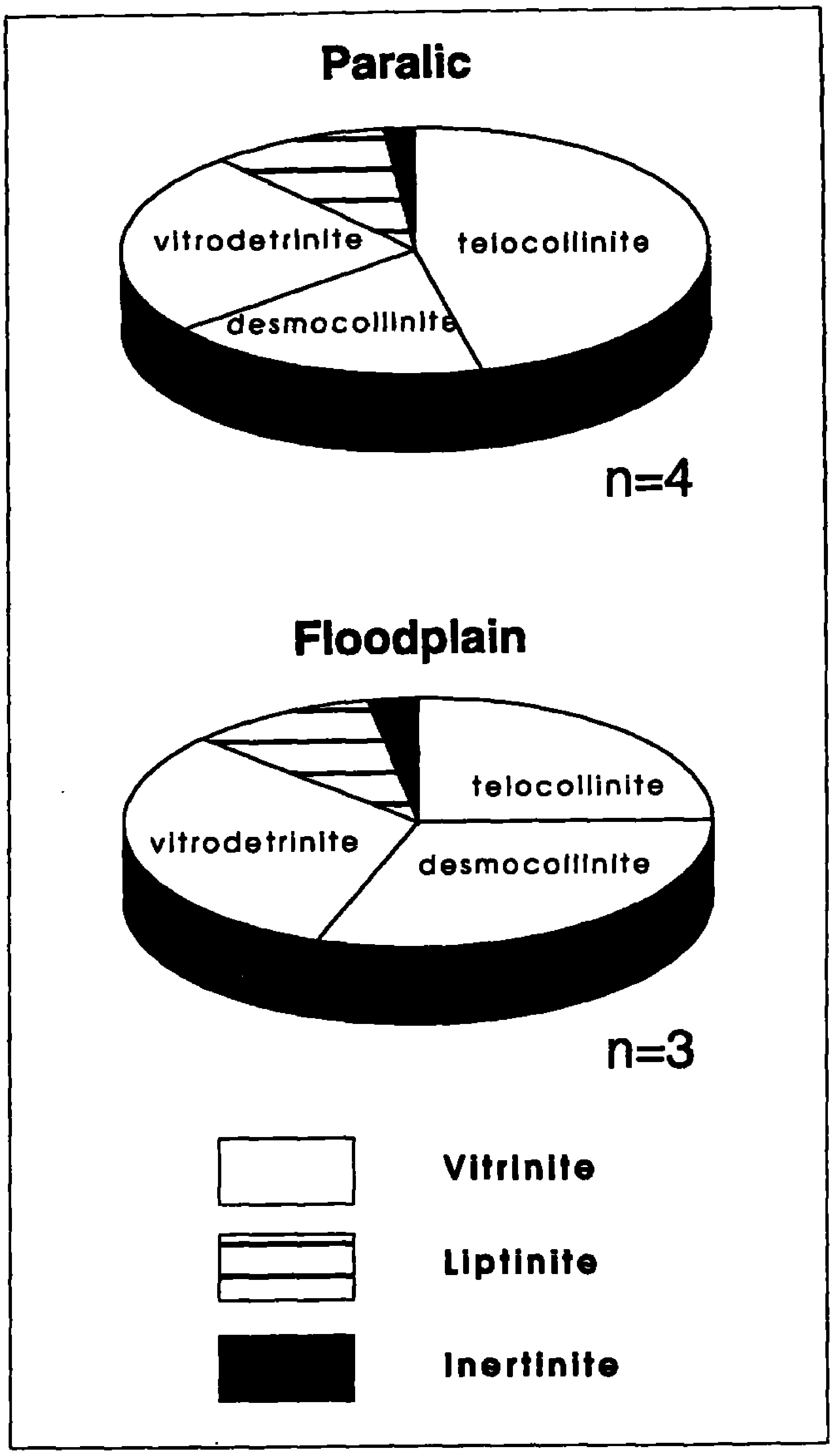

Fig. 7. Pie diagrams summarise maceral counts (Table 1). Main maceral groups show almost no variation between environments, vitrinite being the dominant maceral group. However, there is a much wider variation in vitrinite submaceral groups between environments. For instance, the matrix submaceral (telocollinte) is represented in much larger proportions in the paralic samples compared with the floodplain samples.

Synthesis

Environment of peat accumulation

In a thorough palynofloral study of lower Haumurian Ohai Coals (Southland; figure 1) using proximate and sedimentary data from Shearer (1992), Warnes (1993) was able to identify three palynomorph associations that reflected paleoenvironment. The palynoflora proportions of the Puponga CMM paralic mire is comparable with Warne's "low-lying mire vegetation association" characterised by subequal proportions of podocarps *Podocarpidites* cf. *ellipticus*, *Phyllocladidites mawsonii*, and *Microcachryidites antarcticus* that collectively account for more than half the gymnosperm component.

The palynoflora of the floodplain mires show characteristic differences from Warne's palynomorph associations. For instance, the Oyster Point mire is dominated by the podocarp *Trichotomosulcites subgranulatus*, which may indicate drier

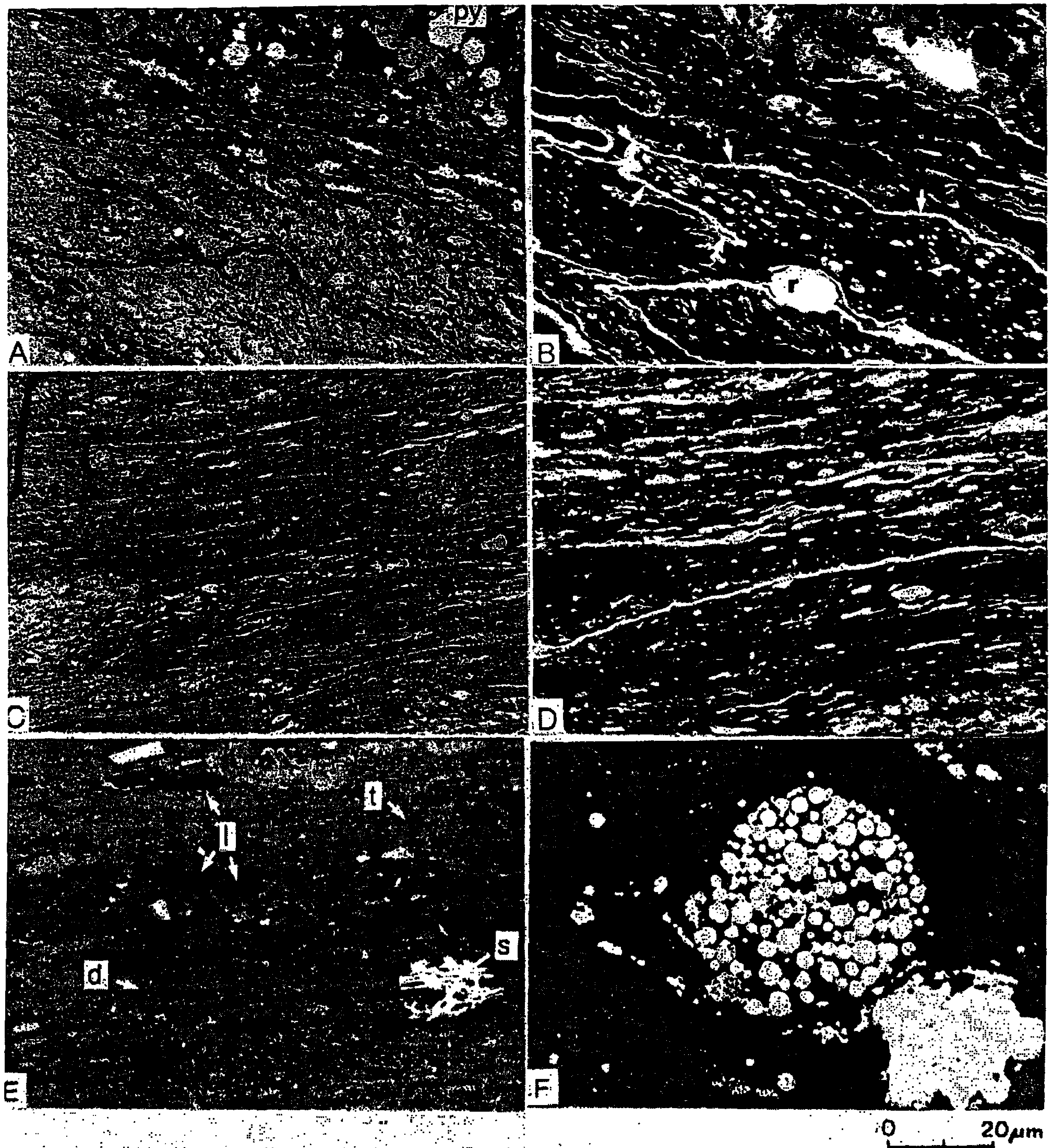

Fig. 8. Representative microphotographs of coals from each of the three localities. Microphotographs (A,B,C,D,F) have been etched according to the Moore & Ferm (1992) technique. Etching enhances the structure of vitrinite so that cell walls and internal cell structures are clearly visible. Internal cell structure is not recognised in unetched blocks (e.g. E).

(A) & (B) Paralic coals from Mangarakau (U90): mostly telinite (recognisable as framework telocollinite in unetched blocks). The high reflecting bright white (upper portion of microphotograph) is framboidal pyrite (py). Microphotographs taken under ultra violet light (B) more clearly depicts the whole plant parts, outlined by fluorescing (white) cutinite (e.g. arrows), characteristic of the paralic samples. Note the presence of fluorescing resins or liptinite within the plant part. The large white fluorescing "blob" is resinite (r). Textures in U90 are characteristic of Mangarakau coal seams.

(C) & (D) Floodplain coals from Oyster Point (O16/17): mostly desmocollinite (matrix) and stringy vitrodeterinite. Fluorescing cutinite in (D) is semi-continuous and often attached to telocollinite. Note the absence of framboidal pyrite. The appearance of laminae and abundant desmocollinite is characteristic of Oyster Point floodplain samples.

(E) Floodplain coal from Puponga Mine (PM1): This is an unetched block typical of the floodplain coals. Comprising desmocollinite (d) with vitrodetrinite (t), discontinuous liptodetrinite (l), and fusinite (s).

(F) Paralic coal from Mangarakau (U90): etched block showing characteristic framboidal pyrite ubiquitous in the paralic coal samples.

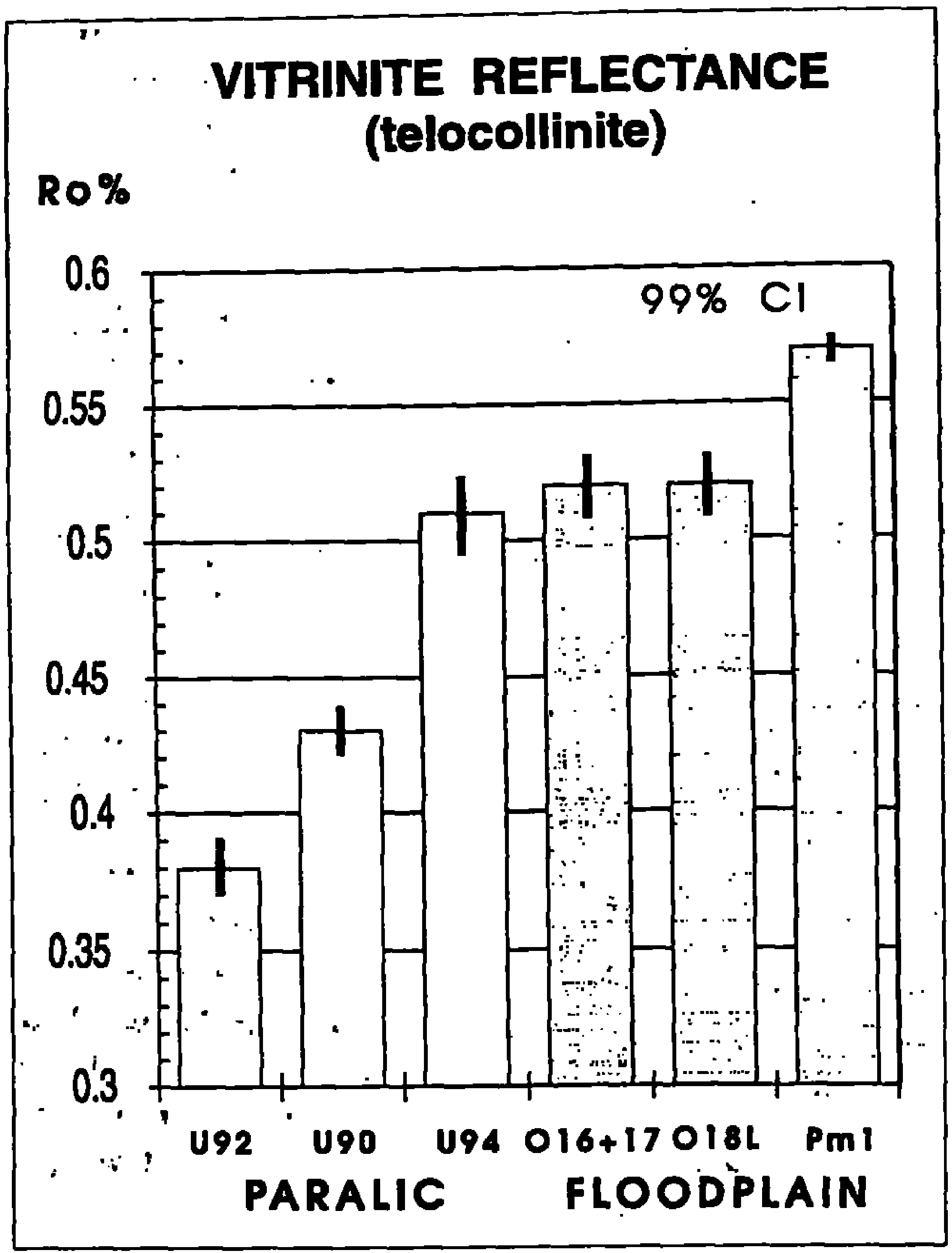

Fig. 9. Paralic coals display wide variations in vitrinite reflectance (measured on telocollinite) despite the fact that samples come from within a continuous 1.5 m section. This indicates that vitrinite reflectance is influenced by both coal type. In the case of the paralic samples, a highly anoxic environment and marine water influence has resulted in hydrogen-rich (perhydrous) vitrinite which is susceptible to suppression of reflectance. Note that the reflectance of sample U94 is not significantly suppressed and has similar reflectance to the floodplain coals. This lends credence to the supposition that the Mangarakau and Oyster Point sections have undergone similar burial histories (see discussion in text).

conditions or better drained conditions relative to the paralic mire. The Puponga Mine mire is atypical since it is characterised by an abundance of Pteridophytes (ferns and club mosses), especially *Trilites verrucatus.* Although *Trichotomosulcites subgranulatus* and *Trilites verrucatus* are inconsequential in the Ohai coals, they are dominant in some coals on the (South Island) West Coast and therefore may represent changes in regional flora between Ohai and the West Coast (pers. comm. S. Ward, 1994). Alternatively, the age difference between the lower Haumurian Ohai Coals and the very late Haumurian Puponga CMM coals may explain these differences in flora between the two regions.

In general, a low-lying mire interpretation for all samples is suggested by the relatively high ash (i.e. mineral) contents of most samples. The ash contents indicate periodic flooding with sediment-laden fluvial water. Free-standing water is also suggested by the presence of drop stones, which were probably introduced on the roots of floating logs. The coal petrology also supports the low-lying mire interpretation. For example, inertinite (oxidised macerals) is either absent or occurs in low proportions thus indicating minimal amounts of subaerial oxidation of the paralic and floodplain mires.

Despite the evidence for minimal oxygenation within both mire regimes, the paralic samples are characterised by better preservation of plant tissue relative to the floodplain samples. The enhanced preservation may be attributed to a more anoxic setting than that achieved on the floodplain. (The corollary is that the floodplain mires were slightly better oxygenated which implies a better drainage system.) Alternatively, the paralic vegetation may have been inherently less susceptible to degradation, for which relatively thick cuticle in the paralic coals may provide some support.

In summary, the above data suggest that both the paralic and floodplain peats accumulated in low-lying mires sustained

Table 3. Contrasting characteristics of coals from paralic and floodplain environments determined by maceral analysis, proximate analysis, specific energy, sulphur content, and Rock-Eval.

	Paralic (Coal Facies 1)	Floodplain (Coal Facies 2)
Facies Definition	presence of framboidal pyrite	absence of framboidal pyrite
characteristics		
vitrinite	88–91%	87–89%
liptinite	7–13%	10–11%
Tissue Preservation Index	0.8–1.5	0.3–0.5
volatile matter %dmmSf (& specific energy Mj/kg dmmSf)	high 44.4-50.3 (30.6)	low 41.0–44.8 (27.5–27.8)
sulphur	> 0.7 wgt%	< 0.7 wgt%
vitrinite reflectance	suppressed 0.38–0.52	"normal" 0.51–0.57
HC conversion potential	30 wgt% TOC	15 wgt% TOC
hydrogen index	300	150

by high water tables. The paralic mires were probably more anoxic and less well-drained than the floodplain mires. Although some podocarp pollens could have been introduced from outside the mire, the overwhelming dominance of podocarp palynomorphs suggest the paralic and Oyster Point floodplain mire itself was dominated by podocarps (cf. Warnes, 1993 for development of this argument with a larger data set with respect to Ohai Coalfield). In contrast, the Puponga Mine floodplain mire is characterised by an abundance of pteridophytes. The presence of podocarps in the paralic mire suggest peat accumulated in a fresh-water environment despite the close proximity of the coast.

The paralic coal samples are characterised by relatively high sulphur contents and the presence of framboidal pyrite when compared with the floodplain samples. This difference requires an explanation. In general, peat accumulating under the influence of saltwater has higher sulphur contents compared with those accumulating under the influence of freshwater (Price & Barker 1985, Chou 1990). Although there is no clear-cut absolute sulphur content that separates a freshwater from saltwater or brackish influence, samples with more than about 0.5%–1.0% total sulphur are likely to be influenced by seawater (Price & Shieh 1979, Bailey et al. 1990, Chou 1990). However, it is difficult to deduce whether introduction of sulphur is syngenetic or diagenetic. For example, freshwater mires may be enriched in sulphur during drowning by seawater or by diagenetic introduction with saline groundwater during early burial (Price & Shieh 1979, Newman 1991).

The process which forms framboidal pyrite is not clear. However, according to Bailey et al. (1990), framboidal pyrite may be formed in both fresh and saltwater mires. Alternatively, New Zealand examples suggest that framboidal pyrite is only developed in mires influenced by marine water during peat accumulation or those drowned by seawater prior to deposition of overlying sediments (pers. comm. Newman, 1993).

The relatively high sulphur content and presence of framboidal pyrite indicates the Mangarakau paralic mire was influenced by brackish or marine water. It is suggested that sulphur enrichment and development of framboids was a consequence of drowning the mire with encroaching seawater which probably terminated peat accumulation. The relatively high sulphur coal sequence is therefore explained by proximity to a shoreline with fluctuating sea-level episodes with corresponding expansion and contraction of the mire within the estuarine complex. The Snuggedy Swamp in South Carolina is a present-day analog for such a dynamic system (cf. Beyer & McCabe 1986). On the basis of association with fluvial sediments, absence of marine palynomorphs, and low sulphur contents, the more inland (floodplain) mires (e.g. Oyster Point and Puponga Mine mire) were neither inundated nor affected by marine water.

Thus, the presence or absence of framboidal pyrite define two coal facies that differentiate paralic mires (those influenced by marine water) and floodplain mires (those not influenced by marine water). Table 3 summarises the contrasting physical and chemical characteristics of the two coal facies.

Source rock type and quality

The modified van Krevelen diagram is frequently used to classify source rock type (Tissot & Welte 1984, Peters 1986). Generally, type I is characterised by algal organic matter and is interpreted as highly oil-prone; type II is characterised by structureless organic matter comprising liptinites (other than algae) and is interpreted as oil-prone; type III is characterised by organic matter rich in vitrinite (coals) and is interpreted as gas-prone.

The paralic and floodplain coals are clearly distinguished on the modified van Krevelen diagram (hydrogen index vs oxygen index) and hydrogen yield vs total organic matter cross plots (figure 10). The paralic coals plot in the type II source rock field whereas the floodplain coals plot in the type III field. Both coals fall within the area of other New Zealand coals outlined by Suggate & Boudou (1993) and world wide coals outlined by Peters (1986), although in both cases the paralic coals could have to be classified as anomalous.

Figure 10B illustrates the difference in yield potential of both coals. Although three points are meagre evidence for a line, this type of plot is typically linear for immature source rocks of the same type (e.g. see fig.1 of Langford and Blanc-Vallon 1990). The slopes of these lines quantify the quality of the coal (or source rock) in terms of capacity to generate hydrocarbons during pyrolysis. The paralic coals have about twice the hydrocarbon generative capacity as floodplain coals. Similar conclusions can be drawn from proximate analysis where paralic coals display the highest volatile matter (which is comparable with Rock-Eval yield, see Newman, this volume) and specific energy values.

According to conventional views, the maceral group liptinite is considered to be the main component that sources hydrocarbons (e.g. Tissot and Welte, 1984. These are the main components of type I and II source rocks (Tissot and Welte, 1984). However, the maceral group proportions of both the paralic and floodplain coals are very similar, with liptinite occurring in small proportions (7–13%, figure 7). The contrasting hydrogen index and yield capacity are therefore attributed to variations in maceral chemistry and not group proportions. Because vitrinite comprises 88–90% of the macerals it is suggested that variations in vitrinite chemistry account for the physicochemical differences between paralic and floodplain coals. In particular, because the hydrogen index of the paralic coal is high relative to the floodplain coal it is postulated that vitrinite in the paralic coals is enriched in hydrogen (i.e. perhydrous vitrinite).

Desmocollinite (i.e. vitrinite matrix) is usually considered to be enriched in hydrogen relative to telocollinite (vitrinite tissue; e.g. Toxopeus 1983). A positive relationship would therefore be expected between hydrogen (as measured by Rock-Eval yield, volatile matter, or hydrogen index) and desmocollinite, but this study shows the proportion of desmocollinite decreases with increasing hydrogen: suggesting that telocollinite is selectively enriched in hydrogen. However, vitrinite reflectance suggests that the vitrinite submacerals are not selectively enriched in hydrogen (see below), rather that depositional history is the overriding factor similarly enriching all vitrinite submacerals in hydrogen.

Newman et al. (1992), referring to previous work, shows that variations in vitrinite chemistry are not attributable to a single depositional influence. One or more factors may be causative, for example: variations in oxygen access to peat, related to mire drainage, variation in mire flora and/or climate, and marine influence during and immediately after accumulation.

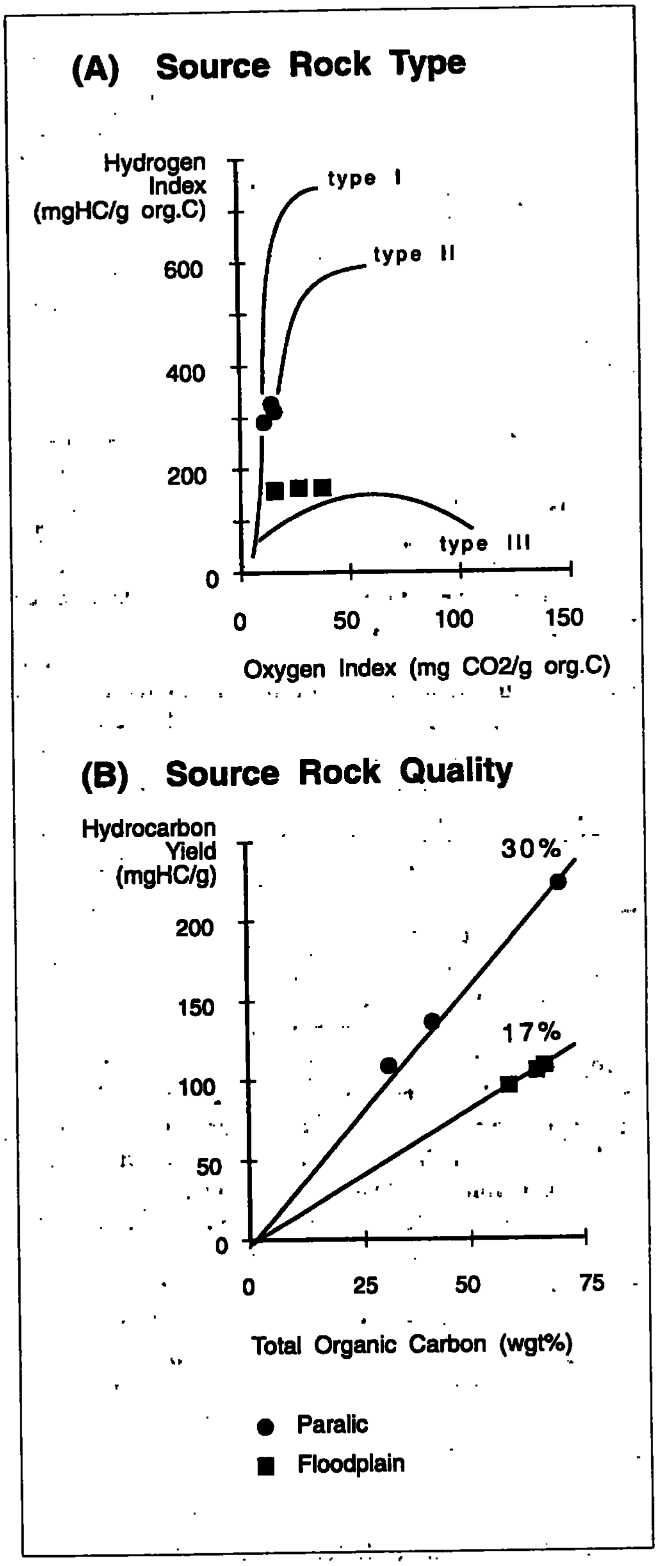

Fig. 10. Source rock type and quality as assessed by Rock-Eval parameters. (A) Modified van Krevelen diagram shows that the chemical properties of the two coal facies are distinct. The paralic coals have an appreciably higher hydrogen content that is attributed to hydrogen-rich vitrinite. Samples are immature and therefore plot anomalously in the mature area of the modified van Krevelen diagram. (B) Hydrocarbon yield (S1+S2) vs total organic carbon. Paralic coals have a much higher hydrocarbon generative capacity (30% of TOC) than the floodplain coals.

Data from this study is consistent with Newman & Newman's (1982) interpretation that anoxic conditions result in the highest volatile matter (such as hydrocarbons) and that volatile matter values were further enhanced by brackish/ marine water influences. For instance, paralic coal sample U94 has minimal marine influence, as indicated by the absence of under- or overlying tidal mud flats (figure 4), poorly developed framboidal pyrite, and relatively low sulphur, and consequently has a volatile matter comparable with the floodplain coals.

Rank (burial history) and maturity

In the petroleum industry, the magnitude of vitrinite reflectance is the most frequently used parameter for calibrating burial history or estimating thermal maturity of source rocks. However, the generally accepted underlying assumption that vitrinite reflectance is invariant to coal (or source rock) type is, in some cases, invalid (Suggate 1959, Suggate & Lowery 1982, Newman & Newman 1982, Toxopeus 1983, Price & Barker 1985, Newman et al. 1992, Quick 1992).

In the case of the paralic coals, vitrinite reflectance ranges from 0.38% to 0.52% (figure 9). All of these samples were taken from a continuous section within 1.5 m of each other. They therefore have the same rank (i.e. degree of metamorphism). Thus the observed range reaffirms that reflectance depends on more than just burial history.

Association of vitrinite with liptinite-rich kerogen is the most commonly cited reason for variations in vitrinite reflectance of isorank samples (Price & Barker 1985). However, since the small proportion of liptinites are about the same for all samples (figure 7), its presence is unlikely to have affected the magnitude of reflectance. The spread in reflectance may, however, be attributed to the suppressing ability of perhydrous vitrinite. Those samples with the highest hydrogen content (measured by yield or volatile matter) have the lowest vitrinite reflectance. (Although the relationship is not a simple one since the hydrogen index of sample U94 goes against this trend:) Vitrinite suppression due to perhydrous vitrinite is also observed by Newman & Newman (1982) and Quick (1992).

The above shows that if coal type is ignored, interpreting burial history or maturity on the basis of vitrinite reflectance will lead to erroneous conclusions regarding kitchen area and depth to maturity.

Suggate (1959) was first to recognise the dependence between generally accepted rank parameters and coal type, and devised a scheme to 'normalise' coal type with respect to rank so that chemical parameters could be compared. This scheme is a bivariant plot of volatile matter and specific energy with isorank lines resolved with empirical data. The use of this scheme for 'correcting' suppressed vitrinite reflectance has been more recently described by Newman et al. (1992). Quick (1992) also outlines a scheme based on empirical data to correct suppression using vitrinite fluorescence as a variable. Quick warns that both the Suggate scheme and his own scheme may only be valid for vitrinite-rich coals.

Using the Newman et al. (1992) scheme, the corrected vitrinite reflectance for the paralic coals is about the same as that measured at Oyster Point: Ro 0.52%. The paralic and floodplain samples have therefore undergone similar burial histories despite the disparate measured reflectance. Also note that paralic sample U94, having the least marine influence, has about the same reflectance as the floodplain coals which lends credence to the corrected reflectance (figure 9). The Puponga Mine sample (PM1), from about 10 km to the northeast, may have had a marginally deeper burial accounting for the slightly higher vitrinite reflectance.

In this study, it has not been possible to empirically establish when the onset of hydrocarbon generation (or expulsion), relative to suppressed (or corrected) vitrinite reflectance, begins or ends. However according to Rock-Eval data (Production Index in table 1), both the floodplain and paralic samples are shown to be immature at "normal" vitrinite reflectance of 0.57% Ro.

Price & Barker (1985) postulated that "hydrogen-rich macerals, of any kind, mature at a *reduced rate* compared to macerals with lower hydrogen contents and higher oxygen contents" suggesting "this is reflected by a retardation of all maturation indices, including vitrinite reflectance" (p. 74, own emphasis). However, data from this study suggest that Price & Barker's posit is not generally applicable (also see Newman this volume). Although the Rock-Eval parameter Tmax is considered a maturity index, fundamentally it represents the temperature of maximum hydrocarbon generation during pyrolysis. It is therefore interesting that Tmax is lower for the perhydrous paralic coals (ca. 422°C) than the floodplain coals (ca. 430°C; figure 11). Since the samples in this study are isorank (have similar burial histories), the Tmax results suggest that at least some hydrogen-rich macerals mature at a *faster rate* compared to macerals with lower hydrogen contents, similar oxygen contents, and similar maceral compositions.

It is possible that the sulphur content may have had an influence on the Tmax (maturation rate) of the paralic samples. Baskin & Peters (1992) highlight the importance of kerogen-bound sulphur for the onset of hydrocarbon generation by demonstrating a negative relationship between the proportion of kerogen-bound sulphur and Tmax. In this study it is noted that the higher total sulphur contents correspond with lower Tmax (figure 11), an observation consistent with Baskin & Peters (1992) since kerogen-bound sulphur positively correlates with total sulphur.

Maturation of paralic coals at a faster rate (i.e. shallower depth) has major implications for mapping kitchens. For instance, kitchens for paralic coals are shallower than those for floodplain coals. Coal type, in the sense of vitrinite chemistry, must therefore be considered when evaluating hydrocarbon prospects.

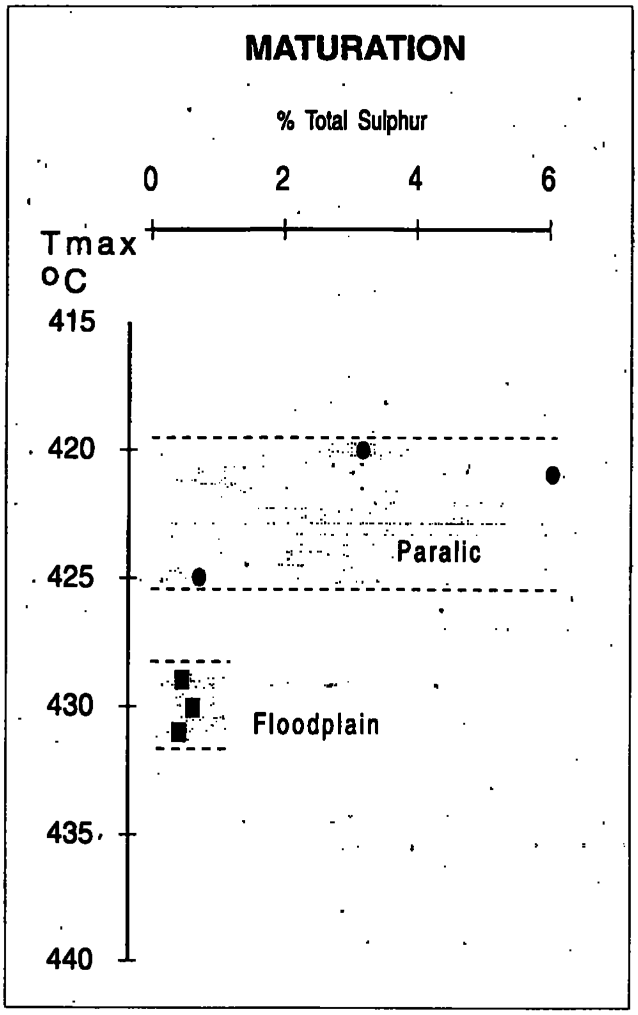

Fig. 11. Plot of total sulphur vs. Rock-Eval parameter Tmax. Overall, paralic coals generates hydrocarbons at rates faster (lower Tmax temperatures) than floodplain coals, despite all samples having similar burial histories. This suggests paralic coals may mature and generate hydrocarbons earlier (shallower) than floodplain coals. Note that the low sulphur transitional sample U94 has a higher Tmax than the other two paralic samples, suggesting that sulphur may enhance maturation rates.

Conclusions

1. On the basis of sedimentology, two distinct peat accumulating environments are recognised; paralic and floodplain. The presence or absence of framboidal pyrite in the coals can be used to distinguish these environments in the absence of sedimentary structures (e.g. from drill cuttings). The presence of framboidal pyrite indicates a mire influenced by encroaching marine water which probably terminated peat accumulation. This environment is consistent with Hirner & Robinson's (1989) requirement for a (partly) closed marine-sulphate system to explain the observed sulphur isotopes in Taranaki Basin hydrocarbons. The distribution and volume of paralic versus floodplain coals in the Taranaki Basin is presently unknown. However, with respect to the Pakawau Group, it is likely that only those coals closely associated with the estuarine to marine North Cape Formation are paralic, i.e. uppermost Rakopi Formation and lowermost Puponga CMM.

2. Pollen and spores suggest differences in dominant mire vegetation. The paralic mire vegetation has affinities with fresh water Ohai coals dominated by subequal proportions of podocarps *P.* cf. *ellipticus*, *P. mawsonii*, and *M. antarcticus*. It is argued that brackish/marine water encroached into the fresh-water mire system terminating peat accumulation. The Oyster Point floodplain mire is characterised by podocarp *T. subgranulatus*. The Puponga Mine mire is atypical since it is characterised by an abundance of pteridophytes (ferns and club mosses), especially *Trilites verrucatus*.

3. Despite the significant difference between the Oyster Point and Puponga Mine floodplain mire vegetation, the floodplain samples have indistinguishable chemical behaviour suggesting depositional environment, and not initial vegetation, explains most of the chemical variations between paralic and floodplain samples. Moreover, both the Oyster Point floodplain and paralic mires are dominated by

podocarps (albeit different species) despite the dissimilarity in chemical behaviour of coals from their different environments. In the context of this study, variations in petrology, proximate, and Rock-Eval data are amply explained by depositional environment. Paralic coals have higher hydrogen indices (300) and hydrocarbon yields (30% of TOC) compared with floodplain coals (150, 17% of TOC). Hydrocarbon yield potential is enhanced if influenced by marine water.

4. The observed wide spread in vitrinite reflectance of samples that have undergone the same burial history is attributed to variations in vitrinite chemistry. In this study, anoxicity and marine influences have resulted in perhydrous vitrinite which is susceptible to suppressed vitrinite reflectance.

5. Given the same burial history, paralic coals may mature and expel sooner (Tmax 422°C) than floodplain coals (430°C). Furthermore, early maturation may be enhanced by higher sulphur contents. This conclusion has implications for the aerial distribution and depth of Taranaki Basin source-rock kitchens. The implications depend on whether presently used kitchen maps are calibrated against suppressed or "normal" vitrinite reflectance (or both), and whether kitchens contain paralic or floodplain coals. Interpretation of kitchen maps and potential migration paths will be ambiguous if these variables are not acknowledged and 'sorted' out.

6. Petrographic, proximate, specific energy, Rock-Eval, and sulphur data are essential for an adequate understanding of source rock quality, maturity, and rank of coals. Proximate analysis is rarely used in the oil industry, but provides important and inexpensive information quantifying rank-type relationships.

7. Future geochemical work associated with oil-source and maturation studies must recognise that Taranaki Basin coals do not have a unique hydrocarbon generation potential and maturation profile. Classifying potential source samples (and corresponding geochemical data) according to depositional environment may help elucidate the so-called "mixed terrestrial/paralic/marine" Taranaki Basin source rock.

8. Although the above conclusions are internally consistent, and consistent with available data and concepts of other authors, more data from both paralic and floodplain coal facies is required to substantiate the conclusions (most of which are based on bivariate plots with only 3–6 data points).

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