

Petroleum source rock potential of North Cape Formation (Late Cretaceous) coaly sediments, Taranaki Basin

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Abstract

The Wainui and Puponga coal measure members of North Cape Formation (Late Cretaceous) are potentially important source rock units within the Western Stable Platform and Pakawau, Maui and Manaia sub-basins of Taranaki Basin. This paper presents a regional study of the petroleum potential of their coaly sediments, based mainly on seven widely spread wells, and emphasises the identification of depositional controls on genetic potential and oil-proneness. Most of the coals are mature enough to have commenced generation of oil, but only in Taranga-1 have they begun expulsion.

The total genetic potential and oil-proneness of the coaly sediments are generally underestimated by the Rock-Eval parameters S1+S2 and HI, but projection of these parameters to the inferred onset of oil expulsion (Rank(S) 12.5) allows the true potential and oil-proneness to be estimated. All coaly sediments with TOCs above ~2.5% have good genetic potential. The three primary lithologies – carbonaceous (coaly) mudstone, shaly coal and coal – form a continuum of Type III source rocks, all parts of which contribute to the total genetic potential of the coal measures in proportion to their mean organic content and total volume. The continuum is estimated to range in HI at the onset of expulsion, from 235–420 mg HC/g C_{org}, indicating mixed gas- and oil-prone to oil-prone kerogen.

Variable marine influence throughout coal measure deposition has resulted in pronounced lateral and vertical variations in the genetic potential and oil-proneness of the source rock continuum. Wainui Member coaly sediments in Wainui-1 generally have greater genetic potential and are more oil-prone than lithologies of equivalent TOC in, for example, North Tasman-1, Tane-1 and Taranga-1, which are generally less marine-influenced, as judged by coal sulphur content and dinoflagellate abundance. Similarly, wide variations in volatile matter, atomic H/C and HI – and therefore in oil-proneness – within the North Tasman-1 and Tane-1 sequences in particular, are attributed to variations in the degree of marine influence at these sites.

Introduction

Late Cretaceous to Eocene coal-bearing formations are the principal petroleum source rock units both onshore and offshore in the Taranaki Basin. The regionally transgressive North Cape Formation, the upper formation of the Late Cretaceous Pakawau Group, has been generally downgraded as a source rock unit because of the predominance of organic-poor, shallow marine siltstones and coastal sandstones. Two paralic coal measure members within it – the Wainui and Puponga members – are, however, important source rock units. The Wainui Member extends over much of the Western Stable Platform into the Maui sub-basin of the Southern Inversion Zone, whereas the Puponga Member is confined to the Manaia and Pakawau sub-basins of the Southern Inversion Zone, extending from the latter to crop out onshore in the Collingwood district of northwest Nelson (Figure 1).

In contrast to coaly sediments of the terrestrial Rakopi Formation (lower Pakawau Group), regarded by King and Thrasher (1996) as the principal source rock unit within the basin, coaly sediments of the Wainui and Puponga members may have greater oil potential and generate oil earlier (i.e. at shallower depths) as a result of syndepositional marine influence leading to higher hydrogen and organic sulphur contents. The Wainui and Puponga members may therefore have significantly different petroleum generation characteristics to the Rakopi Formation.

Scope and objectives

This paper presents the results of a comprehensive, regional study of the petroleum generative potential of coaly sediments within the Wainui and Puponga members. New Rock-Eval and standard coal analyses are presented for about 200

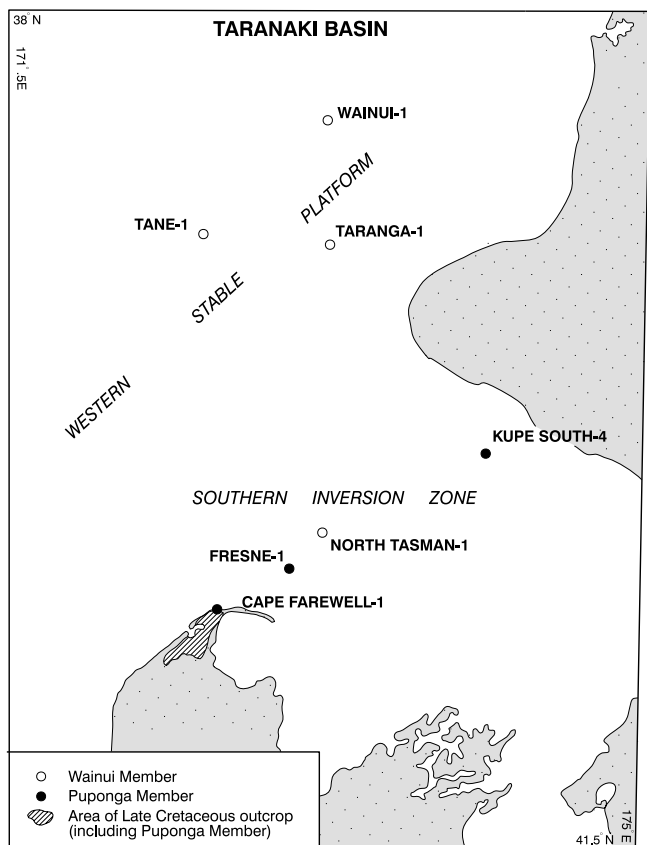


Figure 1: Wells penetrating Wainui and Puponga members, and area of Late Cretaceous outcrop in the Collingwood district of northwest Nelson.

samples collected from the seven petroleum wells (Figure 1) in which the members are intersected, as well as from outcrops in the Collingwood district. The objectives of the study were to:

1. identify stratigraphic variations in the petroleum genetic potential and oil-proneness of Wainui and Puponga member coaly sediments using Rock-Eval pyrolysis;
2. establish the major depositional controls on the basic source rock parameters; and
3. determine regional variations in coal rank and organic maturity.

The study used lithology-based samples and has integrated rank and source rock data to maximise the quality and applicability of the source rock data obtained. All coaly lithologies – coals, shaly coals and carbonaceous (coaly) mudstones – contribute to varying degrees to the petroleum genetic potential of coal measure sequences. Accordingly, all coaly lithologies are included in the study. Like most previous studies of Taranaki Basin source rocks, this study was heavily reliant on well cuttings for samples. However, whereas previous studies generally used bulk cuttings, comprising mixtures of lithologies (e.g. Analabs 1984, Robertson Research 1984, Crisp 1986, Cook 1987), this study analysed separate coaly lithologies collected from the cuttings samples. Only by doing this can the amounts and types of petroleum potentially generated by specific lithologies and the facies controls on petroleum generation and expulsion be examined. This type of information is crucial for modelling

the petroleum generation histories of specific kitchen areas and for the transfer of generic relationships to other areas or basins.

Recent studies of New Zealand coals have shown that the basic source rock parameters, total genetic potential (S1+S2) and hydrogen index (HI), are strongly dependent on coal rank or the degree of maturation (e.g. Suggate and Boudou 1993; King and Thrasher 1996; Killops et al. 1997, 1998; Sykes et al. 1998). This rank dependence has pronounced effects on the apparent genetic potential and oil-proneness of immature coals in particular. For this reason, coal rank determinations using the Rank(S) scale of Suggate (1959, see also Sykes et al. 1992 and Suggate and Boudou 1993) have been closely integrated within this study, to establish maturity levels and to permit more reliable assessment of the measured source rock parameters than would otherwise have been possible.

Stratigraphy and depositional environment

Thrasher (1992, 1992a) and King and Thrasher (1996) recognised the Wainui and Puponga members and a Fresne Conglomerate Member within the otherwise marine North Cape Formation (Figure 2). They identified the Wainui Member as laterally equivalent to and underlying the North Cape Formation marine strata in Wainui-1, Tane-1 and Taranga-1 wells on the Western Stable Platform, where it forms an extensive unit up to ca. 500 m thick, and in North Tasman-1 in the Maui sub-basin (Figure 3). In contrast, the Puponga Member, up to ca. 300 m thick, is laterally equivalent to and overlies the North Cape Formation marine strata. This member is recognised in Kupe South-4 in the Manaia sub-basin and in Cape Farewell-1, Fresne-1 and outcrop in the Pakawau sub-basin (Figures 2, 3).

The large distances between well intersections mean that the lateral continuity of the members cannot always be established by seismic mapping and thus, some of the correlations shown in Figure 2 are tentative (Thrasher 1992, 1992a). It also seems likely that the distribution of coal measures within the North Cape Formation is more complex than portrayed by the stratigraphy of Thrasher (1992, 1992a) and King and Thrasher (1996), and may record a more complex history of marine transgressive and regressive events. Suggate (1956), for example, stated that coal seams worked in the Wharariki and North Cape Vertical mines in the Puponga district lie some 150 m below the Puponga [Formation] Member. These seams presumably accumulated during a lower-order regressive event within an overall transgressive North Cape Formation sequence. Though these seams apparently do not lie within the Puponga Member, they are grouped with the Puponga Member coals for the purposes of this study.

Any uncertainties regarding the definition and correlation of the Wainui and Puponga members have no significant effect on this study, which is concerned only with determining the source rock characteristics of North Cape Formation coaly sediments. Accordingly, the correlations of Thrasher (1992,

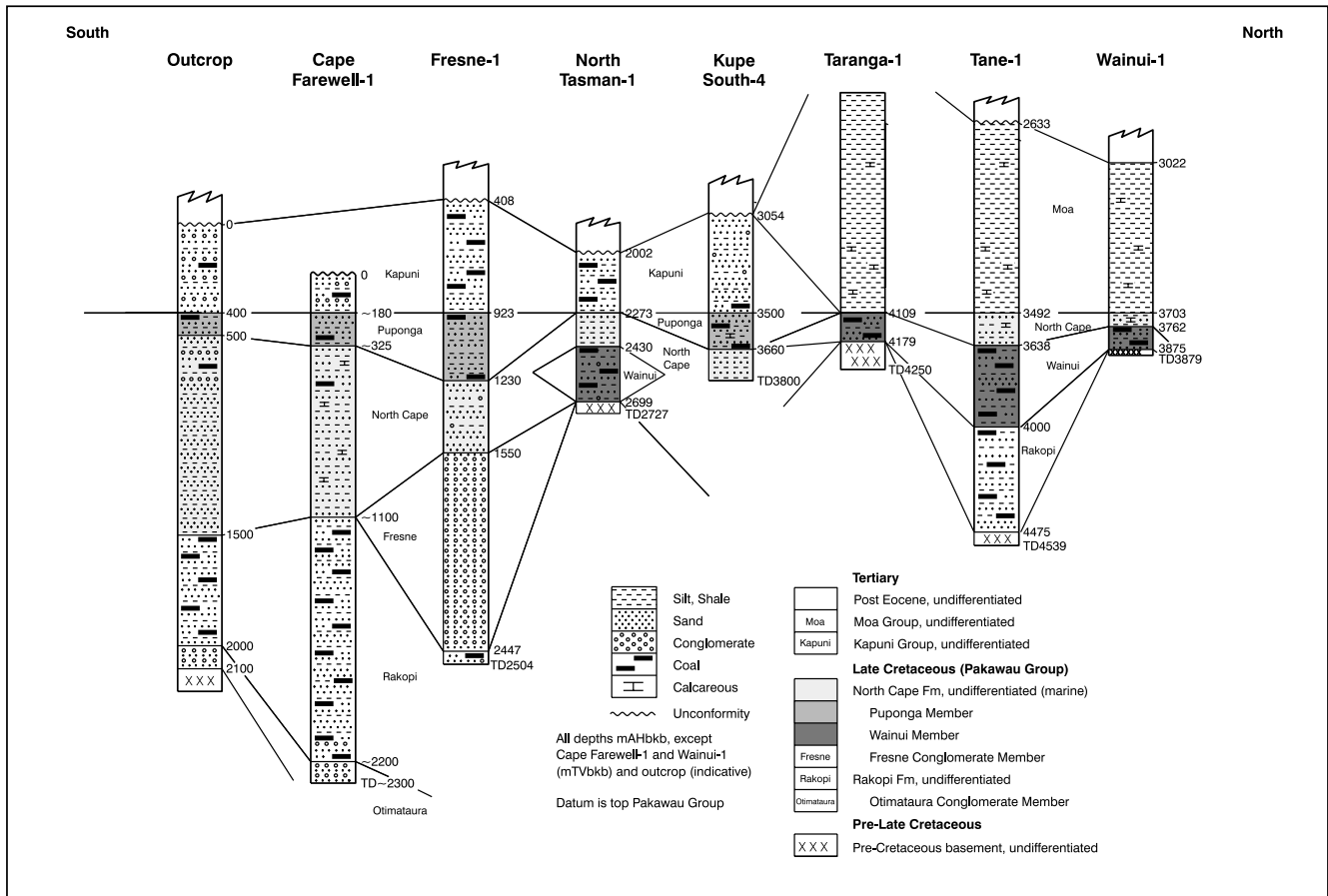


Figure 2: Lithostratigraphy of North Cape Formation and surrounding units in outcrop and wells penetrating Wainui and Puponga members (diagram modified from Thrasher 1992). See Figure 1 for well locations.

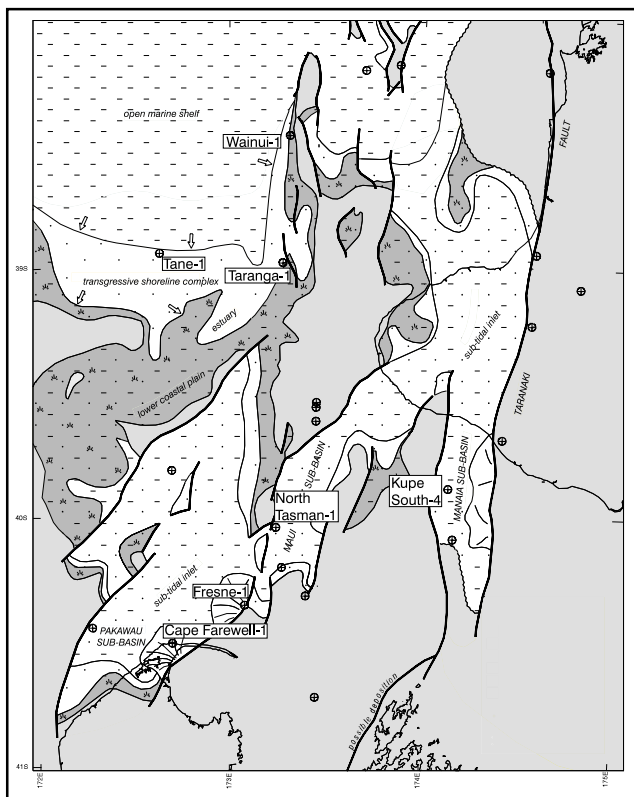


Figure 3: Latest Cretaceous paleogeography of Taranaki Basin showing deposition of Wainui and Puponga members in lower coastal plain environments (dark shade; diagram modified from King and Thrasher 1996). Light shade indicates basement. Wells intersecting Wainui and Puponga members are labelled.

1992a) and King and Thrasher (1996), as shown in Figure 2, were adopted for this study.

The Wainui and Puponga members are interpreted as having formed in lower coastal plain environments fringing basement highs and in close proximity to generally transgressing though fluctuating shorelines (Figure 3; King and Thrasher 1996). In the Whanganui Inlet area (Figure 1), for example, marginal marine conditions within the Puponga Member are indicated by the presence of dinoflagellates and lithofacies of tidal origin (e.g. Bal 1992, Bal and Lewis 1994, Thrasher 1992a). Similarly, dinoflagellate cysts have been recorded from the top of the Wainui Member in Tane-1 well (Mildenhall and Raine 1977) and from throughout the same member in Wainui-1, where the depositional environment is interpreted as having included protected coastal, lagoonal, estuarine and deltaic environments (Mildenhall and Wilson 1982).

Coal seams in both members are typically thin, and in the Collingwood district are known to be discontinuous and commonly high in ash or split by clastic sediments (e.g. Suggate 1956, Bal and Lewis 1994). Most of the many seams in North Tasman-1 appear less than ca. 1 m thick, whereas Taranga-1 and Wainui-1 both intersected a few thicker seams, up to ca. 5 m. The typically thin nature of the seams suggests they formed in generally short-lived, planar or topogenous mires of limited lateral extent. The abundance of seams within the members varies widely from relatively sparse in Cape Farewell-1, Fresne-1 and Kupe South-4, to common in Tane-1, and abundant in North Tasman-1, Taranga-1 and Wainui-1.

Samples and sampling procedures

The study draws on four sample sets:

1. The largest was collected from the Ministry of Commerce (MoC) core store in late 1998/early 1999. This comprised 64 mostly unwashed cuttings samples and six core samples from coal- and/or carbonaceous mudstone-bearing horizons within the 7 wells (Table 1, Figure 4);
2. Six unwashed cuttings samples of North Cape Formation coals from Cape Farewell-1, North Tasman-1 and Tane-1, collected and analysed for a coal maturation study in 1991 (Sykes et al. 1992);
3. Eleven coal and six carbonaceous mudstone samples collected from Puponga Member outcrops in the Collingwood district in early 1997. The sampled outcrops are around southern Whanganui Inlet (Wairoa River Bridge, Mangarakau River Mouth, Mangarakau Swamp Shore and Oyster Point localities) and at the entrance of Puponga Mine;
4. Samples of 23 coals from the Wharariki, Westhaven, Puponga, North Cape and Pakawau mines in the Collingwood district (analytical data from Suggate 1956, 1959 and unpublished data).

The combined sample set includes samples from a large majority of the Wainui and Puponga member coal seams intersected by petroleum wells, as well as outcrop and mined seams in the Collingwood district. The set also includes many of the carbonaceous mudstones interbedded with the coal seams throughout the sampled sequences. The depths of samples from five of the well sequences are shown in Figure 4.

The well cuttings samples were washed, dried and weighed. Bulk coal (i.e., all coal density fractions) was separated from the dried cuttings by flotation using sodium polytungstate (a heavy liquid) with specific gravity (SG) 2.0, then washed and dried. If more than 10 g of bulk coal was recovered for a sample, this was separated into two SG fractions: <1.5 and 1.5–2.0. The <1.5 SG fraction can be classified as “coal”, having low–medium clastic content (ash values <~20% – see Figure 10), and the 1.5–2.0 SG fraction comprises “shaly coal”, rich in clastics (ash ~40–60%). If less than 10 g of coal was recovered in the initial separation, this was retained and analysed as a “bulk coal” sample. Bulk coals have very variable clastic contents (ash <~40%)

After removal of the coal from the cuttings, mudstone samples of 1.1–17.8 g were handpicked using tweezers. The picked mudstones range from light–medium grey, slightly carbonaceous mudstone to black coaly shale, with dark brown carbonaceous mudstone generally being the dominant lithology. As the mudstones are a component of the “sinks” fraction in the initial separation, their specific gravities are >2.0.

All coal samples collected from outcrop are designated as “bulk coal” samples, given that their specific gravities were not determined and their ash contents vary widely.

Thus, the coaly sediment samples consisted of:

1. coal (SG <1.5), with low–medium clastic content;
2. shaly coal (SG 1.5–2.0), with high clastic content;
3. bulk coal (SG <2.0 or undetermined), with low–high clastic content; and
4. carbonaceous mudstone (SG >2.0).

All the samples for which sufficient material was available were crushed to –1 mm and small representative subsamples were removed for later maceral and vitrinite reflectance analyses. The remaining material from these and all other (small) samples was then milled and separate sets of representative subsamples were taken for a range of standard coal and Rock–Eval analyses.

Analyses

The analyses of coal properties were undertaken by CRL Ltd., Lower Hutt, and ACIRL Ltd., Sydney, following international and in-house standard procedures. These analyses included: proximate analysis (moisture, ash, volatile matter and fixed carbon), ultimate analysis (C, H, N), total sulphur and calorific value. This suite of analyses allows determination of both coal type (on a chemical basis) and rank, while sulphur contents also provide a record of the degree of marine influence within the coal-forming environment. Low- to medium-ash coals and bulk coals were preferred for analysis because they yield more reliable Rank(S) values than do shaly coals. This is because the required adjustments of rank parameters to the mineral-matter-free basis are more precise when mineral matter contents are low. The specific analyses undertaken on samples from each well are listed in Table 1.

Rock–Eval analyses were undertaken by the Geological Survey of Canada, Calgary, using Rock–Eval II and more recently, Rock–Eval 6 machines. The results from the two generations of Rock–Eval machines were compared and found to be very similar.

Results and discussion

Coal rank

Wainui and Puponga member coals and bulk coals (hereafter referred to collectively as “coals”) with ash contents <20% (dry basis) are plotted on Rank(S) diagrams in Figure 5. These diagrams depict the coalification pathway of coals from peat [Rank(S) 0] to meta-anthracite [Rank(S) >25] on axes of volatile matter and calorific value (both on the dry, mineral matter- and sulphur-free basis) or atomic H/C and atomic O/C (mineral matter-free basis). The New Zealand Coal Band, within which the vast majority of NZ coals plot, is also shown. The base of the band is deemed to be the coalification line of “average-type” coal. This line and the Coal Band itself provide references against which coals of different type can be compared independently of any differences in rank (see Suggate 1959, Sykes et al. 1992 and Suggate and Boudou 1993 for further details). Most of the Wainui and Puponga

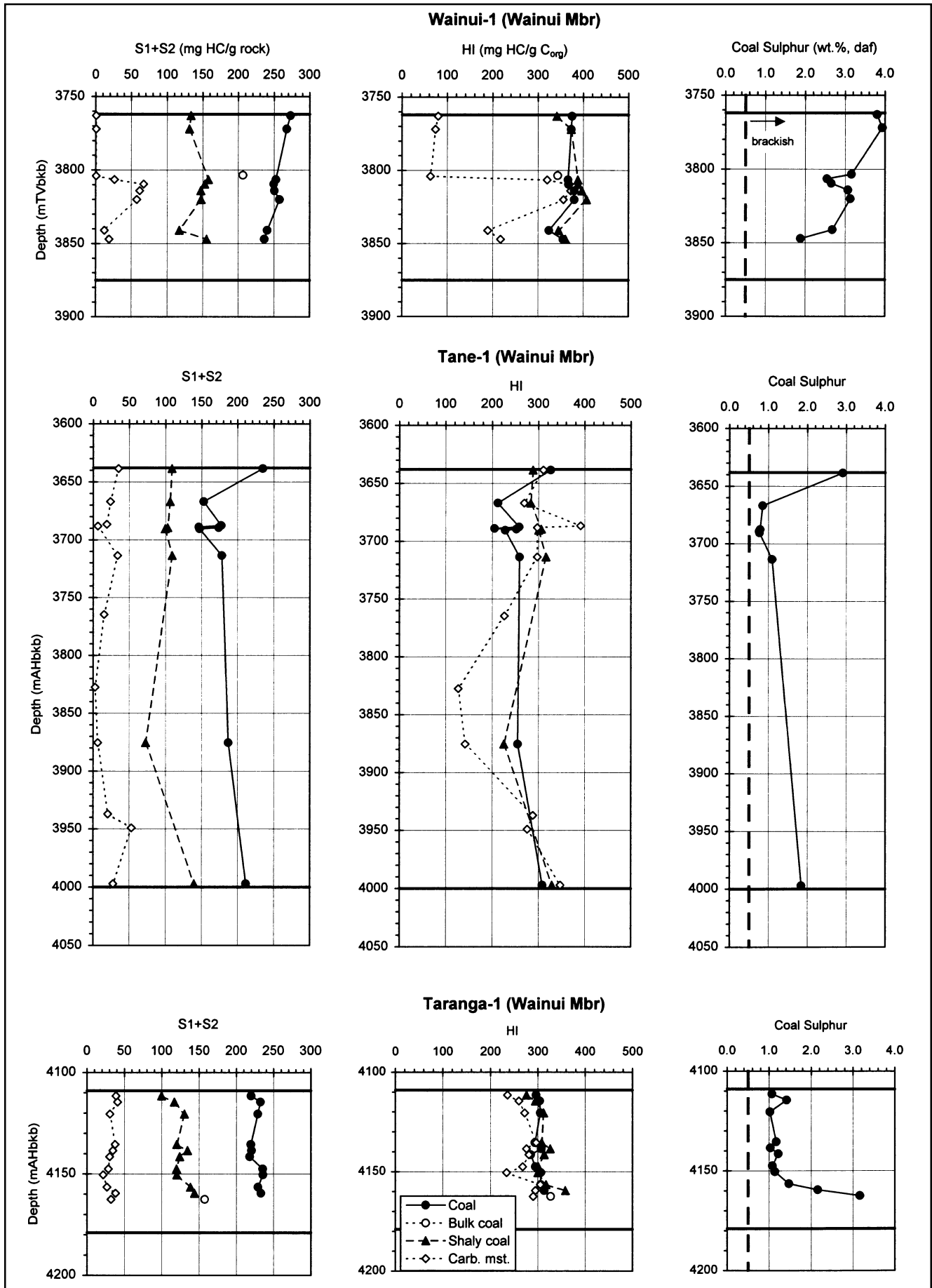


Figure 4: Stratigraphic variations in total genetic potential (S1+S2), hydrogen index (HI) and coal sulphur content in five well sequences. Horizontal scales are the same for each well. Thick horizontal lines indicate top and bottom of member. Sulphur values above 0.5% (dry, ash-free) indicate marine influence.

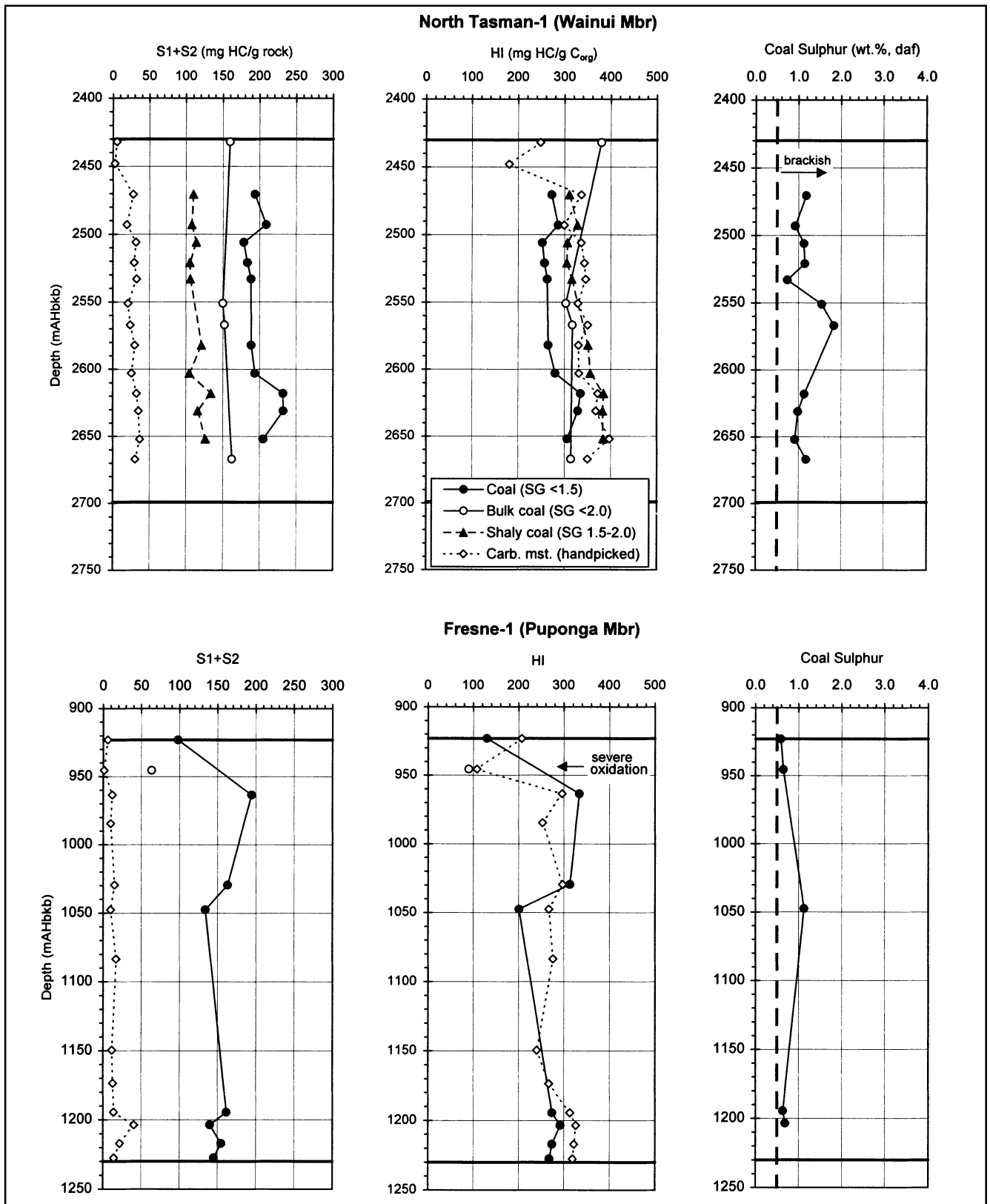


Figure 4 (cont.): Stratigraphic variations in total genetic potential (S1+S2), hydrogen index (HI) and coal sulphur content.

member coals plot within or just above the NZ Coal Band, but four coals plot well below the band (Figure 5).

All of the Wainui and Puoponga coal analyses are expected to have been affected to a greater or lesser degree by one or more of the following oxidation processes:

1. oxidation in storage;

2. oxidation in outcrop; or

3. oxidation through over-vigorous drying of well cuttings.

Because of the reduction in calorific value and increase in oxygen that accompany oxidation, the indicated ranks of many of the Wainui and Puoponga member coals (Figures 5, 6) will be somewhat lower than their true ranks. The

Location	Date drilled	Member	Depth (m) ¹	Samples ²		Coal analysis ³				Rock-Eval analysis	
				Lithology	N	Prox./S/CV	Ult	Prox./S	M/A/S	REII	RE6
North Tasman-1	1978	Wainui	2430–2699	Coal	13	7	7	4	3	10	
				Bulk coal	4	1	2	4			
				Shaly coal	10						
				Carb. mst.	15			15			
Tane-1	1976	Wainui	3638–4000	Coal	10	10	8		1	9	
				Shaly coal	7		5	7			
				Carb. mst.	11			11			
Taranga-1	1992	Wainui	4109–4179	Coal	10	10	4			10	
				Bulk coal	1		1	1			
				Shaly coal	10						
				Carb. mst.	11			11			
Wainui-1	1981	Wainui	3762–3875	Coal	8	7	4	1		8	
				Bulk coal	1		1	1			
				Shaly coal	8						
				Carb. mst.	9			9			
Cape Farewell-1	1986	Puponga	~180–325	Coal	3	3	2		1	2	
				Bulk coal	3			3			
				Carb. mst.	5			5			
Fresne-1	1976	Puponga	923–1230	Coal	1	1	1			1	
				Bulk coal	8		4	8			
				Carb. mst.	13			13			
Kupe South-4	1989	Puponga	3500–3660	Coal	1	1	1		1		
				Bulk coal	6	2					
				Carb. mst.	6			6			
Collingwood	-	Puponga		Bulk coal	34 ⁴	29	8	5	11		
				Carb. mst.	6			6			
Totals					214 ⁴	71	35	5	18	23	168

¹ mAHbkb except mTVbkb for Cape Farewell-1 and Wainui-1.

² Refer to text for definition of lithologies.

³ Prox. = proximate analysis, S = total sulphur, CV = calorific value, Ult. = ultimate analysis, M = moisture, A = ash.

⁴ Includes 23 coal analyses from Suggate (1956, 1959 and unpublished data).

Table 1: Summary of samples and analyses. Sample depths in North Tasman-1, Tane-1, Taranga-1, Wainui-1 and Fresne-1 are shown in Figure 4.

reduction, however, is quite small for a large majority of the samples, which appear to have experienced only mild oxidation during prolonged storage in the MoC core store. The effects of “storage oxidation” on measured coal ranks can be seen by comparing analyses obtained at different times in a sample’s history. Four examples are shown in Figure 6. Coal “a” from Tane-1 (3689 m) was analysed in 1977 within a year of the well being drilled and has a Rank(S), based on CV vs. VM, of 12.1 (Fig. 6a); in comparison, coal “b”, from the same depth, was collected and analysed in 1998 and has a measured Rank(S) of 11.4, an apparent reduction of 0.7 rank units over 21 years of storage. Similarly, coals “c” (3709–12 m) and “d” (3709–18 m) are also from similar depths in Tane-1; sample “c” was collected and analysed in 1991 and has a measured Rank(S) of 11.8 (Fig. 6a, c), whereas sample

“d”, analysed in 1998, has a Rank(S) of 11.2, a reduction of 0.6 units over seven years (rank values based on CV vs. VM). The two other examples shown in Figure 6 include essentially no reduction in rank for a pair of coals from North Tasman-1 (samples “e” and “f” from 2615–21 m; Fig. 6a, c) and a reduction of 1.9 rank units for a pair of coals from Cape Farewell-1 (samples “g” and “h” from 220–230 m; Figure 6b); in both these cases, the coals were analysed seven years apart.

The oxidation of coals in storage is unavoidable without taking special precautions (e.g. sample storage under argon – see Glick and Davis 1991). However, as the effects of up to 21 years storage of Wainui and Puponga member and other Taranaki Basin coals (GNS unpublished data) appear to generally amount to a reduction in the measured Rank(S) of

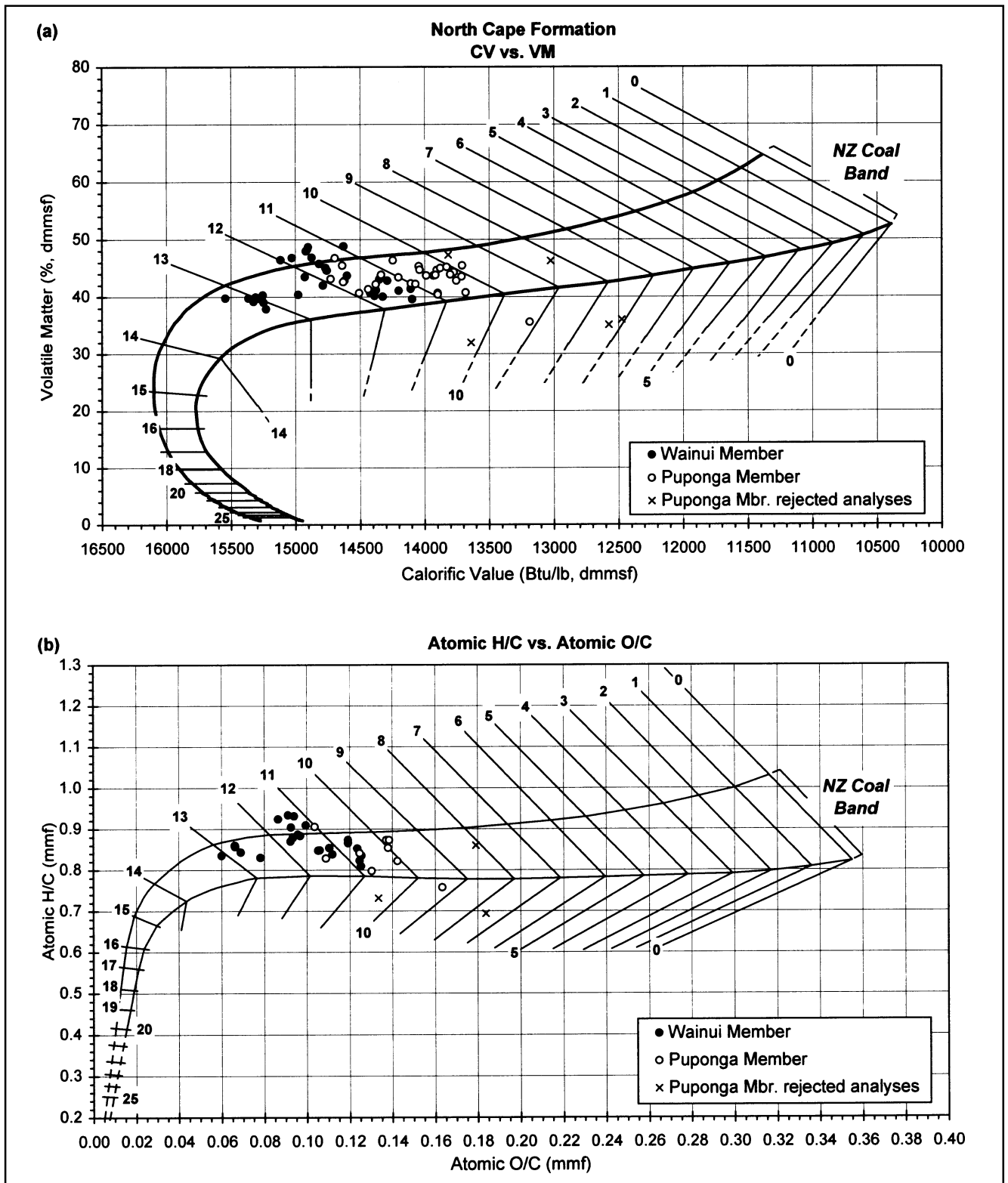


Figure 5: Wainui and Puponga member coals plotted on axes of (a) calorific value and volatile matter and (b) atomic H/C and O/C, and shown in relation to the NZ Coal Band and rank scale of Suggate (Suggate 1959, Sykes et al. 1992, Suggate and Boudou 1993). All coals plotted have <20% ash (dry). Refer to text and Figure 6 for details of rejected analyses.

<1 rank unit, and the normal accuracy of Rank(S) values is ± 0.5 rank units, all except five of the Wainui and Puponga analyses shown in Figures 5 and 6 are accepted herein without adjustment and are used in the following sections to identify the maturity and petroleum potential of the coals.

The five rejected analyses (Fig. 5) are of coals that appear to have experienced moderate to severe oxidation. They include:

- A sample from Fresne-1 (941–50 m) that plots well below the Coal Band (Fig. 6b). Previous petrographic examination of a Fresne-1 coal from 947–50 m revealed abundant and severe oxidation cracks and rims, probably resulting from over-vigorous drying of the original well cuttings.
- Two 1998 samples from Cape Farewell-1 (190–200 and 220–30 m – sample “h”), which have ranks of 1.9–2.1

lower than sample “g” from 220–30 m (Fig. 6b) analysed in 1991, presumably because of significant oxidation in storage.

- Two outcrop samples, “j” and “l” (Fig. 6b), which appear to have suffered significant oxidation through weathering. Coal “j” has a much lower calorific value than coal “i” from the same Wairoa River Bridge locality, and coal “l”, from the Mangarakau Swamp Shore locality, has a much lower calorific value than the nearby coal “k” from the Mangarakau River Mouth locality.

Based on the accepted analyses and without adjustment for oxidation in storage, North Cape Formation coals have measured Rank(S) values of 9.2–13.2 (Figs 5, 6, Table 2). The highest rank coals are the Wainui Member coals in Taranga-1, which have an average Rank(S) of 13.0 on the CV vs. VM diagram (Figure 6a, Table 2), significantly greater than the average ranks of equivalent coals in North Tasman-1 (11.7), Tane-1 (11.4) and Wainui-1 (11.6). The average rank of the Tane-1 coals is raised slightly by the inclusion of the 1977 and 1991 analyses, at which times the coals were less oxidised. Comparison of the 1998 analyses with the 1998 analyses of Wainui-1 and North Tasman-1 coals suggests ranks are ca. 0.5 units lower in Tane-1 (assuming a similar degree of oxidation, which is reasonable given the three wells were drilled within a span of five years).

Most Puponga Member coals in Cape Farewell-1, Kupe South-4 and the Collingwood district have ranks of 9.2–11.9, disregarding the Fresne-1, Cape Farewell-1 and outcrop samples that are apparently strongly affected by oxidation. Coals from the Wharariki Mine are on average 1.0 units greater in rank than those from Westhaven Mine (Figure 6b), perhaps reflecting their slightly lower stratigraphic position.

There is little downhole increase in rank through the seven drilled Wainui and Puponga member sequences, all of which are <400 m thick; the greatest rank increase is 1.2 in Tane-1, in which the thickest section has been intersected. Greater rank variation is displayed between the wells, reflecting regional variations in depth of burial and heat flow.

Comparison of the ranks and burial depths of North Cape Formation coals among the seven wells is not straightforward because of the substantial sections missing in the four wells in the Southern Inversion Zone as a result of Late Miocene–Pliocene uplift and erosion. Approximately 2400 m of section are estimated to be missing from the Cape Farewell-1 sequence, for example, and 1700–1900 m from the sequence in North Tasman-1 (Sykes et al. 1992). In contrast, the three wells on the Western Stable Platform have experienced little or no uplift and their coals are likely to be presently at their maximum depths of burial. The Wainui Member coals in Wainui-1 and Tane-1 have been buried an average of 3800 m in each well and have very similar mean ranks of 11.6 and 11.4, respectively. The equivalent coals in Taranga-1 have a greater mean rank of 13.0 (Table 2), having been buried an average of 350 m deeper and having experienced earlier burial beneath the northwestward prograding Plio-Pleistocene Giant Foresets Formation.

Coal type

The New Zealand Coal Band represents the coalification or maturation pathway of relatively perhydrous Type III kerogen (Suggate and Boudou 1993). On axes of CV vs. VM and atomic H/C vs. atomic O/C, almost all Wainui and Puponga member coals plot within or slightly above, the Coal Band (Figures 5, 6), indicating that they comprise perhydrous Type III kerogen typical of, or slightly more hydrogen-rich than, New Zealand coals in general. The only exceptions are the Puponga Member coals from Cape Farewell-1 and Fresne-1, which plot well below the band. Previous petrographic examination of coals from 220–30 m in Cape Farewell-1 and 947–50 m in Fresne-1 revealed that they comprised mostly telinite (humified woody material) from dispersed vitrain lenses, or “coaly spars”, rather than from true coal seams, and as such, these coals would be expected to be relatively poor in volatile matter and hydrogen.

The plots in Figure 6 indicate a wide range of coal types within the North Cape Formation. Wainui Member coals in Wainui-1, for example, are consistently volatile- and hydrogen-rich, with all except one coal plotting above the Coal Band (Figure 6a, c), while in North Tasman-1 and Tane-1, the equivalent coals span a range of compositions from near the base of the band to just above it in a few cases (Figure 6a, c). Wainui Member coals in Taranga-1 are more tightly clustered in the middle to upper part of the band, indicating slightly less variation in coal type. Puponga Member coals span the width of the Coal Band and in a few cases, plot below it (Figures 5, 6b), but with the exception of a single outcrop sample from the Wairoa River Bridge locality, none of the Puponga coals plots above the band. The depositional factors believed responsible for the variations in chemistry and hence in kerogen type, are discussed below.

Organic maturity

King and Thrasher (1996) and Killops et al. (1998) have recently published new understandings of the oil and gas potential of Taranaki Basin coals and of the maturity thresholds for oil generation and expulsion. The identification of generation and expulsion thresholds has been aided by the development of coal bands on plots of S1, S2 and HI vs. Rank(S) (e.g. King and Thrasher 1996). New NZ coal bands on axes of S1+S2 and HI vs. Rank(S) are presented in Figure 7. The HI band, which is very similar to that presented for a smaller set of Taranaki Basin coals in King and Thrasher (1996, Figure 6.19c), depicts a uniform range of HI of 60–170 (mg HC/g C_{org}) up to a Rank(S) of ~9.5, beyond which HI increases to a peak of 240–380, then decreases (Figure 7b). The increase in HI at Rank(S) ~9.5 and peak at ~12.5 are unexpected given that hydrocarbon generation should result in a decrease in HI, not an increase. It is thought that the HIs of coals below Rank(S) ~12.5 are suppressed partly as a result of oxygen-group suppression of the FID during Rock-Eval analysis (Boudou et al. 1994, Killops et al. 1998). Another and perhaps more important process is that of structural rearrangement within the coal during diagenesis and catagenesis, leading to an increase in potentially

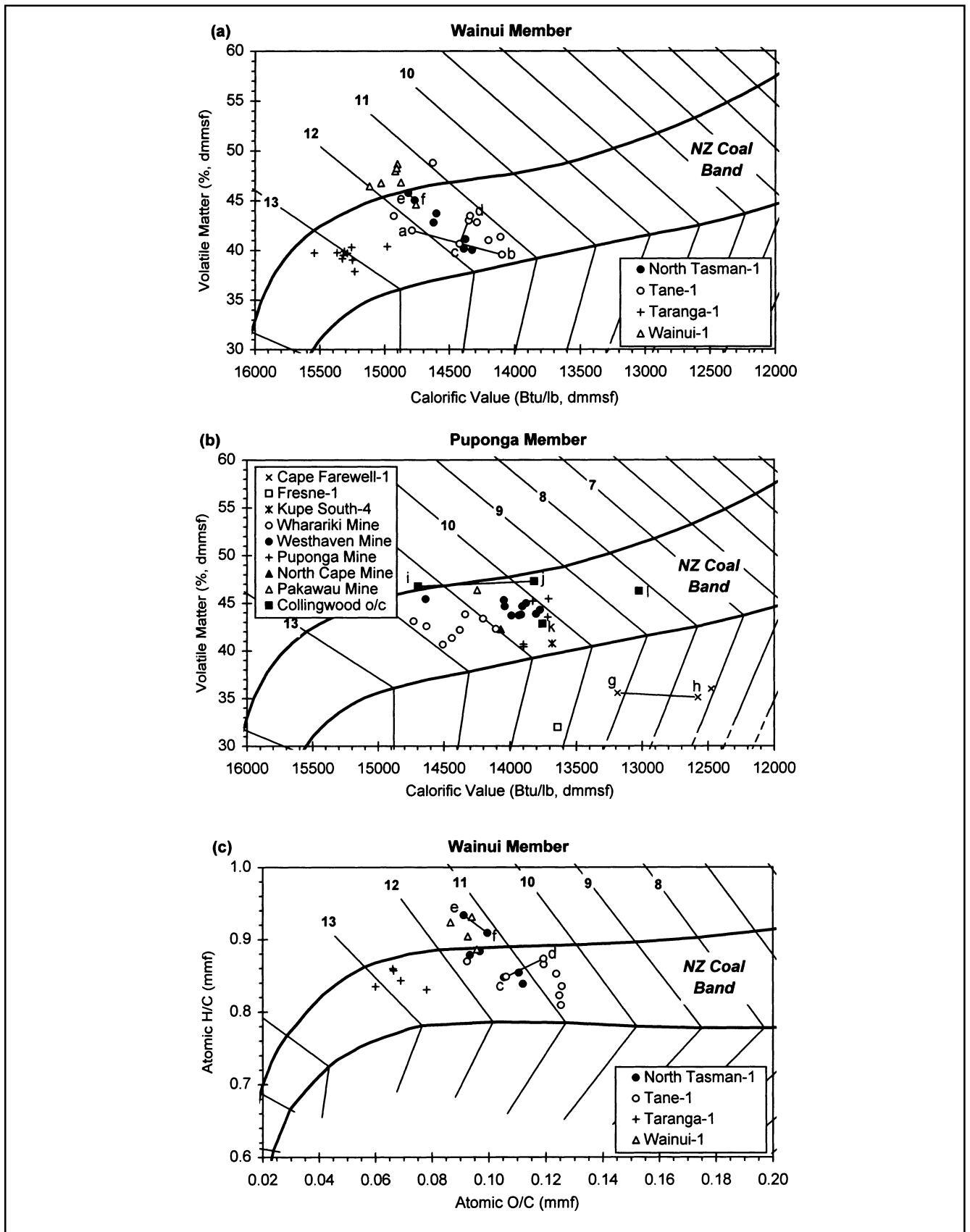


Figure 6: Wainui and Puponga member coals plotted on axes of (a, b) calorific value and volatile matter and (c) atomic H/C and O/C, and shown in relation to the NZ Coal Band and Suggate rank lines. Tie lines link pairs of samples from the same well depth or outcrop and which have experienced different degrees of oxidation in storage or outcrop (see text for sample details).

hydrocarbon-generating units (Killops et al. 1998). For example, recent work on Australian Bowen Basin Permian coals has shown that mature coals are more oil-prone, as a

result of re-incorporation of H-rich volatile components into the coal matrix, compared with predictions from immature coals (Boreham et al. 1999).

Location			Coal Properties ¹			Rock-Eval Properties								
Sulphur (% daf)			Rank(S) ²		R _o (%)	Samples ³		TOC (wt.%)		S1+S2 (mg/g)		HI (mg/g)		
N	Mean	Range	N	Mean	Range	Lithology	N	Mean	Range	Mean	Range	Mean	Range	
North Tasman-1														
14	1.14	0.74–1.83	7	11.7	11.6–11.8	0.55–0.61 ⁴	Coal	13	70.1	64.4–80.2	204.6	178.4–245.5	283	241–335
							Bulk coal	4	46.2	40.5–49.8	156.2	150.3–162.3	329	303–380
							Shaly coal	10	32.5	28.3–36.2	114.3	104.6–133.7	342	305–385
							Carb. mst.	15	7.3	1.4–9.3	25.5	2.6–36.9	328	180–397
Tane-1														
15	1.25	0.67–3.01	9	11.4	10.9–12.1	0.38–0.57 ^{4,6}	Coal	10	68.6	63.1–77.6	175.3	145.2–234.7	249	183–326
							Shaly coal	7	34.8	30.7–40.3	105.5	72.5–139.6	292	225–329
							Carb. mst.	11	7.7	2.2–18.6	22.2	2.9–53.1	270	127–391
Taranga-1														
11	1.45	1.02–3.16	10	13.0	12.6–13.2	0.72–0.77 ⁷	Coal	10	69.8	66.8–73.5	227.0	217.8–235.4	301	285–313
							Bulk coal	1	44.1		157.5		327	
							Shaly coal	10	37.2	32.7–40.4	124.6	99.6–143.8	311	276–358
							Carb. mst.	11	11.1	8.1–14.8	32.6	21.7–40.7	274	234–305
Wainui-1														
9	2.98	1.88–3.93	7	11.6	11.3–12.0	0.55–0.58 ⁵	Coal	8	65.6	62.4–70.0	253.5	236.4–273.1	365	324–380
							Bulk coal	1	56.8		206.5		343	
							Shaly coal	8	35.5	31.2–40.2	142.8	117.0–158.0	375	341–407
							Carb. mst.	9	8.1	0.9–17.0	27.3	0.7–67.3	227	63–372
Cape Farewell-1														
3	0.70	0.66–0.73	1	9.2		0.50 ⁸	Coal	3	66.5	64.6–69.6	43.4	38.7–48.7	64	60–66
							Bulk coal	3	61.9	57.7–64.6	46.7	38.8–55.7	75	59–95
							Carb. mst.	5	1.7	0.5–3.9	4.9	0.6–12.7	206	103–325
Fresne-1														
5	0.74	0.59–1.13	1	10.2?		0.49–0.61 ^{4,6}	Coal	1	69.1		63.5		90	
							Bulk coal	8	56.4	46.7–69.6	148.7	98.1–194.4	261	130–334
							Carb. mst.	13	4.9	1.2–12.2	14.2	1.3–40.6	269	108–326
Kupe South-4														
3	0.73	0.61–0.95	1	10.5			Coal	1	73.5		96.4		128	
							Bulk coal	6	50.0	46.2–53.3	84.1	71.7–96.3	166	142–192
							Carb. mst.	6	6.0	4.5–8.5	10.3	6.6–14.9	168	143–211
Collingwood														
34	1.15	0.33–6.19	27	10.8	9.8–11.9	0.38–0.57 ⁹	Bulk coal	11	60.1	45.7–73.8	156.5	111.0–263.4	256	193–357
							Carb. mst.	6	7.7	1.3–20.3	22.0	0.7–69.9	229	54–343

¹ Coal properties determined on coals (SG<1.5) and bulk coals (SG<2.0)

² Rank(S) values based on plots of CV v. VM (both dmmsf)

³ Refer to text for definition of lithologies

⁴ Analabs (1984)

⁵ Lowery (1988)

⁶ Robertson Research (1984)

⁷ Shell Todd Oil Services (1993)

⁸ GNS unpublished data

⁹ Bal (1994)

Table 2: Summary of Wainui and Puponga member coal and Rock-Eval analyses by location.

King and Thrasher (1996) interpreted the increase in HI at Rank(S) ~9.5 (R_o ~0.5–0.6%) to mark the commencement of oil generation and the peak in HI at Rank(S) ~12.5 (R_o ~0.7–0.8%) to mark the onset of oil expulsion. The commencement of generation also coincides with a rise in S1 (King and Thrasher 1996, fig. 6.19a) and the beginning

of coking properties in coals, while the inferred onset of expulsion at Rank(S) 12.5 coincides with the beginning of the decrease in atomic H/C shown by the NZ Coal Band (Fig. 5b; Suggate and Boudou 1993). Sykes et al. (1998) placed the generation and expulsion thresholds at Rank(S) 10.5–11.5 and Rank(S) 12.5–13.5, respectively, for coals in Tara-1

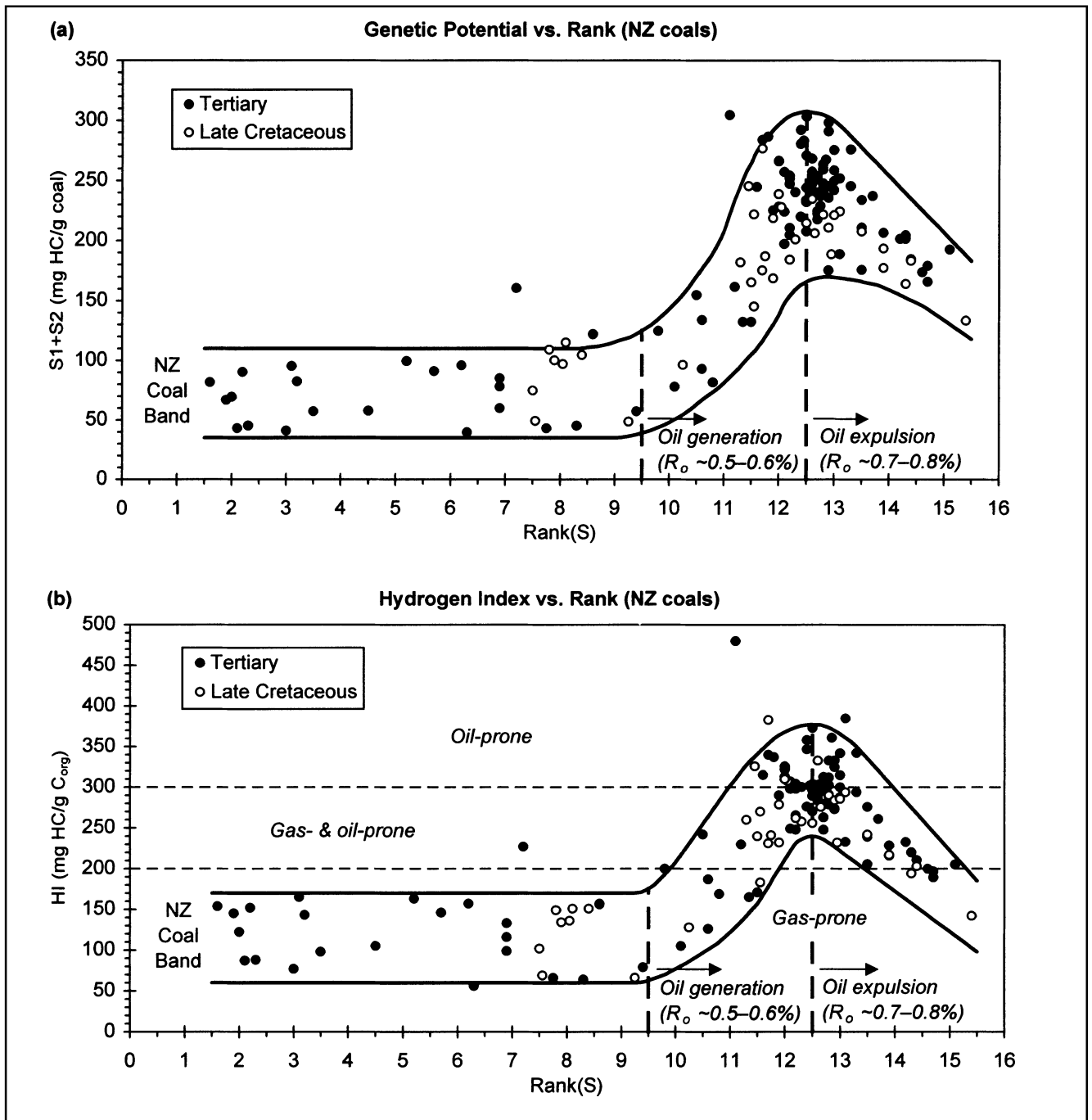


Figure 7: (a) Total genetic potential and (b) hydrogen index versus Rank(S) for NZ Tertiary and Late Cretaceous, vitrinite-rich coals, including those in Taranaki, Wanganui, West Coast, Ohai, eastern Southland and Great South basins. All coals plotted have <20% ash (dry). These plots define the NZ Coal Band, against which Wainui and Puponga member coals are compared (see Fig. 8). Plots based on data from Suggate and Boudou (1993), Norgate et al. (1997), Killops et al. (1998) and GNS database.

well in the Great South Basin, based on strong downhole trends in the Rock-Eval parameters S1, S2, BI (bitumen index = $S1 \cdot 100 / TOC$) and HI, while Killops et al. (1998), drawing on a wider range of geochemical parameters, inferred the onset of significant oil generation at Rank(S) 12 and expulsion at ~12.0–14.5 for Taranaki and Great South Basin coals.

Further work is required to define the generation and expulsion thresholds more precisely for specific kitchen areas, taking into account variations in source rock facies and burial and thermal histories. However, based on the thresholds suggested by the NZ Coal Band in Figure 7, all of the North Cape Formation coals (Figure 8) in North Tasman-1, Tane-1,

Taranga-1, Wainui-1, Kupe South-4 and the Collingwood district are judged to have attained sufficient maturity to have generated oil but only those in Taranga-1 appear to have reached sufficient maturity to have expelled oil. In contrast, Puponga Member coals in Cape Farewell-1 appear not quite mature enough for generation, based on a single Rank(S) value of 9.2 (Figure 8). No new vitrinite reflectance data were collected for this study but existing data for all wells except Kupe South-4 (Table 2), support the maturity assessment inferred from Rank(S); that is, only Wainui Member coals in Taranga-1 have reflectances (R_o 0.72–0.77%) indicative of oil expulsion.

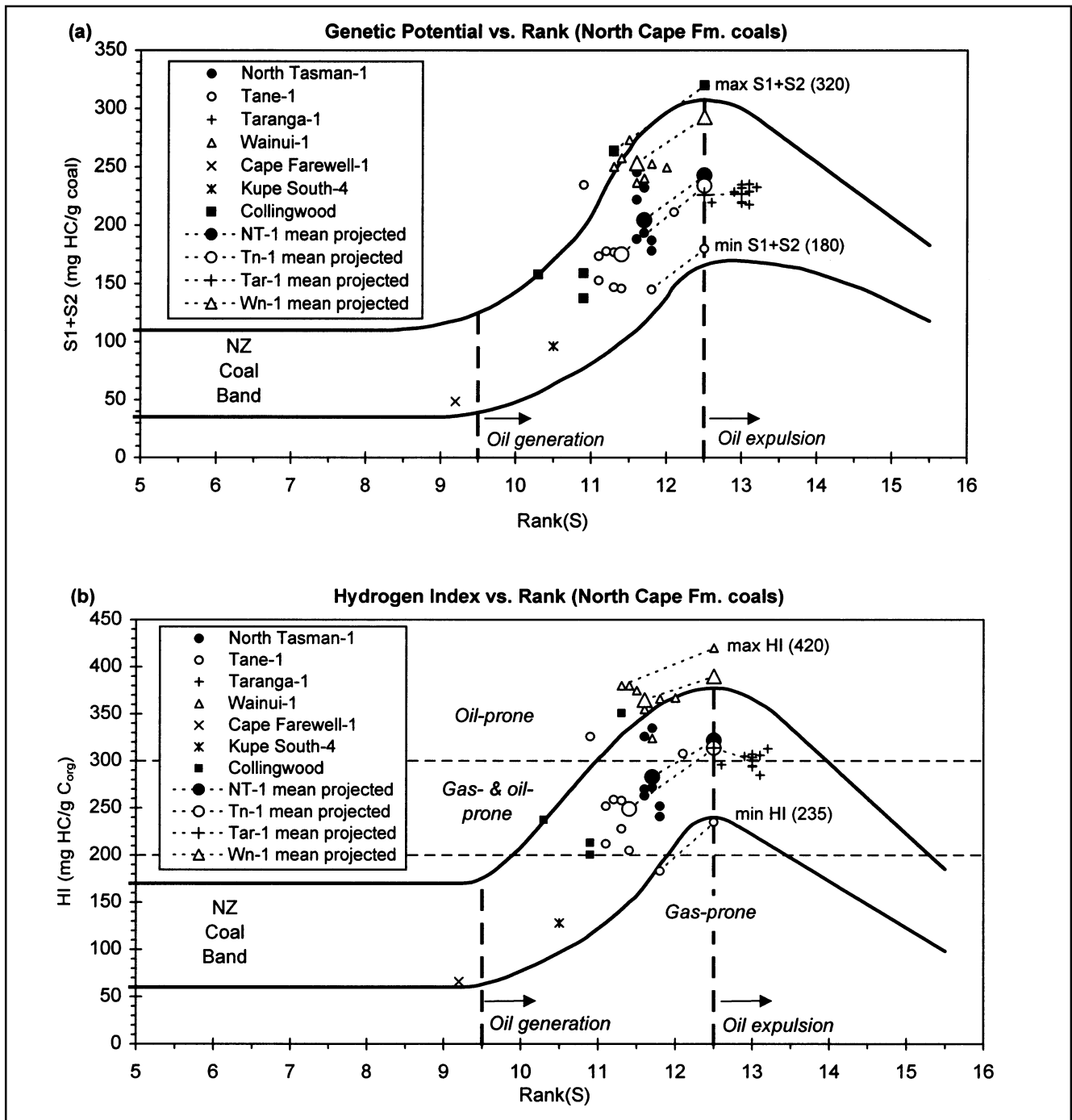


Figure 8: (a) Total genetic potential and (b) hydrogen index versus Rank(S) for Wainui and Puponga member coals in relation to the NZ Coal Band. Fine dashed lines project the minimum and maximum measured S1+S2 and HI values, as well as mean values in selected wells, to their expected values at the inferred onset of oil expulsion at Rank(S) 12.5. Only coals with <20% ash (dry) and reliable Rank(S) values are plotted.

The Western Stable Platform is commonly perceived to be immature for expulsion of significant quantities of hydrocarbons. The results of this study concur with those of previous studies (e.g. Shell Todd Oil Services 1993, King and Thrasher 1996), which concluded that the Wainui Member sequences in Tane-1 and Wainui-1, although having generated some hydrocarbons appear not to have reached sufficient maturity to have expelled them, whereas the slightly greater rank Wainui Member sequence in Taranga-1 appears to have just-passed the expulsion threshold. The expulsion of oil in Taranga-1 appears to be confirmed by the presence of oil impregnations in sandstone at 4127.1 m, which are

inferred to represent locally expelled hydrocarbons from the surrounding just-mature source rocks (Shell Todd Oil Services 1993). It is important to bear in mind that most wells are drilled on structural highs and that more mature source rocks are likely in deeper sections of the Western Stable Platform.

Petroleum genetic potential

The total genetic potential and organic carbon content of source rocks are expressed by the Rock-Eval parameters S1+S2 and TOC, respectively. These are plotted for Wainui and Puponga member coaly lithologies in Figure 9. A key

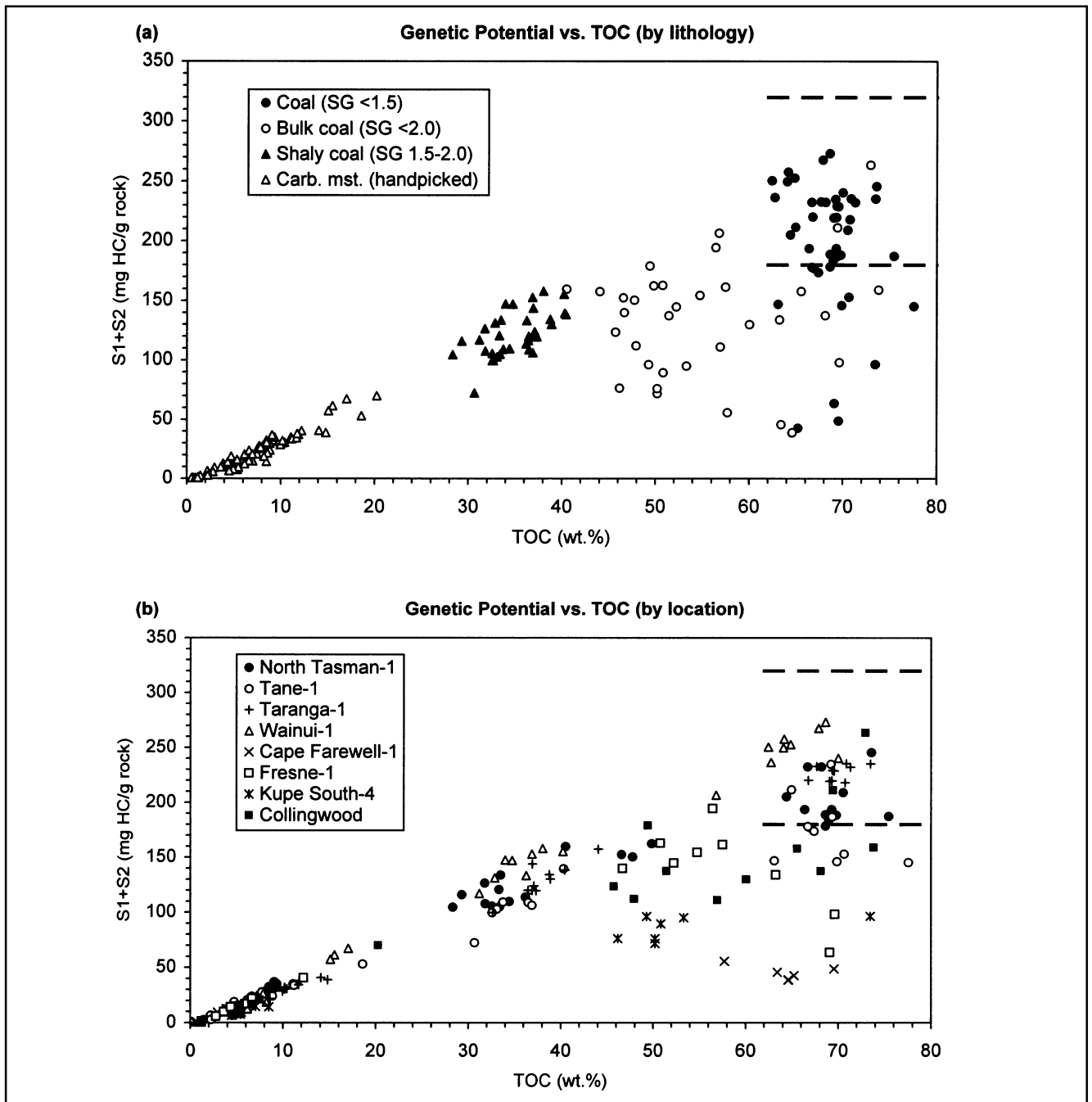


Figure 9: Total genetic potential versus and organic carbon content for Wainui and Puponga member coaly sediments by (a) lithology and (b) location. Dashed lines depict the expected range of genetic potential (180–320 mg HC/g rock) for coals at the inferred onset of oil expulsion (see Figure 8a).

finding of this study is that the three primary lithologies – carbonaceous (coaly) mudstone, shaly coal and coal – essentially form a Type III source rock continuum increasing in organic carbon content from <0.5% in the leanest of mudstones to almost 80% in the most organic-rich coals (Figure 9a). TOCs of the carbonaceous mudstones range up to ~25%, the shaly coals range from ~25–40%, and the coals and bulk coals, from ~40–80%. Within the coal class, the <2.0 SG bulk coals mostly have TOCs in the range 40–60% but extend up to 74%, whereas the <1.5 SG coals are consistently in the higher TOC range from 60–80%, as expected given their generally lower clastic contents. There appears to be a gap in organic carbon content between the mudstones and shaly coals (Figure 9a) but this is almost

certainly an artefact of the sampling procedure. The source rock continuum, from organic-poor mudstones to organic-rich coals, simply represents a declining contribution of clastic mineral matter and a concomitant increase in the proportion of organic matter. Among the coals and shaly coals, there is a strong inverse linear relationship between their TOC and ash contents (Figure 10), the latter of which provides a close approximation of clastic content; no ash content data are available for the carbonaceous mudstones.

Peters and Moldowan (1993) define a source rock as having good generative potential if its TOC exceeds 1% and S2 exceeds 5 mg HC/g rock. On this basis, all of the Wainui and Puponga member coals and shaly coals and a large majority

of medium to dark carbonaceous mudstones analysed are deemed to be good to very good source rocks and the effective source rock continuum commences at TOCs above ~2.5%.

Organic matter type is broadly similar throughout the continuum and therefore it is expected that the total genetic potential should increase linearly with increasing organic carbon content, from the leanest mudstones to the richest coals. Such an increase is apparent through the mudstones and shaly coals (Figure 9a), but there is considerable scatter among the coals. That is, for any level of coal organic carbon content, there is a wide range of hydrocarbon volumes generated during Rock-Eval pyrolysis. Coals with 70% TOC, for example, produce between 50 and 270 mg HC/g coal.

This variation in genetic potential among coals of equal organic content is the result of geographic and stratigraphic variation in both coal rank and type (or facies). As seen in Figure 7a, S1+S2 values for low- to medium-ash (<20%) New Zealand coals increase markedly from a range of 35–110 (mg HC/g coal) in immature coals (i.e. <Rank(S) 9.5) to 170–310 at the inferred onset of expulsion. Hence, there is a “rank effect” causing suppression of S1+S2 for coals below Rank(S) 12.5. In contrast, the height of the Coal Band at any particular rank reflects the range in genetic potential resulting from variation in coal type among the majority of New Zealand low- to medium-ash coals, including variation in organic matter abundance and type. This combination of rank and type variation is responsible for the wide scatter in S1+S2 values among Wainui and Puponga member coals (Figure 9a). The Puponga Member coals in Cape Farewell-1, Fresne-1, Kupe South-4 and the Collingwood district generally have lower S1+S2 values than the Wainui Member coals (Figure 9b), mainly as a result of their lower ranks.

Adjustment for the rank effect is possible by projecting the measured S1+S2 values for Wainui and Puponga member coals to their equivalent vertical positions within and above the Coal Band at Rank(S) 12.5. This gives an estimated range of S1+S2 at the inferred onset of expulsion, of 180–320 mg HC/g coal (Figs 8a, 9a), for coals with <20% ash (dry).

The Wainui Member coals in North Tasman-1, Taranga-1, Tane-1 and Wainui-1, for which more complete data sets are available, occupy a range of vertical positions within the Coal Band and thus comprise a range of coal types or facies (Figure 8a). The mean TOC and S1+S2 values for the coals and other coaly lithologies within these wells are shown in Figure 11a and listed in Table 2, and represent the measured genetic potential of the source rock continuum in each well. The S1+S2 values of the coals and bulk coals are, however, known to be variably suppressed by the rank effect. Hence to correct for this effect and to allow direct comparison of genetic potentials independent of rank, the mean coal S1+S2 values for the four wells are projected to their respective positions within the Coal Band at Rank(S) 12.5 (Figure 8a). This projection increases the indicated genetic potentials of North Tasman-1, Tane-1 and Wainui-1 coals significantly but leaves those of the Taranga-1 coals virtually unchanged (Figure 8a).

The rank-adjusted, mean coal S1+S2 values shown in Figure 11b present a slightly different picture of the source rock continuums for the four wells to that shown in Figure 11a. At the onset of expulsion, the source rock continuums for North Tasman-1, Tane-1 and Taranga-1 have very similar mean genetic potentials for a particular organic content, whereas the Wainui-1 continuum has a significantly greater potential. There is, however, considerable stratigraphic variation in the genetic potentials of Wainui Member coal seams within North Tasman-1 and Tane-1, with some of these seams having genetic potentials comparable to those of some seams in Wainui-1 (Figure 8a).

Oil-proneness

A general indication of the oil-proneness of kerogen is provided by the hydrogen index, which is defined by S2 normalised to organic carbon content (i.e. $S2 \cdot 100 / \text{TOC}$). HIs of 50–200 (mg HC/g C_{org}) are deemed to indicate gas-prone kerogen, 200–300, mixed gas- and oil-prone kerogen, and >300, oil-prone kerogen (Peters and Moldowan 1993). It can be seen from Figure 7b, however, that HI, like S1+S2, is significantly affected by coal rank. It would be quite erroneous to classify New Zealand immature coals as gas-prone based on their HI range of 60–170 (Figure 7b). To do so would grossly underestimate the oil potential of NZ basins. Rather, classification is probably best based on HI values at the peak in the Coal Band at Rank(S) 12.5, the inferred threshold of expulsion. On this basis, New Zealand coals in general are classified as mixed gas- and oil-prone to oil-prone (Figure 7b). Translation of HIs for Wainui and Puponga member coals to their respective positions within and above the Coal Band at Rank(S) 12.5 yields a predicted range of HI at the onset of expulsion of 235–420 mg HC/g C_{org} (Figure 8b). This range of HI indicates mixed gas- and oil-prone to oil-prone kerogen.

On a plot of HI vs. Rank(S) (Figure 8b), Wainui and Puponga member coals plot throughout the height of and above the NZ Coal Band, indicating a wide range of coal types with varying propensity to generate oil. Wainui Member coals in Wainui-1 are collectively the most hydrogen-rich, and accordingly are the most oil-prone. The equivalent coals in Tane-1 and North Tasman-1 span much of the height of the Coal Band, indicating a wide range of hydrogen-richness and thus oil-proneness. In contrast, the equivalent coals at Taranga-1 site are relatively tightly clustered within the centre of the band and thus appear to comprise a relatively restricted range of coal types. Projecting the mean HIs of Wainui Member coals at these four well sites to Rank(S) 12.5 permits direct comparison of their expected HIs at the inferred onset of expulsion, independent of differences in their current ranks. The resulting projection reveals a mean HI for the Wainui-1 coals of 390 (mg HC/g C_{org}), significantly greater than the range of 314–322 for the mean HIs of the equivalent seams in North Tasman-1, Tane-1 and Taranga-1 (Figure 8b; see also Figure 13b). The mean HIs at all 4 sites exceed 300 mg HC/g C_{org} , thus ranking Wainui Member coals, on average, as oil-prone.

Few Puponga Member coals have both reliable Rank(S) and HI values but judged by the data for coals in Cape Farewell-

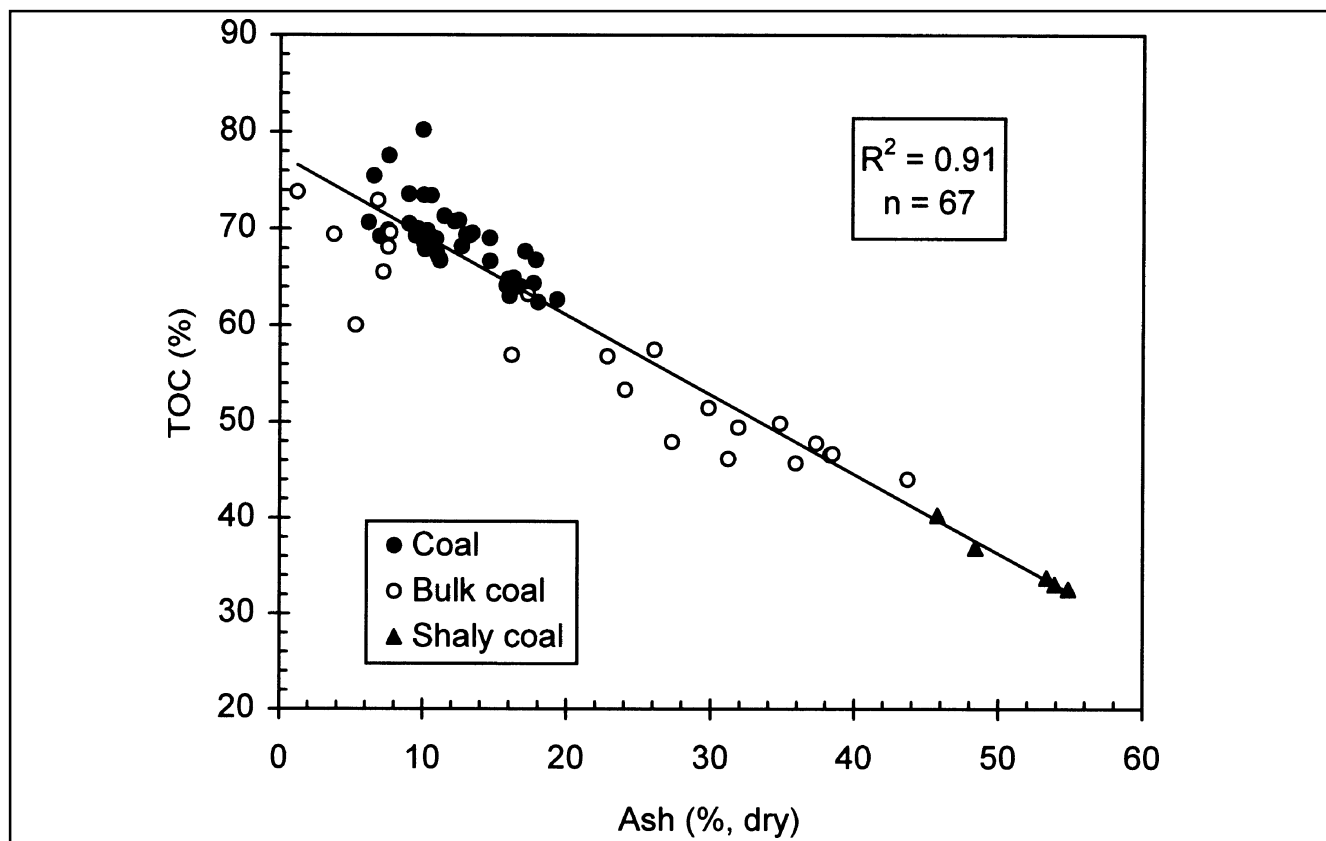


Figure 10: Relation between ash and total organic carbon for Wainui and Puponga member coals and shaly coals.

1, Kupe South-4 and the Collingwood district, these coals are likely to comprise a similar range of coal types and have similar propensity to generate oil as their Wainui Member counterparts. The single Cape Farewell-1 and Kupe South-4 samples lie within the lower half of the Coal Band, while outcrop samples from Collingwood lie within the upper half of to just above, the band (Figure 8b).

Measured hydrogen indices of Wainui and Puponga member coaly source rocks are plotted by lithology and location in Figures 12a and b, respectively. These plots, like those of S1+S2, are affected by the rank effect and much of the scatter among the coals (and bulk coals) to low HIs is attributed to the immaturity of the Puponga Member coals in particular (Fig. 12b). No shaly coal samples were available from the more immature Puponga Member sequences in Cape Farewell-1, Fresne-1, Kupe South-4 and the Collingwood district and so it is uncertain whether the relative lack of scatter in HI among the shaly coals is because of the absence of lower rank samples or because HI values are not suppressed in shaly coals.

The range of HI for coals at the onset of expulsion, estimated above to be 235–420 mg HC/g C_{org}, is essentially the same as that measured for the shaly coals (Figure 12a), so that, in the absence of petrographic data, it is inferred that Wainui and Puponga member coals and shaly coals contain essentially similar Type III kerogen. The same is probably also true for many of the medium to dark carbonaceous mudstones to coaly shales but it is expected that organic matter within the relatively low (<2%) TOC mudstones with HIs <150 (Fig. 12a) may be more highly oxidised.

The general similarity of kerogen type and hence of oil-proneness, throughout the source rock continuum can be seen by a plot of the mean HIs of Wainui Member carbonaceous mudstones, shaly coals and coals in North Tasman-1, Taranga-1, Tane-1 and Wainui-1 (Figure 13a, b; data in Table 2). The HIs are reasonably consistent within each well except for the carbonaceous mudstones within Wainui-1, which have a significantly lower mean HI (227 mg HC/g C_{org}) compared to those of the coals (365) and shaly coals (375) within the same well. This is attributed to an abundance of relatively organic-poor, medium grey, non-coaly mudstones, possibly with somewhat oxidised organic matter (see below). The coal–shaly coal part of the continuum in Wainui-1 is, however, more hydrogen-rich than in North Tasman-1, Taranga-1 and Tane-1 (Figure 13b).

Lateral and vertical variations in source rock characteristics

Downhole variations in total genetic potential, hydrogen index and coal sulphur content within the Wainui Member sequences in North Tasman-1, Tane-1, Taranga-1 and Wainui-1, and the Puponga Member sequence in Fresne-1, are shown in Figure 4. These sequences have a maximum thickness of 362 m (Tane-1), over which rank increases by ~1 rank unit. Consequently, within each of the sequences the indicated variations in Rock–Eval parameters are largely the result of variations in organic matter abundance and type rather than rank.

In each sequence, the genetic potential (S1+S2) of the three primary lithologies increases from carbonaceous mudstone

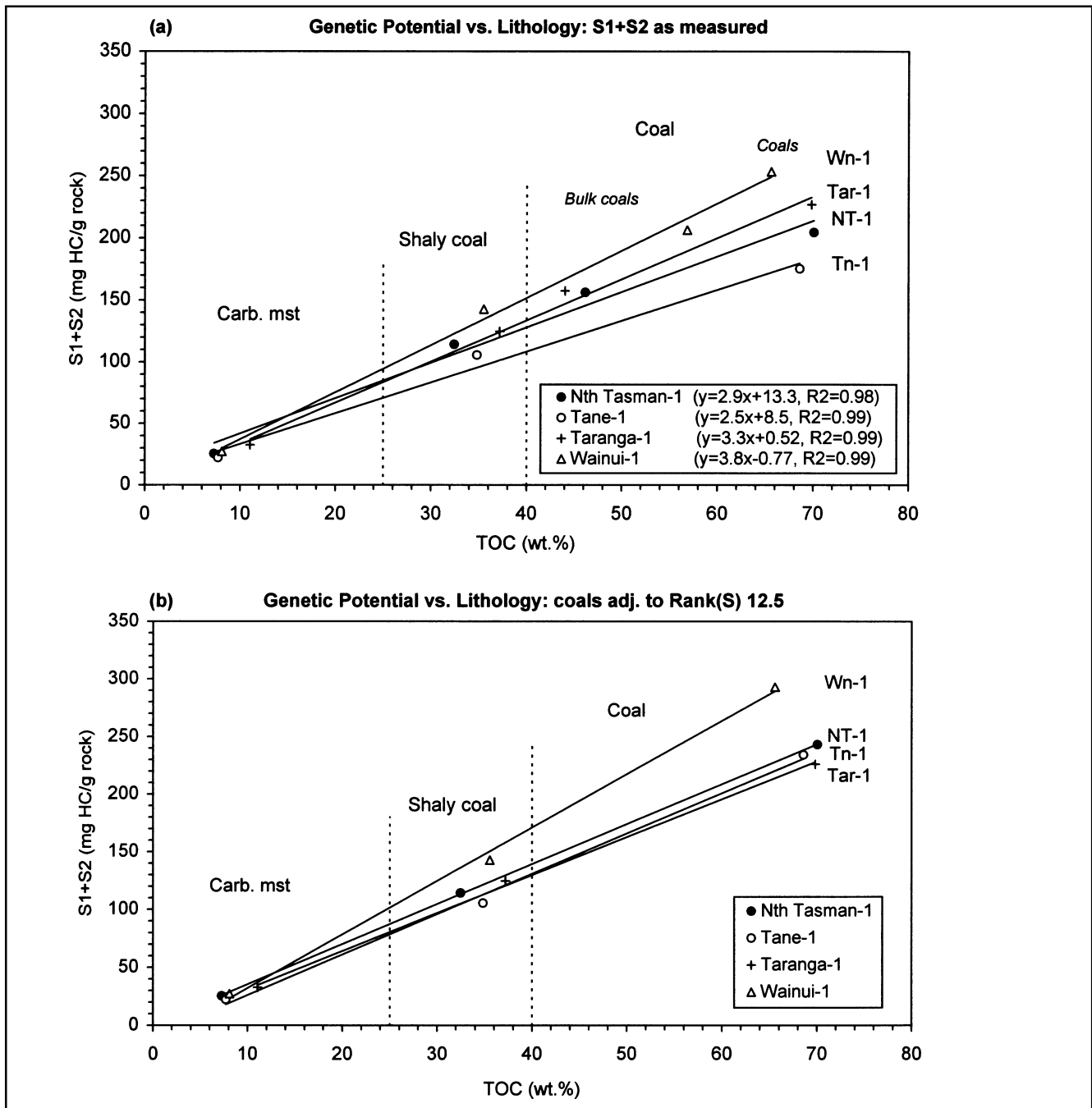


Figure 11: (a) Total genetic potential of the Wainui Member coaly source rock continuum at different well sites. Data points are the mean properties of each lithology in each well (Table 2). In (b) coal S1+S2 values are adjusted to Rank(S) 12.5 (see Fig. 8a) to better estimate total genetic potential at the onset of expulsion.

→shaly coal→coal (Figure 4). Within the coal class, bulk coal samples ($SG < 2.0$) generally have lower potential than coal samples ($SG < 1.5$). There is more overlap in the hydrogen indices for the three lithologies, further suggesting that the organic matter within the three lithologies is, in general, broadly similar. The differences in genetic potential between the lithologies primarily reflect variations in the abundance rather than type, of organic matter.

Some large differences in the hydrogen indices of carbonaceous mudstone, shaly coal and coal samples from the same stratigraphic level within some wells may result from differences in organic matter type and depositional facies. For example, the three uppermost and two lowermost

mudstone samples in Wainui-1 have very low HIs compared to the shaly coal and coal samples, as well as to mudstone samples in the middle of the sequence (Figure 4). The five mudstone samples with low HI contain large proportions of a homogeneous, medium grey shaly mudstone to siltstone with common iron staining but without coaly fragments, quite distinct from the dark brown carbonaceous mudstone to coaly shale which is more common within the Wainui and Puponga member sequences. The medium grey, non-coaly mudstone facies is significantly poorer as a source rock than the coaly, carbonaceous mudstones, and its relative abundance in Wainui-1 is chiefly responsible for the low mean HI of carbonaceous mudstones in general in this well (Figure 13). Similarly, mudstones in the middle part (3826–80 m) of the

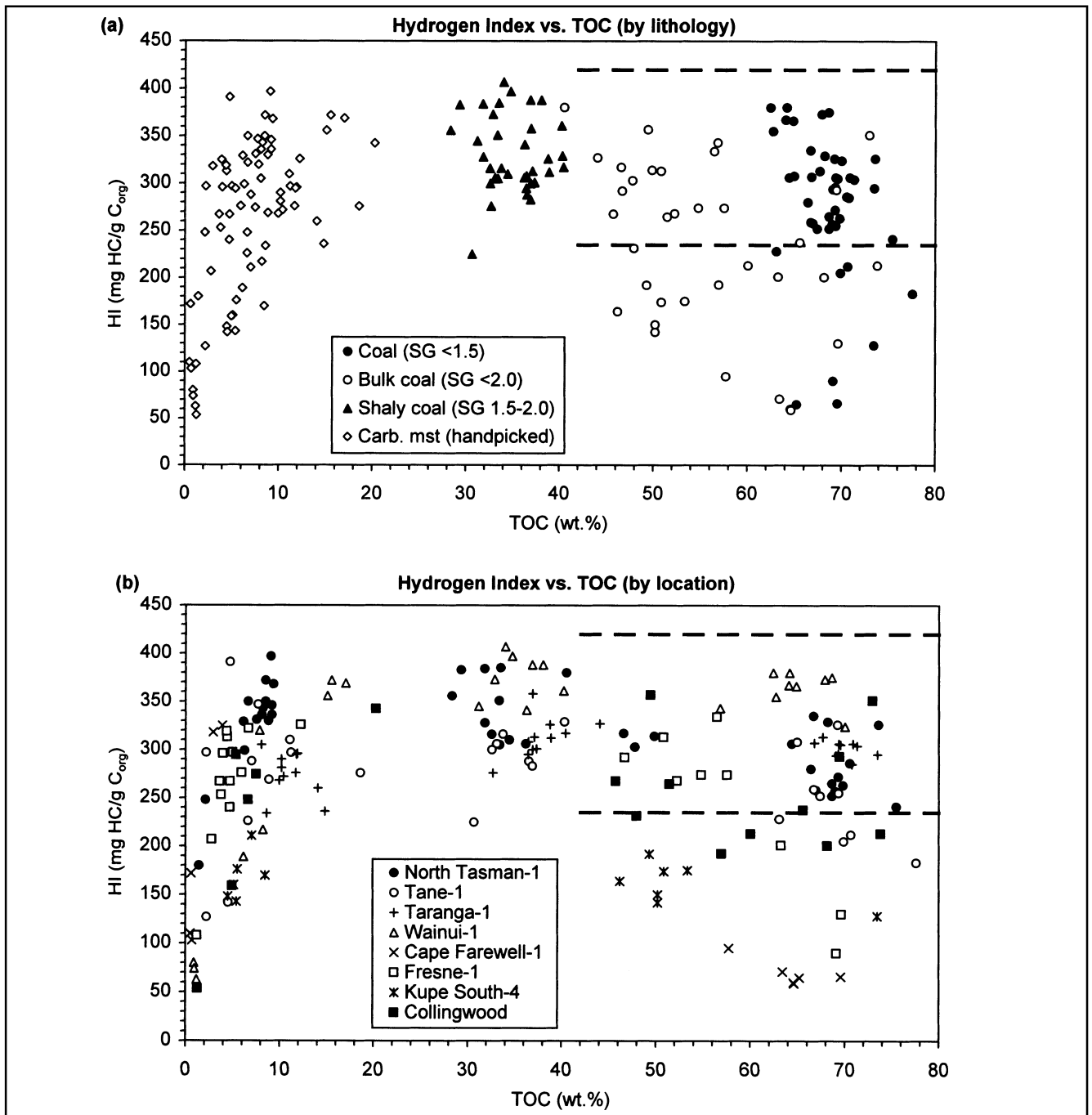


Figure 12: Hydrogen index versus organic carbon content for Wainui and Puponga member coaly sediments by (a) lithology and (b) location. Dashed lines depict the expected range of hydrogen indices (235–420 mg HC/g C_{org}) for coals and bulk coals at the inferred onset of oil expulsion (see Figure 8b).

Wainui Member sequence in Tane-1 and the upper part (2429–51 m) of the same member in North Tasman-1 have significantly lower HIs than the coals and shaly coals from these intervals, as well as all other mudstones within these sequences (Figure 4). The mudstone in these low-HI samples is predominantly light–medium grey and contains very little of the more typical dark brown carbonaceous mudstone.

Hydrogen indices of the coals (including bulk coals) and shaly coals show significant variation within and between the well sequences shown in Figure 4. Some of this variation is the result of differences in rank between the well sites (as discussed above) but most is attributed to changes in depositional facies. Of particular importance from a source

rock perspective are the generally greater HIs of coals and shaly coals in Wainui-1 compared to the other wells. Within individual Wainui Member sequences, there are increases in the HIs of coals and shaly coals towards the top and bottom of the member in Tane-1, towards the top and bottom and in the middle (2548–70 m) of the member in North Tasman-1, and towards the base of the member in Taranga-1 (Figure 4). In the Puponga Member in Fresne-1, there appears to be an interval of coals with high HI in the upper part of the sequence but with low-HI coals at the top (Figure 4). The indicated variations in source rock characteristics within Fresne-1 are, however, likely to be affected by severe oxidation of at least some of the samples (as discussed above).

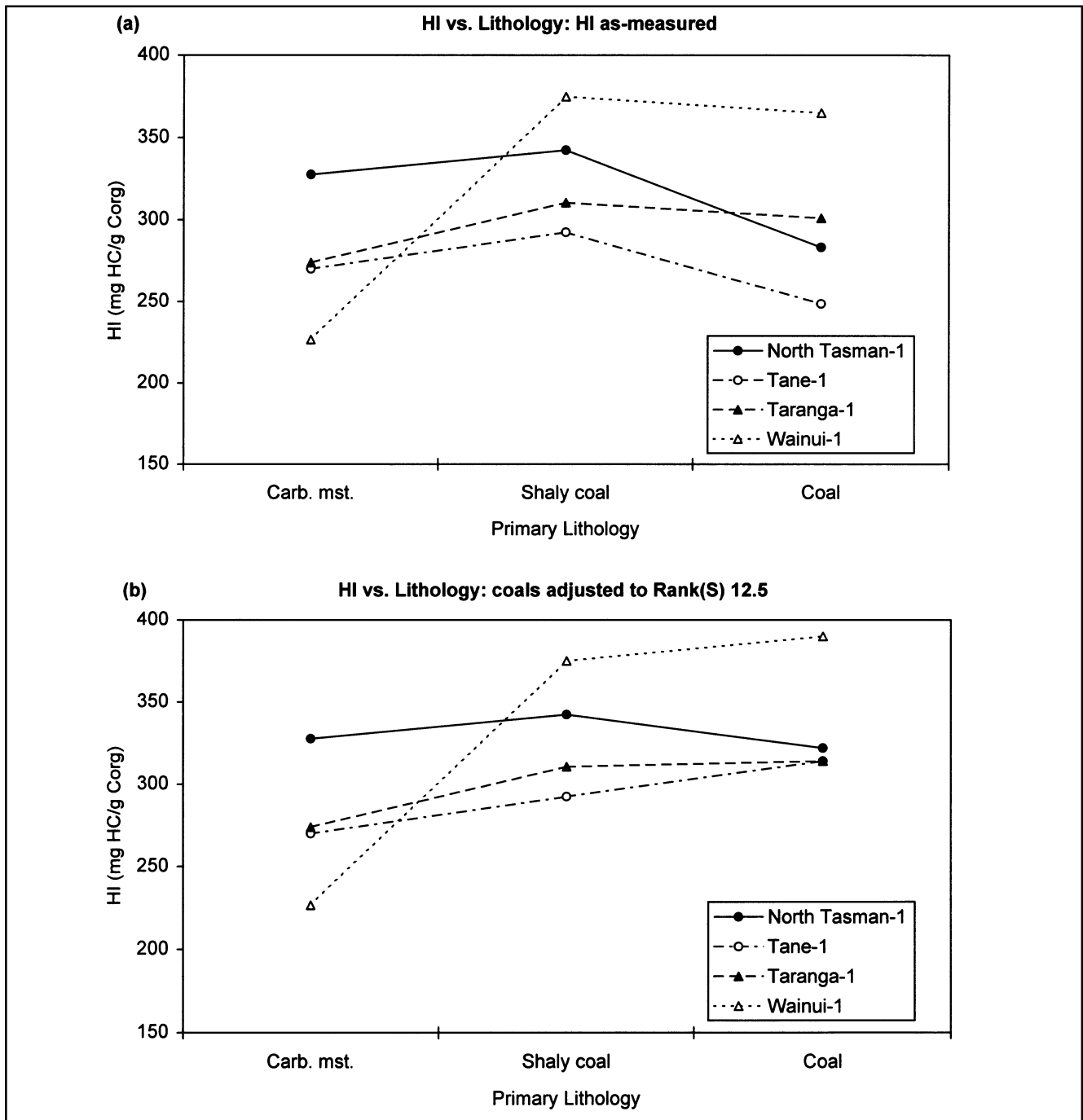


Figure 13: (a) Hydrogen indices of Wainui Member primary lithologies at different well sites. Data points are the mean properties of each lithology in each well (Table 2). In (b) coal HI values are adjusted to Rank(S) 12.5 (see Figure 8b) to better indicate oil potential at the onset of expulsion.

Depositional controls on source rock characteristics

The Wainui and Puoponga members were deposited within lower coastal plain environments in generally close proximity to the sea (Figure 3; e.g. Bal 1992 1994, Thrasher 1992a, Bal and Lewis 1994, King and Thrasher 1996). The continuum of coaly source rocks within the members, from carbonaceous mudstone to coal, represents a range of depositional facies within the coastal plain setting in which predominantly terrestrial organic matter has been preserved and diluted with clastic sediments, to a greater or lesser degree. Most of the dark carbonaceous (coaly) mudstones probably formed in

poorly drained floodplain areas subjected to frequent flooding and clastic inundation. Total organic carbon contents are consequently relatively low but are generally still sufficient to give good petroleum yields. In contrast, the medium grey mudstones that are common, for example, in the upper and lower parts of the Wainui Member in Wainui-1 and the middle part of the same unit in Tane-1, may have formed in better drained floodplain areas, in which the more oxidising conditions resulted in poorer preservation of organic matter, with lower oil potential.

The coals and shaly coals represent a range of peat mire facies varying principally in the amount of introduced clastic

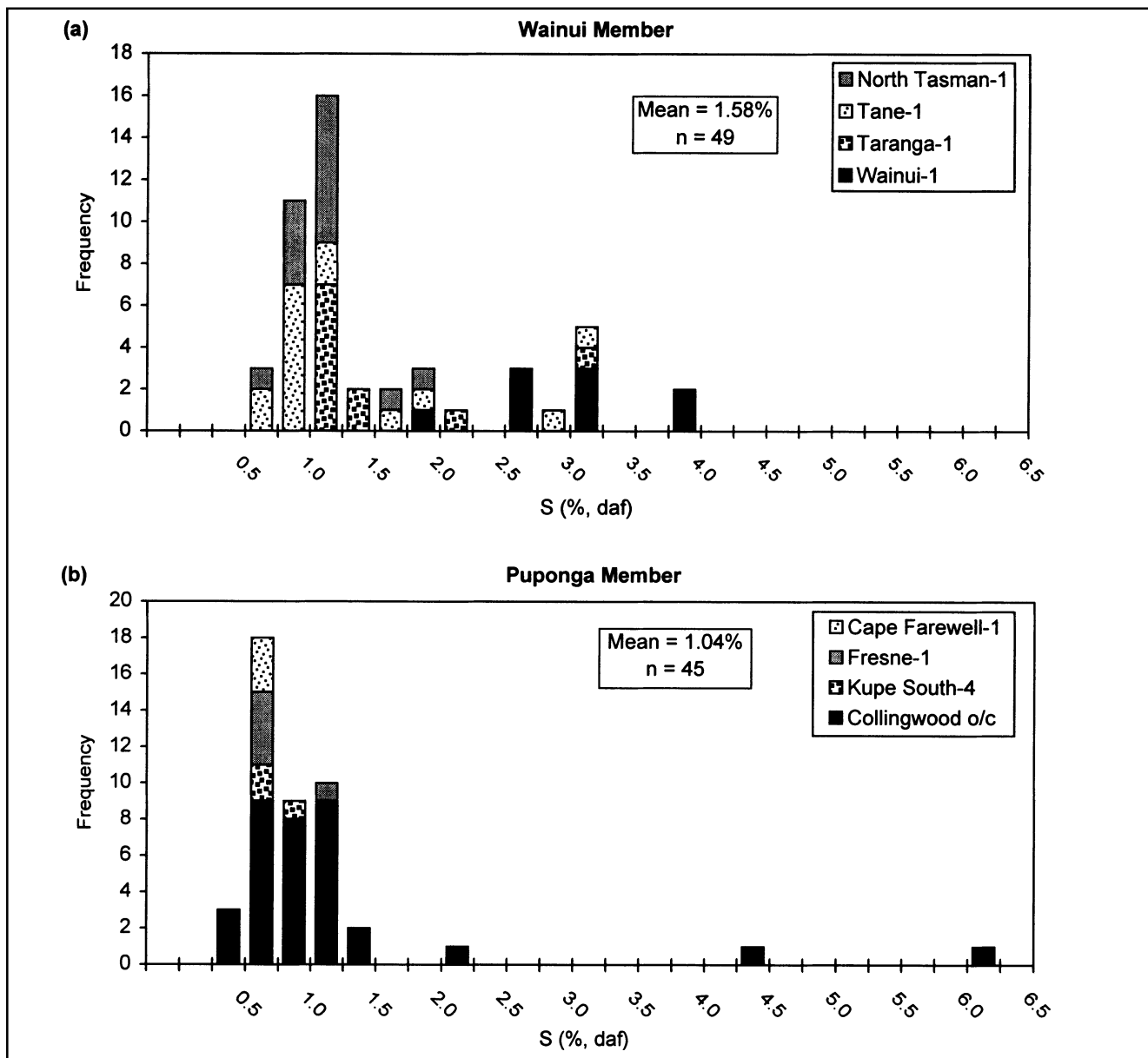


Figure 14: Total sulphur contents of (a) Wainui and (b) Puponga member coals by member and locality.

sediment. Shaly coals probably formed in poorly developed mires or at the base and margins of better developed mires, in areas periodically subjected to flooding. Coals with low to medium ash contents will have formed in the more interior areas of the better developed mires, further away and therefore better protected from clastic sedimentation. Petroleum yields increase with decreasing clastic content, from shaly coal to coal, and hence will be greatest where peat mires/coal seams are better developed.

Brackish conditions appear to have been the norm throughout deposition of much of the members, judged by the prevalence of moderate to high coal sulphur contents and the presence of dinoflagellate cysts at some horizons (as noted above). Studies of Waikato Basin and other New Zealand coals have shown coal seams that have experienced no sulphur enrichment from marine or brackish waters generally have sulphur contents of <0.4% (wt. %, dry basis; Wellman 1952, Edbrooke et al. 1994, Sykes 1998), whereas those that have experienced some marine influence have higher and greatly

variable whole-seam sulphur contents, up to ~8%. Comparison of coal sulphur values on a dry, ash-free (daf) basis eliminates most of the effects of varying ash content on sulphur values. On this basis, 0.5% sulphur (daf) is taken as the approximate upper limit of entirely non-marine coals.

The sulphur contents of 94 Wainui and Puponga member coals are plotted by location in Figure 14, while stratigraphic variations in sulphur at five well sites are shown in Figure 4. The calculated mean sulphur content of Puponga Member seams (1.04%) is less than that of Wainui Member seams (1.58%, Figure 14) but this result is unlikely to be representative of the members as a whole because of the relatively large number of Puponga Member analyses included from the Wharariki and Westhaven mines. Of the coals plotted in Figure 14, only three Collingwood mine samples have <0.5% S, while most values are 0.5–2.0%, ranging up to 6.19%. Marine influence raises pH and with it, bacterial activity, within peat-forming environments, leading to the formation of generally more perhydrous and therefore

more oil-prone coals and other coaly sediments (Diessel 1992). The brackish conditions under which Wainui and Puponga member coals were deposited are inferred to have been a major factor contributing to the generally perhydrous character and oil-proneness of the coals and coaly source rock continuum in general.

The degree of marine influence varies laterally and vertically within the Wainui and Puponga members as a result of varying proximity to a fluctuating shoreline. Conditions overall appear to have been most marine-influenced in the area around the Wainui-1 well site, where coal sulphur contents are generally greatest (Figures 4, 14) and dinoflagellate cysts most abundant (see Mildenhall and Raine 1977, Hayward and Raine 1978 and Mildenhall and Wilson 1982). As a result, the coaly source rock continuum in Wainui-1 has a significantly greater genetic potential and is more oil-prone (as judged by S1+S2 and HI) than in other Wainui Member sequences in North Tasman-1, Tane-1 and Taranga-1 (Figures 11b, 13b). Wide variations in volatile matter (Figure 6a), atomic H/C (Figure 6c) and HI (Figures 4, 8b) – and therefore in oil-proneness – within the North Tasman-1 and Tane-1 sequences in particular, are attributed to variations in the degree of marine influence at these sites, judged by large stratigraphic variations in coal sulphur content from relatively low to high values.

Stratigraphic variations in coal sulphur content in the well sequences provide a partial record of shoreline advance and/or retreat at these sites and thus provide a tool for mapping the distribution of the more strongly marine-influenced, more oil-prone coaly facies within the Wainui and Puponga members. In Wainui-1, for example, consistently high (>~2%) and overall upward-increasing sulphur contents (Figure 4) indicate persistently strong marine-influenced conditions throughout the member, caused by a single, overall transgressive episode. As a result, the coal and shaly coal facies within this well are very perhydrous and oil-prone (Figure 8b). In contrast, in Taranga-1 the upward-decreasing sulphur contents to moderate values (~1%) indicate a regressive episode and a change from strongly to slightly marine-influenced conditions (Figure 4). Consequently, the most oil-prone coaly facies are at the base of the sequence, and throughout the remainder of the sequence the facies are borderline gas- and oil-prone (Figures 4, 8b). In Tane-1, coal sulphur contents are greatest at the base and top of the member, suggesting a regressive-transgressive cycle within the member. Though sulphur contents are absent in the middle of the section (perhaps reflecting the sparsity of coal during lowstand conditions), the pattern of HI variation appears to provide a record of changing pH and Eh conditions through the member. More brackish, less oxidising conditions appear responsible for the more perhydrous, more oil-prone coaly facies at the base and top of the member, whereas a change to less brackish, more oxidising conditions during shoreline retreat appears responsible for the decrease in HI and increase in the medium grey, non-coaly mudstone facies in the middle of the section (Figure 4).

Conclusions

A lithology-based sampling and analytical programme has been used to investigate the petroleum source rock potential

of the North Cape Formation coal measure members over much of their known extents. While the main objective was to identify the depositional controls on source rock characteristics, assessed from Rock–Eval properties, the study has also shown that in estimating the petroleum generation potential of coaly source rocks it is essential to make allowance for the strong dependence of S1+S2 and HI on coal rank. Specific conclusions of the study are as follows:

Depositional environment

1. The Wainui and Puponga members were deposited within lower coastal plain environments, judged by coal sulphur contents and dinoflagellate occurrences, and are marine-influenced to varying degrees both laterally and vertically throughout their known extents.

Source rock rank and maturity

2. Wainui and Puponga member coals have Rank(S) values of ~9.2–13.2 and vitrinite reflectances of 0.38–0.77%.
3. The highest rank coals are the Wainui Member coals in Taranga-1 (average Rank(S) of 13.0), significantly higher than the equivalent coals in North Tasman-1, Wainui-1 and Tane-1 (Rank(S) 11.4–11.7). Most Puponga Member coals onshore and offshore have Rank(S) values in the range 9.2–11.9.
4. The range of ranks indicates that most of the Wainui and Puponga member sequences examined are sufficiently mature to have commenced generation of oil, but that only the sequence in Taranga-1 will have begun expulsion of oil.

Source rock kerogen type, genetic potential and oil-proneness

5. The key source rock parameters, total genetic potential (S1+S2) and hydrogen index (HI), are strongly affected by variations in rank. At Rank(S) values below 12.5 (the inferred threshold of oil expulsion), the genetic potential and oil-proneness of coals are underestimated by S1+S2 and HI and need to be adjusted to corresponding values at Rank(S) 12.5 when estimating genetic potential and oil-proneness. Failure to recognise the rank-dependence of HI may have led to previous downgrading of the oil potential of Taranaki Basin coals.
6. Coaly sediments within the Wainui and Puponga members form a continuum of source rocks, increasing in organic carbon (TOC) and total genetic potential from carbonaceous (coaly) mudstone → shaly coal → coal.
7. All parts of the source rock continuum above ~2.5% TOC contribute significantly to the total genetic potential of kitchen areas and should be included in calculations of expelled hydrocarbon volumes. This may be best achieved in practical terms by estimating volumes of the three primary source rock lithologies (i.e. carbonaceous mudstone, shaly coal and coal), which are distinguishable by density and other properties recorded in wireline logs.

8. Wainui and Puponga member coals, which plot within or slightly above the NZ Coal Band, generally comprise perhydrous Type III kerogen typical of, or slightly more hydrogen-rich than, New Zealand coals in general.
9. Hydrogen indices of the source rock continuum typically range from 235–420 mg HC/g C_{org} at the inferred onset of oil expulsion, indicating mixed gas- and oil-prone to oil-prone kerogen.
10. The genetic potential and oil-proneness of the coaly sediments have been enhanced by the brackish conditions in much of the depositional environment. Stratigraphic variations in the degree of marine influence have influenced the oil potential, which is generally greatest in Wainui-1.

The results of this study are intended to provide a broad framework for integrating spatial and temporal variations in Wainui and Puponga member source rock characteristics into future petroleum generation models. Further work on organic petrography and palynofacies will better define and interpret individual facies within the source rock continuum, including subdivision into non-, slightly and strongly marine-influenced facies. Perhaps the greatest need, however, is to ascertain whether marine influence has had any effect on the temperatures required for oil generation and expulsion.

No openfile kerogen kinetics data are available for North Cape Formation coals but it is speculated that marine-influenced source rocks may generate and expel petroleum earlier (i.e. at shallower depths) than their fully non-marine equivalents because of their greater content of organically bound sulphur. If this is so, the prospectivity of the Western Stable Platform and other areas underlain by North Cape Formation coaly source rocks would be enhanced. Formation- and facies-specific compositional kinetics for North Cape Formation coaly sediments are needed in order to fully utilise the results of this study in more sophisticated modelling of petroleum generation and expulsion from these rocks.

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