A REAPPRAISAL OF THE ORGANIC GEOCHEMICAL IMPLICATIONS FOR OIL GENERATION IN THE TARANAKI BASIN

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Abstract

From a basin-wide evaluation of organic geochemical data, it has been possible to characterise and differentiate various source rock units and to establish the genetic relationships of oils. Among the primarily terrestrially sourced oils, varying contributions from source rocks within the Kapuni and Pakawau Groups are recognised. This distinction is attributable to the rise to dominance of angiosperms over gymnosperms in coastal plain swamp communities by the Eocene. A low level marine influence is also apparent in these oils. Apart from the Maui family (i.e. Maui Field, Maui-4 and Moki-1) oils, the inferred relative contributions from the main source rock types generally correlate with the relative proportions of suitably thick and mature units near reservoirs. Maui family oils appear to be primarily sourced by Rakopi Formation coals. In the northern part of the Tarata Thrust Zone Mangahewa/Kaimiro Formation coals seem to be the chief source of oils. Biomarkers suggest that onset of oil expulsion from coals at a maturity level corresponding to a vitrinite reflectance of ca. 0.8% R_0 is possible, and may be aided by the evolution of large volumes of carbon dioxide. The terrestrial influence on Paleogene source rocks diminishes to the north-northwest of the basin, and a marine phytoplankton signature, apparently associated with a Late Paleocene shale, dominates biomarker distributions in some oils (e.g. Kora-1 well). It is possible that shales interbedded with coals, reflecting periodic marine incursions of coastal floodplains, also contribute to oil generation throughout much of the basin.

Introduction

On the basis of organic carbon content, hydrogen-richness and maturity, Paleogene (Kapuni Group) and Late Cretaceous (Pakawau Group) coals are believed to be the major petroleum source rocks in the Taranaki Basin (figures 1 and 2) and possess mixed oil and gas potential (e.g. Cook, 1987; Kirkland et al., 1987; Powell, 1988; Powell et al., 1991). Table 1 presents Rock-Eval data illustrating the petroleum potential of various formations on a regional basis. The Rakopi Formation (figure 2) is widespread and contains abundant coal. However, the distribution of coal-rich units in Paleogene strata reflects the general extent of marine transgressional cycles, with progressively terrestrial-dominated sediments being deposited towards the east-southeast. The Eocene Mangahewa Formation (figure 2) is particularly coal-rich (Table 1) and is found throughout the onshore part of the basin and in the Maui-4 area. It is significantly thickened within the northern part of the Tarata Thrust Zone (figure 1). The Kaimiro Formation is coal-rich within the Tarata Thrust Zone, but westwards around New Plymouth it is appreciably marine-influenced and appears to have poor oil potential. The Paleocene Farewell Formation generally contains less coaly material and exhibits varying degrees of marine influence. In the Maui-4 area it is predominantly terrestrial with oil potential, but in the Kupe Field only the lower half of the unit contains carbonaceous and coaly material in significant quantity, while the upper half is organic-poor and marine-influenced. The marine, Paleogene, Turi Formation predominates to the west and north, and is generally organic-poor. The equivalent unit of the Late Cretaceous, the North Cape Formation, represents a major marine transgression between deposition of the potential terrestrial source rocks

Table 1. Mean Rock-Eval data for formations in various regions of the Taranaki Basin (after Analabs, 1984).

Field/region	Formation	TOC (%)	S2 (‰)	HI (‰)
Kaimiro	Mangahewa	14.0	42	240
	Turi + Kaimiro	1.5	2	120
Kapuni	Mangahewa	13.0	28	135
Kupe	Farewell (upper)	1.0	1	80
	Farewell (lower)	2.5	2	90
McKee	Mangahewa (upper)	9.5	30	230
Maui-4	Mangahewa + Kaimiro	10.5	22	195
	Farewell	9.5	16	175
	North Cape	1.0	1	75
	Rakopi	9.0	23	245
Tane-1	Turi	0.5	<1	15
	North Cape	0.5	<1	25
	Rakopi	5.0	5	120

of the Rakopi Formation and the Mangahewa/Kaimiro/Farewell formations.

The bulk chemical constitution and petroleum potential of Pakawau and Kapuni Group coals are similar, as demonstrated by the maturity trend of the New Zealand coal band on van Krevelen-type diagrams (e.g. Suggate, 1959; Sykes et al., 1992). The oil potential of these coals appears to be related to the abundance of the hydrogen-rich, amorphous, submaceral desmocollinite, which may be predominantly derived from lipid-rich leaf cuticular membranes and bacterial cell walls (Killops et al., 1994a and references therein). Typically, the hydrogen index (HI) of New Zealand coals rises to ca. 300‰ at Suggate rank 12-13 (at the onset of oil generation/expulsion; equivalent to vitrinite reflectance of ca. 0.7-0.9% RO) and the Rock-Eval S2 parameter is ca. 200‰ (Suggate and Boudou, 1993).

Various studies of biomarker distributions have been undertaken in an attempt to correlate oils with specific source rock intervals (e.g. Cook, 1987; Cook, 1988; Czochanska et al., 1988; Johnston et al., 1991). These studies have centred on the ubiquitous hopanes and steranes, with the most useful source indications being gained from the relative abundance of the angiosperm-derived compound 18α(H)-oleanane. More recently, the source-specific potential of gymnosperm-derived diterpanes (Weston et al., 1989) and various angiosperm-derived triterpanes (Woolhouse et al., 1992) has been recognised and partially applied in subsequent correlation studies (Johnston et al., 1990; Collier and Johnston, 1991; Johnston, 1992). Precise oil-source rock correlation has proven elusive, a major reason being the paucity of potential source rock samples from depths >4000 m, at which oil generation and expulsion apparently occurs from coaly sediments in the basin. The study reported in the following sections attempts to apply source indicators to identify genetically related families of oils and their most likely source rocks. Basin-wide oil generation and expulsion is then considered in the light of the distribution and maturity of potential source rock units. The locations of wells from which oil/condensate and sediment samples were obtained are shown in figure 1, and the corresponding reservoirs are shown in the stratigraphic section in figure 2.

Materials and Methods

Organic-rich sediment samples, in the form of cuttings, were selected from the wells
Ariki-1 (Turi Formation: 4122, 4125 m)
Awakino-1 (Turi Formation: 2600, 2800 m)
Fresne-1 (Rakopi Formation: 2500, 2502 m)
Kaimiro-1 (Mangahewa Formation: 3790–4045 m; Turi Formation: 4450–4480 m, Kaimiro Formation: 4936, 4975 m)
Kapuni Deep-1 (Mangahewa Formation: 3450, 3550 m; Kaimiro Formation: 3850 m; Farewell Formation: 4693 m)
Kupe-1 (Turi Formation: 3652 m)
Kupe South-1 (Turi Formation: 3280, 3470 m)
McKee-1 (overthrusted Mangahewa Formation: 2408–2459 m; in situ Mangahewa Formation: 3482-3869 m)
Maui-4 (Mangahewa Formation: 2100 m; Kaimiro Formation 2469 m; North Cape Formation: 2926 m; Rakopi Formation: 3249–3892 m)
Tane-1 (North Cape Formation: 3667 m; Rakopi Formation: 4063–4408 m),
Urenui-1 (overthrusted Mangahewa Formation: 3179, 3182 m; in situ Mangahewa Formation: 3557–3844 m)
Waihapa-1 (Mangahewa Formation: 4296–4746 m; Kaimiro Formation: 4941 m).

Oil/condensate samples were taken from
Ahuroa-1 (Otaraoa Formation)
Kaimiro-1 and Stratford-1 (McKee Formation)
Kapuni-2, Mangahewa-1, Maui-1, Maui-3, Maui-4 and Okoki-1 (Mangahewa Formation)
Kora-1 (Mohakatino Formation)
Kupe South-1 and Toru-1 (Farewell Formation)
McKee-3, Pouri-1A, Pukemai-2A, Toetoe-1A and Urenui-1 (McKee Formation overthrust)
Moturoa-2 (Matemateaonga Formation)
Moki-1 (Moki Formation)
Waihapa-1A (Kaimiro Formation)

Well locations are shown in Fig. 1.

After milling to a fine powder, sediment samples were solvent-extracted using either Soxhlet or ultrasound. Saturate fractions were isolated from oils and sediment extracts by TLC on silica gel with hexane eluant. Where necessary, *n*-alkanes were removed from saturates by 5Å molecular sieve or urea adduction prior to GC-MS analysis of biomarkers using a DB-5 column and monitoring selected ions. Relative biomarker abundance was calculated from peak heights in m/z 123 (diterpanes), m/z 191 (triterpanes, including hopanes) and m/z 217 (steranes) mass chromatograms, as shown in figure 3.

Various indices and ratios were obtained from the above mass chromatograms. An angiosperm response factor was calculated from the summed m/z 191 response for the angiosperm markers 18α(H)-oleanane (O), the C_{24} A-ring degraded analogues of oleanane (dO), lupane (dL) and ursane (dU), and a C_{30} pentacyclic triterpane (a) thought to be a bicadinane (Killops et al., 1994a and references therein). The summed m/z 123 response was calculated for the gymnosperm indicators 8β(H)-labdane (βL), rimuane (R), 17-nortetracyclane (NT), *ent*-beyerane (B), 4α(H)-18-noriospimarane (18NIP), 4β(H)-19-norisopimarane (19NIP), isopimarane (IP), 16β(H)-phyllocladane (βP) and *ent*-16β(H)-kaurane (βK). This value was then multiplied by the ratio of m/z 191/123 response for isopimarane (a conversion factor to yield an equivalent m/z 191 response for comparison with triterpane abundance; most of the diterpanes do not give an appreciable m/z 191 response). The resulting value was divided into the summed angiosperm response to yield the angiosperm/gymnosperm index. A terrestrial/marine index was calculated from the ratio of the m/z 217 response for 20S and 20R epimers of C_{29} 13β(H),17α(H)-diasteranes (29DβαS and 29DβαR) to their C_{27} counterparts (27DβαS and 27DβαR). A hopane/sterane ratio was obtained from the summed m/z 191 response for 17α(H)-hopane (30αβ) and its C_{24} E-ring degraded counterpart (dH) relative to the summed m/z 217 response for C_{29} 5α(H)-steranes (29ααS, 29ββR, 29ββS and 29ααR) and 13β(H),17α(H)-diasteranes (29DβαS and 29DβαR). A tricylic terpane to regular hopane ratio was calculated from the m/z 191 response for the C_{23} tricyclic terpane (23T) relative to the summed responses for 17α(H)-hopane (30αβ) and its C_{24} E-ring degraded counterpart (dH).

Oil-source rock correlation

A detailed description of biomarker, isotopic and trace metal distributions in Taranaki Basin oils has recently been undertaken (Killops et al., 1994a), and so a full discussion of

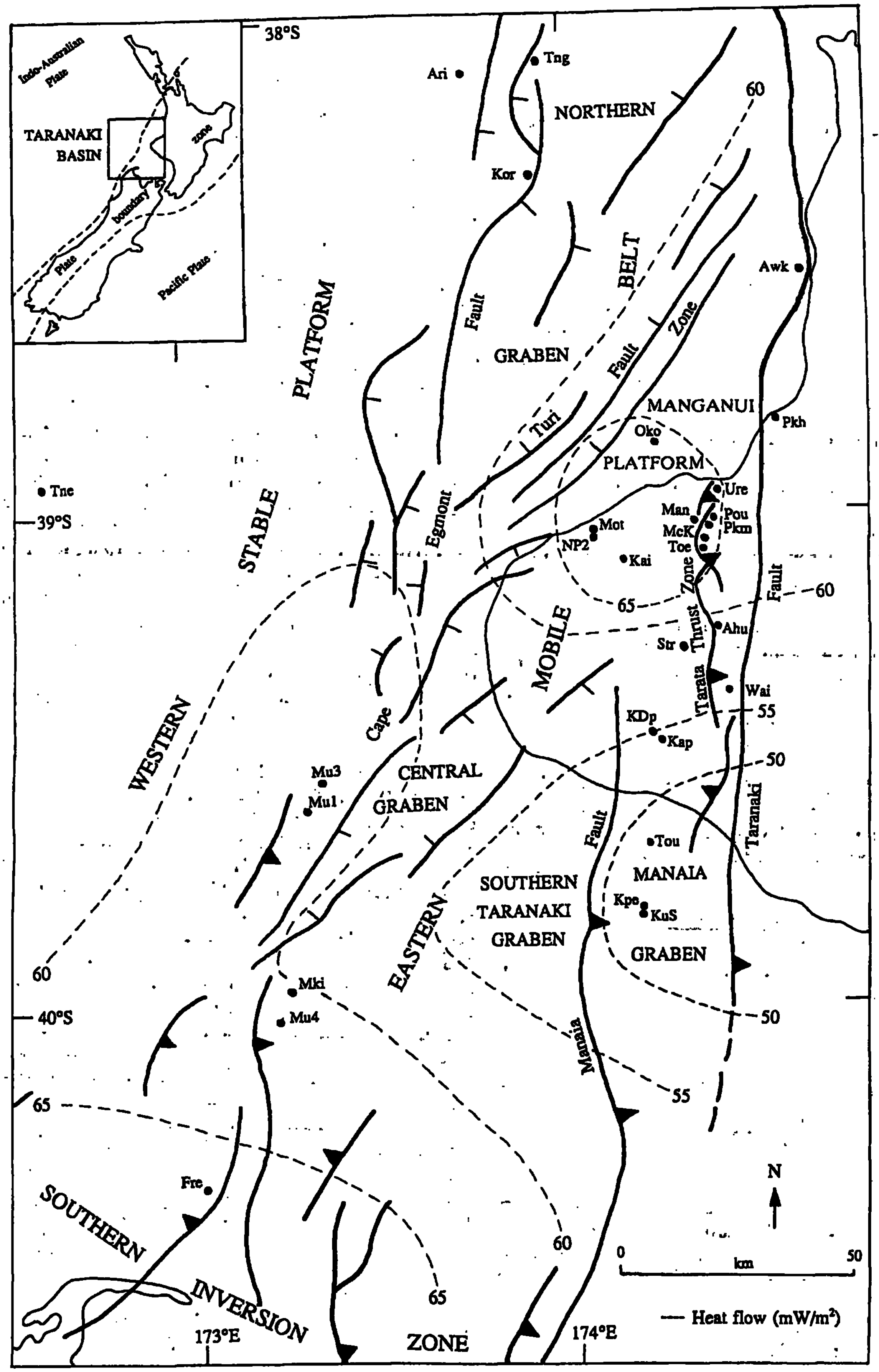

Fig. 1. Well location map for the Taranaki Basin, showing general heat-flow contours. (Ahu = Ahuroa-1, Ari = Ariki-1, Awk = Awakino-1, Kai = Kaimiro-1, Kap = Kapuni-2, KDp = Kapuni Deep-1, Kor = Kora-1, Kpe = Kupe-1, KuS = Kupe South-1, McK = McKee-1 and McKee-3, Man = Mangahewa, Mu1 = Maui-1, Mu3 = Maui-3, Mu4 = Maui-4, Mki = Moki-1, Mot = Moturoa-2, NP2 = New Plymouth-2, Oko = Okoki-1, Pou = Pouri-1A, Pkh = Pukearuhe-1, Pkm = Pukemai-2A, Str = Stratford-1, Tng = Tangaroa-1, Toe = Toetoe-1A, Tou = Toru-1, Ure = Urenui-1, Wai = Waihapa-1.)

the basis for grouping oils into genetically related families will not be presented here. In brief, from the pollen record gymnosperms, particularly podocarps and araucarians, dominated the higher plant communities of coastal floodplains during the Late Cretaceous and were still major members throughout the Paleocene, but had become subordinate to angiosperms by the Eocene (Mildenhall, 1980). Biomarker distributions reflect these changes in the flora. Coals and interbedded shales from the Late Cretaceous Rakopi Formation exhibit very high levels of gymnosperm-derived diterpanes, often dominated by isopimarane, and extremely low levels of 18α(H)-oleanane [- 2% relative to 17α(H)-hopane from m/z 191 response]. In contrast, Eocene Mangahewa and Kaimiro Formation coals exhibit relatively high levels of angiosperm-derived triterpenoids, particularly oleanoids, ursanoids and lupeoids, and much reduced levels of diterpanes. Paleocene coals in Kapuni Deep-1 (i.e. belonging to Kapuni Group cycle A) appear to exhibit biomarker source characteristics more like those of Late Cretaceous coals (Johnston et al., 1990).

The above biomarker characteristics can be represented by an angiosperm/gymnosperm index (AGI), which is calculated from the relative amounts of selected diterpanes and triterpanes in m/z 123 and 191 mass chromatograms, respectively. The relative contributions of terrestrial- and marine-derived organic material in sediment samples can be expressed in the form of a terrestrial/marine index (TMI), which is based on the assumption that the ratio of C_{29} to C_{27}

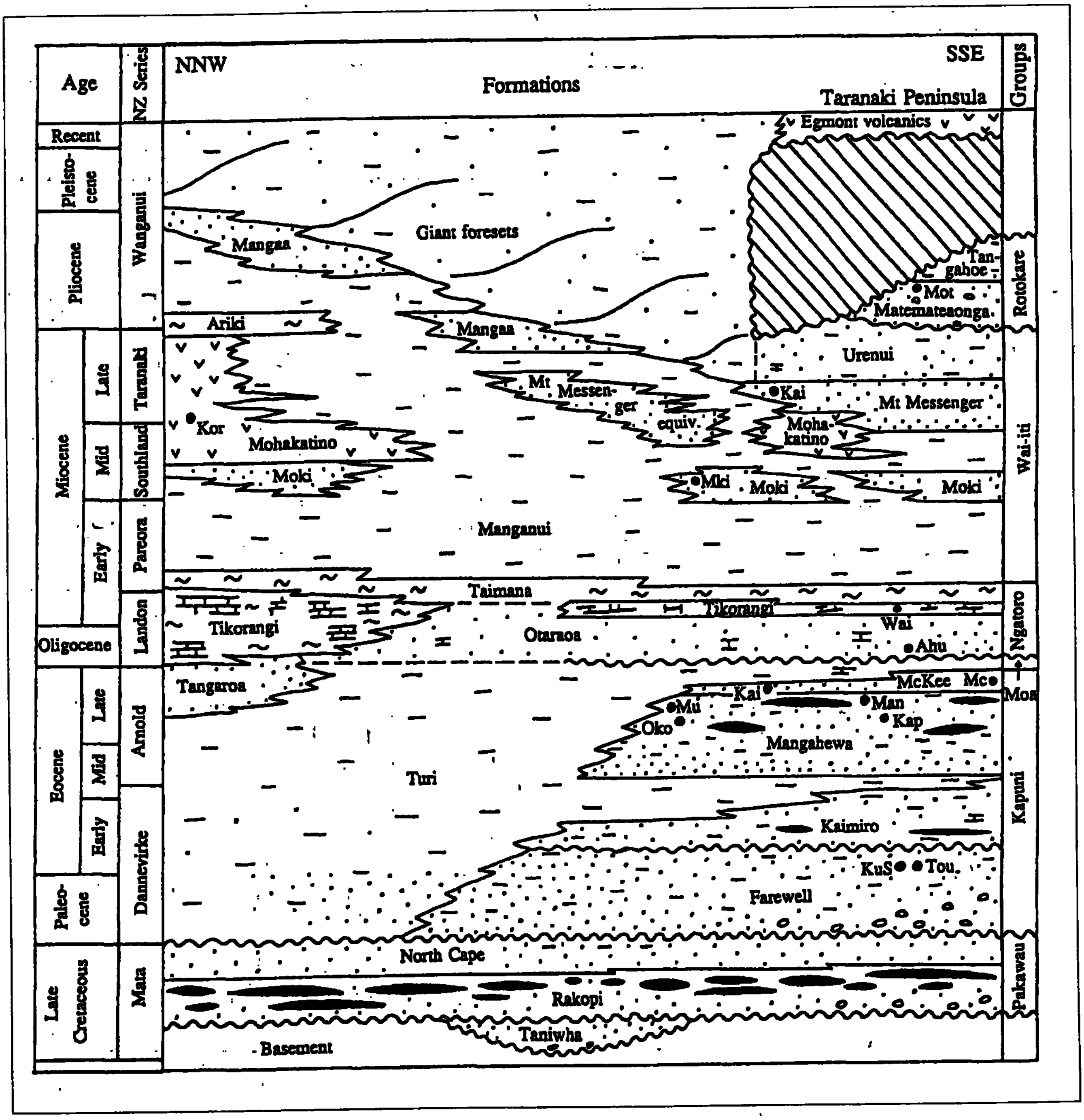

Fig. 2. Generalised stratigraphy of the Taranaki Basin (after Bennett et al., 1992), showing main oil/condensate accumulations. (N.B. in Pukearuhe-1 Paleogene and Cretaceous strata are absent and oil shows were present in a fracture zone associated with intra-basement thrust in L. Triassic/E. Jurassic sediments. Mc = oils from McKee-3, Pouri-1A, Pukemai-2A, Stratford-1, Toetoe-1 and Urenui-1; Mu = oils from Maui-1, Maui-3 and Maui-4; see figure 1 legend for key to other well name abbreviations.)

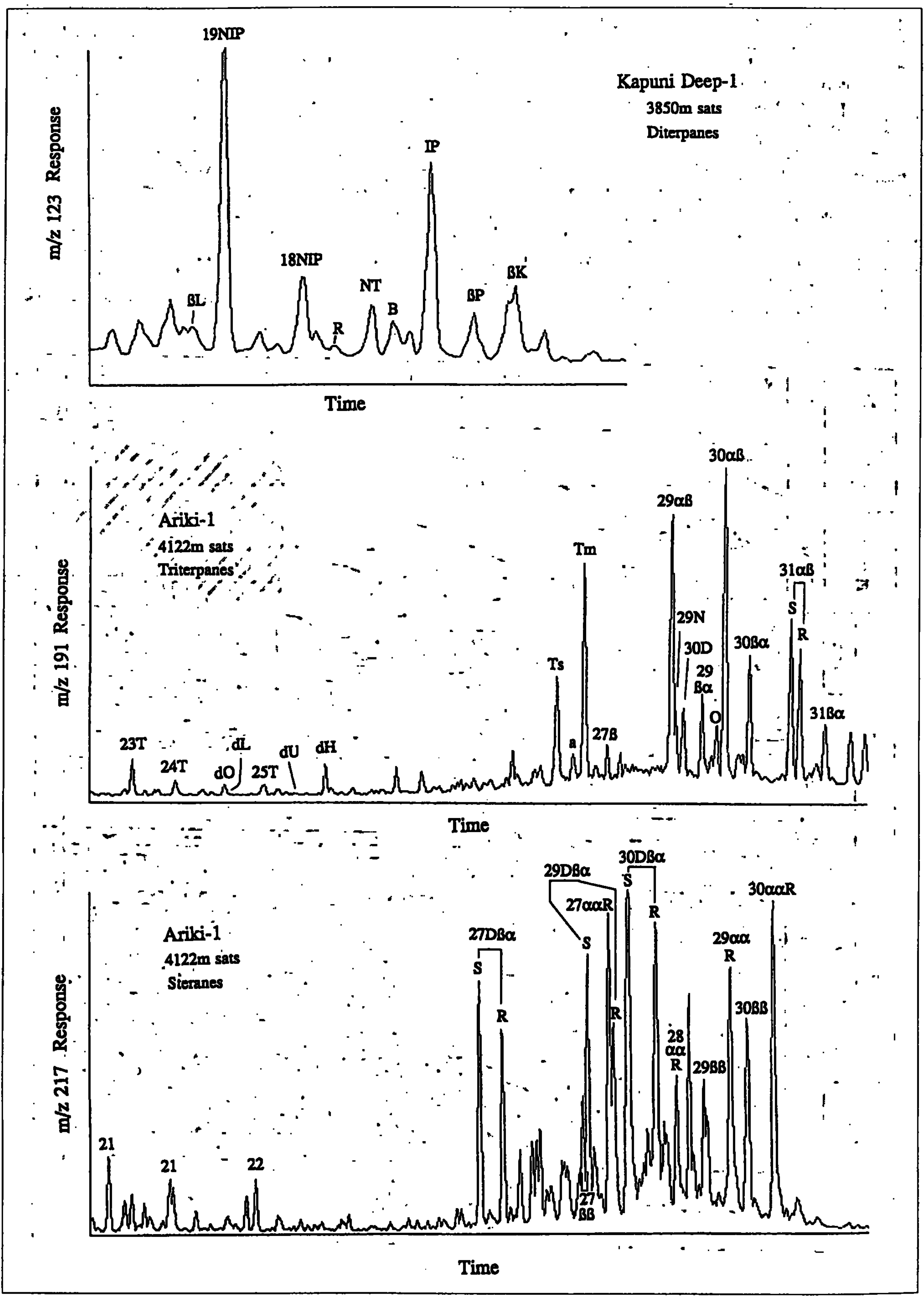

Fig. 3. Mass chromatograms showing diterpane (m/z 123), triterpane (m/z 191) and sterane (m/z 217) distributions in saturates fractions of bitumen extracted from sediments in Kapuni Deep-1 and Ariki-1 (See Materials and Methods section for component identification).

steranes is higher for terrestrially sourced sediments, a trend which appears to be generally applicable in the Taranaki Basin (Killops et al., 1994a). Calculation of both indices is described in the previous section and representative mass chromatograms are shown in figure 3. A plot of log AGI vs. log TMI for various sediment samples, labelled according to formation, is presented in figure 4. As expected, coals and shales of the Mangahewa and Kaimiro formations generally plot at high AGI, while those of the Rakopi Formation plot at low AGI. The lowest AGI values (<0.5) for Eocene sediments were recorded for samples from the Kaimiro and deepest Mangahewa Formation in Waihapa-1, and are consistent with the expected slightly lower angiosperm contribution in the Early Eocene compared with Mid to Late Eocene.

For Rakopi and Mangahewa/Kaimiro Formation sediments, TMI values are generally >2. Within the predominantly terrestrial sediments, however, varying marine contributions are suggested by the presence of marine organisms (e.g. dinoflagellates) and are reflected in biomarker distributions. For example, a bulk upper Rakopi sample from Fresne-1 exhibited a TMI of 2.4, while coal isolated from this sample yielded a TMI of 8.4. It appears that the shales interbedded with coals represent relatively brief marine incursions during an overall regressive phase, but in which the input of terrestrial organic detritus is still significant. Rakopi samples from Maui-4 have lower TMI values (<6) than those from Tane-1, suggesting a greater marine contribution in the Maui-4 region.

Only limited data are available for the Turi and Farewell formations. For all but a Farewell coal from Kapuni Deep-1, AGI values range from intermediate to high (ca. >0.1), as expected for Paleogene samples, while TMI values are low (ca. <2), consistent with significant marine contributions. The Farewell Formation sample exhibiting the lowest AGI value was taken from near the base of the main Farewell coal unit (within the D cycle, 4693 m) in Kapuni Deep-1. The sample exhibits similar AGI and TMI values to the earliest Rakopi Formation coals.

Oils and condensates from the Taranaki Basin are also plotted in Fig. 4. Most of the oils can be considered primarily terrestrial in origin, their waxy nature and relatively high hopane content suggesting that leaf cuticles and bacterial membranes are generally important kerogen components. A strong correlation between oils of the northern part of the Tarata Thrust Zone (figure 1) and Mangahewa coals is observed in biomarker distributions in general (Killops et al., 1994a) and is reflected in the plotted positions of McKee-3, Pouri-1A, Urenui-1, Toetoe-1, Pukemai-2A and Ahuroa-1 in figure 4. A predominantly Eocene source is suggested for these oils. There also appears to be a major Eocene contribution to Stratford-1, Okoki-1 and Kaimiro-1 oils from figure 4, but TMI values are significantly lower than for the previous group of oils. The Maui and Moki oils appear to correlate well with Rakopi coals, as does the oil from Waihapa-1. A predominantly Late Cretaceous source is proposed for the Maui oils, at least, but there may be an additional Paleocene contribution to Waihapa and Moki oils. Oils/condensates of the Kapuni/Kupe fields, Mangahewa-1 and Moturoa-2 wells plot at intermediate AGI, suggesting Paleocene or mixed Eocene/Late Cretaceous sources, however the Kapuni/Kupe field samples are characterised by high TMI values, suggesting a greater terrestrial component than in the other two samples. None of the sediment samples exhibited an exclusively marine signature, due to the input of varying quantities of terrestrial detritus to shelf environments.

The area of the circle surrounding each oil represents the hopane/sterane ratio (see previous section for calculation method), which provides a measure of the bacterial contribution to the corresponding source rock. High hopane/sterane ratios are usually associated with terrestrial plant material that has undergone pronounced biodegradation of lignified tissue, resulting in the concentration of lipid-rich structures, such as leaf cuticles and waxes and bacterial cell walls. It is not unexpected, then, that the highest hopane/sterane (H/S) ratios are recorded for the most waxy oils, from Kupe South-1, Stratford-1 and McKee-3, and that a slight positive correlation is found between H/S and TMI for all the oils (r = 0.46).

Relative terrestrial and marine contributions can be evaluated from a plot of $\delta^{13}C$ for aromatics vs. saturates fractions of oils, as shown in figure 5. It has been established that oils tend to plot on or near the terrestrial or marine lines in figure 5, depending on the origin of their source kerogens (Sofer, 1984). The low TMI value for Kora-1 oil is consistent with its position in figure 5, suggesting a chiefly marine source. Although this oil has the greatest marine component of all the oils analysed, it should be noted that it is not entirely marine-sourced, as it contains oleanoid biomarkers of angiosperm origin. A somewhat smaller marine contribution to Pukearuhe-1 oil is also suggested by a low TMI value and a plot point to the marine side of the terrestrial line in figure 5. The marine input in both oils is characterised by C_{30} steranes (Moldowan et al., 1990), and it is dominant in the oil from Kora-1 (Reed, 1992) and in an oil show in Late Paleocene strata in Tangaroa-1, but is present at lower relative abundance in Pukearuhe-1 oil. In addition, the levels of tricyclic terpanes relative to hopanes is higher in these oils than in the terrestrially sourced oils, suggesting that the tricyclics derive from bacteria dwelling in saline environments. A negative correlation factor is recorded for the tricyclic/hopane ratio (see previous section for a description) and TMI for both oils and sediments (r = -0.52 and -0.34, respectively). Similar to Pukearuhe-1 oil, the Maui/Moki oils exhibit $\delta^{13}C$ characteristics suggestive of a slight marine contribution to their source kerogen (figure 5), although not apparently exhibiting a C_{30} sterane signature.

Kora-1 and Tangaroa-1 oils exhibit good biomarker correlation with a Late Paleocene shale at 4120–30 m in Ariki-1 (cf. Fig. 3 with Reed, 1992), although the latter is less mature than the oil. This shale appears to be the equivalent of the Waipawa Black Shale, which outcrops in the onshore area of the East Coast Basin (Leckie et al., 1994), and is also present in South Island basins (e.g. Galleon-1 well in Canterbury Basin; Gibbons and Fry, 1986). Geographically, it is quite extensive and the marine biomarker signature is augmented by varying levels of angiosperm-derived biomarkers [e.g. wax *n*-alkanes and 18α(H)-oleanane]. A shelf depositional environment is suggested under a highly productive photic zone. The development of anoxicity in surface sediments is indicated by an intense γ-log signal for the shale in both Ariki-1 and Galleon-1. While the shale is only some 10 m thick in Ariki-1 and 7 m thick in Galleon-1, it has a high petroleum genetic potential (table 2).

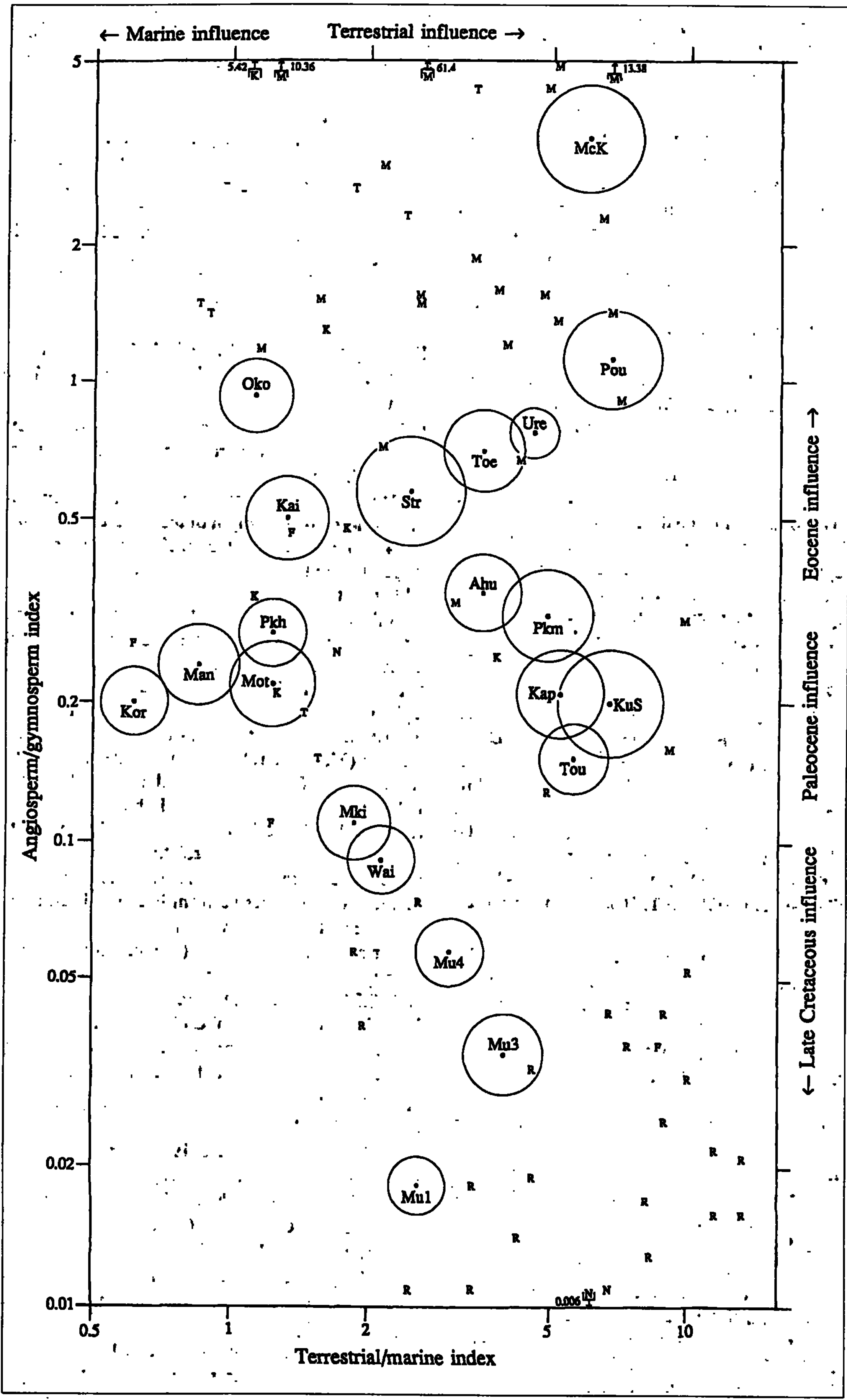

Fig. 4. Logarithmic plot of angiosperm/gymnosperm vs. terrestrial/marine indices for sediment extracts (labelled according to formation: F = Farewell, K = Kaimiro, M = Mangahewa, N = North Cape, R = Rakopi, T = Turi) and oils. Area of circles represents a measure of relative bacterial contribution to oil source rocks (hopane/sterane ratio). (See Materials and Methods section for calculation of indices.)

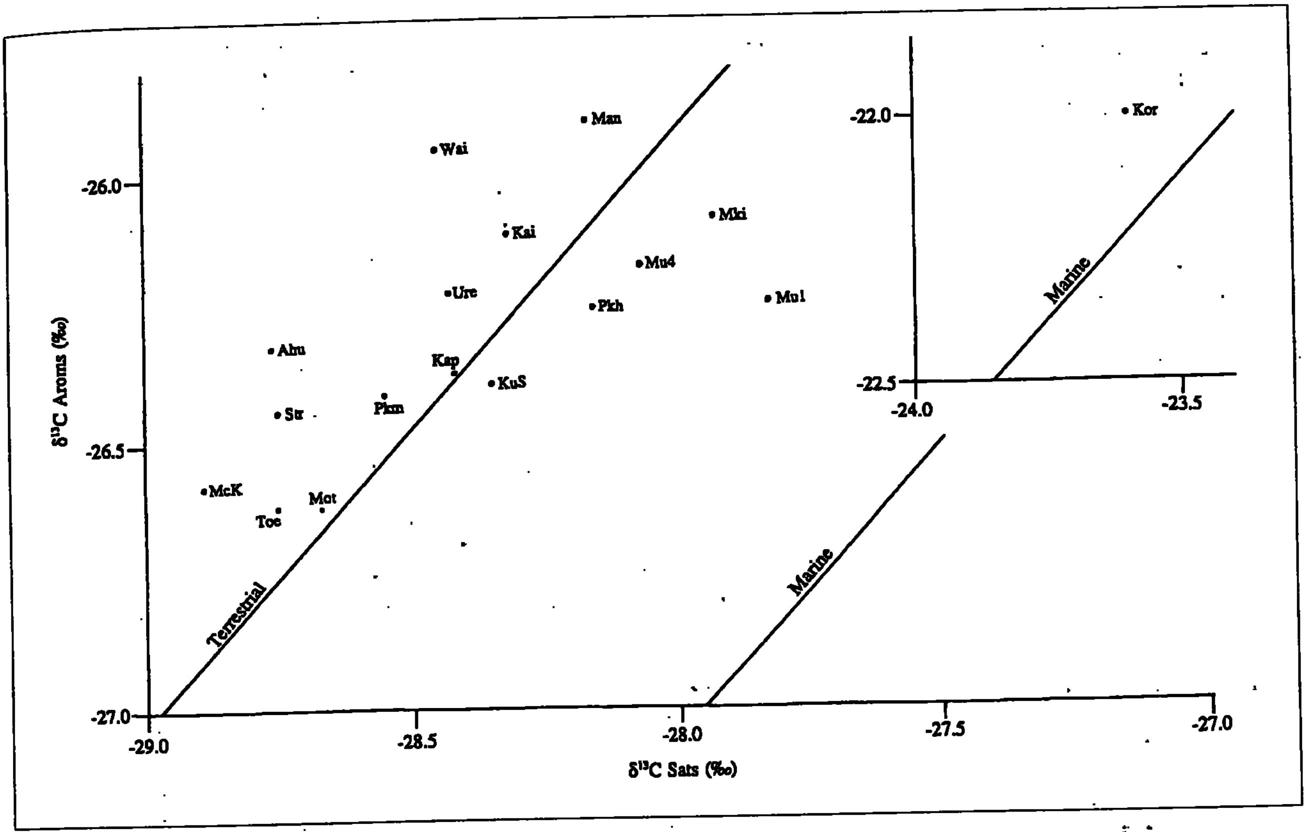

Fig. 5. Plot of $\delta^{13}C$ values for aromatics vs. saturates for Taranaki oils. (Data after Weston et al., 1988; Reed, 1992. See figure 1 legend for key to well abbreviations.)

All Taranaki oils exhibit some evidence of a marine contribution, when compared with TMI values for isolated coals, originating from shales interbedded with coals for the most highly terrestrially influenced oils. Low sulphur content (- 0.2%) and $\delta^{34}S$ values >+8‰ for all but the New Plymouth oils (Hirner and Robinson, 1989), together with V/(V+Ni) ratios of 0.04–0.29 (data after Frankenberger et al., 1992), suggest that the marine contribution is associated with limited sulphate supply in a restricted depositional environment (Lewan, 1984; Hirner and Robinson, 1989). It is possible to recognise minor marine inputs from sulphur isotopic composition because the sulphur content of terrestrial plants and sulphate availability in freshwater environments are low. $\delta^{34}S$ values for oils from the New Plymouth area generally lie in the range +3 to +5‰, which is intermediate between the ranges observed for open marine and restricted marine environments (Hirner and Robinson, 1989). A possible interpretation is a mixed signature from marine and terrestrial source rocks, the latter being deposited in a marginal sub-basin in which water exchange with the open sea is restricted (possibly on a seasonal basis involving development and breaching of barrier sand-bar complexes; Other interpretations are possible Killops et al., 1994a).

Oil Generation and Expulsion

Although oil can be generated by coals at a rank of ca. 0.7% R_0, it has been proposed that it is not expelled until significantly higher maturity levels of ca. 1.0% R_0 because of the chemisorption and molecular sieve properties of coals (Cook, 1987; Cook, 1988). Because exploration wells have not penetrated source rock horizons exhibiting biomarker maturity levels as high as those recorded for oils, it has not proven possible to establish exact generation and expulsion maturity thresholds. However, a guide to expulsion threshold can be obtained assuming, from the above discussion, that McKee Field and nearby oils are largely sourced by Eocene coals, while Maui oils are predominantly sourced by Late Cretaceous coals. Because the relative amount of 5α(H),14β(H),17β(H)-24-ethylcholestanes compared with 5α(H),14α(H),17α(H)-24-ethylcholestanes can vary at the end of diagenesis due to source-related effects (Peakman et al., 1989), it is not possible to obtain absolute maturity estimates of the expulsion threshold from this ratio in oils alone. However, such estimates are possible when potential source rock data are available, permitting discrimination between source and maturity related effects. In figure 6 the extent of isomerism at C-14 and C-17 in 5α(H)-24-ethylsteranes is plotted vs. depth for Mangahewa Formation sediments from McKee-1 and Urenui-1, and the maturity trend is extrapolated to the mean value exhibited by oils from the area. The corresponding vitrinite reflectance (%R_0) and Suggate rank [R(S)] values for the source rock at the time of oil expulsion are obtained by reference to the adjacent plots for McKee-1 coals (based on established trends, after Lowery, 1988; Sykes et al., 1992). The expulsion threshold is ca. 0.8±0.1% R_0, or ca. 13.2±0.5 R(S), at a depth of just over

Table 2. Mean Rock-Eval data for Waipawa Shale, East Coast Basin (after Leckie et al., 1994) and equivalent in the Canterbury Basin (after Gibbons and Fry, 1986).

	TOC (%)	S2 (‰)	HI (‰)
Angora Stream, East Coast Basin	3.2	7.5	236
Galleon-1 well, Canterbury Basin	6.1	19.9	323

4000 m in McKee-1 (allowing for uncertainties in vitrinite reflectance and Suggate rank trends), and is consistent with peak HI for New Zealand coals being reached around 13 R(S) and thereafter decreasing due to the expulsion of generated hydrocarbons (Bertrand, 1989; Sykes et al., 1992). This threshold represents an average rank for all the source rock strata that have contributed to the pooled oil and so is likely, if anything, to over-estimate the maturity at which expulsion commences. The potential for early generation of oil from hydrogen-rich coals, such as those of the Taranaki Basin, and the limited extent of absorption processes that might hinder expulsion have recently been recognised (e.g. Noble et al., 1991; Sandvik et al., 1992). Clearly, primary migration may occur at significantly shallower depths than has been generally thought possible in the Taranaki Basin.

A similar biomarker maturity approach can be adopted for Maui oils. While the actual source area for the oils is not known, because the oils seem to be derived primarily from Rakopi coals, an approximation of generation threshold can be made by considering biomarker maturity–depth trends in Rakopi Formation sediments in Maui-4 and Tane-1. The oil expulsion threshold in Tane-1 appears to be ca. 0.9±0.1% R_0 or 13.8±0.5 R(S), and for Maui-4 0.9±0.1% R_0 or 13.3±0.5 R(S). These values are self-consistent and do not appear to be affected by differing thermal regimes for the two regions and the loss of ca. 1300 m of sediment in the Maui-4 area during Late Miocene uplift and erosion. While the Maui oils appear slightly more mature than the northern Tarata Thrust Zone oils on the basis of implied vitrinite reflectance values for their source rocks during expulsion, Suggate rank values, which more accurately represent absolute maturity, are similar. Because of the chemical similarities of Paleogene and Late Cretaceous New Zealand coals, they would be expected to exhibit similar petroleum generation and expulsion characteristics.

The cross-sections in figure 7 show the main source rock units in various regions of the basin and horizons likely to have entered the oil window (i.e. generation and expulsion), based on preliminary kinetic models for oil generation that take into account heat flows (after Funnell et al., 1994)

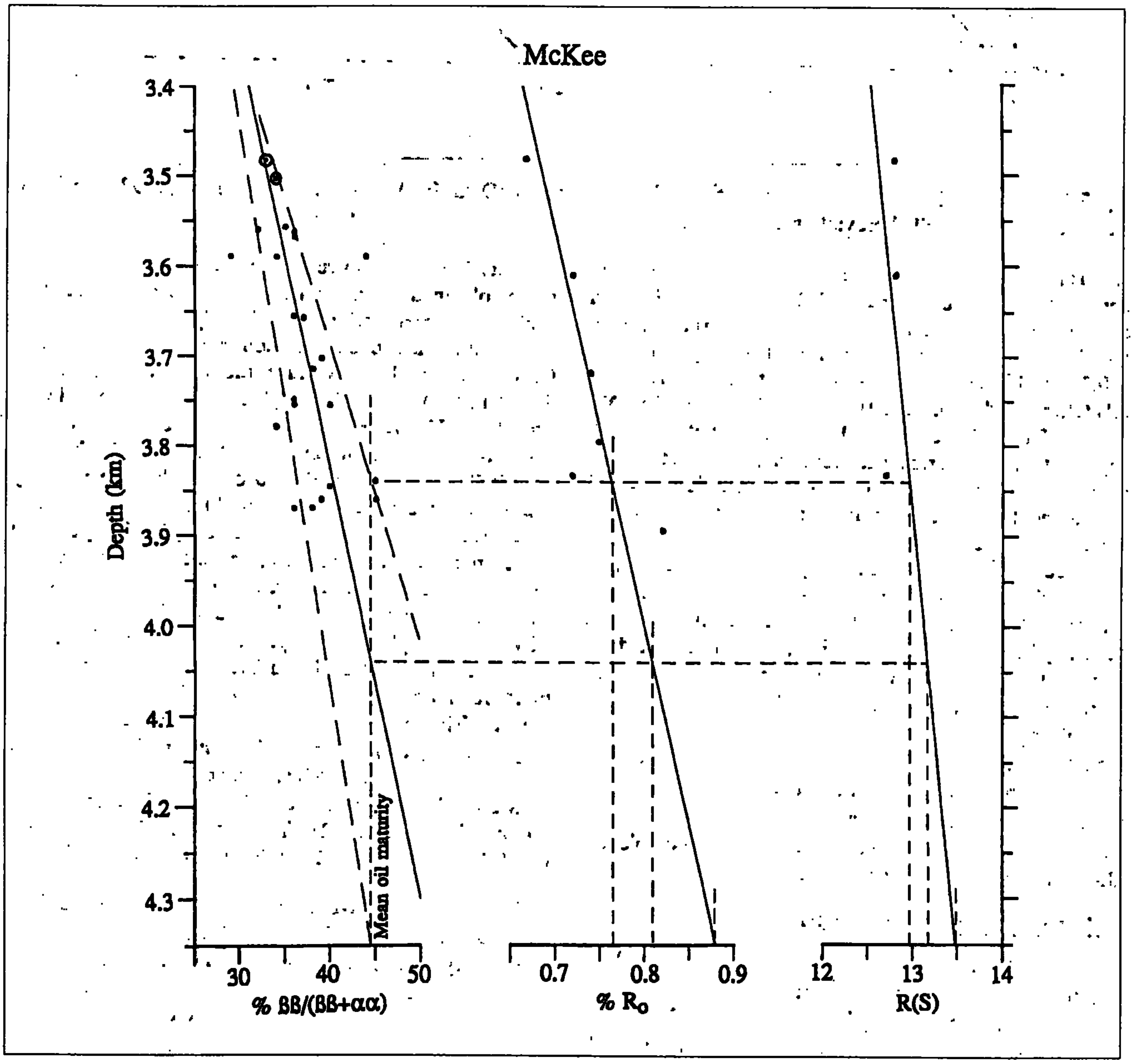

Fig. 6. Depth correlation of the extent of isomerism at C-14 and C-17 in 5α(H)-24-ethylsteranes for Mangahewa Formation sediment extracts from McKee-1 and Urenui-1 with vitrinite reflectance (R_0) and Suggate rank [R(S)] for coals in McKee-1. (Vitrinite reflectance and Suggate rank depth calibration after Sykes et al., 1992, data after Lowery, 1988.)

shown in figure 1 and biomarker indications of generation thresholds. Modelling of the maturation process suggests the oil expulsion window is reached when around 30% of genetic potential has been realised (allowing for saturation of source rock pore space). This occurs at a depth of at least 5 km in the low heat-flow area in the southeast of the basin (including Kapuni and Kupe fields), at ca. 4 km in the higher heat flow area of the northern Taranaki Peninsula (encompassing New Plymouth, Kaimiro and McKee fields), and at intermediate depths over much of offshore Taranaki Basin (depending on heat flow, figure 1). In the Southern Inversion Zone, where up to 3 km of uplift and erosion has occurred since the Late Miocene, source rocks which were in the oil window have had their maturation reactions "frozen" by the uplift. Research into the depth, timing and rate of oil and gas generation is continuing, the initial modelling results being presented during this conference (Armstrong et al., 1994).

In the examples shown in figure 7, the composition of oil accumulations generally reflects the uppermost large volume of source rock unit lying within the oil window in the vicinity. It appears that oils of distinctly Rakopi origin, with the exception of those from the Maui Field, and the Maui-4 and Moki-1 wells, have largely escaped from the system. The oils of the northern Tarata Thrust Zone, such as those from the McKee Field (figure 7a), appear to be sourced from mainly Mangahewa coals at the base of the overthrust, the oils having migrated up structure to reservoirs in the McKee Formation sandstones. Further west, towards New Plymouth (figure 7a), Moturoa-2 and Kaimiro-1 oils appear to exhibit an increased marine contribution, which would be anticipated from the increasingly marine character of Paleogene units (labelled as Turi Formation, Turi/Kaimiro Formation and Turi/Farewell Formation in figure 7a). Although not particularly organic-rich, these units are quite thick. It appears that mature, terrestrial, Paleocene (Farewell Formation) strata to the west of the Tarata Thrust Zone also make a contribution to the oils of the New Plymouth area, while the Eocene signature in Kaimiro-1 oil (figure 4) can be attributed to adjacent, mature, Eocene coals. In contrast, the lower heat-flow regime in the south of the Taranaki Peninsula indicates that Eocene coals have not reached sufficient maturity to contribute to the oils of the Kapuni/Kupe and Waihapa fields (figures 7a and 7b), and so a mixed Eocene/Late Cretaceous origin seems far less likely than a predominantly Paleocene (i.e. Farewell Formation) coal source.. All these postulated source rock contributions are consistent with the sulphur isotopic data discussed in the previous section.

Only thin and immature Rakopi sediments are encountered in the Maui wells and in Moki-1 (figure 7b). Preliminary thermal modelling indicates that, in areas where Late Cretaceous sediments are thickest, the Rakopi Formation first entered the oil window in the early–mid Tertiary, and the resulting oil may have escaped. The source area for the Maui oils is most likely to be found where the Rakopi Formation is currently near the beginning of the oil window (figure 7b). Two possible source regions that satisfy this criterion have previously been proposed, one lying to the northeast in the vicinity of New Plymouth (figure 7a; Haskell, 1991; Haskell, 1992), and the other lying to the east (Southern Taranaki Graben) across the Cape Egmont Fault (figure 7b; Thrasher, 1990). It is not possible to eliminate either on the basis of presently available data. If the former source is correct, it would require a secondary migration pathway that excludes significant vertical component in order to account for the lack of a Rakopi signature in oils of the New Plymouth and Kaimiro fields. The presence of anomolously high $^3He/^4He$ ratios in gases from both Maui and New Plymouth areas does not necessarily establish a link (Giggenbach et al., 1993). This mantle-gas signature could be due to crustal fractures in the Quaternary rift zone identified under the Central Graben and southern part of the North Taranaki Graben (King and Thrasher, 1992), and so may be a feature of the entire rift zone. If the source region of the Maui oils is in the Southern Taranaki Graben, a fault-controlled, multi-stage, secondary migration mechanism is required.

The probable source of the Kora-1 oil, the Waipawa Shale equivalent, probably enters the oil window at 5.0–5.5 km burial depth to the east of Kora-1 well (figure 7c), and migration up into the Kora volcanic structure appears straightforward. From NS and EW stratigraphic cross-sections for the region (King et al., 1991) the likely drainage area for the Kora oil is ca. 500 km^2. Assuming the shale is consistently 10 m thick, a gas:oil ratio of 0.3 for the shale from Galleon-1 (Gibbons and Fry, 1986), a porosity of 10% and wet density of 2.5 g/cm^3 (typical for the burial depth), and using the Rock-Eval data in table 2, the oil potential of this source rock unit is ca. 155 Mt or ca. 170 x 10^6 m^3 under surface conditions (ca. 200 x 10^6 m^3 under reservoir conditions of density ca. 0.74 g/cm^3 at 178 bar and 68°C). The volume of oil in the Kora-1 reservoir is estimated at 5 x 10^6 barrels (McManamon, 1993), or just under 10^6 m^3. This represents no more than ca. 1% of the genetic potential of the assumed drainage area, and so the shale is a reasonable source for the Kora oil on quantitative grounds. It appears probable that the Waipawa Shale equivalent extends into the Northland Basin and is a potential oil source rock (Isaac et al., 1994).

Large quantities of carbon dioxide are associated with gas/condensate accumulations within the upper part of the Mangahewa Formation in onshore wells where this formation has not yet entered the oil window. For example, ca. 40% of gas is CO_2 in the Kapuni Field (McBeath, 1977). Mass balance, compositional and isotope studies are consistent with the CO_2 originating from carboxyl group elimination from coals during the lignite to early high-volatile bituminous coal stages (Boudou et al., 1984; Giggenbach et al., 1993; Killops et al., 1994b). It appears that various removal processes and dilution with methane from more deeply buried coals probably lead to a quite rapid decline in CO_2 concentrations once its generation ceases, but that considerable amounts are still being evolved by the onset of significant oil generation (Killops et al., 1994b), as demonstrated by the generalised diagram of fluid generation vs. Suggate rank in figure 8. Under typical subsurface temperature and pressure regimes for accumulations in the Taranaki Basin, CO_2 is a supercritical fluid, possessing considerable solvating potential for hydrocarbons which aids the primary migration of oil (see also McKirdy and Chivas, 1992). The large volume of CO_2 evolved prior to oil generation would also be anticipated to aid primary migration, but indirectly, by effecting micro-fracturing of the source rock (Killops et al., 1994b). It may also be responsible for remobilising oils generated at greater depth that have become trapped beneath the upper Mangahewa coal unit. The fluid

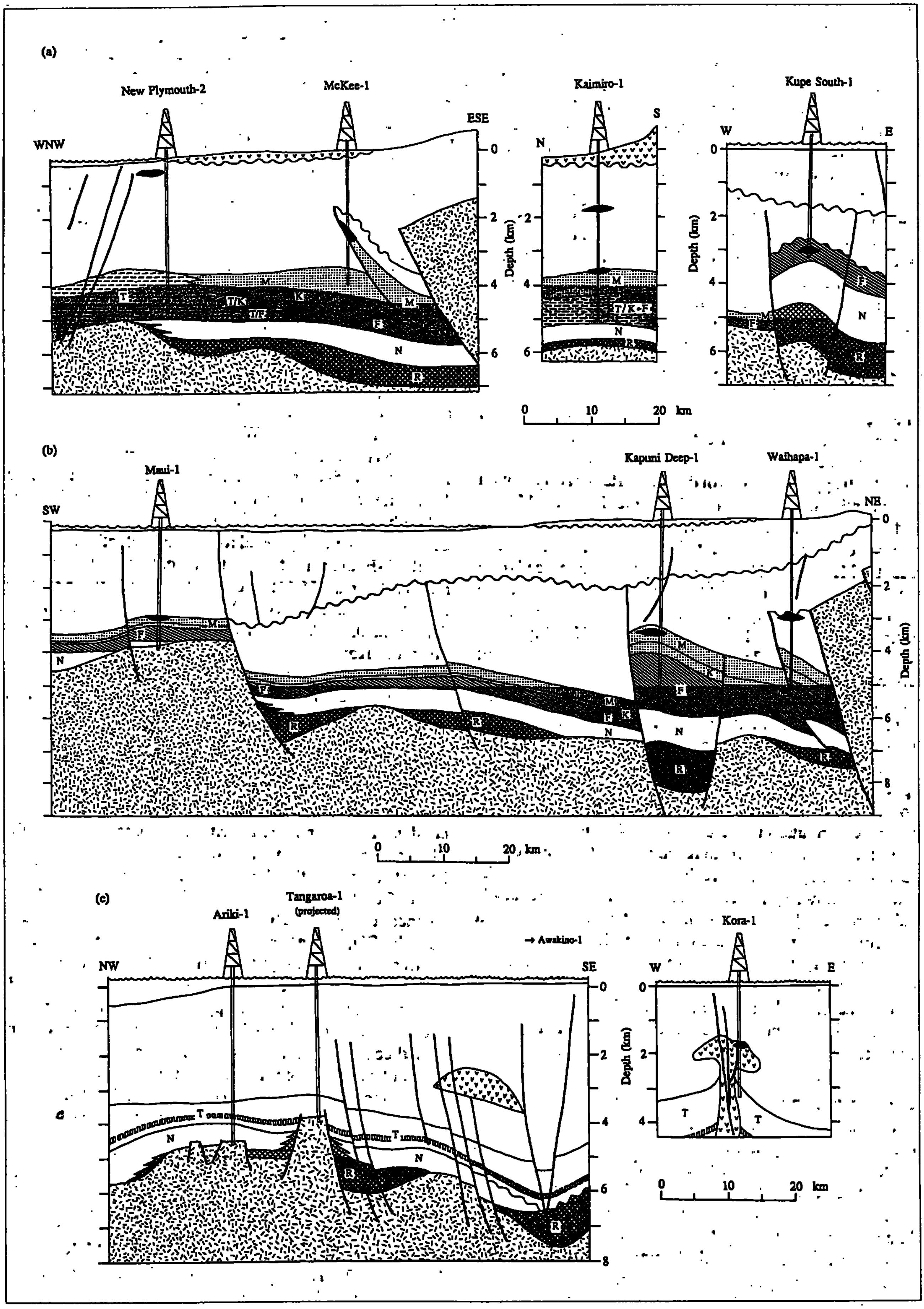

Fig. 7. Cross-sections for various regions of the Taranaki Basin (after King et al., 1991) showing the main petroleum source rock formations (F = Farewell, K = Kaimiro, M = Mangahewa, N = North Cape, R = Rakopi, T = Turi) and their spatial relationships to oil accumulations (black lenses). (Shading of formations does not depict lithology but represents types of organic matter present in source rocks, as discussed in the text. Grey tone is used to indicate where formations have probably entered the oil window.)

is less dense than oils and may displace the latter past reservoir spill points, causing what may be termed tertiary migration into shallower traps. This process may account for the dominance of gas (under surface conditions) in the major Kapuni and Maui reservoirs, as well as the accumulation of oils/condensates of the Kaimiro and adjacent fields in the Late Miocene, Mount Messenger Formation sandstones (figures 2 and 7).

Conclusions

In addition to distinguishing between terrestrial and marine source rocks by the carbon number distributions of steranes, it is also possible to follow the trend in increasing importance of angiosperms in coastal floodplain plant communities from Late Cretaceous through to Eocene by monitoring the relative proportions of angiosperm-derived triterpanes and gymnosperm-derived diterpanes. The use of a plot of angiosperm/gymnosperm index vs. terrestrial/marine index permits the source of Taranaki Basin oils to be determined with reasonable accuracy when combined with maturity considerations based on heat-flow data and derived kinetic models of petroleum generation.

It appears that oil sourced by Rakopi Formation coaly sediments mostly escaped prior to Neogene trap formation, and is only represented by the Maui/Moki accumulations and possibly by a minor contribution to the Waihapa Field. There is the possibility, however, that some Rakopi oil could be trapped in deeper reservoirs where secondary porosity has developed. Kapuni/Kupe Field oils seem to be predominantly sourced by Paleocene (Farewell Formation) sediments, as do oils from the southern part of the Tarata Thrust Zone (e.g. Waihapa Field). In the north of the Taranaki Peninsula there is a high heat-flow area centred on New Plymouth, and mature source rock units lie nearer the surface. Oils of the northern part of the Tarata Thrust Zone originate mainly from Eocene coals of the Mangahewa Formation and, to a lesser extent, the Kaimiro Formation. Towards New Plymouth, coal-rich strata within the Kaimiro and Farewell formations grade into relatively organic-lean, marine shales of the Turi Formation, which appear to make significant contributions to the oils of the area (e.g. Kaimiro and Moturoa fields). Mangahewa coals are still present but are early mature and so their contributions are relatively limited. There is also, probably, a significant contribution from mature Farewell coals lying immediately to the east of the New Plymouth/Kaimiro region. To the northwest of the basin an equivalent of the Late Paleocene Waipawa Shale is present and has been sufficiently deeply buried to source some oil, such as that in the Kora volcanic structure.

Hydrogen-rich, Late Cretaceous and Tertiary New Zealand coals appear to be capable of generating and expelling oil by Suggate rank 13 throughout the Taranaki Basin. This threshold is based on extrapolation of measured biomarker maturity for Mangahewa coals, and may be a slight over-estimation of the required maturity for the onset of expulsion. The corresponding vitrinite reflectance is ca. 0.8% R_0 in the region of the McKee Field, but it may vary in other parts of the basin. On the basis of preliminary kinetic modelling (subject to modification upon completion of more rigorous studies), the expulsion threshold corresponds to a depth range of 4–5.5 km, depending on thermal regime. Primary migration appears to be aided by the generation of large volumes of supercritical carbon dioxide from coals, creating expulsion pathways via microfracturing and transporting the first phase of generated oil in solution.

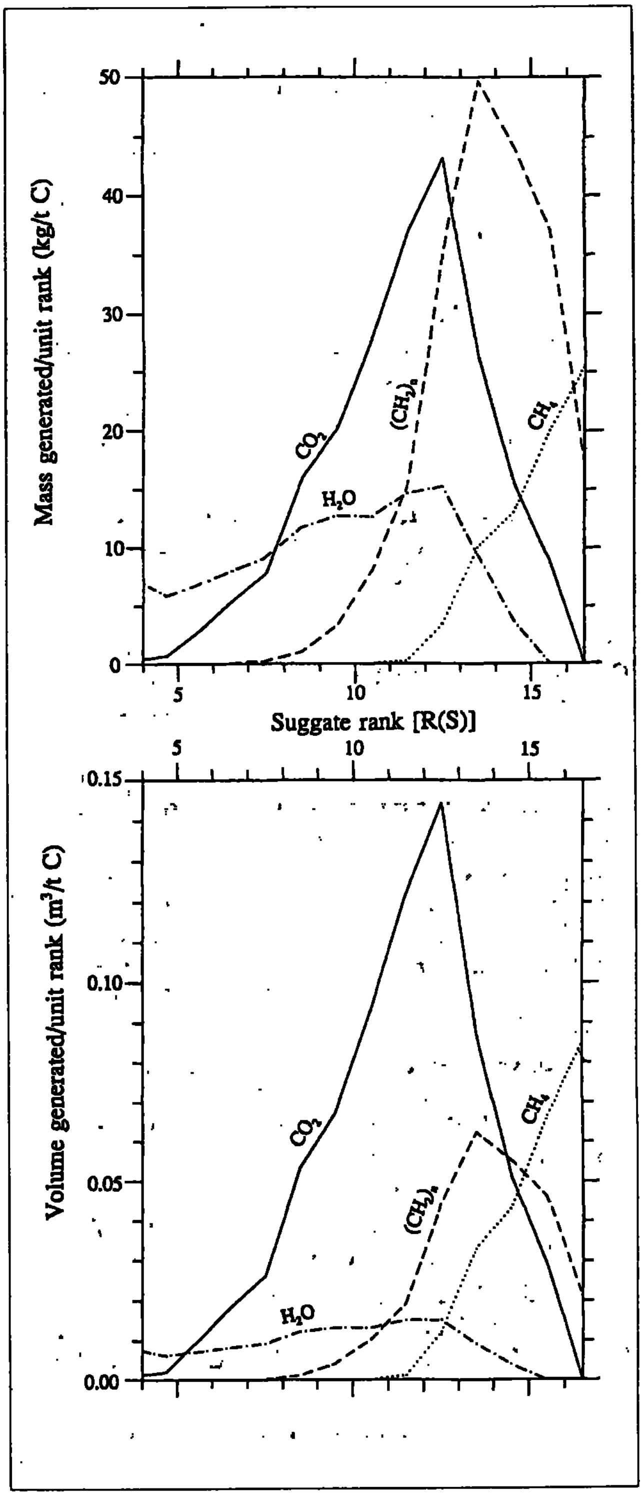

Fig. 8. Generalised representation of mass and volume of fluids generated from New Zealand coals with increasing Suggate rank per tonne of carbon in lignite of initial R(S) ca. 4. (Volumes are based on typical reservoir densities of 0.3 g/cm³ for CO_2 and CH_4, 0.8 g/cm³ for oil [represented by $(CH_2)_n$] and 1.0 g/cm³ for H_2O.)

References

ANALABS, 1984: Petroleum geochemistry of the Taranaki Basin. IGNS Pet. Rep. 1013, Inst. Geol. & Nucl. Sci., Lower Hutt.

ARCO, 1988: Final Well Report, Kora-1 and Kora-1A. Pet. Report 1374, Inst. Geol. & Nucl. Sci., Lower Hutt.

ARMSTRONG P.A., CHAPMAN D.S., FUNNELL R.H., ALLIS R.G. & KAMP, P.J.J., 1994: Thermal state, thermal modelling and hydrocarbon generation in the Taranaki Basin, N.Z. Proc. N.Z. Pet. Conf. 1994, this volume: 289–307.

BENNETT C, GREGG R. & KING P., 1992: Petroleum geology of the Taranaki Basin, with emphasis on the north-eastern quadrant. Pet. Explor. NZ News, May, 1992. 14–25.

BERTRAND P.R., 1989: Microfacies and petroleum properties of coals as revealed by a study of North Sea Jurassic coals. Int. J. Coal Geol. 13, 575–595.

BOUDOU J.-P., DURAND B. & OUDIN J.-L., 1984: Diagenetic trends of a Tertiary low-rank coal series. Geochim. Cosmochim. Acta 48, 2005–2010.

COLLIER R.J. & JOHNSTON J.H., 1991: The identification of possible source rocks, using biomarker geochemistry, in the Taranaki basin, New Zealand. J. SE Asian Earth Sci. 5, 231–239.

COOK R.A., 1987: The Geology and Geochemistry of Crude Oils and Source Rocks of Western New Zealand. NZ Geol. Survey Pet. Rep. 1250. Inst. Geol. & Nuc. Sci., Lower Hutt.

COOK R.A., 1988: Interpretation of the geochemistry of oils of Taranaki and west coast region, western New Zealand. Energy Explor. Exploit. 6, 201–212.

CZOCHANSKA Z., GILBERT T.D., PHILP R.P., SHEPPARD C.M., WESTON R.J., WOOD T.A. & WOOLHOUSE A.D., 1988: Geochemical application of sterane and triterpane biomarkers to a description of oils from the Taranaki Basin in New Zealand. Org. Geochem. 12, 123–135.

FRANKENBERGER A., BROOKS R.R. & COLLEN J.D., 1992: Trace elements in some New Zealand oils and condensates. In Proc. NZ Oil Explor. Conf. 1991, pp. 351–355. Ministry of Commerce, Wellington.

FUNNELL R.H., ALLIS R.G., CHAPMAN D.S. & ARMSTRONG P.A., 1994: Thermal regime of the Taranaki Basin, New Zealand. Inst. Geol. & Nucl. Sci. Rep., in prep.

GIBBONS M.J. AND FRY S., 1986: A geochemical study of the Galleon-1 Well, Canterbury Basin, offshore New Zealand. IGNS Pet. Rep. 1146, Inst. Geol. & Nucl. Sci., Lower Hutt.

GIGGENBACH W.F., SANO Y. & WAKITA H., 1993: Isotopic composition of He, and CO_2 and CH_4 contents in gases produced along the New Zealand part of a convergent plate boundary. Geochim. Cosmochim. Acta 57, 3427–3455.

HASKELL T., 1991: An analysis of Taranaki Basin hydrocarbon migration paths; some questions answered. Pet. Explor. NZ News, Jan., 1991. 19–25.

HASKELL T., 1992: An analysis of Taranaki Basin hydrocarbon migration systems. Proc. NZ Oil Explor. Conf. 1991. p. 146 Ministry of Commerce, Wellington.

HIRNER A.V. & ROBINSON B.W., 1989: Stable isotope geochemistry of crude oils and of possible source rocks from New Zealand — 2: sulphur. Appl. Geochem. 4, 121–130.

ISAAC M.J., HERZER R.H., BROOK F. & HAYWARD B.W., 1994: Cretaceous and Cenozoic Sedimentary Basins of Northland, New Zealand. IGNS Basin Studies Monograph, Inst. Geol. & Nucl. Sci., Lower Hutt, in prep.

JOHNSTON J.H., 1992: The characterisation of potential hydrocarbon-generative source rocks in the North Taranaki Basin by geochemical biomarkers. In Proc. NZ Oil Explor. Conf. 1991, pp. 357–363. Ministry of Commerce, Wellington.

JOHNSTON J.H., COLLIER R.J. & COLLEN J.D., 1990: What is the source of Taranaki oils? Geochemical biomarkers suggest it is the very deep coals and shales. In Proc. NZ Oil Explor. Conf. 1989, pp. 288–295. Ministry of Commerce, Wellington.

JOHNSTON J.H., COLLIER R.J. & MAIDMENT A.I., 1991: Coal as source rocks for hydrocarbon generation in the Taranaki Basin, New Zealand: a geochemical biomarker study. J. SE Asian Earth Sci. 5, 283–289.

KILLOPS S.D., WOOLHOUSE A.D., WESTON R.J. & COOK R.A., 1994a: A geochemical appraisal of oil generation in the Taranaki Basin, New Zealand. Am. Assoc. Pet. Geol. Bull. In press.

KILLOPS S.D., ALLIS R.G. & FUNNELL R.H., 1994b: Evidence for CO_2 generation from coals in on-shore Taranaki Basin, New Zealand, and implications for petroleum expulsion. In prep.

KING P.R. & THRASHER G.P., 1992: Post-Eocene development of the Taranaki Basin, New Zealand; convergent overprint of a passive margin. In Geology and Geophysics of Continental Margins (eds. J.S. Watkins, F. Zhiqiang and K.J. Miller). Am. Assoc. Pet. Geol. Mem. 53, Tulsa. 93–118.

KING P.R., NAISH T.R. & THRASHER G.P., 1991: Structural cross sections and selected palinspastic reconstructions of the Taranaki Basin, New Zealand. NZ Geol. Survey Rep. G-150. Inst. Geol. & Nuc. Sci., Lower Hutt.

KIRKLAND D.W., TSUI T.-F. & STOCKTON M.L., 1987: Generation of oil from coals and carbonaceous shales. Am. Assoc. Pet. Geol. Bull. 71, 577.

LECKIE D.A., MORGANS H.E.G., FRANCIS D., KILLOPS S.D., CUTTEN H., URUSKI C.I., WILSON G.J. & DELTEIL J., 1994: Stratigraphic framework and hydrocarbon potential of east coast, North Island, New Zealand. In prep.

LEWAN M.D., 1984: Factors controlling the proportionality of vanadium to nickel in crude oils. Geochim. Cosmochim. Acta 48, 2231–2238.

LOWERY J.H., 1988: Catalogue of Vitrinite Reflectance Measurements and Coal Analyses from Oil Prospecting Wells in Taranaki Basin, New Zealand. Rep. M168. Inst. Geol. & Nucl. Sci., Lower Hutt.

MCBEATH D.M., 1977: Gas-condensate fields of the Taranaki Basin New Zealand. NZ J. Geol. Geophys. 20, 99–127.

MCKIRDY D.M. & CHIVAS A.R., 1992: Nonbiodegraded aromatic condensate associated with volcanic supercritical carbon dioxide, Otway Basin: implications for primary migration from terrestrial organic matter. Org. Geochem. 18, 611–627.

MCMANAMON D., 1993: Kora exploration and drilling results. Pet. Explor. NZ News, July, 1993. 18–27.

MILDENHALL D.C., 1980: New Zealand Late Cretaceous and Cenozoic plant biogeography: a contribution. Palaeogeogr. Palaeoclim. Palaeoecol. 31, 197–233.

MOLDOWAN J.M., FAGO F.J., LEE C.Y., JACOBSON S.R., WATT D.S., SLOUGUI N.-E., JEGANATHAN A. & YOUNG D.C., 1990: Sedimentary 24-n-propylcholestanes, molecular fossils diagnostic of marine algae. Science 247, 309–312.

NOBLE R.A., WU C.H. & ATKINSON C.D., 1991: Petroleum generation and migration from Talang Akar coals and shales offshore N.W. Java, Indonesia. Org. Geochem. 17, 363–374.

PEAKMAN T.M., TEN HAVEN H.L., RECHKA J.R., DE LEEUW J.W. & MAXWELL J.R., 1989: Occurrence of (20R)- and (20S)-Đ$^{8(14)}$ and Đ^{14} 5α(H)-sterenes and the origin of 5α(H),14β(H),17β(H)-steranes in an immature sediment. Geochim. Cosmochim. Acta 53, 2001–2009.

POWELL T.G., 1988: Developments in concepts of hydrocarbon generation from terrestrial organic matter. In Petroleum Resources of China and Related Subjects (eds. H.C. Wagner, L.C. Wagner, F.F.H. Wang and F.L. Wong) pp. 807-824. Earth Sci. Ser. vol. 10, Circum-Pacific Council for Energy & Mineral Resources, Houston.

POWELL T.G., BOREHAM C.J., SMYTH M., RUSSELL N. & COOK A.C., 1991: Petroleum source rock assessment in non-marine sequences: pyrolysis and petrographic analysis of Australian coals and carbonaceous shales. Org. Geochem. 17, 375–394.

REED J.D., 1992: Exploration geochemistry of the Taranaki Basin with emphasis on Kora. In Proc. NZ Oil Explor. Conf. 1991, pp. 364–372. Ministry of Commerce, Wellington.

SANDVIK E.I., YOUNG W.A. & CURRY D.J., 1992: Expulsion from hydrocarbon sources: the role of organic absorption. Org. Geochem. 19, 77–87.

SOFER Z., 1984: Stable carbon isotope compositions of crude oils: application to source depositional environments and petroleum alterations. Am. Assoc. Pet. Geol. Bull. 68, 31–49.

SUGGATE R.P., 1959: New Zealand Coals: their geological setting and its influence on their properties. Bulletin 134. Inst. Geol. & Nuc. Sci., Lower Hutt.

SUGGATE R.P. & BOUDOU J.P., 1993: Coal rank and type variation in Rock-Eval assessment of New Zealand coals. J. Pet. Geol. 16, 73–88.

SYKES R., SUGGATE R.P. & KING P.R., 1992: Timing and depth of maturation in Southern Taranaki Basin from reflectance and rank(S). In Proc. NZ Oil Explor. Conf. 1991. 373–389. Ministry of Commerce, Wellington.

THRASHER G.P., 1990: The Maui Field and the exploration potential of Southern Taranaki; a few unanswered questions. Pet. Explor. NZ News, July, 1990. 26–30.

WESTON R.J., ENGEL M.H., PHILP R.P. & WOOLHOUSE A.D., 1988: The stable carbon isotopic composition of oil from the Taranaki Basin of New Zealand. Org. Geochem. 12, 487–493.

WESTON R.J., PHILP R.P., SHEPPARD C.M. & WOOLHOUSE A.D., 1989: Sesquiterpanes, diterpanes and other higher terpanes in oils from the Taranaki Basin of New Zealand. Org. Geochem. 14, 405–421.

WOOLHOUSE A.D., OUNG J.-N., PHILP R.P. & WESTON R.J., 1992: Triterpanes and ring-A degraded triterpanes as biomarkers characteristic of Tertiary oils derived from predominantly higher plant sources. Org. Geochem. 18, 23–31.

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