SOURCE ROCK POTENTIAL OF THE SOUTH WANGANUI BASIN

L S Murphy[1], W L Leask[2], J D Collen[3]
[1]Ministry of Commerce, P O Box 1473,Wellington
[2]Ian R. Brown Associates Ltd., P O Box 9043, Wellington
[3]Research School of Earth Sciences, Victoria University of Wellington, P O Box 600, Wellington

Abstract

Hydrocarbon source rock characteristics of upper Miocene and Pliocene sediments of the South Wanganui Basin have been measured, with samples analysed for Total Organic Carbon and biomarker content by gas chromatography and gas chromatography/mass spectrometry. Results have been integrated with values previously reported for the basin. TOC values are generally low, in the range of 0.17% to 4.23% TOC, with the highest values in the basal Matemateaonga Formation. Biomarkers and vitrinite reflectances indicate that the sediments tested are immature for hydrocarbon generation. However a few samples of Mangaweka Mudstone and Utiku Sandstone contain traces of migrated mature oil that may have formed from a unit deposited in a marine environment with terrestrial input. These samples suggest at least small amounts of hydrocarbon generation in the basin. Favoured source sediments are coal- and shale-bearing facies in the basal Matemateaonga Formation, or as yet undiscovered organic-rich facies within Tangahoe Mudstone.

Introduction

This paper presents results of a study of the hydrocarbon source rock characteristics of upper Miocene and Pliocene sediments of the South Wanganui Basin. The South Wanganui Basin is a Pliocene to Recent back-arc basin with its origin controlled by interaction between the subducted Pacific Plate and the overriding Australian Plate (Stern et al., 1992; Thompson et al., 1994). The basin covers an area of 22 500 km² both onshore and offshore, and has been little explored to date.

It has been argued in the past that the South Wanganui Basin had low prospectivity mainly because of the lack of a credible hydrocarbon source (Cope, 1966; Lock, 1979). This view has, however, more recently been challenged by Katz and Leask (1990a, b) and Thompson et al. (1994).

The sediments exposed or encountered during drilling are young and immature for hydrocarbon generation, and most have low organic carbon contents. Attempts have been made to demonstrate possible migration routes for hydrocarbons from Taranaki Basin to the west, but these have not met with widespread acceptance.

The present study examines the organic content of a suite of the South Wanganui Basin samples collected both from outcrop and well material, by total organic carbon (TOC) analysis, gas chromatography (GC) and gas chromatography/mass spectroscopy (GC/MS). Results have been compared with those from past studies.

Studies of the geochemistry and maturity of potential source sediments that have included the South Wanganui Basin samples have been conducted by Robertson Research (1980), Analabs (1984) and Katz and Leask (1990a, 1990b) on both outcrop and well material. The most recent phase of exploration in progress by American New Zealand Exploration Ltd (ANZEX) and Allegheny-Western Exploration New Zealand Ltd. has also obtained geochemical data.

Geological Setting

The stratigraphic succession in the South Wanganui Basin consists of late Miocene to Recent sediments up to 4000 m thick (figures 1 and 2) overlying Mesozoic metasedimentary rocks. The Miocene to Pliocene part of the succession is briefly described below, and also in Thompson et al.,(1994).

Seismic surveys show that the thick Cretaceous to Miocene section in the Taranaki Basin to the west does not continue into the South Wanganui Basin (Anderton, 1981), and only a few isolated outliers of Oligocene strata, at Paraparaumu (MacPherson, 1948) and Picton (Nicol and Campbell, 1990), are preserved on the basin margins. The southern extent of the Oligo–Miocene succession in the North Wanganui Basin to the north is unknown; Cope (1966) proposed a hypothetical "Pipiriki High" to separate the two basins. Gravity modelling by Hunt (1980) showed no evidence for such a feature; on the contrary, the North Wanganui Basin was inferred to extend almost to the south Taranaki coast in a progressively narrower graben bounded by the Strathmore and Ohura faults, and it is conceivable that additional elongate grabens extend southwards into more eastern parts of the South Wanganui Basin.

This study focuses on late Miocene and Pliocene sediments of the South Wanganui Basin, which could be buried sufficiently deeply to generate hydrocarbons. Outcrops, with visual evidence of organic content, from the Matemateaonga, Tangahoe and Mangaweka formations were selectively sampled. Samples were also selected from these formations in the Manutahi-1 and Young-1 exploration wells.

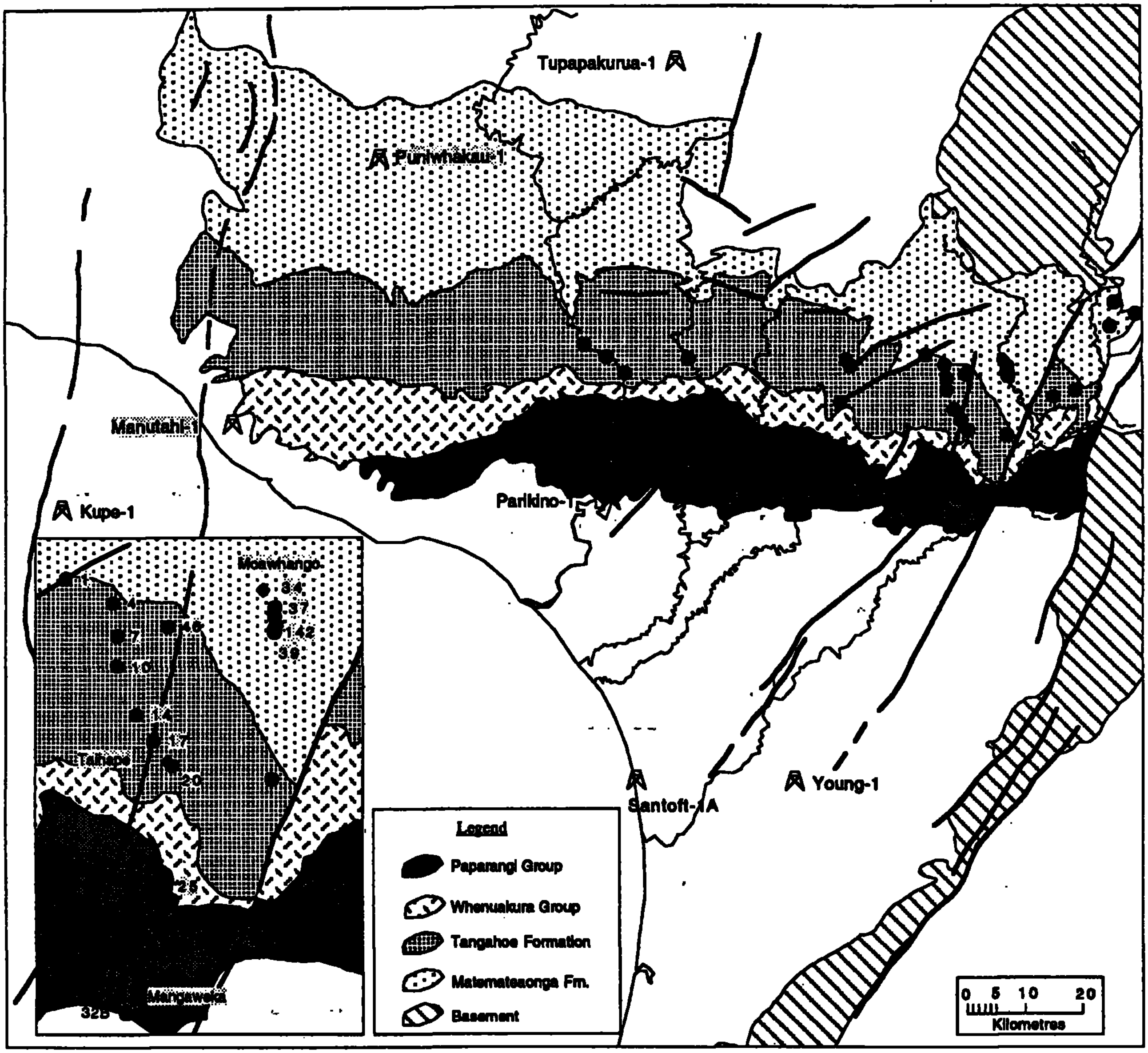


Fig. 1. Location map of the South Wanganui Basin, showing the outcrop of Pliocene strata, petroleum wells, and geochemical sample locations of Katz and Leask (1990a) and this study.

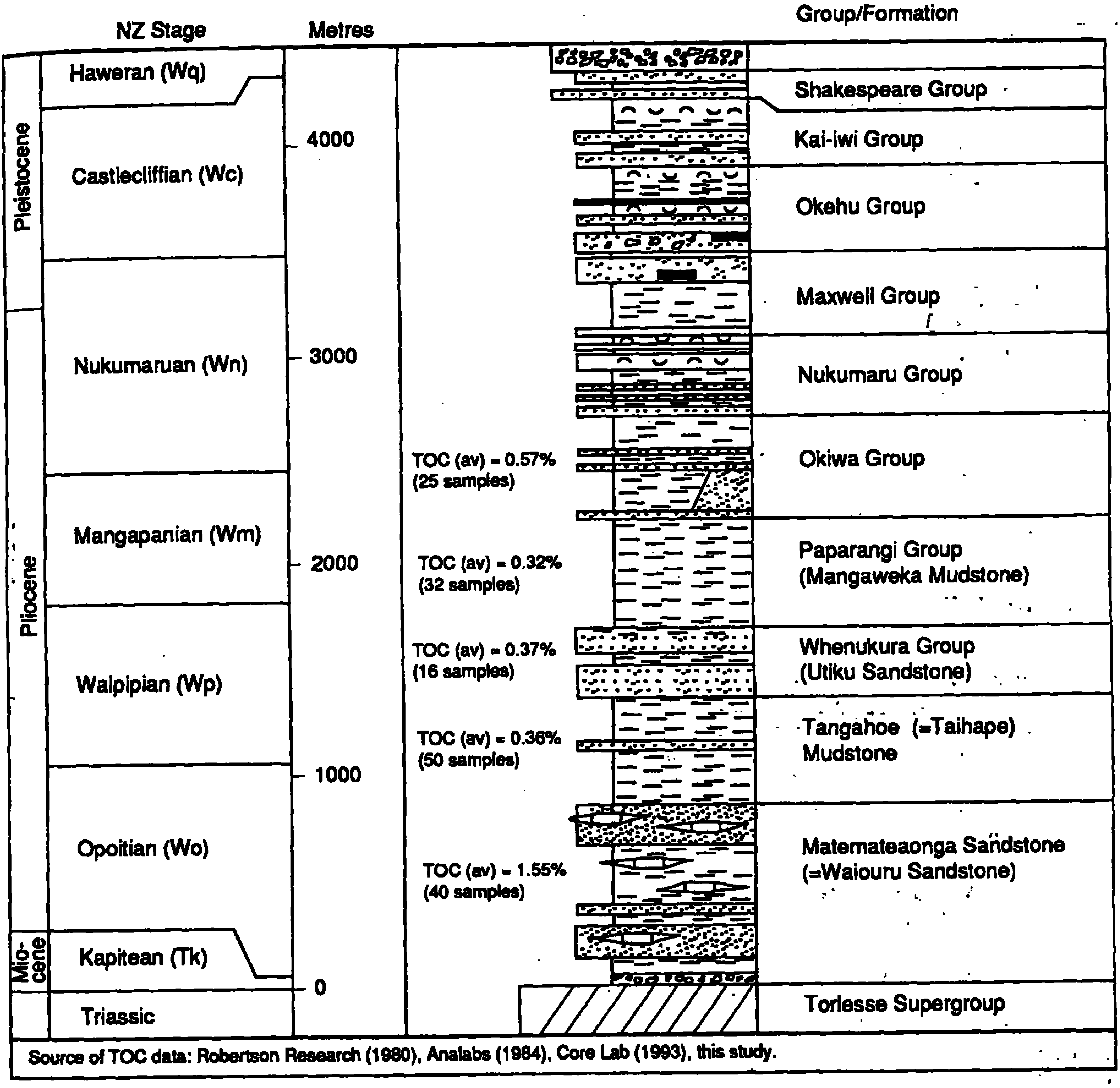
Matemateaonga Formation
The oldest widespread Tertiary sediments known in the South Wanganui Basin belong to Matemateaonga Formation, which is mainly Opoitian (lower Pliocene) in age, but locally Kapitean (uppermost Miocene) at its base in the east (Ker, 1991) and extends downwards to the Tongaporutuan Stage (upper Miocene) (Hay, 1967; Robinson et al., 1987) to the west in Wanganui River and Taranaki Basin. The formation consists of fine to coarse sandstones with interbedded siltstones and lenticular pebbly coquina limestones. Coarse sandstone and pebble conglomerate with thin sub-bituminous coal seams crop out on the basin margin. The name Waiouru Formation is in use for this same formation on the eastern side of the basin (e.g. Ker, 1991), but for consistency we use the name Matemateaonga in this paper.

Robinson et al. (1986) inferred an inner to middle shelf environment for most of the formation, with a strong tidal current indicated by large scale channels and winnowed concentrations of shells and pebbles.

Basal Matemateaonga Formation Park (1890), Feldmeyer et al (1943) and Browne (1978) identified thin carbonaceous or coaly intervals in the basal Matemateaonga Formation. The most extensive of these are in the upper Moawhango River area in the southern Kaimanawa Range, where five coal seams up to 0.5 m in thickness are interbedded with *Austrofusus*-rich shell beds within a 110 metre thick coarse conglomerate unit (R. Black, pers comm).

Studies in the Mangaohane catchment south of the Taihape-Napier road indicate that carbonaceous beds there are thin and of limited extent. A half-metre thick carbonaceous siltstone bed occurs within a dominantly fine sandstone interval at grid reference U21/772837. At U21/731817, in lower Mangaohane Stream, an 8 cm bed of brown carbonaceous claystone overlies 10–15 m of basal conglomerate; Park (1890) recorded a 2.4 m thick slumped bed of carbonaceous shale from this locality.

On the western basin margin, a widespread "coastal facies" (Matthews, 1985, Matthews & Bennett, 1987) occurs within lower Matemateaonga Formation. This is dominated by pebble conglomerates and fine- to medium-grained sandstones, with minor mudstones and thin coal seams (figure 3). Correlation from Puniwhakau-1 southwards



Source of TOC data: Robertson Research (1980), Analabs (1984), Core Lab (1993), this study.

Fig. 2. Stratigraphic column of Pliocene–late Miocene strata in the South Wanganui Basin with summary of TOC values collected from all studies.

through Manutahi-1, Toru-1 and the Kupe South wells to Tahi-1 (figure 4) shows that this facies persists over almost 80 km, with coal horizons becoming more prominent to the south.

Age ranges for the "coastal facies" vary markedly between wells, with Tongaporutuan to Kapitean ages determined for the Manutahi-1 and Kupe South-1 wells (Robinson et al, 1987: Matthews and Bennett, 1987), but Opoitian ages determined for Toru-1, Kupe-1 and Kupe South-2, -3 and -5 (e.g. Scott, 1988). Given the sparse faunas in paralic sediments and the possibility of downhole contamination, the older age rangeis favoured here. This facies probably continues eastwards across the Patea High and into the basal succession in what is now the deepest part of the South Wanganui Basin. Coal horizons in the Retaruke catchment may be distant time- and facies-equivalents.

Upper Matemateaonga Formation Finer units becoming progressively more common in Matemateaonga Formation towards the east, so that in Moawhango River section about 70% of the formation is siltstone (Feldmeyer et al, 1943). Siltstone- or mudstone-dominated intervals persist in the upper part of the formation in Mangawhero and Wanganui Rivers and in Parikino-1 to the west. Within these intervals, thin beds of dark brownish-grey mudstone are among the most organic-rich mudstones yet encountered in the basin. Samples were collected in Moawhango Valley east of Taihape, from about 40 m below the No. 1 Reef (a coquina limestone marker bed), which is in turn about 120 m below the top of the Matemateaonga Formation (the formation here is 830 m thick in total). The depositional environment is interpreted here to be shallow shelf, below wave base and with restricted circulation, although a lagoonal environment in a paralic setting is also possible.

Tangahoe Mudstone

The Tangahoe Mudstone (named Taihape Mudstone in the east of the basin) is massive, dark grey mudstone and brownish grey siltstone, with common large calcareous concretions and minor interbedded fine to medium

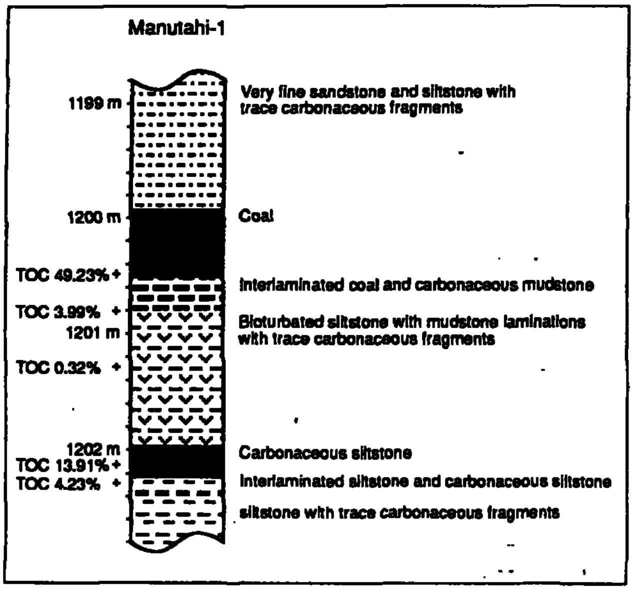


Fig. 3. Stratigraphic column of "coastal facies" in Manutahi-1 well, showing TOC values recorded in this study and Core Laboratories (1991).

sandstones. The formation reaches maximum thicknesses of 625 m in the Turakina River and 645 m in the Tangahoe River, and ranges from upper Opoitian to Waipipian in age (Collen, 1972). Arnold (1957) considered the poor sorting of the muds to reflect the combined effect of rapid sediment influx and rapid rate of subsidence. Collen (1972) suggested deposition in water depths of 300–400 m in the Wanganui River section, and 150–350 m in the Rangitikei River section.

The Tangahoe Mudstone was favoured by Feldmeyer et al (1943) as the most likely source rock in the South Wanganui Basin, on account of its "dark, organic aspect". Systematic sampling by Katz and Leask (1990a) across the basin for geochemical analysis demonstrated that total organic carbon contents are less than 0.5%, with some evidence of an increase in TOC towards the upper part of the formation in the west.

Whenuakura Group
The Whenuakura Group is a poorly defined unit of interbedded sandstone and mudstone transitional between the Tangahoe Mudstone and Paparangi Group. We include the Utiku Sandstone of eastern South Wanganui Basin here, based on correlations by Collen (1972) and Thompson et al (1994). Thickness varies from 420 m on the east coast of the Tangahoe River, to 1050 m in Waitotara River and 250 m in Wanganui River. The group is Waipipian in age (Fleming, 1953; Arnold, 1957; Collen, 1972). Environments of deposition vary from shallow subtidal to estuarine formations cropping out on the coast near Waitotara (Fleming, 1953), to upper bathyal depths at the base of the Whanganui River section (Collen, 1972). Visually organic-rich horizons have not been reported from this group.

Paparangi Group (including Mangaweka Mudstone)
This consists of muddy fine sandstone (Paparangi Sandstone) grading eastwards into massive blue-grey mudstone (Mangaweka Mudstone). Thicknesses range from 310 m in Waitotara Valley to 890 m in Parikino-1 and 520 m in Rangitikei River. The group is of Mangapanian age, locally ranging into upper Waipipian (Fleming, 1953; Collen, 1972).

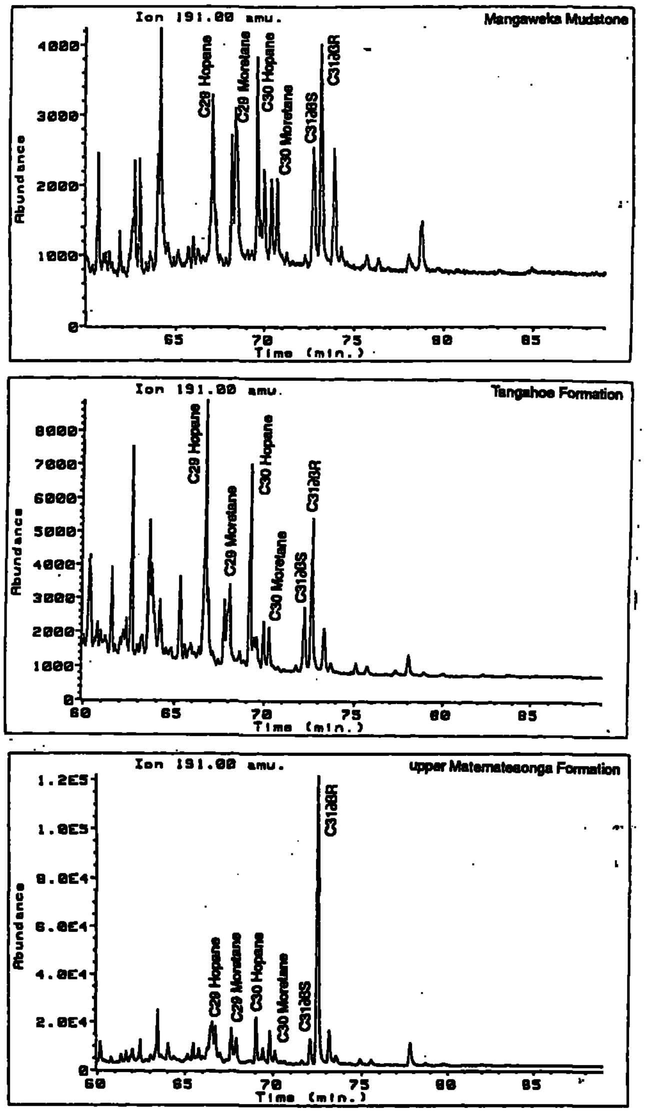


Fig. 4. Examples of the triterpane distribution from each of the formations tested.

Although shoreface and inner shelf sandstones occur in the western facies (Fleming, 1953), the Mangaweka Mudstone which forms the bulk of the group was deposited generally at middle to outer shelf depths (Collen, 1972; Hoskins & McGuire, 1990).

In the Wanganui River section, Parikino-1 and wells to the south (Thompson et al, 1994 Fig 3b), the group consists of a series of mudstone formations interspersed with fine to medium sandstones (named Makokako, Atene and Ahurangi sandstones). St John et al. (1964) reported sporadic coal fragments from the Atene Sandstone in Parikino-1 (541–652 m). Otherwise visually organic-rich horizons appear to be confined to the Ahurangi Sandstone (e.g. the Young-1 sample described below).

Okiwa Group and younger strata
The Okiwa Group consists of sandy mudstone with minor but laterally persistent fine to medium sandstones and shell beds, up to 500 m thick. It ranges from late Mangapanian to early Nukumaruan age (Fleming, 1953). Carbonaceous intervals, mainly thin lignite/peat and clay beds associated with shoreface and intertidal sediments, occur in the Nukumaruan Maxwell Group (Fleming, 1953) and in Haweran sediments in the Manawatu–Horowhenua region

(Sewell, 1991). The Okiwa Group and overlying strata are relatively unindurated compared to older formations and are unlikely to be effective sealing materials, or to have ever been buried to sufficient depth to attain thermal maturity.

Experimental

A suite of siltstone outcrop samples was collected from upper Matemateaonga Formation adjacent to Moawhango River, and two outcrop samples came from basal Matemateaonga Formation in the Mangaohane Stream area. In addition, three core samples from Manutahi-1, from the basal Matemateaonga Formation, were analysed. Regular outcrop sampling was carried out from the base of the Tangahoe Mudstone to the top of the Mangaweka Mudstone along State Highway 1. An additional siltstone sample from the "Mangawhero Sandstone" interval within Tangahoe Mudstone was collected from Mangawhero Valley. One core sample from the Ahurangi Sandstone, within the Paparangi Group in Young-1 was also analysed (figure 1).

Samples were crushed finely and split. Approximately 1 gm was used for Total Organic Carbon analysis and approximately 80 gm for organic extraction as described by Johnson et al. (1988). The latter sample was refluxed using soxhlet extraction in dichloroethane for 72 hours. Solvent was removed by rotary evaporation and the extract left for 24 hours in n-pentane. Saturate and aromatic fractions were separated by column chromatography using a silica gel/alumina column. The extract was then split, with part used for gas chromatography and part refluxed with a molecular sieve in iso-octane for 12 hours for GC/MS analysis.

Results

Results from the present study and previous studies are presented in table 1, together with a discussion of results for the same formations.

Total Organic Carbon

Matemateaonga Formation The six samples from the basal Matemateaonga Sandstone analysed here gave varying results. Manutahi-1 well samples (figure 3) from 1200.8 m and 1202.4 m represent the silty bases of thin coal seams 0.5 and 0.2 m thick respectively. These had values of 3.99% and 4.23% TOC. Core Laboratories (1991) sampled the 0.5 m coal seam at 1200.5 m and the carbonaceous shale at 1202.2 m, recording 49.23% and 13.91% TOC respectively. The 1202.2 m sample was also reported as containing significant quantities of oil prone kerogen. The 1201.3 m sample is a bioturbated silt with some sand, mud laminae and carbonaceous fragments, with 0.32% TOC.

Sample 146, from 1 cm thick beds of pale brown, fissile claystone alternating with bluish green claystone and medium sandstone beds, had 0.09% TOC and sample 147 from an 8 cm thick carbonaceous claystone had 1.47% TOC. Core Laboratories (1993) tested the same two samples and recorded 0.17% and 1.3% TOC for samples 146 and 147 respectively.

Two samples from the upper Matemateaonga Formation in Moawhango Valley gave TOC contents of 0.28 and 0.36%. Core Laboratories (1993) reported higher TOC values from Moawhango Valley samples of 0.67 and 0.60%.

Twenty cuttings and two sidewall core samples from the Matemateaonga formation were tested in Parikino-1 (Analabs, 1984; Robertson Research, 1980), ranging from 0.23% to 1.01% TOC (averaging 0.58% TOC). From Manutahi-1 38 core samples ranged from 0.14% to 49.23% TOC in this formation (Core Laboratories, 1991). Analabs (1984) measured TOC values of up to 5.93% from cuttings at the base of the formation in Kupe-1; high values (up to 12.02%) for samples of the underlying Urenui and Manganui formations suggest downhole contamination from Matemateaonga coal intervals. Kerogen of the upper and lower Matemateaonga Formation in Santoft-1A was gas-prone, with macerals of exinite and vitrinite in equal abundance. In Kupe-1, however, vitrinite significantly dominates macerals in Matemateaonga samples. Robertson Research (1980) data from Parikino-1 indicate mature shales with moderate amounts of sapropelic kerogen. Production indices indicated that hydrocarbons had already been generated and resided in the sediment. Vitrinite reflectance values of 0.37% and 0.42% in Parikino-1 and 0.31% in Kupe-1 were reported by Analabs (1984).

Tangahoe Formation Six samples analysed in this study ranged from 0.17% to 0.28% TOC (average 0.22%). One sample from a siltstone within the "Mangawhero Sandstone" recorded 0.63% TOC. Katz and Leask (1990a) reported that twelve samples from the formation across the South Wanganui region had 0.21 to 0.47% TOC, with some evidence of an increase in TOC towards the upper part of the formation in the west. Rock-Eval data from their study indicated poor generating potential. Core Laboratories (1991) reported TOC values from 0.30% to 0.37% from three samples within the Tangahoe Formation in Manutahi-1.

Samples from Parikino-1 and Santoft-1A wells had slightly higher values. Twenty-nine samples in the two wells ranged from 0.12% to 0.83% TOC (averaging 0.51%) (Analabs, 1984; Robertson Research, 1980). The organic matter contained mainly inertinite with very low quantities of sapropelic and vitrinitic kerogen, which suggested poor hydrocarbon source potential. Results from kerogen typing indicated that exinite predominated over vitrinite, with lesser amounts of inertinite, and the samples had poor mixed oil and gas generating potential (Analabs, 1984).

Whenuakura Group Sixteen samples from the Whenuakura Group in Santoft-1A and Parikino-1 recorded a range of 0.29% to 0.56% TOC. Vitrinite reflectance ranged from 0.37% to 0.39% Ro (Analabs, 1984; Robertson Research, 1980).

Paparangi Group Three samples from the Mangaweka Mudstone in this study had values of 0.24, 0.28 and 0.30% TOC. The Young-1 sample (from siltstone within the Ahurangi Sandstone at 1010 m) contained a 1 cm thick disseminated carbonaceous band and recorded 0.9% TOC.

Previous studies (Analabs, 1984; Robertson Research, 1980) reported a range of 0.21% to 1.38% TOC (averaging 0.38%) over 32 samples from Santoft-1A and Parikino-1. The value of 1.38% was from an otherwise lean sequence in Ahurangi Sandstone (Santoft-1A).

Okiwa Group Analabs (1984) conducted TOC analysis on 25 cuttings samples from Santoft-1A. A range of 0.24% to 0.92% TOC (averaging 0.57%) was recorded.

Source and maturity information from biomarkers

Results from gas chromatography and gas chromatography-mass spectrometry are presented in table 2.

Alkane distribution Alkane distribution in 28 samples analysed by whole rock extract gas chromatography show an overall consistency in nature and distribution, suggesting

STUDY	EXPLORATION WELL	Matemateaonga Formation		Tangahoe Formation		Whenuakura Group/ Utiku Sandstone		Paparangi Group/ Mangaweka Mudstone		Okiwa Group	
		Range	Ave. (n)	Range	Ave. (n)	Range	Ave. (n)	Range	Ave. (n)	Range	Ave. (n)
Robertson Research (1980)	Santoft-1A	ND	ND	0.61	0.61 (1)	0.31	0.31 (1)	0.42	0.42 (1)	ND	ND
	Parikino-1	0.79-1.01	0.9 (2)	ND	ND	ND	ND	ND	ND	0.24-0.92	0.57 (25)
Analabs (1984)	Santoft-1A	0.14	0.14 (1)	0.12-0.49	0.26 (7)	0.29-0.49	0.36 (6)	0.21-0.31	0.28 (6)	ND	ND
	Parikino-1	0.23-0.87	0.55 (20)	0.42-0.83	0.59 (21)	0.29-0.56	0.39 (9)	0.24-1.38	0.40 (25)	ND	ND
	Kupe-1	4.39-5.93	5.16 (2)	ND	ND	ND	ND	ND	ND	ND	ND
Katz & Leask (1990a)		ND	ND	<0.5	>0.5 (11)	ND	ND	<0.5	<0.5	ND	ND
Core Lab (1991, 1993)	Manutahi-1	0.14-49.23	1.91 (48)	0.30-0.37	0.35 (3)	ND	ND	ND	ND	ND	ND
Present study		0.09-4.23	1.53 (7)	0.17-0.63	0.28 (7)	ND	ND	0.24-0.90	0.43 (3)	ND	ND
Maxm. vitrinite reflectance		Ro = 0.75%		Ro = 0.61 %		Ro = 0.39 %		Ro = 0.42 %		Ro = 0.41 %	
Depth		2103 m		2225 m		2140 m		2065 m		1270 m	

Table 1. Total Organic Carbon ranges and averages, and maximum vitrinite reflectance values of the South Wanganui Basin sediments.

a common provenance for the organic matter throughout the sections sampled. Bimodal distribution is evident, with main peaks occurring in the region of nC15–nC18 and nC24–nC30. Variation does occur in the proportion of these two main peaks depending on whether the sediment is terrestrial- or marine-derived. The Ahurangi Sandstone sample from Young-1, is the exception which shows a third peak in the nC20–nC23 region.

The nC15–nC18 peak is interpreted to be marine-derived. This peak commonly displays a marked even-to-odd predominance and a narrow peak. The narrowness of the peak suggests an algal rather than bacterial origin for the marine derived organic material. Even-to-odd predominance may be an indicator for marine carbonate deposition (Peters, 1986). The nC24–nC30 peak generally displays marked odd-to-even carbon chain predominance, characteristic of immature organic material. One Mangaweka Mudstone sample is characterised by a mature terrestrial n-alkane signature.

Pr/Ph ratios for all formations are low, suggesting that the sediments were deposited in predominantly marine environments (Geotech, 1991). The Wanganui Basin suite shows consistently lower Pr/Ph ratios than typical Taranaki Basin crude oils.

Triterpane distribution Examples of the triterpanes from each of the formations analysed are shown in figure 4. The Tm/Ts ratio (table 2) is a maturity indicator that decreases from about 5 down to 1 with increasing maturity (Seifert and Moldowan, 1978). The Ts value tends to vary with the source and diagenetic conditions, therefore the ratio is not reliable in very immature samples (Moldowan et al. 1986). Tm/Ts ratios for the South Wanganui Basin samples generally suggest low maturity; however, four samples (sample 14 from the Tangahoe Formation, sample 25 from the Utiku Sand and samples 27 and 31 from the Mangaweka Formation) show a maturity level approaching that of peak oil generation.

Robinson (1987) observed that high values of Tm/Ts were observed in oils from terrestrial sources, medium values from marine oils and low values in lacustrine crudes. For the Wanganui suite, this would suggest that the Matemateaonga Formation was deposited in more oxic conditions than the Tangahoe and Mangaweka formations.

The C30 moretane to C30 hopane ratio is maturity dependent. Values decrease from approximately 0.4 at the onset of oil generation to the equilibrium value of 0.1, which is believed to represent a maturity level just after the onset of oil generation (Seifert and Moldowan, 1979; Mackenzie et al. 1980; Volkman et al. 1983). Moretane/hopane ratios are therefore useful as maturity indicators for immature samples. In samples through the Tangahoe Formation, no significant trend in decreasing maturity is indicated. Overall, five samples analysed approach the value of 0.1: sample 14 from the Tangahoe Formation and samples, 25, 27, 31 and 32a from the Utiku Sand and Mangaweka Mudstone. Mangaweka Mudstone samples range from 0.09 to 0.15.

New Zealand oils generally exhibit a range in the C30 moretane to C30 hopane ratio of 0.09 to 0.20 (Cook, 1987). The basal and upper Matemateaonga samples, including well samples, record C30 moretane to C30 hopane values indicating slightly lower maturity than the younger Tangahoe Formation sequence.

The C31(22S)/C31(22R) and C32(22S)/C32(22R) ratios approach a 60:40 ratio at equilibrium prior to the onset of oil generation (Ourisson et al. 1979; Waples and Machihara, 1991). Two Mangaweka Mudstone samples (17 and 32a) and that from the Utiku Sand (25) have close to a 60:40 C31(22S)/C31(22R) ratio. The C32(22S)/C32(22R) ratio in the samples analysed here indicates an anomalously high number of samples with a 60:40 ratio for the age and depth of burial of the rocks, and it is possible that an unidentified compound has co-eluted with the C32(22S) hopane.

In contrast to Tangahoe and Mangaweka samples, which have a dominant C29 peak, most basal and upper Matemateaonga samples are characterised by a very high C31 hopane peak, which may be due to a peat or coal source of organic matter.

Oleanane has not been found in the Wanganui Basin sediments sampled in this study, indicating a lack of an angiosperm higher plant input. Gammacerane, thought to be derived from non-marine protozoa (Hills et al., 1966), is also notably absent in this suite of samples. By comparison the terpane series in New Zealand oils is dominated by the C27–C35 hopane series of which the most abundant is C30 hopane. The oils may also contain oleanane and a little gammacerane (Analabs 1984).

Sterane distribution Examples of the steranes from each of the formations tested are shown in figure 5. The C29ααS/C29ααS + C29ααR ratio is considered to be the most reliable maturity biomarker indicator (Waples and Machihara, 1991), with ratios of 0.25 to 0.5 representing the onset to peak of oil generation and corresponding to a vitrinite reflectance range of 0.6 to 1.0%. The basal and upper Matemateaonga Formation, including the well samples, gave values indicating very low maturity. Apart from one sample (14) from the Tangahoe Formation with a value of 0.23, all samples from that section are also very immature. Five Mangaweka Mudstone samples and that from the Utiku Sand have values close to 0.5 (samples 25, 27, 29, 31, 32a and 32b), ranging from 0.46 to 0.53, which suggest a comparative vitrinite reflectance approaching Ro = 1.0%.

By comparison, Taranaki Basin source rocks give ratios ranging from 0.40 to 0.49 and the corresponding oils range from 0.49 to 0.59. New Zealand oils generally fall between 0.35 and 0.42, indicating overall low maturity (Cook, 1987).

The C29ββ(S+R)/C29αα(S+R) + C29ββ(S+R) ratio is also a maturity parameter where equilibrium between the biological αα form and the geological ββ form is reached at 65% ββ compounds. That ratio is approximately equivalent to a vitrinite reflectance of 0.9% VR (Geotech, 1991). This ratio is less reliable than the C29ααS/C29ααS + C29ααR as it is affected by diagenesis (Waples and Machihara, 1991). Basal and upper Matemateaonga samples generally show values between 25% and 51%, but do not show the peak separation of the C29ββS and ββR epimers which indicates a low maturity intermediate compound prior to the formation of C29ββ steranes. Two Tangahoe Mudstone samples (14 and 15) give values of 52% and 51%; however, co-elution of unidentified peaks in the vicinity of the C29ββS and C29ββR peaks has possibly distorted these values.

Three Mangaweka Mudstone samples and that from the Utiku Sandstone show ratios greater than 48% and show clear separation of the C29ββ peaks into S and R forms (samples 25, 27, 31 and 32a). Typical Taranaki Basin oils lie in the range of 50% to 62% ββ steranes (Cook, 1987).

UNIT	SAMPLE NUMBER	ALKANES			TRITERPANES				STERANES			
		Pr/ Ph	Pr/ nC_{17}	Ph/ nC_{18}	Tm/ Ts	$C_{30}M$/ $C_{30}H$	$C_{31}S$/ S+R	$C_{32}S$/ S+R	$C_{29}\alpha\alpha\alpha S$/ S+R	$\%\beta\beta C_{29}$	nC_{27}/ $nC_{29}\alpha\alpha\alpha 20R$	nC_{29}/ $nC_{29}\alpha\alpha\alpha R$
Tangahoe Formation	1	1.19	0.75	0.32	2.32	0.28	0.14	0.56	0.07	0.34	1.00	0.91
	4	0.87	0.93	0.83	2.38	0.26	0.35	0.56*	0.11	0.40	1.12	0.53
	14	1.16	1.06	0.74	1.25	0.15	0.32*	0.44	0.23	0.52	1.58	0.85
	17	1.56	0.56	0.53	1.85	0.27	0.31	0.55	0.14	0.46	1.70	1.20
	20	1.07	1.09	0.59	2.08	0.25	0.21	0.54	0.08	0.51	1.15	0.84
	180A	0.25	4.90	13.18	7.69	0.77	0.30	*	0.03	0.39	4.77	1.50
Utiku Sandstone	25	0.37	0.75	1.17	1.01	0.09	0.62	0.71	0.47	0.72	3.37	2.71
Mangaweka Mudstone	26	1.60	0.63	0.85	2.44	0.41	0.39	0.53*	0.17*	0.22*	1.54	0.72
	27	0.81	0.68	0.26	1.16	0.13	0.50	0.56	0.48	0.48	1.77	0.98
	29	0.59	0.81	1.09	2.72	0.57	0.39	0.75	0.46	0.37	2.77	0.38
	31	1.10	0.46	0.40	1.26	0.15	0.42	0.60	0.41	0.50	1.89	0.71
	32A	1.47*	0.88	1.00	1.98	0.13	0.48	0.59	0.53	0.56	1.06	0.56
	32B	0.93	0.67	1.06	1.89	0.31	0.41	0.64	0.50	0.45	1.98	0.93
Ahurangi Sandstone	Young-1	1.00	1.07	1.20	1.40	0.55	0.06	*	0.11	0.25	0.92	0.46
Upper Matemateaonga Sandstone	35	2.25	1.22	0.74	2.54	0.21	0.19	0.57	0.24	0.26	0.67	0.59
	36	1.66	1.10	0.71	2.12	0.45	0.09	0.39	0.08	0.35	0.60	0.53
	38	1.75	1.10	0.53	4.31	0.43	0.06	0.48	0.07	0.38	0.73	0.53
	39	2.32	1.05	0.39	1.69	0.21	0.12	0.51	0.17	0.42	1.34	0.92
	40	1.14	1.40	0.96	2.56	0.31	0.11	*	0.11	0.41	1.19	0.68
	41	1.55	0.91	0.48	3.25	0.36	0.07	0.50	0.15	0.35	0.47	0.47
	142A	1.58	2.70	0.57	2.21	0.36	0.07	0.44	0.11	0.41	0.50	0.50
	142C	1.58	1.78	0.69	2.85	0.21	0.09	0.54	0.16	0.39	1.89	0.57
Basal Matemateaonga Sandstone	146	1.63	0.58	0.11	1.47	0.16	0.31	0.54	0.29	0.40	0.87	0.62
	147	2.03*	1.4*	0.40*	2.36	0.28	0.12	*	0.10	0.50*	1.43	0.31
	Man-1A	1.54	0.31	0.41	0.53*	0.59*	0.03	*	0.06	0.36	0.19	0.37
	Man-1B	2.39	0.77	0.56	4.02	0.33	0.15	0.66	0.09	0.51	0.95	0.62
	Man-1c	1.54	1.43	1.05	3.20	0.49	0.04	*	0.06	0.27	0.28	0.24

Table 2. Gas chromatography and gas chromatography/mass spectrometry results for the South Wanganui Basin sediments. * denotes poor or no data

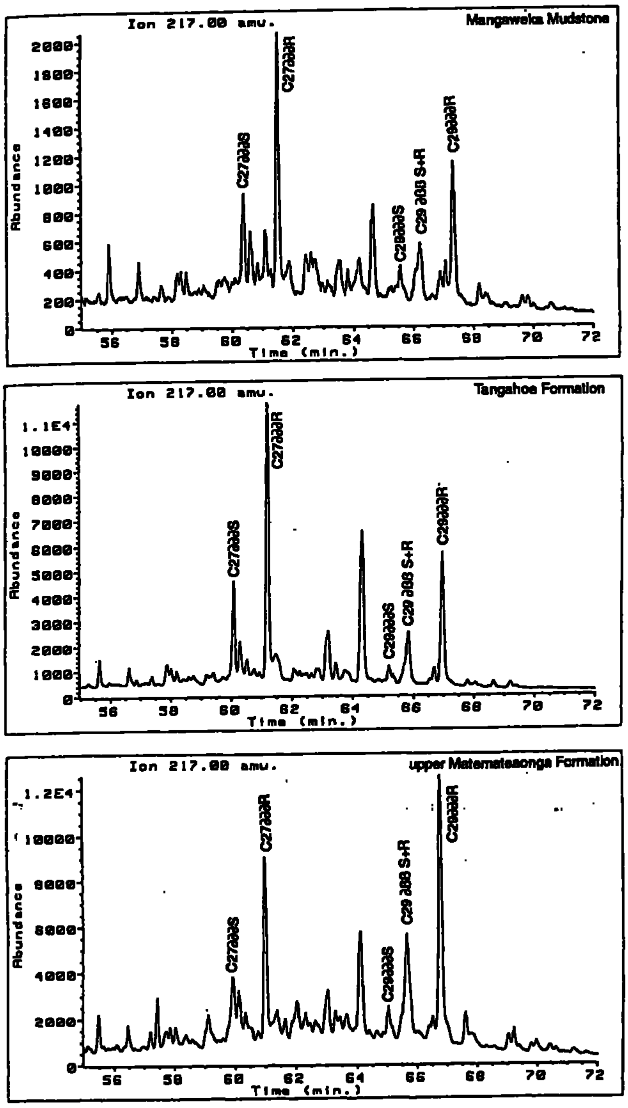


Fig. 5. Examples of the sterane distribution from each of the formations tested.

The C27 and C29 diasteranes are more stable than regular steranes and therefore become more dominant with increasing maturity. The Utiku Sandstone sample and four Mangaweka Mudstone samples (25, 27, 31, 32a, 32b) show high abundances of these compounds. In addition, diasteranes have been shown by Seifert and Moldowan (1981;1986) to migrate earlier than the normal steranes and may imply movement of hydrocarbons in these samples.

The C27αα steranes, although useful maturity indicators in marine sediments, have not been considered in this study because of difficulty in assigning values to each of the C27αα sterane peaks due to co-elution with the C29 diasteranes. The relative abundance of C27 to C29 steranes is, however, particularly useful as a source indicator and an attempt has been made in figure 6 to categorise the sediments according to Huang and Meinschein (1979). On the ternary plot of C27ααR, C28ααR and C29ααR steranes (figure 6) the C29 diasterane has not been isolated from the C27ααR peak, skewing the data for these samples towards an open marine category in samples showing a high abundance of diasteranes (Mangaweka Mudstone 27, 31, 32a, 32b; and Utiku Sandstone sample 25).

Generally the C29ααR to C27ααR sterane ratio of New Zealand oils is 51.18–73.18%, showing that the oil precursors

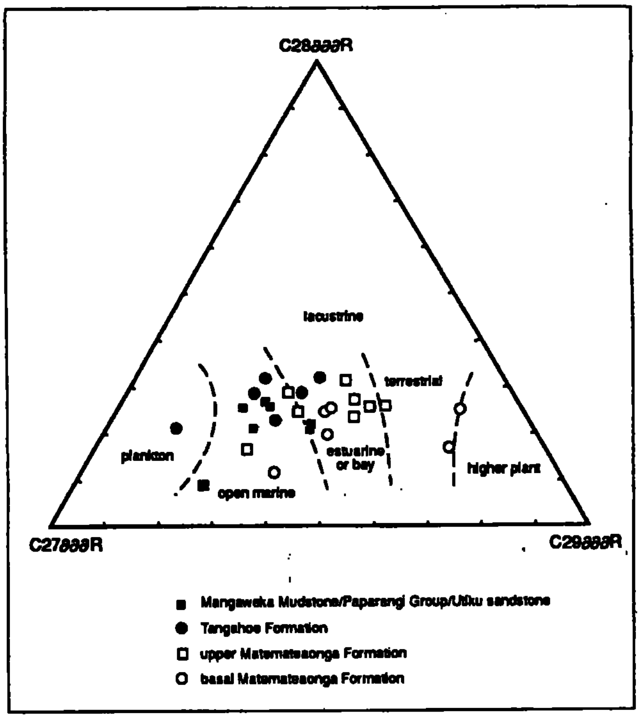


Fig. 6. Ternary plot of C27ααR, C28ααR and C29ααR after Huang and Meinschein (1979).

are higher plants (Cook, 1987). The Tangahoe and Mangaweka sediments have C29ααR sterane contents less than 50%, suggesting a marine-derived source. The Matemateaonga sediments have variable C27 and C29 contents depending on the coal content in the sample.

Discussion of geochemistry

The biomarker content and vitrinite reflectance values of the South Wanganui Basin samples generally indicate low maturity in all formations sampled, as would be expected in young, mainly surface samples. Exceptions are the Mangaweka Mudstone and overlying Utiku Sandstone for which five of the seven samples show indications of a mature oil. Figure 7 shows the triterpane and sterane distributions for the contaminated Mangaweka Mudstone samples. The contrasting immaturity of sample 26 from the Mangaweka Mudstone and the remainder of the Wanganui Basin sequence strongly suggests that an oil has migrated into the sediments as a contaminant. This is also supported by the presence of C27 and C29 diasteranes.

From biomarker analysis the oil appears to be of dominantly marine origin. The marine character is supported by a general dominance of C27 over C29 steranes, low Pr/Ph ratios, and apparent lack of oleanane and gammacerane. The GC traces, however, suggest a more terrestrial influence. The bimodal distribution of the n-alkanes with a dominant mature terrestrial peak and the even to odd predominance of the marine peak may imply a marine (perhaps calcareous) environment with a significant mature terrestrial input.

Further, the Utiku Sandstone sample shows features of biodegradation of the oil. The n-alkane series has been preferentially removed from the GC trace, and regular steranes which degrade preferentially before diasteranes and triterpanes (Seifert and Moldowan 1981) are in very low abundance.

Biomarker fingerprinting of formations sampled in this study suggests that the most likely source for the hydrocarbons

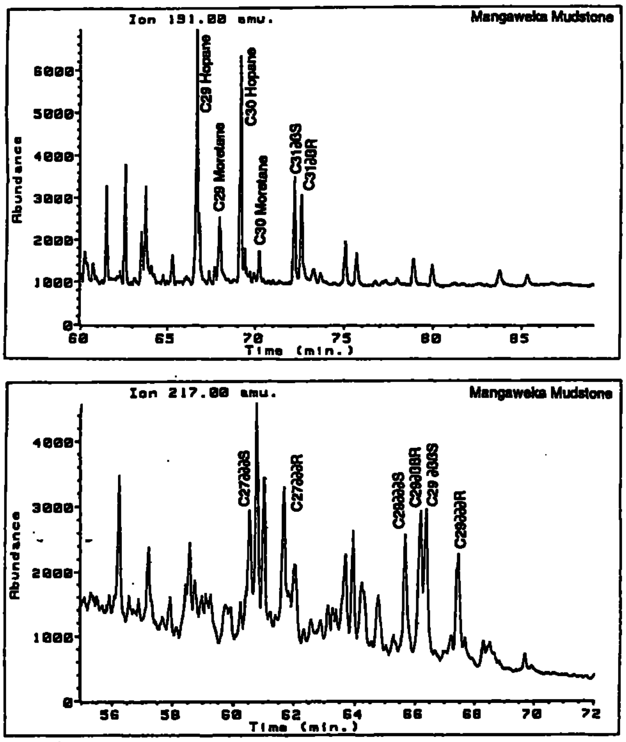


Fig. 7. Triterpane and sterane distributions of contaminated Mangaweka Mudstone samples.

is the Tangahoe Formation, due to the similar biomarker fingerprint. Allowing for a high abundance of C29 diasteranes in the contaminated samples, the ternary plot of steranes (figure 6) shows comparable marine character. In contrast, the distinctive C31 (22R) epimer of the Matemateaonga Formation is not seen in the oil-bearing samples.

Maturity of the oil calculated from geochemical data approaches Ro = 0.9–1.0%, almost as high as that of Taranaki Basin oils (around 1.0% Ro; Cook 1987). For a marine oil, this suggests depths of $2^1/_2$–3 km at normal geothermal gradients.

Discussion

Most of the new analyses presented here indicate that the known sediments of significant thickness generally have low organic carbon contents and hence low hydrocarbon generating potential. The high TOC values encountered in this study have been obtained from relatively thin carbonaceous facies, of unknown lateral extent.

Thermal modelling carried out by Katz and Leask, (1990a) and Thompson et al. (1994) based on temperature parameters from Parikino-1 indicates adequate maturity for oil generation in the deepest part of the basin. However, it is unlikely that the sediments in the Mangaweka area have attained sufficient depth to achieve maturity.

The traces of mature marine-derived oil in the Mangaweka area must have migrated from a source elsewhere. Possible sources are:

- relatively unindurated parts of basement
- presently unknown formations, perhaps similar to the older Tertiary of North Wanganui Basin, present at depth
- known South Wanganui Basin sediments buried to the oil window

One possibility is generation from low rank "basement" lithologies. Harmsen et al., (1989) postulated that isolated Jurassic carbonaceous beds in the Canterbury Basin were a potential source of hydrocarbons, and Ministry of Commerce (1992) suggested that Triassic and Jurassic strata in the Kawhia syncline adjacent to the North Wanganui Basin had gas-bearing potential. Basement rocks to the north and east of the South Wanganui Basin, however, are metamorphosed from zeolite to stilpnomelane facies (Baker and Staveley Parker, 1989) and thus have passed beyond oil or gas generation capability.

Possible generation of hydrocarbons from older sediments within the South Wanganui Basin is speculative, and depends on the presence of:

- remnants of Oligocene or older sediments as at Paraparaumu and Picton
- southward extension of Oligo–Miocene sediments from the North Wanganui Basin

The absence of any pre-Matemateaonga strata in the Mangaweka area, or adjacent to the basement 22 km to the east or 34 km to the north, does not favour the second option.

Outcrop samples from the South Wanganui Basin are young, mainly organically lean, and immature for hydrocarbon generation. However, an important consideration is that most of the exposed sediments are from offlapping sequences, deposited north or northwest of the basin depocentre. These deposits represent the least favourable part of the sedimentary sequence for organic source potential. In contrast, the onlapping facies on the south or southwest side of the basin depocentre is likely to be much more favourable for organic-rich sediments, but this facies is present in only a few wells and some outcrops in the south Kaimanawa and Ruahine ranges.

There are two possible source facies in the South Wanganui Basin. Firstly the "coastal facies" of the basal Matemateaonga Formation, which is likely to extend from the Kupe field wells (figure 8) eastwards across the Patea–Tongaporutu High and into the basal succession in what is now the deepest part of the basin. Anderton (1981) showed that considerable basement relief existed on the southern margin of the basin during late Miocene–early Pliocene onlap. Restriction of drainage patterns by such features may have favoured lacustrine or restricted marine deposition.

The second possible source facies is the Tangahoe Mudstone. Due to onlap of the succession to the south (cf. Thompson et al. 1994), Tangahoe Mudstone replaces Matemateaonga Formation as the basal formation just south of the current basin depocentre. The same topographic highs which controlled Matemateaonga sedimentation may still have been exposed, and thus have continued to restrict bottom-water circulation. Alternatively (or in addition), relative sea-level falls may have temporarily isolated parts of the basin, causing restricted, anoxic, organic-rich environments in those areas. Facies from such environments have not been identified in outcrop or in the wells drilled to date. A 2 m thick diatomite bed in the Mangaweka Mudstone in Turakina River (Hoskins and McGuire, 1990) is a possible indicator of restricted hyposaline facies.

Anderton's (1981) seismic interpretation suggested a deeply indented southern coastline, comparable with the present Marlborough Sounds, for much of the basin's history. Speculation is made here on facies that might be encountered in such sound-like features, as these may be present at the base of the sequence in the South Wanganui Basin. Bottom sediments in the Sounds are mainly soft silt and clay with

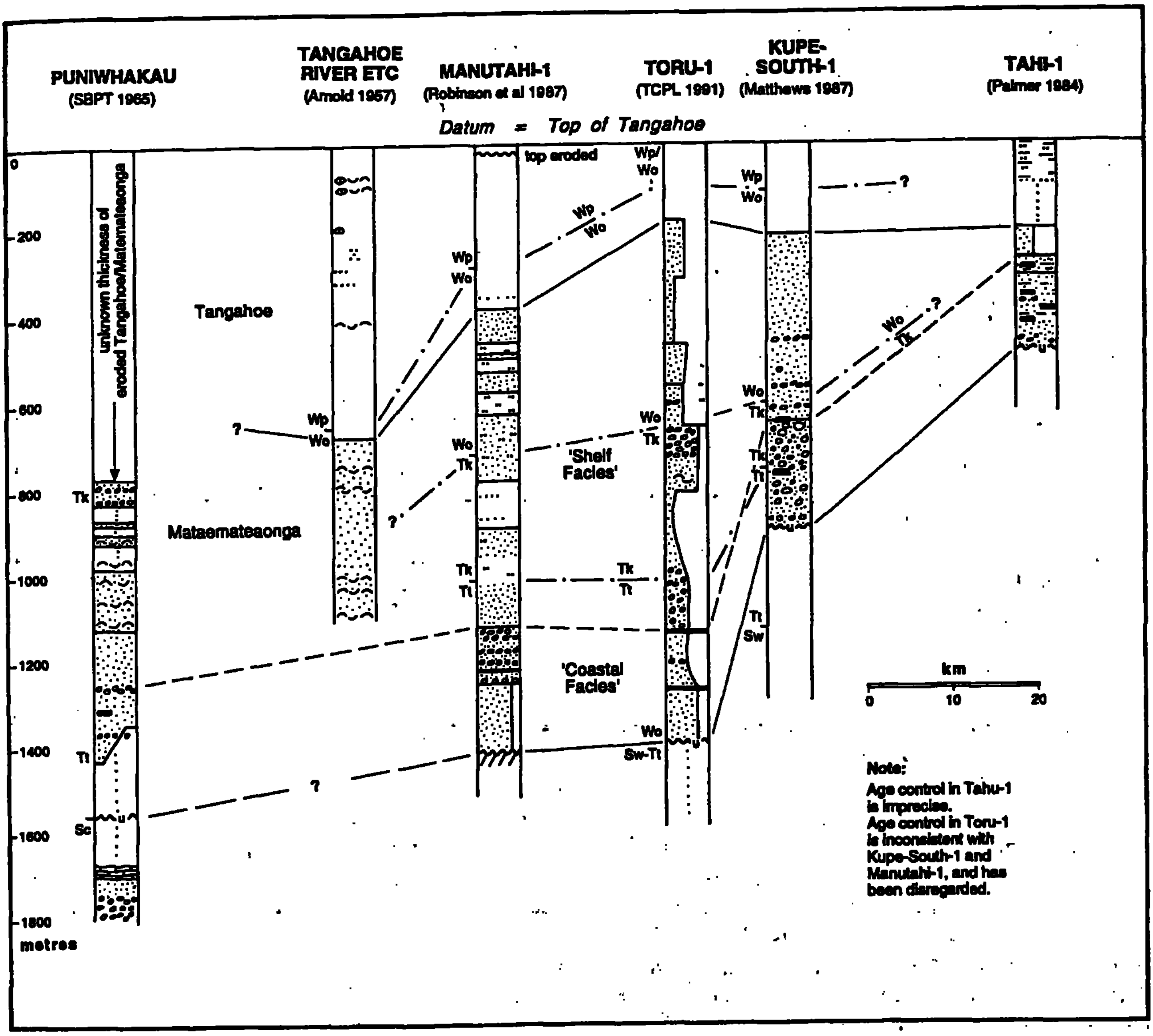


Fig. 8. Fence diagram of the Tangahoe and Matemateaonga formations north to south along the western margin of the Taranaki Basin.

less than 10% sand, of which up to 10 m have accumulated since sea-level stabilised about 5000 years ago (Estcourt 1967; Carter 1976). By contrast, the shoreline consists of beaches of cobbles, sand and shell fragments, separated by rocky headlands. At the heads of the Sounds, river-transported sediments have built out extensive deltas. The innermost reaches consist of intertidal sand and mudbanks separated by narrow channels. Large areas of these banks are densely covered with attached algae, whose prolific growth is attributed to river-transported nutrients and high light intensities in shallow water (Estcourt 1967).

Marine bottom sediments are typically bluish-grey muds, with little apparent organic content. A piston core from a relatively low energy setting contained 0.60–1.02% TOC, whereas core from a higher energy environment contained 0.34–0.58% TOC (L J Singh, Victoria University of Wellington, pers. comm.) These data do not support a prevalence of potential source sediments in the present Marlborough Sounds, but the higher TOCs, the possibility of algal deposits and the potential for peat deposits in adjacent deltaic or estuarine areas, suggest that similar environments could provide hydrocarbon source rocks.

Emplacement of the hydrocarbons in the Mangaweka area may be due to its location between two apparently strike-slip fault systems (the Rangitikei and Omatane faults of Kingma (1962). The horizontal migration of an oil sourced at depth to the southwest is possible in the highly permeable and laterally continuous Utiku Sandstone. From the Utiku Sandstone vertical migration could then occur via microfracturing associated with transextension between the fault zones, thereby permeating through the Mangaweka Mudstone.

Conclusions

Some previous authors have considered the South Wanganui Basin to have little hydrocarbon prospectivity because of the lack of a demonstrable source rock within the basin and the difficulty of arguing for migration of hydrocarbons from outside the basin. These views were based on the low organic carbon contents and low thermal maturity of known South Wanganui Basin sediments, the lack of hydrocarbon traces in outcrop and wells, and the known structure of the basin which precluded migration from source rocks in Taranaki Basin.

Most of the samples analysed during the present study also have low TOC values and are immature for hydrocarbon generation. However, a few samples from the Mangaweka Mudstone and Utiku Sandstone contain biomarkers indicating traces of crude oil of moderate-high maturity which has originated from a marine source with probable terrestrial input. Maturity considerations require that this oil must have migrated from a source elsewhere. Possible sources for the oil include known late Miocene and Pliocene formations buried to the oil window, older and previously unknown formations at depth in the basin, and generation from low rank basement. Migration to the Mangaweka Mudstone and Utiku Sandstone sites may be facilitated by transextension between two strike-slip faults.

References

ARNOLD, H. C. 1957: The Pliocene stratigraphy of south Taranaki. Shell BP and Todd Oil Services Ltd. Unpublished open-file petroleum report 414.

ANALABS 1984: Petroleum geochemistry of the Taranaki Basin. Unpublished open-file petroleum report 1013.

ANDERTON, P. W. 1981: Structure and evolution of the South Wanganui Basin, New Zealand. New Zealand journal of geology and geophysics 24: 39–63.

BAKER, C.K., STAVELEY PARKER, R.J. 1989: Coalification and metamorphism in Torlesse Supergroup rocks, North Island, New Zealand. New Zealand journal of geology and geophysics 32: 429–435.

BROWNE, G.H. 1978: Wanganui strata of the Mangaohane Plateau, northern Ruahine Range, Taihape. Tane 24: 199–210.

CARTER, L. 1976: Sediment transport and deposition in Pelorus Sound, South Island, New Zealand. New Zealand journal of marine and freshwater research 10: 263–282.

COLLEN, J. D. H. 1972: Studies in the Wanganui Series: Pliocene foraminifera from Wanganui Basin. Unpublished Ph.D. thesis in Geology, Victoria University of Wellington.

COOK, R.A. 1987: The geology and geochemistry of the crude oils and source rocks of western New Zealand. Unpublished Ph.D. thesis in Geology, Victoria University of Wellington.

COPE, R.N. 1966: The hydrocarbon prospects of the Wanganui Basin, New Zealand. Shell BP and Todd Oil Services exploration report. Unpublished petroleum report No. 394.

CORE LABORATORIES, 1991: Geochemical evaluation of fifty-one core and three outcrop samples from the Manutahi-1 well, Wanganui Basin, New Zealand. Unpublished report to ANZEX.

CORE LABORATORIES, 1993: Geochemical evaluation of four South Wanganui Basin, New Zealand outcrop samples. Unpublished report to ANZEX.

DE CAEN, R.F. 1968: Oil seepage at Waiotapu, North Island, New Zealand. BP Shell Aquitaine and Todd Petroleum Development Ltd. Unpublished petroleum report No. 380.

ESTCOURT, I. N. 1967: Distribution and associations of benthic invertebrates in a sheltered water soft-bottomed environment (Marlborough Sounds, New Zealand). New Zealand journal of marine and freshwater research 1: 352–370.

FELDMEYER, A.E.; JONES, B.C.; FIRTH, C.W.; KNIGHT, J.R. 1943: Geology of the Palmerston North - Wanganui basin, "West side" North Island, New Zealand. Superior Oil Co. of New Zealand Ltd. Open-file petroleum report PR 171.

FLEMING, C.A. 1953: The geology of Wanganui Subdivision. New Zealand Geological Survey bulletin n.s.52.

GEOTECH 1991: Petroleum geochemistry for exploration geoscientists. Unpublished notes for short course, Wellington, June 1991.

HARMSEN, F.A.; PERRY, S. M.; HASKELL, T.R. 1989: The Canterbury Basin, a geological and seismic evaluation of the basin's hydrocarbon potential. Unpublished proprietary report, Haskell Exploration Services Ltd.

HAY, R. F. 1967: Sheet 7 Taranaki. Geological Map of New Zealand 1:250 000. Wellington, New Zealand. Department of Scientific and Industrial Research.

HILLS, I.R., WHITEHEAD, E.V. 1966: Triterpanes in optically-active petroleum distillates. Nature, London 209: 977–979.

HOSKINS, R.H., McGUIRE, D. 1990: The location and stratigraphy of samples from the Turakina River section, South Wanganui Basin, New Zealand. NZGS Report PAL 150.

HUANG, W., MEINSCHEIN, W.G. 1979: Sterols as ecological indicators, Geochimica et Cosmochimica Acta 43: 739–745.

HUNT, T.M.; 1980: Basement structure of the Wanganui Basin, onshore interpreted from gravity data. New Zealand journal of geology and geophysics 23: 1–16.

JOHNSTON, J.H., COLLIER, R.J., CRAIG, J.T. 1988: Oil-source rock correlations in the Maui-4 exploration well, South Taranaki Basin. Energy Explor. Exploit., 6: 233–247.

KATZ, H. R., LEASK, W. L. 1990a: The South Wanganui Basin Report, New Zealand. Unpublished proprietary report by Pacific Geo Consultants and Ian R. Brown Associates Ltd.

KATZ, H. R., LEASK, W. L. 1990b: The South Wanganui Basin — a neglected hydrocarbon prospect. Petroleum Exploration in New Zealand Newsletter 25 (July 1990): 19–25.

KER, D. S. 1991: Provisional geological map of 1:50 000 Sheet T21AC Hautapu. New Zealand Geological Survey report G144.

KINGMA, J. T. 1962: Sheet 11 Dannevirke. Geological Map of New Zealand 1:250,000. Department of Scientific and Industrial Research, Wellington

LOCK, R. 1979: South Wanganui Basin petroleum prospects. Petrocorp (Exploration) Ltd. Open-file petroleum report PR 764.

MATTHEWS, E. R. 1985: Manutahi-1 well completion report, PPL 38084. Petroleum Resources Ltd. Unpublished open-file petroleum report 1102.

MATTHEWS, E. R.; BENNETT, D. J. 1987: Kupe South-1 well completion report, PPL 38116.

MACKENZIE, A.S.; PATIENCE, R.L.; MAXWELL, J.R.; VANDENBROUKE, M.; DURAND, B. 1980: Molecular parameters of maturation in the Toarcian shales, Paris Basin, France - I. Changes in the configuration of acyclic isoprenoid alkanes, steranes and triterpanes. Geochimica et Cosmochimica Acta 44: 1709–1721.

MACPHERSON, E. O. 1948: The Otaihanga faulted outlier and notes on the greensand deposit. New Zealand Journal of Science and Technology B30: 70–83.

MINISTRY OF COMMERCE; 1992: An introduction to the petroleum geology of New Zealand. New Zealand Petroleum Prospectus.

MOLDOWAN, J.M.; SUNDARARAMAN, P.; SCHOELL, M. 1986: Sensitivity of biomarker properties to depositional environment and/or source input in the Lower Toarcian of SW Germany. Organic Geochemistry, 10: 915–926.

MORGAN, P.G. 1927: Minerals and mineral substances in New Zealand. New Zealand Geological Survey bulletin 32.

NICOL, A., CAMPBELL J. K. 1990: Late Cenozoic thrust tectonics, Picton, New Zealand. New Zealand Journal of Geology and Geophysics 33: 485–494

OURISSON, G., ALBRECHT, P.; ROHMER, M. 1979: The hopanoids: Pure Applied Chemistry 51: 709–729.

PARK, J. 1890: Coal in the upper Rangitikei valley. NZ Geological Survey reports of geological exploration 1888-89: 64–67.

PETERS, K.E. 1986: Guidelines for evaluating petroleum source rocks using programmed pyrolysis, Bulletin of the American Association of Petroleum Geologists, 70: 318–329.

ROBERTSON RESEARCH 1980: Petroleum geochemical evaluation of samples from the Northland, Waikato, North Wanganui and South Wanganui basins, North Island, New Zealand. Report for Petrocorp Exploration Ltd. Unpublished open-file petroleum report 768.

ROBINSON, K.M. 1987: An overview of source rocks and oils in Indonesia, in Proceedings of the Indonesian Petroleum Association, Sixteenth Annual Convention, Volume 1: Jakarta, Indonesian Petroleum Association, p. 97-122.

ROBINSON, P., SHERWOOD, A., MORRIS, B. 1986: Neogene sediments of the Taranaki region. Geological society of New Zealand miscellaneous publication 35: B1–14.

ROBINSON, P.H., MORRIS, B.D., SCOTT, G.H. 1987: Lithologic log and micropaleontology of Manutahi-1 well core, onshore South Taranaki, New Zealand. NZGS Report PAL 121.

SCOTT, G.H. 1988: Revision of foraminiferal biostratigraphy of Kupe-1 offshore well. New Zealand Geological Survey report PAL 131.

SEIFERT, W.K., MOLDOWAN, J.M. 1978: Applications of steranes, terpanes and monoaromatics to the maturation, migration and source of crudes oils. Geochimica et Cosmochimica Acta 42: 77–95.

SEIFERT, W.K., MOLDOWAN, J.M. 1979: The effect of biodegradation on steranes and triterpanes, Geochimica et Cosmochimica Acta 43: 111–126.

SEIFERT, W.K., MOLDOWAN, J.M. 1981: Paleoreconstruction by biological markers, Geochimica et Cosmochimica Acta 45: 783–794.

SEIFERT, W.K., MOLDOWAN, J.M. 1986: Use of biological markers in petroleum exploration, in R.B. Johns, ed., Biological Markers in the Sedimentary Record: Amsterdam, Elsevier, p. 261–290.

SEWELL, A.H. 1991: Paleoenvironmental analysis of Quaternary strata in the Levin area. Unpublished M.Sc. thesis, Massey University, Palmerston North.

ST. JOHN, D.H., COPE, R.N., GIBSON, G.W. 1964: Parikino-1 exploration well resume. Shell BP & Todd Oil Services Ltd. Unpublished petroleum report PR 452.

ST. JOHN, D. H., STAINTON, P. W., GIBSON G.W. 1965: Puniwhakau-1 exploration well resume. Shell BP & Todd Oil Services Ltd. Unpublished petroleum report PR 455.

STERN, T.A., QUINLAN, G.M., HOLT, W.E. 1992. Basin formation behind an active subduction zone: three-dimensional flexural modelling of Wanganui Basin, New Zealand. Basin Research 4: 197–214.

THOMPSON, T.L; LEASK, W.L.; MAY, B.T. 1994: Petroleum potential of the South Wanganui Basin (this volume).

VOLKMAN, J.R.; ALEXANDER, R.; KAGI, R.I.; WOODHOUSE, G.W. 1983: Demethylated hopanes in crude oils and their applications in petroleum geochemistry. Geochimica et Cosmochimica Acta 47: 785–794.

WAPLES, D.W.; MACHIHARA, T. 1991: Biomarkers for Geologists. AAPG Methods in Exploration. The American Association of Petroleum Geologists, Tulsa, Oklahoma. USA.

Acknowledgements

We are very grateful to Karyne Rogers and Nils Elgar (Victoria University of Wellington) for running the GC/MS analyses and for valuable discussion, and to Les Singh (Victoria University of Wellington) and Robin Black (Hawke's Bay Regional Council) for helpful discussion and permission to use unpublished data. American New Zealand Exploration Ltd. and Allegheny-Western Exploration New Zealand Ltd. kindly allowed us to use data from unpublished petroleum reports. This study was supported by the Internal Grants Committee of Victoria University of Wellington, and Resource Information, Ministry of Commerce

Authors

LINN MURPHY studied geology at Otago University. She currently works at Resource Information, Energy and Resources Division, Ministry of Commerce. This project was undertaken as part of her professional training programme.

BILL LEASK holds an MSc from Victoria University of Wellington. He is a senior geologist with Ian R Brown Associates Ltd, a geological and engineering consulting firm based in Wellington, New Zealand.

JOHN COLLEN is a Reader in Geology at Victoria University of Wellington. He has a background in exploration geology, and his research interests are in the process controlling the generation and emplacement of hydrocarbons, the diagenesis of reservoir sandstones, and the petroleum geology of western China.