# TIMING AND DEPTH OF MATURATION IN SOUTHERN TARANAKI BASIN FROM REFLECTANCE AND RANK(S)

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## Abstract

Levels of maturity of coals from 15 wells in southern Taranaki Basin are estimated and compared using the parameters of $R_0$ and Rank(S), the latter derived from routine coal analyses following Suggate (1959). In general, both $R_0$ and Rank(S) show progressive increase with depth, but $R_0$ is affected by differences in telinite/telocollinite type and moisture content. Rank(S) proved a more reliable maturity index.

Reflectance/depth and Rank(S)/depth gradients are generalised from wells with sequences presently at or near their maximum depths of burial. Using the generalised gradients, estimates are made of former depths of burial of coals in 8 wells where substantial sequences are missing, either at ground surface or beneath major unconformities within the Cenozoic. From this knowledge and with use of geohistory plots, present levels of maturity in all wells studied are interpreted to have been attained in the Neogene; thicknesses of up to 2400 m were subsequently eroded in those wells with sequences missing.

The maturity level for expulsion of oil is inferred to be at Rank(S) 13-14; corresponding $R_0$ values are less well defined, from ca.0.75 % to 1.0 %.

## Introduction

The Taranaki Basin (Figure1), in western central New Zealand, lies entirely offshore except for the Taranaki Peninsula and the northwestern tip of the South Island. It is the only New Zealand basin producing hydrocarbons, and it continues to be the main focus for exploration. The first major discoveries, the Kapuni and Maui gas/condensate fields, were developed in sandstone reservoirs of the Paleocene-Eocene Kapuni Group, which contains major seams of bituminous coal. Subsequent drilling of the Late Cretaceous Pakawau Group also revealed substantial coal. As a result and in view of the lack of organic-rich marine facies over most of the basin, the possibility that the coal seams are the main source of hydrocarbons has progressively gained credence. Oil is also now produced from Kapuni Group reservoirs (e.g. McKee field) and shows have been detected in the Pakawau Group (e.g. Cape Farewell-1).

Recent geochemical studies have consistently supported a terrestrial origin for hydrocarbons over most of the basin (e.g. Thompson 1982, Analabs 1984, Robertson Research 1984, Cook 1987, Johnston *et al.* 1988, Lipke 1989, Johnston *et al.* 1990 and Robinson 1990). The Pakawau and Kapuni Group coals were interpreted from Rock-Eval pyrolysis data as the major source lithology (Cook 1987), but the contribution from carbonaceous shales is less clear. In the northern part of the basin some oil may have been derived from marine sources (Johnston 1991), judged by marine biomarkers found in oils from Tangaroa-1 on the Western Platform (Cook 1987), and Kora-1 in the Northern Graben (Reed 1991).

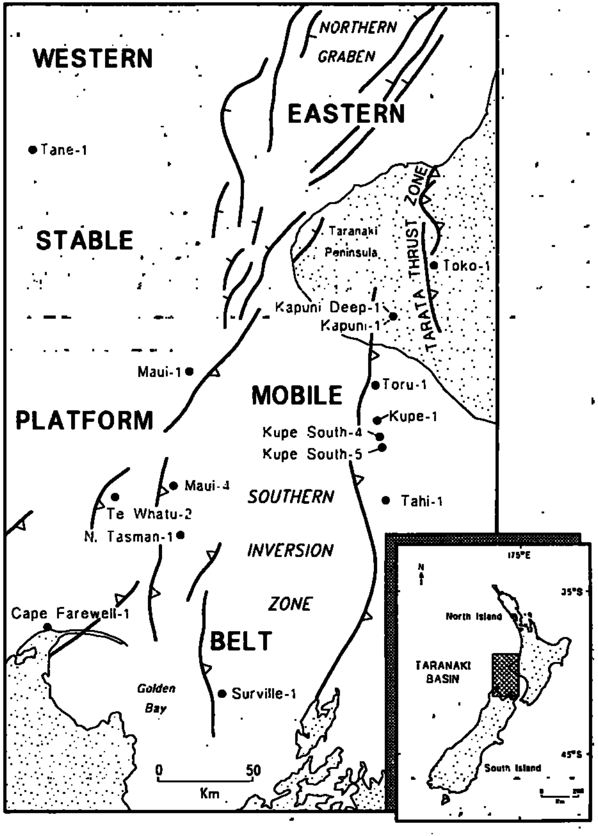

Figure 1: The Taranaki Basin, its structural provinces and location of drillholes studied.

Taranaki coals remain a largely untapped source of valuable, yet inexpensive, exploration data and better knowledge is needed particularly of Pakawau and Kapuni coals, both as source rocks and as indicators of maturity, burial history and paleogeography. For example, little is yet known of the nature and extent of coal type variations within the basin and the implications these may have for hydrocarbon generation (e.g. oil- vs gas-proneness).

### Objectives

This paper uses coals as indicators of maturity and burial history. The principal objectives are:

(i) to characterise the levels of maturation within selected Taranaki wells (Figure 1), using the indices of vitrinite reflectance and Suggate rank (denoted $R_0$ and Rank(S), respectively); and

(ii) using this knowledge, together with geohistory plots, to infer the burial histories and timing of maturation for wells in which maturity levels indicate maximum burial depths greater than at present. A total of 15 southern Taranaki wells were incorporated into the study including: Cape Farewell-1, Maui-1, Maui-4, North Tasman-1, Surville-1, Tahi-1, Te Whatu-2 and Toko-1. The paper also discusses the use of $R_0$ and Rank(S) as maturity indices.

## Development of the Taranaki Basin

### Tectonic history

The Taranaki Basin is a composite basin with a complex tectonic history (King *et al.* 1991). Both of its two main structural provinces, the Western Stable Platform and the Eastern Mobile Belt (Figure 1), have deep sub-basins inherited from a Late Cretaceous-Paleocene rift transform phase with associated rapid subsidence, and an Eocene-mid Oligocene passive margin phase characterised by waning thermal subsidence. In the latest Eocene-mid Oligocene, tectonic quiescence is recorded over much of the basin as a depositional hiatus (Figure 2), without significant erosion. Following the hiatus, particularly rapid subsidence recommenced in the mid-Oligocene over much of the basin, but in the early Miocene in the south. The Western Platform subsided epeirogenically whereas the Eastern Mobile Belt became part of a zone of late Paleogene to Neogene deformation associated with the evolution of the Australia/Pacific subducted plate margin through New Zealand (King 1990, King and Thrasher in press).

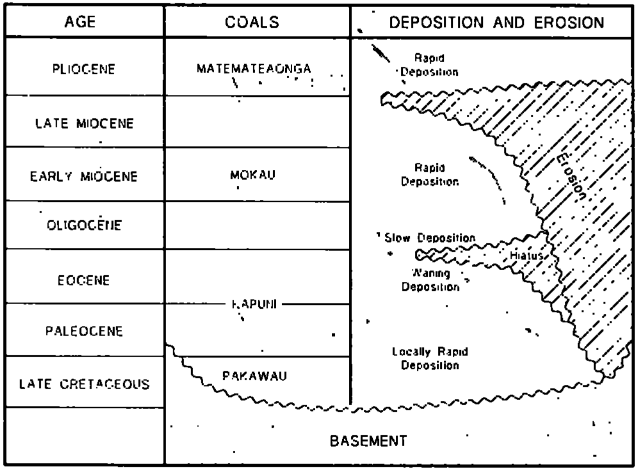

Figure 2: Depositional phases, erosion intervals and coal-bearing units, southern Taranaki Basin. Age units not shown to true time scale.

The Eastern Mobile Belt has several tectonic sub-provinces (King 1991). The Southern Inversion Zone, extending southward from the Taranaki Peninsula to northwestern South Island (Figure 1), is characterised by late Miocene-early Pliocene structural inversion of former rift half-grabens. Seismic reflection profiles indicate that inversion and uplift of individual structures resulted in erosion of up to 2500 m of mainly mid-upper Miocene sediments; in Tahi-1, the erosion extended down into the Late Cretaceous Pakawau Group. In contrast, the Kapuni and Kupe inversion structures have a relatively complete, although thin, mid-upper Miocene sequence, indicating progressive growth but ongoing sedimentation through this period. Another sub-province, the Tarata Thrust Zone, is a region of early Miocene thin-skinned overthrusting in the east of the basin (Figure 1).

Most of the Western Stable Platform (including the area of Tane-1) has remained relatively unfaulted and tectonically quiescent since the end of the Cretaceous, though it has continued to subside. In contrast, the Maui-1 area was affected by structural inversion in the late Miocene, but now lies outside the western limit of the Mobile Belt, defined by a zone of Plio-Pleistocene normal faulting.

### Depositional history and coal occurrences

The maximum sedimentary thicknesses within the basin, about 9 km, are in the north (Thrasher and Cahill 1990). Supra-basement sediments of Early Cretaceous age occur locally in the northeast, but Late Cretaceous sediments are the oldest represented widely across the basin. The latest Cretaceous-Paleogene succession resulted from a broad transgression directed to the south and east, culminating in virtually complete inundation of the basin by the Early Oligocene (King and Robinson 1988, King 1990). During this transgressive period, lower coastal plain coals of the Pakawau and Kapuni Groups (Figure 2) were deposited, the former within rapidly subsiding and infilling rift sub-basins, and the latter bordering a broad passive marginal embayment. Kapuni Group sedimentation was controlled by waning post-rift subsidence and ended with a depositional hiatus in the latest Eocene (Figure 2), in eastern and southern parts of the basin. Oligocene sediments, everywhere thin except in eastern parts of the Taranaki Peninsula, are carbonate-dominated.

The Neogene succession is broadly regressive, with characteristically high sedimentation rates. For most of this period, however, marine sedimentation was assured by high rates of local subsidence within the Mobile Belt and steady subsidence of the Platform as the continental shelf built out progressively to the west. Within the Mobile Belt a pronounced unconformity is roughly coincident with the base of the Pliocene. This unconformity divides the sequence and marks a period of uplift and erosion (Figure 2).

Coals were deposited at two stratigraphic levels within the Neogene (Figure 2). Early Miocene coal measures (Mokau Formation equivalent) are present only in Surville-1. These represent the only known Miocene terrestrial sequence in the Taranaki Basin and probably accumulated following rapid local sedimentation and aggradation above sea level. Comparable coals are widespread in the Pliocene Matemateaonga Formation in the eastern central wells Toru-1, Kupe-1, Kupe South-4 and Tahi-1. High rates of sediment supply into a shallow marine depocentre presumably again caused aggradation above sea level, allowing deposition of the Matemateaonga Formation coals.

## Wells Used and Methods

Fifteen wells are examined in this study (Table 1). Most are located within the Southern Inversion Zone (Figure 1) but Tane-1 and Maui-1, on the Western Stable Platform, and Toko-1, in the Tarata Thrust Zone, are also included.

The objective of this paper is to interpret the burial histories and timing of maturation of wells in which maximum depths of burial were previously greater than at present. These wells include: Cape Farewell-1, Maui-4, North Tasman-1, Surville-1, Tahi-1 and Te Whatu-2, in the southern part of the Southern Inversion Zone (hereafter referred to as "southern wells"), together with Maui-1 and Toko-1. The interpretations are made by comparing levels of maturation in these wells with those of wells which are either judged to be presently at, or close to, their maximum depths of burial, or for which eroded thicknesses are estimated to be small. These wells are referred to as the "calibration wells" (Table 1), and include: Kapuni Deep-1, Kapuni-1, Kupe-1, Kupe South-4, Kupe South-5, Tahi-1 (down to base Pliocene) and Toru-1, all from the northern part of the Southern Inversion Zone, and Tane-1 (Figure 1).

Judged by their stratigraphy, the sequences in Tahi-1 (down to base Pliocene), Tane-1 and Toru-1 are presently at their maximum depths of burial. At Kupe-1, Kupe South-4 and Kupe South-5, undated sediments at the top of each well are accepted as representing Quaternary sedimentation in the period of change between rapid Pliocene sedimentation and late Quaternary erosion. Accordingly, sequences in these wells are accepted as being very close to their maximum depths of burial. In all these wells, except probably Tahi-1, any erosion caused by Miocene structural inversion and uplift is compensated for by a greater amount of Pliocene subsidence and burial. At Tahi-1, 1.1 km of Plio-Pleistocene sediments rest directly on the Pakawau coal measures. Consequently, while the Matemateaonga coals in this well are accepted as being at their maximum depths of burial, there is a distinct possibility that the Pakawau coals are not (this possibility would arise if the thickness missing beneath the base-Pliocene unconformity exceeded 1.1 km); this is discussed later. The Kapuni-1 and Kapuni Deep-1 sequence was estimated (Elphick and Suggate 1964) to have been buried about 400 m more than at present, and with this addition to present depths, the sequence is used as indicative of maximum depths of burial.

The following is a summary of the methodology applied to the use of maturity indices to interpret the burial histories and timing of maturation of wells in which maximum depths of burial were previously greater than at present (i.e. the southern wells plus Maui-1 and Toko-1):

(i) Relations were established between the maturity indices $R_0$ and Rank(S) and maximum depths of burial for the "calibration wells" (Table 1).

(ii) From (i), generalised gradients were drawn depicting the relationships between $R_0$ and maximum depth of burial and between Rank(S) and maximum depth of burial.

(iii) The generalised gradients were then used to estimate maximum depths of burial of coals in the southern wells plus Maui-1 and Toko-1, based on their Rank(S) and/or $R_0$ values.

(iv) Using (iii) in conjunction with geohistory plots, the ages and thicknesses of eroded sequences and the timing of attainment of present levels of maturation were determined for the southern wells, together with Maui-1 and Toko-1.

## Samples and Analyses

All samples collected for the study are from open-file petroleum well cuttings except for Toru-1 3779 m, taken from core. Two suites of samples were used rather than a single set because of different sample requirements for vitrinite reflectance and for coal analysis (the latter from which Rank(S) values are determined). Coal fragments were floated from the cuttings using sodium polytungstate solutions of 1.7 specific gravity for the reflectance samples and 1.45

| Western Stable Platform | Eastern Mobile Belt | | |
|---|---|---|---|
| | Tarata Thrust Zone | Southern Inversion Zone | |
| Tane-1 | | Kapuni-1<br>Kapuni Deep-1<br>Kupe-1<br>Kupe South-4<br>Kupe South-5<br>Toru-1 | Calibration wells[1] |
| Maui-1 | Toko-1 | Cape Farewell-1<br>Maui-4<br>North Tasman-1<br>Surville-1<br>Tahi-1<br>Te Whatu-2 | |

[1] The calorific value and ultimate analysis are not compatible. From the exceptionally high moisture content (21.4%, ash-free), the rank determination from VM/CV is preferred.

Table 1: Wells included in study.

for the coal analysis samples. For vitrinite reflectance, an S.G. of 1.7 recovered most of the coaly material from the samples so that the vitrinite to be analysed would be representative of the organic-rich facies present (see below). The coal parameters used in Rank(S) determination, volatile matter and calorific value (VM and CV) or carbon and hydrogen (C and H), are required to be on the mineral-matter-free basis. Therefore, to minimise errors associated with the estimation of mineral matter content from the measured ash content, low-ash samples were preferred; hence the use of a lower S.G.

The samples were prepared for vitrinite reflectance analysis in the usual manner (Stach *et al.* 1982) and the analyses conducted following standard procedures (ASTM 1990) except that 50 readings were taken per sample instead of 100. A total of 17 reflectances were measured from four wells (Table 2). For convenience, the reflectance measured was $R_0$random rather than $R_0$max, as bireflectance is minimal in the reflectance range of the samples analysed (0.31 to 0.88 %).

By 1988, more than 700 open-file reflectance values were available for 35 wells in Taranaki Basin (Lowery 1988). The data, however, originate from 12 laboratories and the degree of inter-laboratory consistency for many of the wells is very poor. This is well illustrated by the data for Tane-1, originating from seven laboratories (Figure 3). For a given depth, the difference in reflectance between the two extreme reflectance/depth correlation lines (Lab F and Lab D) is ca.0.35 %. This amount of variation greatly exceeds the required precision of 0.02 % for mean reflectance determinations based on 100 readings (ASTM 1990), and casts serious doubt on the validity and usefulness of some of the data available for Taranaki. For Tane-1, this difference of 0.35 % would result in estimates of maximum depths of burial differing by as much as ca.1500 m.

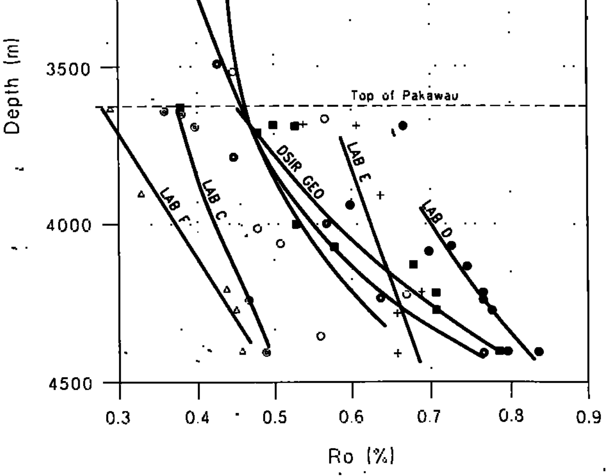

Figure 3: Comparison of vitrinite reflectance data for Tane-1 from 7 separate laboratories, with depth/reflectance gradients approximately determined.

Because of the inter-laboratory differences, only reflectance data obtained at DSIR Geology & Geophysics (incorporating NZGS), by R. Sykes or previously by J. Lowery (1988), are used in this study. As a check, Sykes obtained closely similar results to those of Lowery for Maui-4 samples. While Lowery's readings are all $R_0$max values, they are all less than about 1 % and hence are directly comparable to the $R_0$random values of this study. Vitrinite reflectances for the wells examined range from a possible low of 0.26 % in Tahi-1 (Pakawau Group), to 1.01 % at the base of Toko-1 (Table 2 and Lowery 1988).

Routine coal analyses, comprising proximate and ultimate analyses, sulphur content and calorific value, were undertaken by Coal Research Association of New Zealand, Lower Hutt. In total, 27 samples from 12 wells were analysed (Table 3). The study also uses coal analyses previously reported by Lowery (1988; Table 4). The analyses reveal a rank variation covering the subbituminous to high-volatile bituminous range, with Rank(S) values varying from 5.2 (see Note 1 Table 1), in Tahi-1 (Matemateaonga Formation), to 13.6, again at base of Toko-1.

## Vitrinite Reflectance and Rank(s) as Maturity Indices

### Reflectance

Vitrinite reflectance has long been used as a measure of coal rank and is perhaps the most widely used measure of maturity in petroleum exploration. The reflectance of vitrinite is a function of its aromaticity and ring condensation (Teichmüller 1987) - as these properties increase with increasing burial, so does reflectance.

The increase of reflectance with depth makes $R_0$ a useful rank (=maturity) parameter. Its sensitivity is relatively low, at $R_0$ values of <ca.0.5 % (corresponding to the lignite-subbituminous range), but improves at higher ranks ($R_0$ >ca.0.5 %), concomitant with an increase in the rate of reflectance increase with depth (Tissot and Welte 1984).

A major source of error in the use of reflectance is the non-depth related variation that can result from reflectance differences obtained prior to or during burial. Differences in original plant material and degree of humification and gelification in the peat stage create reflectance variation between different vitrinite macerals (Stach *et al.* 1982, Teichmüller 1987). To minimise the effect of this variation on the precision of mean reflectance determinations for rank estimation, reflectance measurements are now commonly restricted to telinite or telocollinite (=humotelinite in brown coals) (e.g. Marchioni 1984); these macerals are commonly referred to collectively as "vitrinite A" or "band-vitrinite".

The influence of depositional facies is a further cause of reflectance variations. The effect on reflectance of facies changes within coal seams can be studied using sets of "serial samples" - sequential samples from the same seam at the same location, which have necessarily had the same geological history and so by definition are of the same rank. Analysis of serial samples from the Late Cretaceous and Tertiary, vitrinite-rich bituminous seams of the West Coast, South Island, revealed reflectance differences of up to 0.25 % within individual seam profiles (Newman 1985, Quick and Moore 1991). Vertical trends in reflectance within these seams were related to variations in other properties, including ash, volatile matter and hydrogen contents, and were interpreted to result from temporal changes in groundwater influence in the peat-forming mires. Coals with relatively high ash (also high volatile and hydrogen contents) tended to have lower reflectances than equivalent-rank, lower ash coals, as a result of peat formation under higher, more anoxic groundwater conditions. By extension of this concept, vitrinite within carbonaceous shales would be expected to have still lower reflectances. Regardless of origin, any variation in the starting value of reflectance at the initiation of burial diagenesis (=metamorphism) will prevent a unique correlation between vitrinite reflectance and degree of maturation (Suggate 1990).

Variation of reflectance from expected values has also been attributed to processes operating during burial. These include the suppression of reflectance in liptinite-rich facies, thought to result from the absorption by the vitrinite of aliphatic-rich liquids emanating from liptinites during coalification (Raymond and Murchison 1991). Goodarzi *et al.* (1988) inferred reflectance to also be affected by the lithology of the containing strata, with carbonates generally producing the highest reflectances, shale the lowest, with coal having intermediate values. They suggested that this effect may be due to differences in the efficiency of reaction products removal, different thermal conductivities or the existence of a calcium carbonate catalytic mechanism. It is possible, however, that some of the reflectance variation they identified may have been inherited from the depositional environment.

An important corollary to the above discussion is that, for the measurement of reflectance, the recommended restriction to a specific vitrinite type (i.e. vitrinite-A) should include a restriction to a specific sedimentary facies. This would minimise variations resulting from both the depositional and burial processes noted above. To date there has been no formal attempt to further standardise reflectance analysis by restricting the facies from which vitrinite should be measured. Teichmüller (1987) suggested, however, that vitrinite should not be measured from source rocks (which often contain anomalously low reflecting, perhydrous vitrinite) but from "normal" clastic rocks.

Reflectance can be used as a rank parameter throughout all levels of maturation but caution is necessary when interpreting only a few $R_0$ values, particularly in immature sequences, where variability due to vitrinite type effects is greatest.

## Rank(S)

New Zealand's Late Cretaceous and Cenozoic coals cover the full range of rank from peat to semi-anthracite. This provides an excellent opportunity for study of the variations in analytical properties of a set of relatively young coals for many of which the geological history is well-known. An extensive examination of their analytical properties, and comparison with data for northern hemisphere Late Paleozoic coals, led Suggate (1959) to recognise a New Zealand Coal Band and to propose a general coal rank classification - Rank(S). Unit increases in Rank(S) were designed to represent unit increments in depth of burial, assuming uniform geothermal gradient. The original classification (Suggate 1959, Figure 41) was constructed on axes of percent hydrogen and carbon (Figure 4), and a complementary version on axes

| Well name | Stratigraphic unit | (m) | Depth | Reflectance[2] (%) | Organic matter type | Visible oxidation |
|---|---|---|---|---|---|---|
| **Kupe-1** | Matemateaonga | 1823-32 | 0.41 | 0.07 | Seam coal [3] | None |
| | " | 1868-78 | 0.38 | 0.06 | " | " |
| | " | 1878-87 | 0.41 | 0.06 | " | " |
| | Kapuni | 3423 | 0.54 | 0.05 | Vitrain lenses [4] >> seam coal | Minor |
| | " | 3450 | 0.55 | 0.06 | Vitrain lenses & seam coal | Moderate |
| | " | 3600 | 0.58 | 0.05 | Vitrain lenses > seam coal | Minor |
| **Maui-4** | Kapuni | 2109-18 | 0.60 | 0.07 | Seam coal | Major |
| | " | 2566-69 | 0.71 | 0.06 | " | None |
| | Pakawau | 3892-95 | 0.88 | 0.08 | " | " |
| **Tahi-1** | Matemateaonga | 970-80 | 0.41 | 0.06 | Seam coal | None |
| | " | 1040-45 | 0.38 | 0.14 | Seam coal, bimodal telinite | " |
| | " | 1070-75 | 0.31 | 0.08 | Seam coal & carbargilite | " |
| | Pakawau | 1478-80 | 0.42 | 0.04 | Seam coal | " |
| | " | 1744-47 | 0.49 | 0.05 | " | " |
| **Toru-1** | Matemateaonga | 1985 | 0.42 | 0.04 | Vitrain lenses & carbargilite | None |
| | " | 2120 | 0.49 | 0.09 | Seam coal | " |
| | Kapuni | 3779 | 0.50 | 0.05 | Vitrain lens in sandstone | " |

[2] Mean random reflectance based on 50 readings, except for Kupe-1 3423 m based on 99 readings. All reflectance measurements were taken on telinite or telocollinite.

[3] All samples indicated as "seam coal" are also likely to contain some dispersed vitrain (from associated sediments) but in subordinate amounts.

[4] Vitrain lenses comprise telinite or telocollinite and occur in carbonaceous shale and coal.

[5] All samples are well cuttings, except for Toru-1 3779 m taken from core.

Table 2: Vitrinite reflectances.[5]

| Well name | Depth | Unit | CRA | Proximate analysis[6] | | | | CV[6] | S[6] | Ultimate analysis[7] | | | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (m) | | Number | M | A | VM | FC | (MJ/kg) | (%) | C | H | N | (S)[8] |
| **Cape Farewell-1** | 230 | Pakawau | 47/855 | 10.5 | 3.2 | 31.3 | 55.0 | 26.2 | 40.63 | 73.9 | 4.7 | 0.7 | 9.3 |
| | 1170-80 | " | 47/856 | 3.1 | 7.8 | 45.3 | 43.8 | 30.40 | 3.06 | 73.4 | 5.9 | 1.0 | 11.7 |
| | 1930 | " | 47/857 | 2.2 | 10.0 | 38.2 | 49.6 | 30.17 | 1.97 | 73.5 | 5.5 | 1.2 | 12.6 |
| | 2500 | " | 47/858 | 1.8 | 9.0 | 40.9 | 48.3 | 31.42 | 1.22 | 75.9 | 5.8 | 1.3 | 12.6 |
| | 2750 | " | 47/859 | 1.7 | 13.0 | 36.5 | 48.8 | 30.16 | 0.78 | 73.5 | 5.3 | 1.2 | 13.1 |
| **Kapuni Deep-1** | 4693 | Kapuni | 47/877 | 3.1 | 7.3 | 35.1 | 54.5 | 31.07 | 1.18 | | | | 13.0 |
| **Kupe-1** | 1868-78 | Mm[9] | 47/860 | 13.9 | 14.2 | 40.2 | 31.7 | 20.77 | 2.59 | | | | 6.9 |
| **Kupe South-4** | 1635-50 | Mm | 47/861 | 17.1 | 12.9 | 34.3 | 35.7 | 19.60 | 2.66 | 59.9 | 4.3 | 1.0 | 7.7 |
| | 3645-60 | Pakawau | 47/862 | 9.9 | 9.5 | 33.7 | 46.9 | 25.24 | 0.49 | 68.8 | 5.0 | 1.5 | 10.2 |
| **Kupe South-5** | 2936-39 | Kapuni | 47/863 | 12.8 | 8.9 | 32.0 | 46.3 | 23.50 | 0.91 | | | | 8.7 |
| | 3176-82 | " | 47/864 | 11.6 | 10.5 | 32.5 | 45.4 | 23.81 | 0.76 | | | | 10.0 |
| **Maui-4** | 3301-04 | Pakawau | 47/865 | 3.2 | 3.5 | 41.3 | 52.0 | 31.84 | 0.75 | | | | 11.9 |
| **N Tasman-1** | 2082-88 | Kapuni | 47/869 | 5.2 | 9.9 | 36.8 | 48.1 | 27.02 | 0.83 | 69.7 | 5.1 | 1.1 | 10.5 |
| | 2460-66 | Pakawau | 47/870 | 3.8 | 9.6 | 39.0 | 47.6 | 28.82 | 1.08 | 72.0 | 5.4 | 1.3 | 11.5 |
| | 2618-21 | " | 47/871 | 3.3 | 8.7 | 41.2 | 46.8 | 29.83 | 0.84 | 73.4 | 5.8 | 1.2 | 11.4 |
| | 2664-70 | " | 47/872 | 3.7 | 6.3 | 39.4 | 50.6 | 30.17 | 0.92 | 75.6 | 5.6 | 1.3 | 11.7 |
| **Surville-1** | 483-89 | Mokau | 47/873 | 16.3 | 7.7 | 36.1 | 39.9 | 21.01 | 1.20 | | | | 6.2 |
| **Tahi-1** | 910-20 | Mm | 47/866 | 17.8 | 16.7 | 38.0 | 27.5 | 17.85 | 3.55 | 55.2 | 4.3 | 0.7 | 5.2[10] |
| | 1591-97 | Pakawau | 47/867 | 13.3 | 8.6 | 37.6 | 40.5 | 23.37 | 0.52 | 66.6 | 5.0 | 1.1 | 7.9 |
| | 1732-38 | " | 47/868 | 14.3 | 8.0 | 32.9 | 44.8 | 22.23 | 0.56 | 65.9 | 4.5 | 1.0 | 7.5 |
| **Tane-1** | 3709-12 | Pakawau | 47/878 | 6.6 | 7.1 | 36.0 | 50.3 | 28.52 | 0.81 | 73.9 | 5.3 | 1.2 | 11.6 |
| | 4009-12 | " | 47/879 | 3.7 | 4.7 | 40.1 | 51.5 | 31.28 | 1.36 | 77.7 | 5.8 | 1.1 | 12.1 |
| | 4225-28 | " | 47/880 | 2.8 | 7.6 | 34.3 | 55.3 | 31.18 | 0.61 | 77.0 | 5.4 | 1.2 | 13.0 |
| | 4277-80 | " | 47/881 | 2.4 | 9.2 | 37.3 | 51.1 | 31.17 | 0.73 | 5.6 | 5.7 | 1.2 | 12.8 |
| **Te Whatu-2** | 3237-43 | Kapuni | 47/874 | 4.6 | 9.3 | 37.2 | 48.9 | 28.11 | 1.36 | | | | 11.4 |
| **Toru-1** | 2120 | Mm | 47/875 | 15.7 | 9.3 | 35.0 | 40.0 | 21.88 | 1.64 | 65.0 | 4.7 | 1.2 | 8.2 |
| | 3779 | Kapuni | 47/876 | 7.3 | 3.6 | 37.7 | 51.4 | 29.18 | 1.36 | 76.4 | 5.3 | 1.3 | 11.5 |

[6] Air-dried basis.

[7] Dry, not ash-free, basis.

[8] Rank(S) values are the average of those from VM/CV and from C/H, or from VM/CV only where ultimate analysis was not undertaken.

[9] Matemateaonga.

[10] The calorific value and ultimate analysis are not compatible. From the exceptionally high moisture content (21.4%, ash-free), the rank determination from VM/CV is preferred.

Table 3: Coal analyses and Rank(S) values.

of volatile matter and calorific value (Suggate 1959, Figure 42)[11]. By using analyses on the dry, mineral-matter-free (dmmf) basis, the scheme charts the geological changes to the organic fraction of coal (the "coal substance"). All analyses are additionally adjusted for sulphur (dmmsf basis), while H and C are adjusted for nitrogen as well (dmmsnf basis).

The value of the Rank(S) scheme is that it makes allowances for coal type variations that occur in the peat to low volatile bituminous coal range. This is done by incorporating the C-H and VM-CV relations shown by sets of serial samples (Suggate 1959). Five samples of coal from a single seam section in Maramarua Coalfield (south Auckland) - two hydrogen-rich sapropelic coals and three relatively hydrogen-poor humic coals - are plotted on Figure 4, as an example of the scheme's ability to accomodate even extreme variations of coal type. Four of the pointsplotted, including both sapropelic points, indicate the same rank while the fifth shows only a small difference that is within the limits of accuracy of Rank(S) determination in this part of the rank scale.

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[11] The Rank(S) diagram on axes of C and H can be transposed to axes of VM and CV using formulae linking VM and CV with ultimate analyses, together with general relations between VM and H above Rank(S)15 (see Suggate 1959).

| Well name Rank(S)[12] | Depth (m) | CRA Sample Number | Rank(S)[12] | Well name | Depth (m) | CRA Sample Number | |
|---|---|---|---|---|---|---|---|
| **Kapuni-1**[13] | 3266 | 9549 | 10.9 | **Maui-4** | 2109-18 | 13/570 | 10.3 |
| | 3295 | 9550 | 10.5 | | 2548-51 | 13/564 | 11.6 |
| | 3374 | 9551 | 10.3 | | 2566-69 | 13/565 | 11.6 |
| | 3402 | 9552 | 10.6 | | 2661-64 | 13/566 | 11.6 |
| | 3421 | 9553 | 10.4 | | 3249-52 | 13/567 | 12.2 |
| | 3511 | 9554 | 10.4 | | 3892-95 | 13/568 | 13.2 |
| | 3548 | 9555 | 10.8 | | | | |
| | 3902 | 9572 | 11.3 | **North Tasman-1** | 2015-18 | 21/782 | 10.2 |
| | 3975 | 9556 | 11.5 | | 2466-69 | 21/784 | 11.9 |
| | | | | | 2621-24 | 21/785 | 12.2 |
| **Kapuni Deep-1** | 3265-70 | 33/054 | 10.3 | | | | |
| | 3550-55 | 33/278 | 11.4 | **Tane-1** | 3689 | 20/226 | 12.1 |
| | 3985-90 | 33/279 | 13.0 | | | | |
| | 4564-67 | 33/280 | 12.5 | **Toko-1** | 4171-74 | 21/961 | 12.8 |
| | | | | | 4309-12 | 21/974 | 13.0 |
| **Kupe-1** | 3469-75 | 19/995 | 9.5 | | 4411-14 | 21/968 | 12.9 |
| | 3585-91 | 19/998 | 10.7 | | 4531-34 | 21/969 | 13.3 |
| | 3597 | 19/999 | 11.0 | | 4597-600 | 21/991 | 13.3 |
| | | | | | 4783-86 | 21/993 | 13.6 |
| **Maui-1** | 3047 | 13/084 | 10.6 | | | | |
| | 3357 | 13/085 | 12.3 | | | | |

[12] Rank(S) values are the average of those from VM/CV and C/H, or from VM/CV only where ultimate analysis was not undertaken.

[13] Sample numbers are those of the Dominion Laboratory. Only those Kapuni-1 samples for which there are both proximate and ultimate analyses are listed here; for those with only proximate analyses, see Lowery (1988).

[14] All existing proximate and ultimate (Kapuni-1 only) analyses are listed in Lowery (1988). This table excludes some high-ash analyses.

Table 4: Rank(S) values from coal analyses in Lowery (1988).[14]

The Rank(S) plot on axes of carbon and hydrogen has now been reproduced on a van Krevelen diagram (Figure 5), which uses axes of atomic H/C and atomic O/C ratios. The van Krevelen diagram (van Krevelen 1950) is used extensively by the petroleum industry for the identification of kerogen types and for maturation studies (e.g. Tissot and Welte 1984). Transfer of the Rank(S) scheme on to the van Krevelen diagram now provides a graduated rank (=maturity) scale for Type III kerogen. It is necessary first to adjust the ultimate analysis data to the mineral-matter-free basis, which is particularly important for high-ash coal, and then to calculate atomic H/C and O/C ratios[15] in order to use this diagram (Figure 5). Failure to adjust to the mineral-matter-free basis may be the reason for some of the scatter of analytical points for coals published on van Krevelen diagrams. In preparing Figure 5, the New Zealand Coal Band was revised using data acquired since 1959. This has resulted in small changes to the rank lines up to Rank(S)12 and slightly greater changes to the slopes of rank lines 13 to 15. These modifications and resultant corresponding changes to the VM/CV diagram, produced changes to Rank(S) values that are usually less than 0.3 and rarely up to 0.5 for coals of high-hydrogen type. Rank(S) values accordingly may differ slightly from those given by Lowery (1988).

On the van Krevelen diagram, the New Zealand Coal Band plots within the Type III kerogen range, as shown, for example, by Bhar and Vandenbroucke (1986) (inset, Figure 5); this is as expected since Type III kerogen represents terrestrial or "coaly" organic matter. The coal band is perhydrous with respect to that for British Carboniferous coals (Suggate 1959), and consequently may represent a slightly better source rock. Figure 6 shows that most of the Taranaki coals for which ultimate analyses are available lie within the coal band but a few have slightly higher or lower atomic H/C ratios, indicative of coal type differences.

## Downhole Maturation Trends

Downhole trends in maturation are exemplified here using five selected wells, shown in Figure 7; many of the other wells examined do not yet have data over a sufficient range of depth to allow relations between depth and maturity to be assessed. The five selected wells have different stratigraphic sequences and levels of maturation. In Tane-1 all coals are from the Pakawau Group, whereas in Kapuni Deep-1 all are

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[15] In addition to the C, H and N values given in Table 3, A(ash) and S need to be converted to the dry basis by multiplying by 100/(100-M). Correction to the mineral-matter-free basis is then accomplished using:

$Cc = 100C/(100-1.1A)$; $Hc = 100(H-0.01A)/(100-1.1A)$

$Nc = 100N/(100-1.1A)$; $Sc = 100S/(100-1.1A)$;

$Oc = 100-Cc-Hc-Nc-Sc$

where Cc, Hc, Nc, Sc and Oc are the corrected values and C, H, N, S and A are on the dry, not ash-free, basis.

Conversion to atomic H/C and O/C then uses:

$H/C = 12Hc/Cc$; $O/C = 12Oc/16Cc$

within the Kapuni Group; both Pakawau and Kapuni occur in Maui-4. In Kupe-1, the essentially continuous Oligocene and Miocene sequence makes it improbable that there is a break in maturity in the interval between Kapuni and Matemateaonga coals. In Tahi-1, however, the absence of Paleogene and Miocene sediments makes such a break possible.

For Kapuni Deep-1, Kupe-1, Maui-4 and Tane-1, $R_0$ and Rank(S) generally increase progressively with depth (Figure 7). As expected, moisture content shows the reverse trend, generally decreasing with depth, except in Kupe-1, where there is negligible decrease in moisture over an interval of 1700 m (see below). It is important to note that for any particular value of one of these three parameters, the values of the other two differ between wells. Accordingly, inferred maximum depths of burial will differ in individual wells depending on the parameter used. Generalisations of maturity/depth trends over the southern Taranaki Basin reduce, but do not eliminate, the differences.

Reflectance/depth and Rank(S)/depth gradients have not been established for Tahi-1 (Figure 7), due to the possible maturity break in the sequence, uncertain reflectance values, and a paucity of Rank(S) values.

It is clear that the level of maturation in Taranaki wells is not related to age. Eocene (Kapuni) coals are as close to being mature in Kapuni Deep-1 as are Late Cretaceous (Pakawau) coals in Maui-4; Late Cretaceous (Pakawau) coals in Tahi-1 are almost as immature as Miocene (Matemateaonga) coals in Kupe-1.

**Relations of reflectance, Rank(S) and moisture**

The moisture content of the coals appears to influence the general relation between vitrinite reflectance and Rank(S) as shown in Figure 8. Suggate and Lowery (1982) inferred that an increase in the moisture content of iso-rank coals depressed vitrinite reflectance, and this effect is apparent in Taranaki coals. Most notable are the higher Pakawau coals in Tane-1 and the single Kapuni sample in Toru-1 (indicated by *, Figure 8). These coals, of Rank(S) 11.5-12, have far higher moisture contents (8 %) and consequently much lower reflectances ($R_0$ 0.45-0.5 %) than coals of equivalent Rank(S) in Kapuni and Maui-4 wells (3.5 % moisture and $R_0$ 0.65-0.77 %). The atomic H/C ratios of these particular Tane-1 and Toru-1 coals are not atypical of Taranaki coals, thus discounting the possibility that their low reflectances are a result of unusually perhydrous compositions.

The Rank(S) scheme, as noted above, uses analyses on the dry basis. Suggate (1974), however, followed Dulhunty (1947) in recognising that moisture contents can vary substantially between coals of apparently similar dry-basis rank. Noting such variations to be important when comparing data from New Zealand and Australian oil wells, Suggate (1974) suggested that moisture contents and dry-basis calorific values (adjusted for coal type as implicit in the Rank(S)

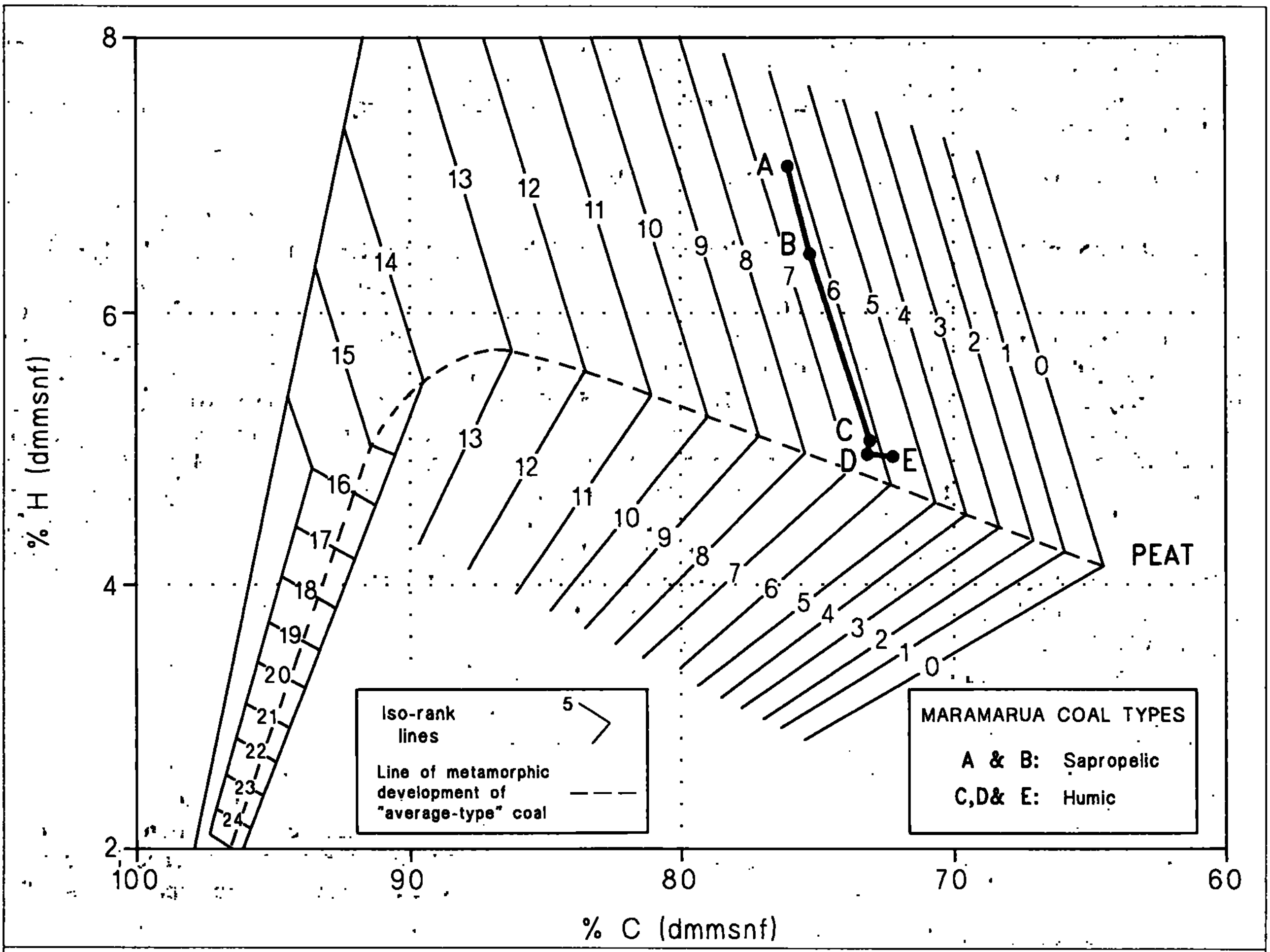


Figure 4: Rank(S) scheme, on axes of percent carbon and hydrogen as originally published by Suggate (1959, fig. 41). Five iso-rank Maramarua analyses exemplify adjustment for coal type variation. The dashed line, indicating the progression in rank of "average-type" coal, is at the low-hydrogen limit of the New Zealand Coal Band (cf. Figure 5). This diagram has recently been updated, then converted to van Krevelen axes (Figure 5).

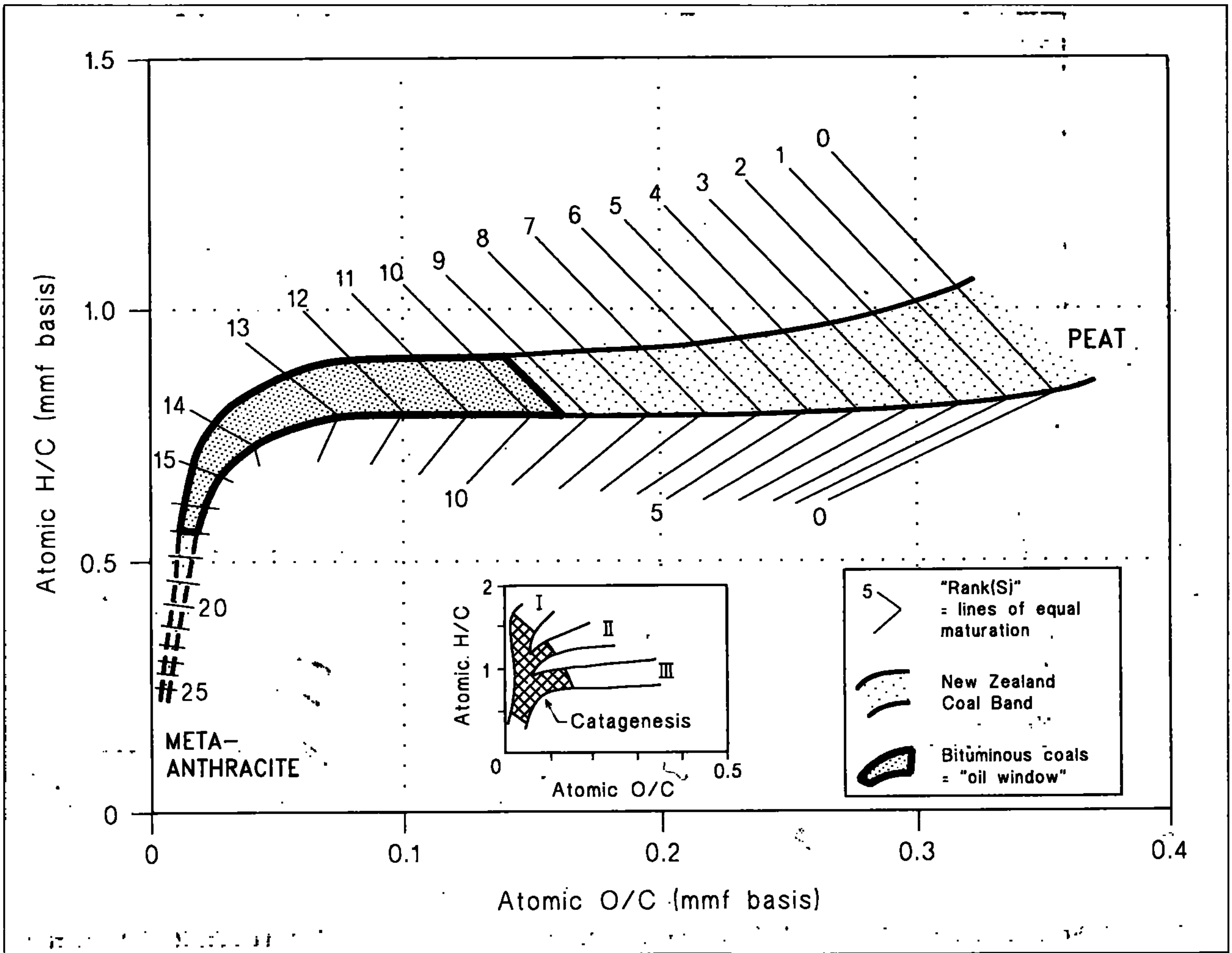


Figure 5: Rank(S) scheme, on van Krevelen axes (atomic H/C and O/C), following minor revision of the New Zealand Coal Band and rank lines. The coal band falls within the Type III kerogen path (inset, after Béhar and Vandenbroucke 1986) and the range covered by bituminous coals is broadly equivalent to the "oil window" (Tissot and Welte 1984, fig. II.1.2.).

classification) could be used to indicate depths of burial and temperatures of coalification, and hence paleogeothermal gradients. A corollary to this is that the Rank(S) classification cannot alone be used to compare estimates of former depths of burial of coals in wells if the geothermal gradients at the times of attainment of rank varied substantially.

The differences of moisture content in relation to the degree of maturation of the coal substance, evident in Figure 8, may result from regional variation in geothermal gradient (cf. Suggate 1974). At Tane-1, however, the higher moisture contents (8 %) at the top of the Pakawau sequence may be related to the severe under-compaction and consequent high fluid pressures in the 500 m thick siltstone lying 400 m above the highest coals (Shell, BP and Todd Oil Services Ltd 1977). The presence of normal pressures within the lower part of the Pakawau sequence, where the moisture contents of the coals are not unusual, indicates that the effects of the high fluid pressures, presumably including the failure of coals to release water in response to increasing burial, are not presently transmitted downward. In contrast, in Kapuni Deep-1, where the moisture contents are apparently normal, overpressuring is not reported (Shell, BP and Todd Oil Services Ltd 1986).

The sample from the top of the Kapuni Group in Toru-1 also has high moisture (8 %) and low reflectance (0.5 %) in relation to its Rank(S) value, although the Matemateaonga coal sample from this well does not. Following a rapid downhole increase in pore pressures close below the Matemateaonga Formation, these pressures remained high throughout the 1.1 km interval down to the top of the Kapuni Group (TCPL NZ Exploration Team 1991). The high moisture and low reflectance in the Kapuni coal sample may be accentuated, however, as a result of the sample being from a vitrain lens in sandstone (Table 2).

The Kapuni coals in Kupe-1 (indicated by #, Figure 8) have apparently high moisture contents (15 %), without low Rank(S) or reflectance values. These coals are of exceptionally low volatile-type, and high moisture contents are therefore to be expected (Suggate 1959, p. 58).

Regardless of the causes of high moisture contents, which produce lower than normal reflectances, the Taranaki data highlight the need for caution in using reflectance values, at least within the reflectance range (0.26 to 1.01 %) of the wells studied. While coal analyses routinely provide information on moisture contents, this is not available when reflectances are determined on dispersed organic matter. The possibility that high fluid pressures in wells may result in higher than normal moisture contents also indicates the need for caution in applying the inferences of Suggate

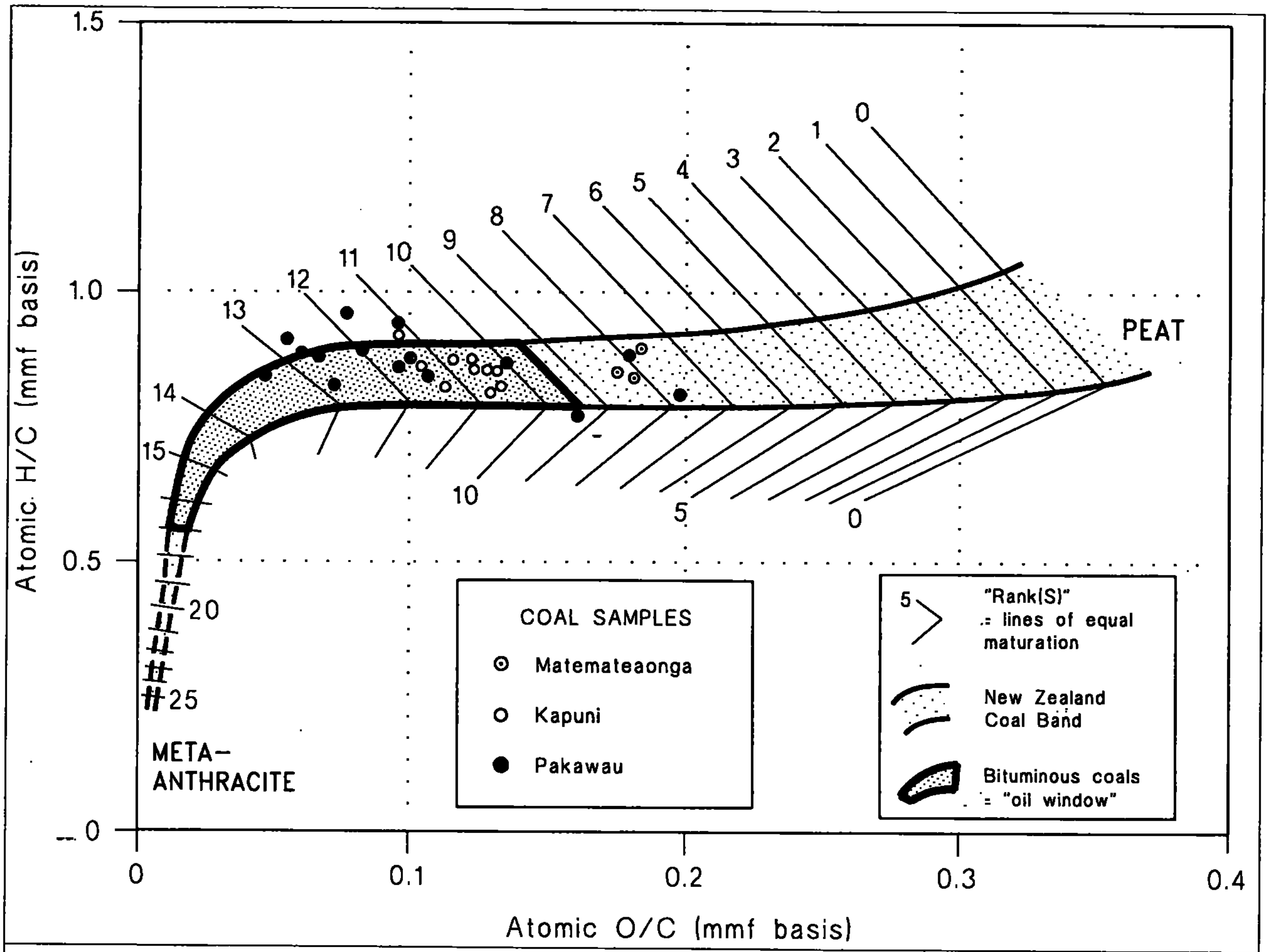


Figure 6: Southern Taranaki Basin coals for which ultimate analyses are available, plotted on the Rank(S) chart (van Krevelen axes).

(1974) on the significance of moisture/calorific value relations to estimating depths of burial and paleogeothermal gradients.

**Reflectance/depth**

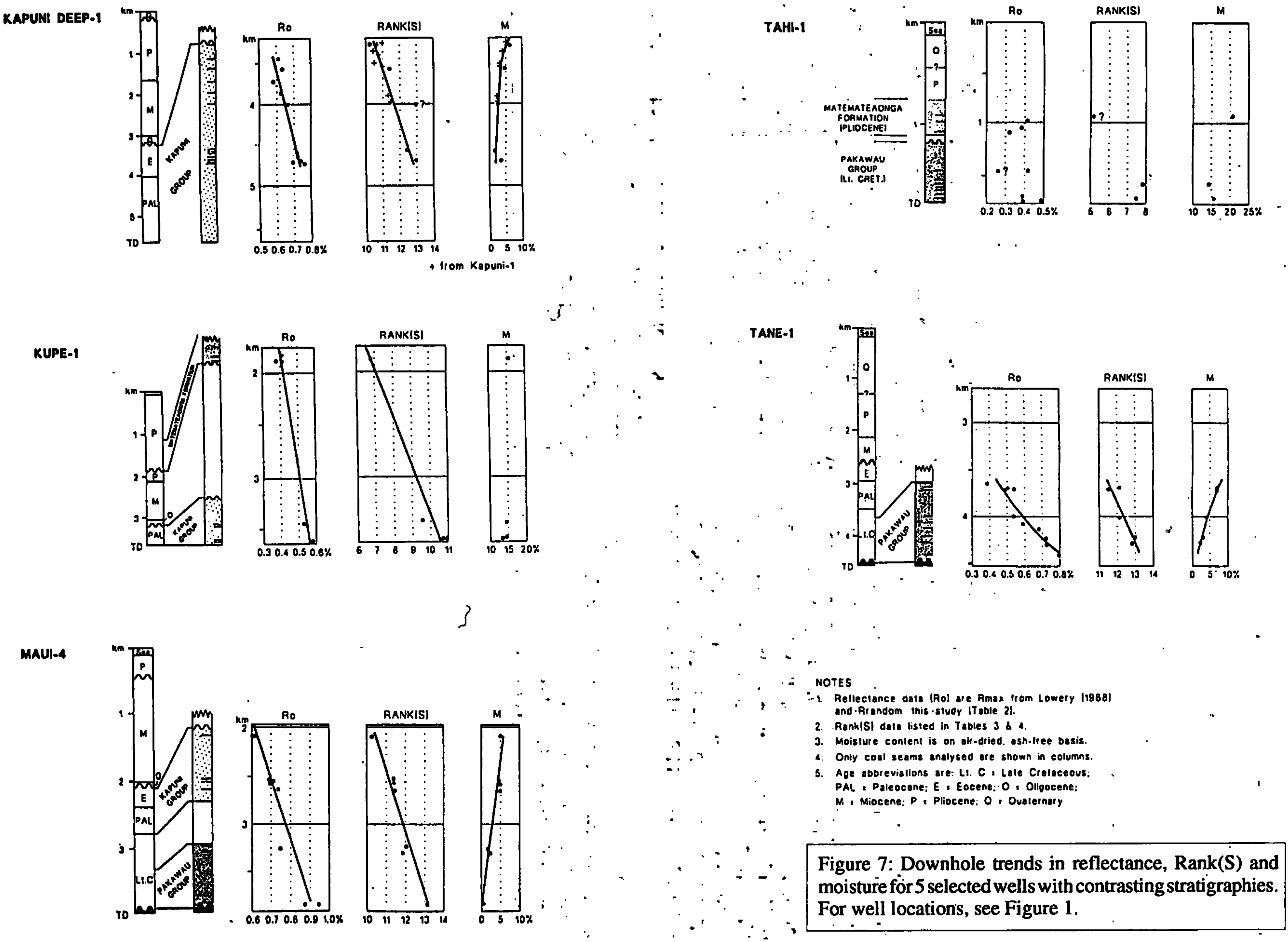
Of the selected wells depicted in Figure 7, reflectance shows a reasonably good downhole increase with depth for Kapuni Deep-1, Kupe-1, Maui-4 and Tane-1. The reflectance range of these wells is 0.40 to 0.90%. Some of the scatter evident in these plots probably results from variation in the relative contributions of different telinite/telocollinite types from carbonaceous shale and coal. In addition, although care was taken to avoid taking readings on visibly oxidised coal (presumably the result of over-vigorous drying of the cuttings), small degrees of oxidation are unlikely to have been detected and will have resulted in slightly higher readings.

In contrast to the above wells, the somewhat lower reflectances for Tahi-1, ranging from 0.26 to 0.49 %, show poor relation to depth (Figure 7). Some of the scatter can be attributed to variation in telinite/telocollinite type, resulting from differences in depositional facies and vegetation type. This is exemplified by the three Matemateaonga samples (Figure 7, Table 2). The deepest of the three samples contains telinite/telocollinite both from coal seams and carbonaceous shales and has a reflectance value 0.1 % lower than the shallowest sample, of which the telinite/telocollinite appears to be predominantly from coal. In addition, the mean reflectance of the sample from 1040-45 m is considerably affected by the presence of an anomalously low reflecting type of telinite, which may have absorbed lipids from resinite bodies infilling some cell lumens (Figure 9).

To establish a generalised relation between reflectance and maximum depth of burial, reflectance/depth gradients were plotted for those wells in which coals are presently at or near maximum depths of burial, or for which amounts of net erosion are estimated to be small (Figure 10). There are clear differences in the reflectance/depth gradients of wells at similar ranks; the gradient for Tane-1 differs from that for Kapuni Deep-1 as a consequence of the high moisture contents of the higher Pakawau coals in Tane-1, and Toru-1 contrasts with Kupe-1 because of the low reflectance of the Kapuni sample in Toru-1 (both discussed above). Nevertheless, a generalised reflectance/depth gradient can be drawn, assuming a reflectance of 0.25 % at the surface (Suggate 1990), and a small increase in the rate of reflectance increase with depth beginning at about 3 km ($R_0$ ca.0.5 %). The three Matemateaonga coals in Tahi-1 are not used because of their large range of mean reflectance (0.31-0.41 %) over a small depth interval (Figure 7).

**Rank(S)/depth**

A generalised gradient is also drawn for the relation between Rank(S) and maximum depth of burial (Figure 10). The Rank(S)/depth gradients used from individual wells are less variable than the reflectance/depth gradients though some variation is apparent. The gradient for Kupe South-4 is steeper than for other wells covering similar depth intervals, but is controlled only by single samples 2 km apart. Kupe



NOTES

1. Reflectance data (Ro) are Rmax from Lowery (1988) and Rrandom this study (Table 2).
2. Rank(S) data listed in Tables 3 & 4.
3. Moisture content is on air-dried, ash-free basis.
4. Only coal seams analysed are shown in columns.
5. Age abbreviations are: Lt. C = Late Cretaceous; PAL = Paleocene; E = Eocene; O = Oligocene; M = Miocene; P = Pliocene; Q = Quaternary

Figure 7: Downhole trends in reflectance, Rank(S) and moisture for 5 selected wells with contrasting stratigraphies. For well locations, see Figure 1.

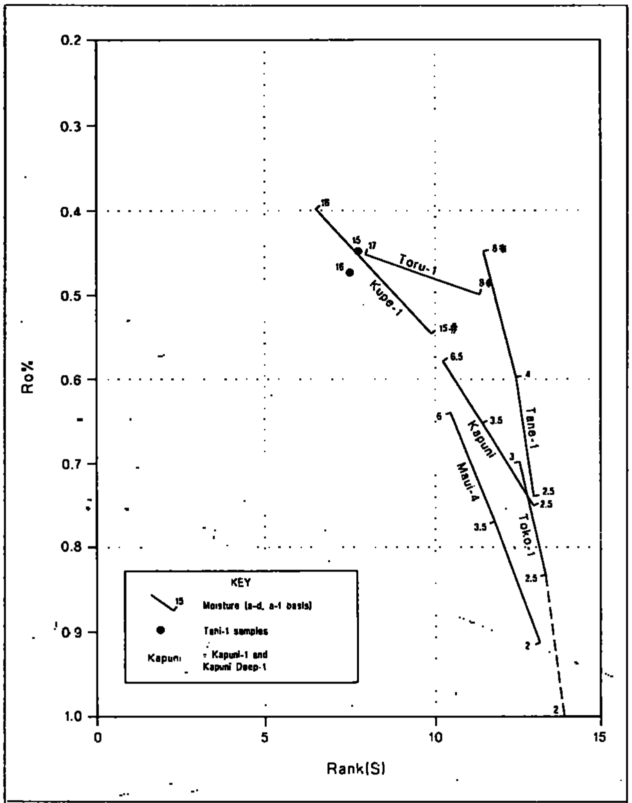


Figure 8: Reflectance/Rank(S) relations, southern Taranaki Basin wells. The lines are generalised from reflectance/depth and Rank(S)/depth plots (cf. Fig. 10), as are the moisture contents (shown on air-dried, ash-free basis). * denotes samples with high moisture and low reflectance in relation to their Rank(S), whereas # denotes high moisture sample without low reflectance or low Rank(S).

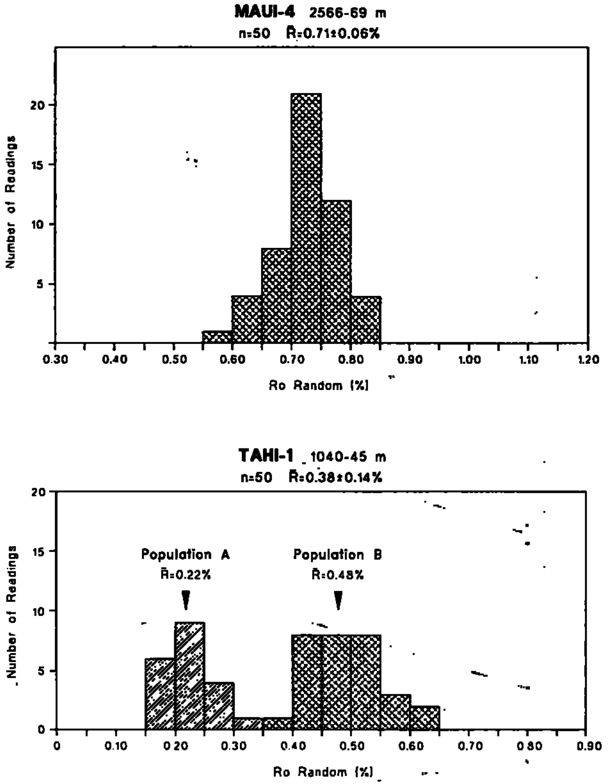


Figure 9: Comparison of reflectograms for samples with one (Maui-4) and two (Tahi-1) telinite types present. The low-reflectance population in the Tahi-1 sample is a telinite type thought to have a high content of absorbed lipids.

South-5 has two close-spaced samples, and warrants only a mean point, and only a single Matemateaonga coal was analysed from Tahi-1. The main contrast between thick sequences is between Kapuni Deep-1 and Tane-1 (Figure 10). The higher rank at a given depth for Tane-1 is probably the result of higher temperatures at depths below 3 km. At 3.5 km and 4.5 km, the estimated formation temperatures in Tane-1 are ca.105 and 135°C (Shell, BP and Todd Oil Services Ltd 1977), compared with ca.85 and 110°C in Kapuni Deep-1 (Shell, BP and Todd Oil Services Ltd 1984).

Tane-1 is on the Western Stable Platform and Kapuni Deep-1 in the Eastern Mobile Belt (Figure 1), and with more information it may be justifiable to produce separate generalised depth/Rank(S) curves for these two different areas. However, a single generalised relation is used here.

## Eroded Thicknesses and Timing of Maturation

For wells with all or parts of their sequences no longer at or near maximum burial depths, estimates of the depths at which the coals attained their present ranks can be made from their $R_0$ and Rank(S) values, using the generalised gradients of Figure 10. For both Pakawau and Kapuni coals, the two possibilities for the timing of maximum burial are in the latest Eocene or latest Miocene, each immediately prior to the formation of the regional unconformities (Figure 2). To judge the more likely timing, the geohistory plots of Hayward and Wood (1989) are used; an example – North Tasman-1 – is shown in Figure 11. For this well, using the Rank(S) value of 12.0 for the deepest Pakawau coal, the maximum depth of burial is estimated at 4200 m. To achieve this thickness prior to the Oligocene unconformity, an additional 3600 m of sediment is required in the Eocene (the thickness preserved beneath the base-Oligocene unconformity is 600 m); this is considered improbable given the conditions of waning subsidence and relative tectonic quiescence inferred for the Eocene. Alternatively, to achieve maximum burial in the late Miocene, 1900 m of additional sediment is required (the preserved thickness beneath the base-Pliocene unconformity is 2300 m), and this is considered quite probable in view of the rapid rate of sedimentation evident for the preserved Miocene deposits. The Rank(S) value of 10.5 for the highest Kapuni coal equates to a missing late Miocene sequence of 1700 m, giving an indication of the variation in estimates using the Rank(S)/depth-of-burial relation.

The thicknesses eroded and the ages of the eroded sediments for Cape Farewell-1, Maui-1, Maui-4, North Tasman-1, Surville-1, Tahi-1, Te Whatu-2 and Toko-1, estimated from Rank(S) values, are listed in Table 5. The range of eroded thicknesses for these wells is from 400 m, for Toko-1 (cf. Kapuni Deep-1), to 2400 m in Cape Farewell-1. Such a wide range of thicknesses reflects the diverse tectonic and sedimentary history of the basin and the varying structural settings of the wells.

Estimates are given in Table 5 based on reflectance values for Maui-4 and Toko-1 (the latter using data from Lowery 1988); these are comparable but not identical to the

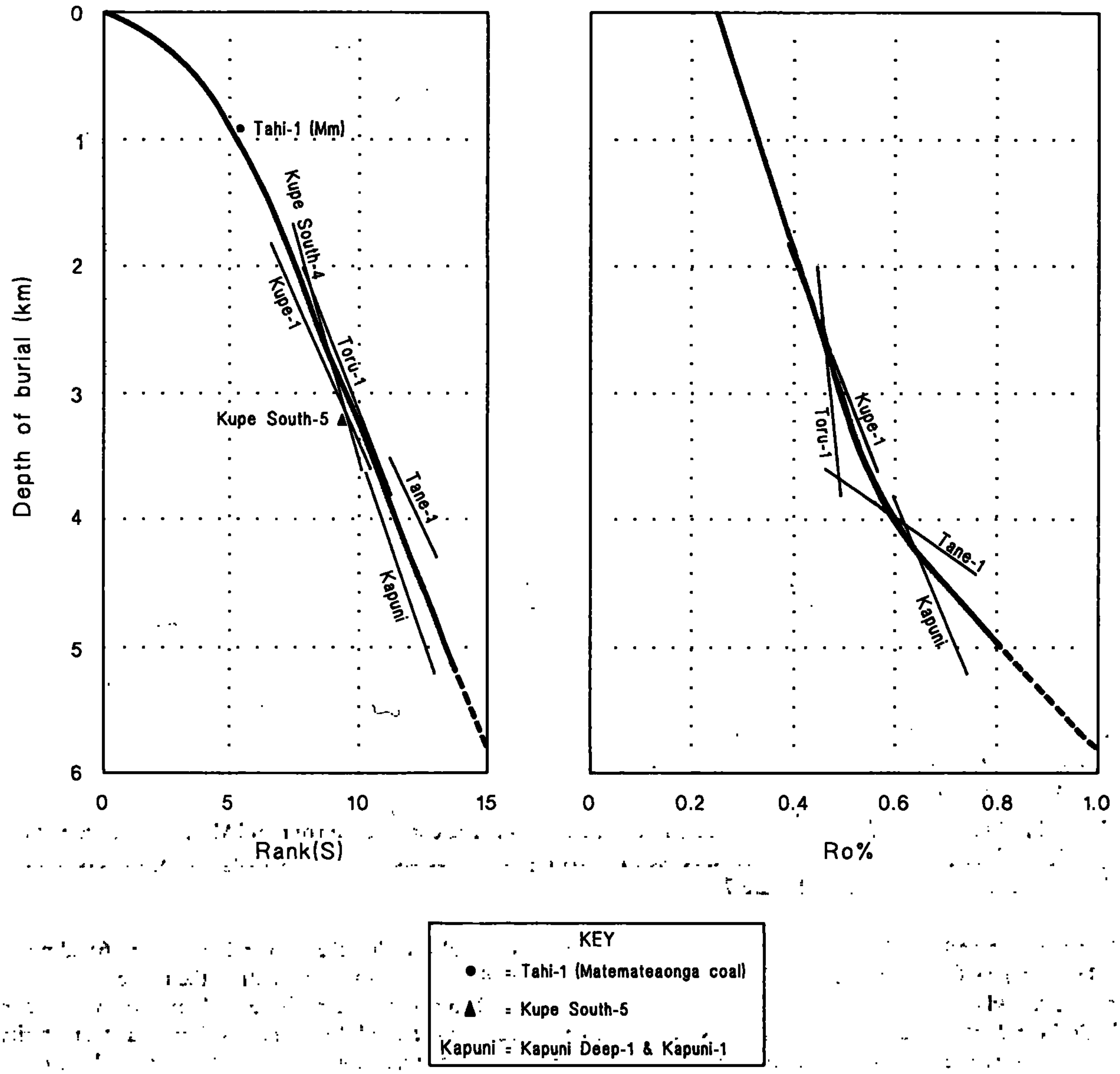


Figure 10: Reflectance/depth and Rank(S)/depth relations for wells in which the sequences are either at or close to their maximum depths of burial, or for which an estimate is made (Kapuni-1 and Kapuni Deep-1) of a small amount (400 m) of net erosion from the top of the well (Pliocene-lower Quaternary sediments eroded, with subsequent deposition of volcanics from Mt. Egmont). The thick lines represent generalised maturity/depth gradients for southern Taranaki Basin.

Rank(S)-derived thicknesses. The differences can be attibuted to the imprecision of using generalised curves for individual wells, the small numbers of Rank(S) and reflectance determinations, and the possibility that some determinations are influenced by factors such as the depression of reflectance values by high moisture contents or perhydrous vitrinite. Nevertheless, the estimates of eroded thicknesses and of their ages are considered to be sufficiently close to provide important inputs for determining the geohistory of the region.

In none of the southern wells, nor Maui-1 or Toko-1, is it likely that the present levels of maturation were attained in the Oligocene or earlier, although this is not ruled out for Tahi-1. The timing of maturation is restricted to the latest Miocene at Maui-1, Maui-4, North Tasman-1 and Te Whatu-2, and the Pliocene at Toko-1. Because of continuing erosion, the age is less closely constrained at Cape Farewell-1 and Surville-1, but in both of these wells it is likely to be at least as young as late Miocene. At Tahi-1, the missing sequence is likely to have included latest Cretaceous to Paleogene sediments, but a substantial part of the estimated missing thickness of 1600 m was probably of Miocene age.

This study has estimated maximum burial depths and eroded thicknesses based on single generalised reflectance/depth and Rank(S)/depth gradients. With additional data, however, maturity/depth relations are likely to prove more complex than shown by the generalisations, differing particularly in relation to geothermal gradients. Separate generalisations may therefore prove useful for the different structural (sub-)provinces (e.g. the Western Stable Platform and Eastern Mobile Belt).

## Maturation Levels for Taranaki Oil

Although not the principal objective of the investigation, some results are pertinent to the maturity levels required for

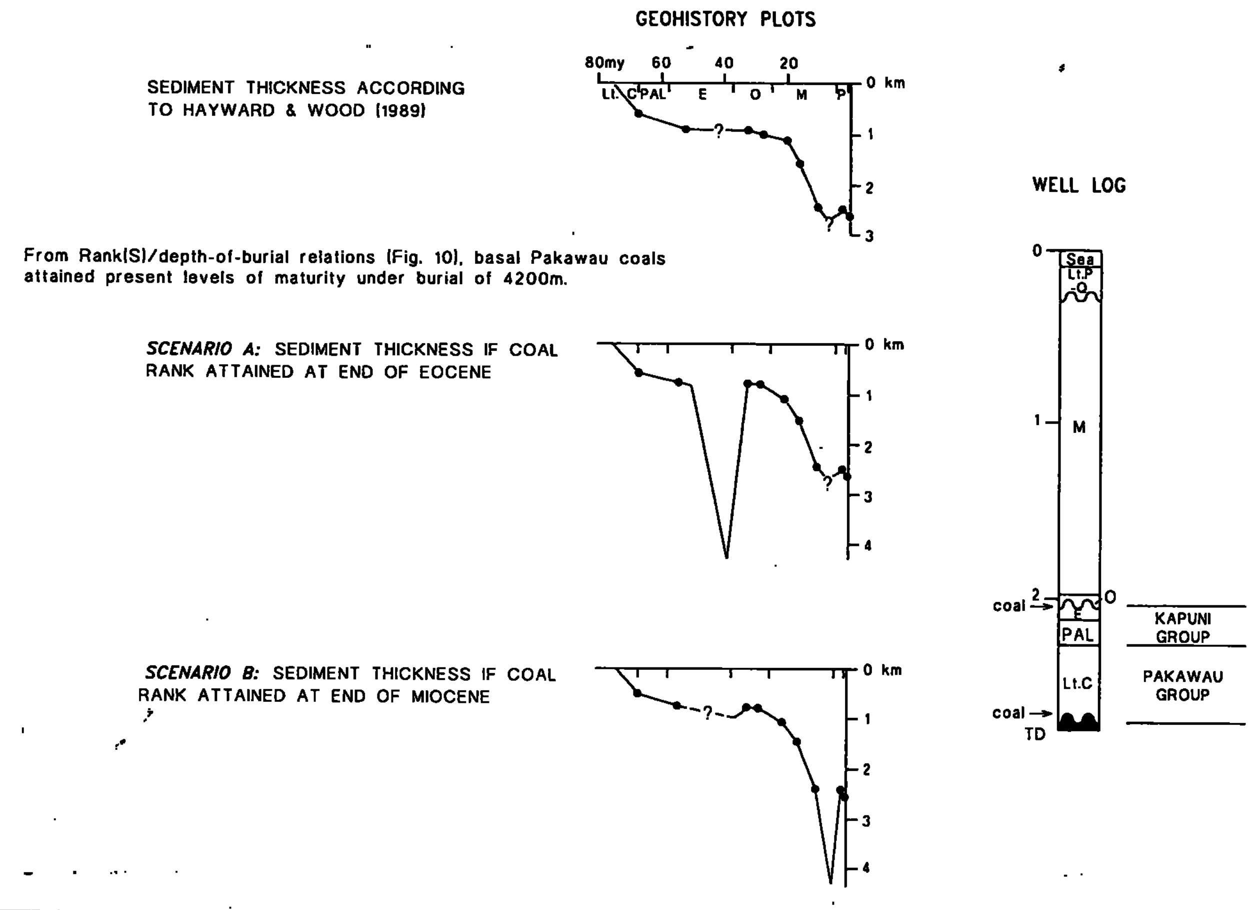


Figure 11: Assessment of timing of maturation: North Tasman-1. The continuation of rapid Miocene sedimentation into the latest Miocene is more probable than an exceptionally rapid subsidence in the late Paleogene. Age abbreviations are the same as those (with key) in Figure 7.

oil generation and expulsion, defined in terms of Rank(S) and reflectance. On a van Krevelen diagram (Figure 5), the range covered by bituminous coals is broadly equivalent to the "oil window" and the zone of catagenesis illustrated by Tissot and Welte (1984, Figure II.7.2) and Béhar and Vandenbroucke (1986, Fig. 1) (inset Figure 5). The beginning of this zone is aligned in a closely similar direction to that of the Rank(S) lines, and accordingly Rank(S) provides a maturity scale. Although most of the Kapuni and Pakawau coals plot within the oil window (Figure 6), almost all are within the low-maturity half of the range.

From biomarker studies, Maui-4 oil was thought by Johnson *et al.* (1988) to have originated at a maturity level attained at a depth a little greater than the base of the well (T.D. 3920 m). As such, it would originate at about Rank(S)13.5. Oil shows between 5466 and 5664 m in Kapuni Deep-1, below the deepest coal examined, are from a maturity level estimated at Rank(S)14. Oil shows in Cape

| Well name | Eroded thicknesses [16] (m) Rank(S) | $R_o$ | Age of missing deposits |
|---|---|---|---|
| Cape Farewell-1 | 2400 | | Lower Miocene - ? |
| Maui-1 | 1300 | | Upper Miocene |
| Maui-4 | 1400-1700 | 1800-2400 | Upper Miocene |
| North Tasman-1 | 1700-1900 | | Upper Miocene |
| Surville-1 | 1000 | | Upper Miocene - ? |
| Tahi-1 | 1600 | Note[17] | Upper Cretaceous - lower Miocene |
| Te Whatu-2 | 1100 | | Upper Miocene |
| Toko-1 | 400 | 200 - 500 | Pliocene |

[16] Thickness estimates are given as ranges when rank indices (Rank(S) or $R_o$) at two or more depths in a well indicate significantly different thicknesses.

[17] Estimate not warranted due to poor consistency of reflectance data between Lowery (1988) and this study (Figure 7).

[18] Estimates are derived from the generalised rank/depth-of-burial gradients of Figure 10, together with the geohistory plots of Hayward and Wood (1989).

Table 5: Estimates of eroded thicknesses.[18]

Farewell-1, such as highly oil-impregnated coal samples now at 2500 and 2750 m, occur at a level with Rank(S)13. While the start of generation of oil (at the start of catagenesis, Tissot and Welte 1984) may begin at Rank(S)9-10 (Figure 5), it seems likely that expulsion may not begin until Rank(S)13-14.

In Maui-4, the reflectance values at Rank(S)13 and 14 are about 0.9 and 1.0 % (extrapolated) respectively, but in Kapuni Deep-1 they are 0.75 % and 0.83 % (both extrapolated, Figure 7). An even lower reflectance, ca.0.65 %, is given by Carter and Kintaner (1987) for the lower part of Cape Farewell-1 where Rank(S)13 coals are found, but this may be due to inter-laboratory differences in reflectance determination. The start of oil expulsion appears less closely defined by reflectance - from 0.75 to 1.0 %, but possibly as low as 0.65 % - than by Rank(S).

## Conclusions

In the context of coals being the probable main source for Taranaki Basin oil and gas, vitrinite reflectance and routine coal analyses provide complementary measures of coal maturity. The use of reflectance is made difficult by poor inter-laboratory consistency of data, by variability in the types of telinite and telocollinite within and between samples, and by the effect of differences in moisture content between coals that are otherwise apparently of similar degrees of maturation. Higher moisture contents, some possibly the result of overpressuring in overlying sediments, suppress the reflectance.

Routine proximate and ultimate analyses, together with calorific values, are used in the Suggate rank scale - Rank(S). This compensates for variations in coal type and provides estimates of relative degrees of maturation. It appears to be more reliable than vitrinite reflectance as a maturity index, at least over the maturity range of the coals studied ($R_o$ 0.26-1.01 %).

Reflectance/depth and Rank(S)/depth relations can be generalised from those wells at or close to their maximum depths of burial, namely Kupe-1, Kupe South-4 and -5, Tane-1 and Toru-1, together with Tahi-1 down to the base of the Pliocene. In addition, Kapuni-1 and Kapuni Deep-1 can be used for the generalisation, assuming 400 m of net loss of section from the top of the well (Elphick and Suggate 1964). These relations can then be used to estimate the maximum depths of burial for coals in the southern wells, namely Cape Farewell-1, Maui-4, North Tasman-1, Surville-1, Te Whatu-2, Tahi-1, plus Maui-1 and Toko-1. Using the depth estimates in conjunction with geohistory plots, the ages of the sediments formerly present in these wells can be identified, and the eroded thicknesses determined. In all the southern wells, plus Maui-1 and Toko-1, the present (hence maximum) levels of maturation were attained in the late Neogene, and in all these wells except Tahi-1 the missing sediments were all of Neogene age; in Tahi-1 they range from Late Cretaceous to Miocene. Estimated thicknesses of eroded sediments range from 400 to 2400 m.

The maturity level for expulsion of oil is inferred to be at Rank(S)13-14. The corresponding reflectance range, however, appears to be much broader, from 0.75 % (but possibly as low as 0.65 %) to 1.0 %.

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