PROVENANCE OF SEDIMENTS IN TARANAKI BASIN– AN ASSESSMENT FROM HEAVY MINERALS

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Abstract

Heavy minerals from cores and cuttings from onshore and offshore drillholes in Taranaki Basin suggest characteristics of provenance areas. Statistical (cluster and factor) analyses show four heavy mineral associations: (1) ilmenite-zircon (2) magnetite with minor hornblende and pyroxene (3) chlorite-epidote-pumpellyite, with minor hornblende and pyroxene (4) biotite-epidote-apatite-garnet-titanite-staurolite. These suites probably correspond to (1) a leached or recycled ultra-resistant suite indicating little about provenance; (2) Late Miocene or later volcanics, and older rocks of the Brook St, Dun Mt, Maitai, and Caples terranes; (3) Murihiku and Torlesse terranes; (4) north-west Nelson – Golden Bay (and possibly Karamea) terrane.

Association 1 is most prominent in the Kapuni Group (Paleogene), much of which has probably been leached. Association 2 is generally strong in Western Platform sediments, and mild in the South Taranaki Graben; in most areas it was probably derived from Maitai or other older terranes, but where it is especially conspicuous near the top of Ariki-1 and Tangaroa-1 it is more likely to be volcanic. Association 3 influence is strong in the South Taranaki Graben, and in the Neogene of onshore Taranaki, but distinctly less (and absent altogether from the Cretaceous) in the Western Platform, even allowing for solution. Association 4 is also strong in the South Taranaki Graben, and slightly less in the Western Platform (though strong in the Cretaceous in Tane-1); a little is present in onshore Taranaki - virtually the only influence still detectable amid the solution effects in the Kapuni Group. Since the Miocene all sources have had a recognizable influence, probably reflecting more pronounced uplift.

Introduction

Heavy minerals from cuttings from Taranaki Basin drillholes (Figure 1) have been examined to try to establish formation characteristics and variations in provenance. Cuttings were selected because cores were not available from many of the formations penetrated by the drillholes, and the object was to achieve representative stratigraphic coverage. However, some core samples were included from earlier studies (Smale & Morton 1987, van der Lingen & Smale in press). As the only material that can effectively be studied for heavy minerals is in the fine sand grade, this governed the selection of some of the material; claystones and limestones were avoided.

Standard Method of Treatment

Samples for heavy mineral analysis are disaggregated as gently as possible by physical means, but where necessary are briefly crushed in a ring mill. Heavy minerals are separated from the 2-4 phi fractions, using tetrabromoethane or sodium polytungstate with a specific gravity of 2.9. The heavy fractions are examined microscopically in a refractive index oil of 1.63, and proportions are established by counting all the grains in successive fields of view until approximately 300 have been counted. Any grain whose identification is doubtful is confirmed using X-ray diffraction powder photography or SEM-EDAX.

Results

Results are shown in approximate stratigraphic order in Table 1. It is clear that above the Otaraoa Formation (Oligocene) there is a much greater variety of minerals present, and similarly where older sediments are at a sufficiently shallow depth to have avoided intrastratal solution (Smale & Morton 1987). The presence of hornblende and pyroxene in P22/s3 from a depth of 3331-3353 m is anomalous, in view of the leaching of these minerals from other samples at comparable depth; a grain of atacamite was also observed in this sample, and some contamination may have occurred. Although this highlights the risk of using cuttings as samples, it is the only such anomaly indicated.

Statistical methods

In order to assess the large number of variables more conveniently, the data were analysed statistically using factor analysis (FUZZY QMODEL - Full, Ehrlich, & Bezdek 1982), and cluster analysis (NTSYS - Rohlf 1985).

The factor analysis program establishes the number of factors (or "end members") that will most readily explain the observed populations, and the proportions of factors that would be present in each sample. The advantages of the FUZZY QMODEL program over other factor analysis programs in dealing with a heavy mineral dataset are that it produces possible compositions of factors when they are not

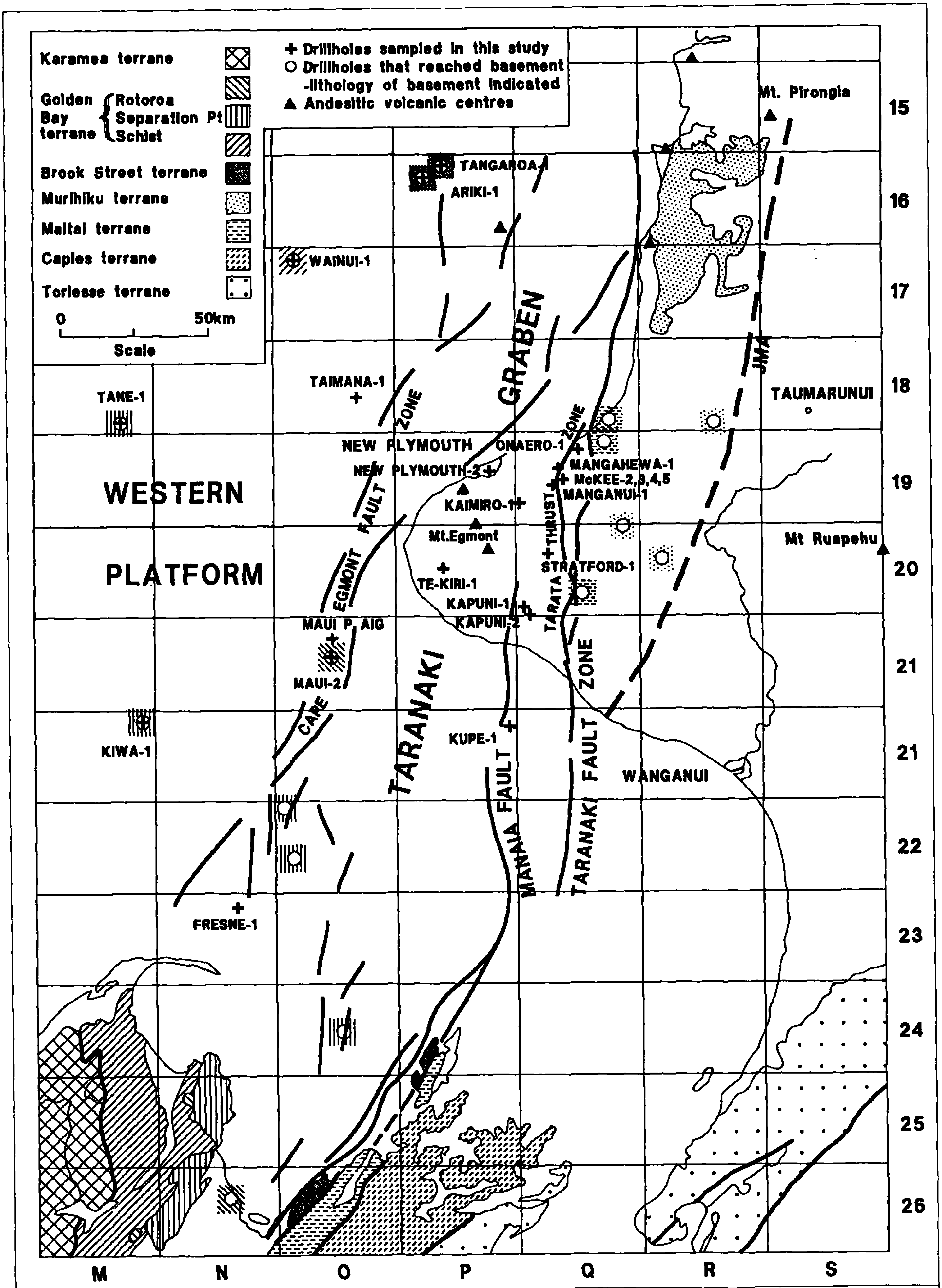
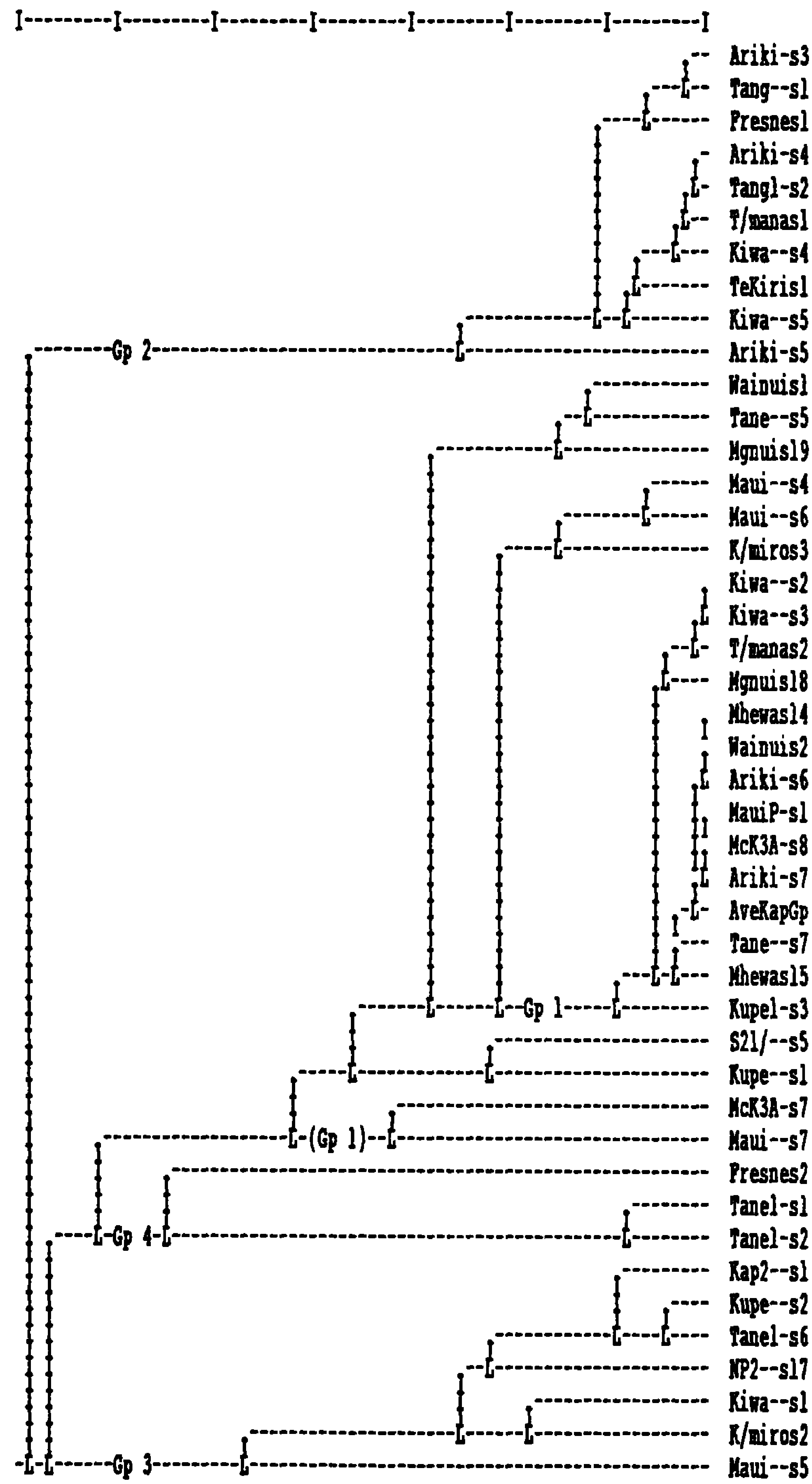


Figure 1: Locality map of Taranaki Basin showing basement geology, major structural elements, and drillholes with basement types where they encountered it (after Wodzicki 1974, Knox 1982, Bishop *et al.* 1985, King and Robinson 1988, and Beggs pers. comm.). The Junction Magnetic Anomaly (JMA) probably separates Murihiku and Torlesse terranes in the North Island.

Sample No	Drillhole and depth	Age	Il	Mt	Sd	Bt	Cl	Gn	Sl	Zn	Tt	Ep	Cz	At	Tm	Pp	Cd	St	Hb	Oy	Cy	Rt	As	Ap	HF	+Por %	+Perm mD	Formation
^P16/ s3	Ariki-1 500-50m	lWn-Wc	6	79	2	0	2	0				0	1	0		0			4	5	1			0	6.0			Gnt Frsets
^P16/ s1	Tangaroa-1 550-600m	lWn-Wc	11	59	3	1	0	5			1	2	3			1			10		1			1	3.8			Gnt Frsets
^P16/ s4	Ariki-1 1150-90m	lWn	31	43	6	3	2	2				4	3			2			2	1				1	4.6			Gnt Frsets
^O17/ s1	Wainui-1 930-80m	Wn	26	4	9	5	2	7			0	18	14	1					13					2	1.5			Gnt Frsets
S21/ s5	934 648 (surface)	?Wp-Wm	20		25	17	7	3		0	2	10	5		0				11			0			1.1			
^P22/ s1	Kupe-1 350-415m	Wp-Wm	39		11	26	4	3		0	1	7	2			3			4					0	2.7			Whenuakura
^M18/ s5	Tane-1 1800-70m	Wp	41	2	7	6	4	5		1	2	14	14	0					2					2	0.6			Gnt Frsets
^O18/ s1	Taimana-1 1000-80m	Wp	26	47	3	6	1	3		0	0	5	3						6						1.9	low		Gnt Frsets
^O21/ s4	Maui-2 503-76m	lWo-Wp	33	12	22	5	5	8		0	0	6	4			1			4	0				0	1.3			Gnt Frsets
^Q21/ s1	Kapuni-2 549-622m	lWo	19	20	29	1	4	3			1	4	3			3		0	7	1	4			1	2.9			M/mateaonga
^M22/ s1	Kiwa-1 1370-410m	lWo-eWp	14	4	24	4	7	7			1	17	7			8			3					3	2.1			Gnt Frsets
^M22/ s2	Kiwa-1 1645-75m	lTt-Tk	59	16	7	3	2	2			1	7	1			1			1						6.7			=Mngnui l
^M22/ s3	Kiwa-1 1735-60m	lTt	55	17	7	1	1	1			2	9	2			2			1					0	7.7			=Mngnui l
^P22/ s2	Kupe-1 2106-70m	lTt	27	17	41		2	1		1	2	2	1			6									3.2			Mngnui l
^O21/ s5	Maui-2 1381-417m	eTt	6	6	19	9	23	1			1	16	13		1					0				6	3.1			Manganui
^P19/ s2	Kaimiro-1 1610-50m	eTt	11	17	23	1	5	3		1	2	12	13		1	5			0		4			2	0.2			Mt Msnger
^Q19/s19	Manganui-1 950-1040m	eTt	29		17	2	4	2		4		13	20			8								1	0.2			Mt Msnger
^O18/ s2	Taimana-1 2870-905m	Sw	56	16	6		2	1			2	6	6			1			2	2					0.9	?5		Wai-iti Gp
^P19/ s3*	Kaimiro-1 2150-200m	lSl	*32	26	15	3	2	1		13		2				2			2		3				*0.4			Moki Fm
^P19/ s4	N P/mouth-2 2438-63m	Sl	2	3	67	1	13	1				4	1			8								0	1.4			
^P16/ s5*	Ariki-1 3000-30m	mPl	*	41	18			1	1	1		11	4			4			11	1	4			3	*2.2			Mngnui Fm
^Q19/s18	Manganui-1 3192-204m	lLw-Po	70	5	17			0		1		3	1			2			0		1				6.7			Taimana
[Q19/s14*	Mangahewa-1 3472.9m		*93	7																					*0.03	9		Otaraoa
^P16/ s2	Tangaroa-1 3561-82m	Ar	36	60	2					2															3.3	19.9		T/roa Sst
[Q19/s15	Mangahewa-1 3597.2		79							21															0.01	9		Kapuni
[O21/ s1	Maui P/fm A1G 2745.5m	E-eO	97				1												1					1	0.05	16		?Kaiata
[O21/ s2	Maui P/fm A1G 2805m	cf E-eO	92					1		2					4			0					1		0.2	16		
[O21/ s3	Maui P/fm A1G 2844.1m	E-eO	70					2		18		0			7			1				2	0		0.3	16		
[P19/ s1	N P/mouth-2 3912.6m	E-eO	91				3		1	3					2										2.5	15		Kapuni
[Q20/ s1	Kapuni-1 3261m	E-eO	76	1					2	20					1							0			2.4	6.1	<0.5	Kapuni
[Q20/ s2	Kapuni-1 3333m	E-eO	83						1	16															>5	9.4	<1	Kapuni?
[Q19/ s1	McKee-2 2358.2m	E-eO	78					2		8		0			10			1				1			0.3	15.1	23	McKee
[Q19/ s2	McKee-3A 2134.8m	E-eO	90							4					3				1				2		<0.1	18.0	6.0	McKee
[Q19/ s3	McKee-3A 2151.5m	E-eO	83			1				6					5		1					4			0.2	15.5	1.2	McKee
[Q19/ s4	McKee-3A 2168m	E-eO	74							8					18										0.2	17	2.6	McKee
[Q19/ s5	McKee-3A 2184.3m	E-eO	70					2	0	8					17		1	0				2	1		0.6	16.2	1.8	McKee
[Q19/ s6	McKee-3A 2202.6m	E-eO	64					6	0	24					4		1	0				1			0.7	18.7	70	McKee
[Q19/ s7	McKee-3A 2217.8m	E-eO	36					27	1	24					11			1							1.2	12.6	2.2	McKee
[Q19/ s9	McKee-4 2356m	E-eO	86					4	1	6					2		0	0				1	0		0.1	17.1	113.7	McKee
[Q19/s10	McKee-4 2458.6m	E-eO	82					4		10					4			0				0	0		2.5	16.5	42	McKee
[Q19/s11	McKee-5A 2292.3m	E-eO	88					3		4					5							0	0		0.1	16.7	31	McKee
[Q19/s12	McKee-5A 2328m	E-eO	92				0	2	0						4		0					0	0		0.2	18.5	150	McKee
[Q19/s13	Onaero-1 3027.5m	E-eO	63	15		1		1	1	15					2							1	1		0.2	6.2	0.01	McKee
[Q19/s16	Manganui-1 3548m	E-eO	87	1					1	9					1							1			0.2	10.5	1.03	McKee
[Q20/ s3	Stratford-1 4119.4m	E-eO	96							2		1											1		0.2	10.9	0.6	McKee
[Q20/ s4	Stratford-1 4136.3m	E-eO	74						1	22					3							0			0.3	11.2	1.3	
[Q20/ s5	Stratford-1 4140.7m	E-eO	99																						0.3	8.8	1.3	McKee
^N24/ s1	Fresne-1 425-49m		16	51	12	8	5	4		1	1	1			1										0.3	22		Kapuni Gp
[Q19/ s8	McKee-3A 2221.5m	E-eO	99																						0.01	3.7	0.01	Mangahewa
^O21/ s6*	Maui-2 3048-63m	mDw-eAb	*42	17	22	11	6			1														1	*0.7	18		e M/hewa
^O21/ s7*	Maui-2 3121-39m	mDw-eAb	*38		24					38															*0.3			e M/hewa
^P20/ s1*	Te Kiri-1 4612-26m	Dt	*25	50	7					18															*0.1	10		Kapuni Gp
^P22/ s3	Kupe-1 3331-53m	Dt	48	16	2	17		2		3	1	1				2			5	1	2				0.7			Kaimiro Fm
^M18/ s6	Tane-1 3238-89m	Dt	30	8	60	1				1															3.0			Tane Fm
^N24/ s2	Fresne-1 1010-31m	C-Pal	11	13	6	19	4	2		6	12	21	4											2	0.4	22		Pakawau Gp
^P16/ s6*	Ariki-1 4451-66m	Mh	*83	11						6															*0.4			Tahi Gp
^P16/ s7	Ariki-1 4682-703m	Mh	99																						0.5			Tahi Gp
^M22/ s4	Kiwa-1 3571-83m	Mh	28	69		2				1															1.4			Tahi Gp
^M22/ s5*	Kiwa-1 3691-94m	Mh	*30	36		11	5	1		11					1									5	*0.3			Tahi Gp
^O17/ s2	Wainui-1 3721-39m	Cret	91	9																					4.1			Tahi Gp
[M18/ s1	Tane-1 3514.7m	Mh	20			34	2	5		12				1	4							2	1	19		26.9	816	Pakawau
[M18/ s2	Tane-1 3515.0m	Mh	32			41	5	4		3					3			1				1	1	9		26.1	477	Pakawau
^M18/ s7*	Tane-1 3727-51m	Mh	*60	9		4	4	9		9					1									4	*0.3	16		Pakawau Gp

Results are percentages of the heavy fractions. Values are given to nearest whole number; hence "0" represents 0 - 0.5%
Figures in the final column represent the heavy fraction as a percentage of the total sample.
Age code: Most symbols are the normal Series/Stage abbreviations. e=early m=mid l=late E-eO = Eocene to e Oligocene
Clinozoisite and zoisite not distinguished; both are probably present. ^ - cuttings [- cores
P22/s3 contained a conspicuous grain of kyanite. It also contained 1% of atacamite, which may be a machinery corrosion product.
Traces of olivine were present in P22/s3 and Q21/s1; that in P22/s3 is forsterite; in Q21/s1 it is more iron-rich.
Traces of monazite were present in Q19/s9 and s12, N24/s2, and M18/s1.
+ - Porosity and permeability values on adjacent material were obtained where available from well completion reports; methods of determination varied, and some were estimates.
Percentages have been recalculated to exclude pyrite, barite and siderite. Carbonates and pyrite are diagenetic, and barite a mud additive. As pyrite probably formed from other opaques during diagenesis, there could be some justification for assigning it to other opaque categories, but the effect is not likely to be great, as most pyrite-rich samples are rich in other opaques anyway. The heavy fraction as a percentage of total sample has also been recalculated to exclude pyrite, barite and carbonates.
* - samples containing >70% pyrite, barite, and carbonates.
Il = ilmenite; Mt = magnetite; Sd = semi-opaque debris; Bi =biotite; Cl = chlorite; Gn = garnet; Sl = spinel; Zn = zircon;
Tt = titanite; Ep = epidote; Cz = clinozoisite; At = allanite; Tm = tourmaline; Pp = pumpellyite; Cd = chloritoid; St = staurolite;
Hb = hornblende; Oy = Orthopyroxene; Cy = clinopyroxene; Rt = rutile; As = anatase; Ap = apatite.

Table 1: Heavy minerals from Taranaki Basin Cretaceous-Tertiary sandstones (in approximate stratigraphic order).



			Factor proportions			
			1	2	3	4
Ariki-s3	lWn-Wc	Giant Foresets		100		
Tang--s1	lWn-Wc	Giant Foresets	6	80	6	9
Fresnes1		Kapuni Gp	8	57	16	19
Ariki-s4	lWn	Giant Foresets	28	50	11	11
Tang1-s2	Ar	Tangaroa Sst	34	68		
T/manas1	Wp	Giant Foresets	20	55	6	19
Kiwa--s4	Mh	Tahi Gp	24	77		3
TeKiris1	Dt	Kapuni Gp	28	64	7	1
Kiwa--s5	Mh	Tahi Gp	24	44		33
Ariki-s5	mPl	Manganui Fm		57	38	13
Wainuis1	Wn	Giant Foresets	21	5	32	43
Tane--s5	Wp	Giant Foresets	38	2	24	37
Mgnuis19	eTt	Mt Messenger	29		45	28
Maui--s4	lWo-Wp	Giant Foresets	30	13	38	19
Maui--s6	mDw-eAb	Mangahewa	34	17	29	20
K/miros3	lSl	Moki Fm	34	32	24	9
Kiwa--s2	lTt-Tk	=l Manganui Fm	57	17	13	12
Kiwa--s3	lTt	=l Manganui Fm	56	19	15	10
T/manas2	Sw	Wai-iti Gp	60	19	14	8
Mgnuis18	lLw-Po	Taimana	72	5	25	
Mhewas14		Otaraoa	94	7		
Wainuis2	Cret	Tahi Gp	92	10		
Ariki-s6		Tahi Gp	88	13		
MauiP-s1	E-eO	Kaiata Fm	100			
McK3A-s8	E-eO	Mangahewa	101			
Ariki-s7	Mh	Tahi Gp	101			
AveKapGp	E-eO	Kapuni/McKee	97			
Tane--s7	Mh	Pakawau Gp	68	12	1	19
Mhewas15		Kapuni Gp	97			3
Kupe1-s3	Dt	Kaimiro Fm	40	18	3	38
S21/--s5	?Wp-Wm		8		45	49
Kupe--s1	Wp-Wm	Whenuakura	23		20	58
McK3A-s7	E-eO	McKee Fm	72			27
Maui--s7	mDw-eAb	Mangahewa	56		41	3
Fresnes2	Cret-Pal	Pakawau Gp		15	20	71
Tane1-s1	Mh	Pakawau Gp				100
Tane1-s2	Mh	Pakawau Gp	9		1	90
Kap2--s1	lWo	Matemateaonga	18	24	51	6
Kupe--s2	lTt	Manganui Fm	27	17	60	
Tane1-s6	Dt	Tane Fm	28	6	74	
NP2--s17	Sl				100	
Kiwa--s1	lWo-eWp	Giant Foresets	7	4	55	34
K/miros2	eTt	Mt Messenger	6	21	52	21
Maui--s5	lTt	Manganui Fm		5	49	55

Figure 2: Cluster analysis of Taranaki Basin heavy mineral samples. Factor proportions are from factor analysis results listed in Table 3.

necessarily represented by samples, and that it uses the collective properties of all the data rather than of extreme values. It can produce suitable solutions in the presence of noisy or "messy" data points.

The cluster analysis uses similarity/dissimilarity coefficients based on a "distance coefficient" computed as the square root of the average squared difference between two variables. A phenogram (Figure 2) is constructed based on the coefficients, using unweighted pair groups and arithmetic averages. To avoid distorting the phenogram by a disproportionately high number of similar Kapuni Group (McKee Formation) samples ("E-eO" in Tables 1 and 3), 20 similar samples are represented by one average.

General Geology and Potential Provenance Rocks

Elements of the regional basement geology and drillhole locations are shown in Figure 1. Major structural elements are the Taranaki Graben, the Cape Egmont Fault Zone separating it from the Western Platform on the west, and the Taranaki Fault Zone separating it from the Patea-Tongaporutu High on the east (Knox 1982). The sedimentary sequence consists of thick Cretaceous to Holocene sediments (4 km to 7 km in the graben) on a basement of Cretaceous granites and pre-Cretaceous igneous and metasedimentary rocks (King and Robinson 1988). All drillholes east of the Taranaki Fault Zone reached indurated Paleozoic-Mesozoic sedimentary basement between 326 m and 2500 m (McLernon 1972). Basement has not been intersected in deeper parts of the basin, namely the North Taranaki Graben and beneath Taranaki Peninsula. Shallow-angled overthrusts along the central-eastern margin of the basin, including allochthonous McKee Formation, resulted from compression in the late Oligocene - early Miocene (King and Thrasher in press).

Areas of basement rock currently known that could represent source areas for the Cretaceous-Holocene sedimentary sequence are:

(i) Murihiku rocks under the central North Island flanked on the west by Maitai and on the east by Torlesse rocks;
(ii) an extension of the basement rocks of the north-west Nelson area beneath the offshore area to the north;
(iii) rocks of eastern Nelson and western Marlborough;
(iv) Neogene and Quaternary volcanics - from west Auckland, Egmont and Taupo volcanoes.

These four potential source areas are discussed below.

Murihiku and Torlesse rocks of the North Island

Though little is known specifically of the heavy minerals in these rocks, source rocks for Murihiku sediments in the Jurassic were acid to intermediate intrusive and volcanic rocks (Suggate *et al.* 1978, p. 253), and abundant plutonic debris in the Moeatoa Conglomerate shows that this type of rock was significant in the source area in the Triassic (Suggate *et al.*,p. 213). In Southland, Brothers (1959) found that apatite, zircon, epidote and hornblende were common heavy minerals in Murihiku rocks, and the few Maitai samples recorded are similar. In the Taringatura Hills (Southland) opaques, biotite and apatite are common detrital heavy minerals, and epidote, pumpellyite and prehnite have formed diagenetically (Coombs 1954). Thus heavy minerals in sediments derived from the Murihiku terrane could be expected to be dominantly opaques, apatite, biotite, zircon and epidote, with hornblende having the potential to be abundant where it has not been leached. Pyroxene and prehnite are unlikely to have survived.

Torlesse sediments, with a similar diagenetic history, may be difficult to distinguish from Murihiku, even though their clastic composition is different (Turnbull 1979). In the South Island Torlesse rocks are characterized by ilmenite, epidote and semi-opaque debris (with biotite also present in the Rakaia sub-terrane), and lesser titanite, zircon, garnet, chlorite and apatite (Smale 1988a, 1990). In Northland heavy minerals from Waipapa (Torlesse) rocks are dominated by ilmenite and semi-opaque debris, with lesser magnetite, zircon, epidote and hornblende (Hayward and Smale in prep.). Hornblende and pyroxene occur sporadically in high proportions.

There is need for greater knowledge of heavy minerals in Murihiku and Torlesse rocks in North Taranaki, and especially in Murihiku rocks outcropping south of Kawhia, to help assess their sedimentary sequence source potential.

Basement rocks of north-west Nelson

Basement rocks of the large and complex north-west Nelson area probably extend offshore to the north for at least 200 km (Wodzicki 1974). Chemical analyses of basement material intersected in Tane-1 and Kiwa-1 show that they are of Separation Point type (A.J. Tulloch, pers. comm.) as in Maui-4 (Wodzicki 1974). The area can be recognised as having provided sediment for Eocene rocks in Maui Platform wells and in onshore wells to the east, in spite of impoverished heavy mineral suites (Smale and Morton 1987). Basement rocks correlated with the Rotoroa Complex (of the Golden Bay terrane) were encountered in a drillhole at Ruby Bay (Watters in Hatherton 1967), which is also similar to basement in Maui-2 (Wodzick 1974).

The nature of the Golden Bay terrane (the largest adjacent north-west Nelson basement area and probably the dominant influence) and the Karamea terrane (a more distant influence) suggests a suite of granitic and metamorphic rocks with some old volcanic and sedimentary rocks. Expected heavy minerals could be hornblende, magnetite, ilmenite, titanite, epidote, biotite, apatite, zircon, garnet, staurolite, and sillimanite. The Rotoroa complex, with its diorite and associated amphibolite, epidiorite and gabbro, would probably have provided a similar suite, perhaps with a greater proportion of biotite (Grindley 1978).

Eastern Nelson and north-western Marlborough

Rocks in this area represent several terranes - from west to east Brook Street/Murihiku, Drumduan, Dun Mountain/Maitai, and Caples (Bishop *et al.*,1985). The heavy mineral assemblages may be indistinguishable, since they have mostly originated from similar basic to intermediate igneous rocks, and Caples sediments may have been derived from Brook Street terrane (Turnbull 1979). Hornblende, pyroxene, magnetite, ilmenite, olivine, and apatite might be derived from the Brook Street terrane. The most abundant heavy mineral is likely to be chlorite, but it would probably be in a fine-grained form unlikely to survive transport in discrete grains. As noted above, Murihiku minerals might be ilmenite, semi-opaque debris, epidote and zircon. The Drumduan terrane, being of small areal extent and mainly argillite, is not likely to have provided much in the way of 2-4 phi heavy minerals.

The Dun Mountain and Maitai terranes are probably volumetrically more significant. From granodiorite, spilite, serpentinite, dunite, and volcanic sandstones associated with the Dun Mountain terrane, clinopyroxene and olivine are likely to be the dominant heavy minerals. However, these are unlikely to survive long in sediments, and the minerals more likely to be encountered are the remaining accessories titanite, apatite, magnetite, ilmenite, and chromite. Maitai minerals, like Murihiku minerals, could be apatite, epidote and zircon (Brothers 1959), but hornblende, pyroxene, and magnetite could be expected from southern areas (Coombs *et al.* 1976).

Caples terrane rocks may be volumetrically abundant. Little information is available on them in Marlborough, but they could be expected to be similar to Caples rocks in western Southland, where they contain dominantly volcanic (andesitic) and plutonic (dioritic) detritus derived mainly from the Brook Street terrane in the west. Heavy minerals vary in different formations in the Caples terrane, but are dominantly epidote, hornblende, pyroxene, opaques and micas (Turnbull 1979). Information on opaques is not available, but in view of the large andesitic and dioritic component a high proportion of magnetite is possible.

Neogene and Quaternary Volcanics

Volcanoes of Miocene age exist off the west coast of Auckland (Hatherton *et al.* 1979, Hayward 1979). Volcanogenic sediments (Waitakere Group) sampled from the east of these volcanoes are characterised by clinopyroxene and minor hornblende; orthopyroxene is present in some samples (Smale 1988b, Hayward and Smale in prep.). Both Egmont and Taupo Volcanic Zone rocks date back only to early Pleistocene (Neall 1979, Cole *et al.* 1986), and would not have influenced any but Nukumaruan or later sediments. Heavy minerals derived from Egmont volcanics are dominated by clinopyroxene with lesser hornblende and magnetite. Those from the Taupo Volcanic Zone are dominated by orthopyroxene, with minor clinopyroxene and hornblende (Cole *et al.* 1986, Smale 1991).

Discussion

Intrastratal Solution

Solution as a result of depth of burial has had a strong influence on some heavy mineral suites in the Taranaki Basin, as indicated by variation in content of hornblende, epidote, semi-opaque debris, staurolite, and garnet. These minerals are nearly all absent below the depths at which they tend to dissolve in other areas with substantial pore-fluid circulation (Morton 1984, Milliken 1988). However, some deep samples (> 3500 m) from Tane-1, Te Kiri-1, Ariki-1, and Kiwa-1 show fewer diagenetic effects than many shallower samples, because pore-fluid circulation has been restricted by impermeable layers or muddy matrix, some of which have caused overpressuring and preserved primary porosity (Hunt 1990, van der Lingen & Smale in press.). Where pyroxene is present it shows no sign of solution, although it must have been removed from some samples, and clearly shows solution effects in other areas such as North Auckland Miocene (Po) sediments.

Statistical analysis

Factor analysis: The program chose four as the optimum number of factors (Tables 2 and 3). Though these are purely statistical artefacts, they happen to correspond fairly closely with some likely provenance influences, and are considerably more meaningful geologically than results using five or six factors. The four factors represent:

(1) An ultra-resistant suite of ilmenite-zircon present in nearly all samples. Where it forms a high proportion of the heavy mineral suite, it may represent either recycled sediments or sediments leached *in situ*.

(2) Dominantly magnetite, with some hornblende and pyroxene, probably representing volcanic sources. Such sources in Pleistocene or later sediments are probably Egmont and the Taupo Volcanic Zone. Miocene sediments could have been affected by west Auckland Miocene volcanics. In earlier sediments the source could be any of the Brook Street, Dun Mountain/Maitai, or Caples terranes.

A north-west Nelson source, such as Devil River volcanics of the Golden Bay terrane, is unlikely because it could be expected to be associated with other Golden Bay terrane source rocks, which factor 2 is not. In view of the wider extent of Caples terrane than other terranes, it may be the most influential of these sources.

(3) Sodeb[1]-chlorite-epidote-clinozoisite-pumpellyite with some hornblende and clinopyroxene. This suite probably reflects a dominantly Murihiku or Torlesse source, in which most major heavy minerals formed diagenetically, and detrital heavy minerals are relatively scarce.

(4) Biotite-epidote-apatite-garnet-titanite-staurolite. This suite probably represents a metamorphic and granitic terrane comparable with the basement of the north-west Nelson area. Epidote and titanite are likely to be from I-type Separation Point and Rahu Suites (Golden Bay terrane). Biotite, apatite and garnet are from S-type Karamea Suite (Karamea terrane) (Tulloch 1983, 1988, Smale 1990b), or from Rotoroa Complex (Grindley 1978).

Cluster analysis: Four clusters or groups are readily distinguished in Figure 2, and can be related to the four factors in the factor analysis. The factor 1 cluster is the largest, and includes mostly McKee and Kapuni samples, reflecting either a high degree of solution that they have undergone, or the reworking of parent sediments. The factor 2 cluster is mostly Giant Foresets, but also includes samples from Tahi Group in Kiwa-1. The factor 3 cluster is rather mixed, but mostly recent. The factor 4 cluster includes most Pakawau Group samples.

	1	2	3	4
Ilmenite	86.1	6.0	2.2	21.9
Magnetite	-	81.9	2.6	-
Sodeb	0.5	2.5	55.9	-5.8
Biotite	-	-	-4.9	32.1
Chlorite	-0.7	-	9.6	6.4
Garnet	2.2	0.7	2.4	5.4
Spinel	0.3	-	-	-
Zircon	9.3	2.1	-2.4	5.5
Titanite	-0.3	0.7	0.9	3.5
Epidote	-0.6	0.8	14.0	11.3
Clinozoisite	-	-0.5	11.0	5.3
Allanite	-	-	-	0.4
Tourmaline	3.4	-1.2	-1.7	2.2
Pumpellyite	-	0.4	6.8	-0.6
Chloritoid	0.1	-	-	-
Staurolite	-	-	-	0.2
Hornblende	-	4.1	4.3	2.6
Orthopyroxene	-	1.1	-	-
Clinopyroxene	-	1.7	1.7	-0.4
Rutile	0.4	-0.2	-0.4	0.7
Anatase	0.2	-	-0.2	0.5
Apatite	-0.4	-	-1.3	8.8

Table 2: Heavy mineral contents of "end-members" for Taranaki Basin, from factor analysis.

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[1] sodeb = semi-opaque debris (Smale 1988a) - a fine-grained, earthy aggregate of epidote or pumpellyite with quartz.

Lithology		1	2	3	4	Age
	Western Platform					
Sltst	^P16/ s1 Tangaroa-1 550-600m	6	80	6	9	lWn-Wc
Mst/sltst	^P16/ s3 Ariki-1 500-550m	-	100	-	-	lWn-Wc
Mst/sltst	^P16/ s4 Ariki-1 1150-90m	28	50	11	11	lWn
Sltst/mst/sst	^O17/ s1 Wainui-1 930-80m	21	5	32	43	Wn
Silty mst	^O18/ s1 Taimana-1 1000-80m	20	55	6	19	Wp
Sandy sltst	^M18/ s5 Tane-1 1800-70m	38	2	24	37	Wp
Mst	^M22/ s1 Kiwa-1 1370-410m	7	4	55	34	lWo-eWp
Sandy sltst	^M22/ s2 Kiwa-1 1645-75m	57	17	13	12	lTt-Tk
Sandy sltst & mst	^M22/ s3 Kiwa-1 1735-60m	56	19	15	10	lTt
Mst/sst/sltst	^O18/ s2 Taimana-1 2870-905m	60	19	14	8	Sw
Mst	^P16/ s5* Ariki-1 3000-30m	-8	57	38	13	mPl
Sst	^P16/ s2 Tangaroa-1 3561-82m	34	68	-	-1	Ar
Sltst	^M18/ s6 Tane-1 3238-89m	28	6	74	-7	Dt
Sltst	^P16/ s6* Ariki-1 4451-66m	88	13	-	-	Mh
Mst	^P16/ s7 Ariki-1 4682-703m	101	-	-	-1	Mh
Mst	^O17/ s2 Wainui-1 3721-39m	92	10	-	-1	Cret
Sst	[M18/ s1 Tane-1 3514.7m	-	-	-	100	Mh
Sst	[M18/ s2 Tane-1 3515.0m	9	-	1	90	Mh
Sst	^M18/ s7* Tane-1 3727-51m	68	12	1	19	Mh
Sst	^M22/ s4 Kiwa-1 3571-83m	24	77	-3	3	Mh
Mst	^M22/ s5* Kiwa-1 3691-94m	24	44	-1	33	Mh
	Average Western Platform	34	32	14	22	
	Southern Taranaki Graben					
Silty mst	^P22/ s1 Kupe-1 350-415m	23	-	20	58	Wp-Wm
Mst/m.sst	^O21/ s4 Maui-2 503-76m	30	13	38	19	lWo-Wp
Mst	^P22/ s2 Kupe-1 2106-70m	27	17	60	-4	lTt
Mst/sltst, sst above	^O21/ s5 Maui-2 1381-417m	-8	5	49	55	eTt
F.sst	[O21/ s1 Maui P A1G 2745.5m	100	-	-	-	E-eO
M.sst	[O21/ s2 Maui P A1G 2805m	100	-	-	-	E-eO
C.sst	[O21/ s3 Maui P A1G 2844.1m	96	-	-1	5	E-eO
Sst	^N24/ s1 Fresne-1 425-49m	8	57	16	19	E-eO
Sltst	^O21/ s6* Maui-2 3048-63m	34	17	29	20	mDw-eAb
Sst	^O21/ s7* Maui-2 3121-39m	56	-	41	3	mDw-eAb
?Silty sst	^P22/ s3 Kupe-1 3331-53m	40	18	3	38	Dt
Thin sst/sltst/mst	^N24/ s2 Fresne-1 1010-31m	-6	15	20	71	C-Pal
	Average of 9 cuttings, S Taranaki Graben	23	16	31	31	
	Onshore Taranaki (excluding Tarata overthrust)					
Sandy mst	S21/ s5 934 648 (surface)	8	-1	45	49	?Wp-Wm
Mst top, sst base	^Q21/ s1 Kapuni-2 549-622m	18	24	51	6	lWo
F.sst(/mst)	^Q19/s19 Manganui-1 950-1040m	29	-1	45	28	eTt
Sltst/sst/mst	^P19/ s2 Kaimiro-1 1610-50m	6	21	52	21	eTt
Sst(/mst)	^P19/ s4 N P/mouth-2 2438-63m	-	-	100	-	Sl
Muddy sltst	^P19/ s3* Kaimiro-1 2150-200m	34	32	24	9	lSl
?Calc.sst	^Q19/s18 Manganui-1 3192-204m	72	5	25	-1	lLw-Po
Muddy sst	[P19/ s1 N P/mouth-2 3912.6m	98	-	-	-	E-eO
Sandy sltst	[Q19/s14* Mangahewa-1 3172.9m	94	7	-	-1	E-eO
Sltst (choc)	[Q19/s15 Mangahewa-1 3597.2m	97	-	-1	3	E-eO
Sst(/mst)	[Q19/s16 Manganui-1 3458m	98	1	-	-	E-eO
Sst	[Q20/ s3 Stratford-1 4119.4m	100	-	-	-	E-eO
F.sst	[Q20/ s4 Stratford-1 4136.3m	97	-	-1	4	E-eO
Muddy sst	[Q20/ s5 Stratford-1 4140.7m	101	-	-	-1	E-eO
Muddy sst (choc)	[Q20/ s1 Kapuni-1 3261m	96	2	-1	3	E-eO
Sst	[Q20/ s2 Kapuni-1 3333m	98	-	-	2	E-eO
Sltst	^P20/ s1* Te Kiri-1 4612-26m	28	64	7	1	Dt
	Average onshore Taranaki	63	9	20	7	
	Tarata Overthrust slab					
Sst	[Q19/ s1 McKee-2 2358.2m	98	-	-	2	E-eO
Sst	[Q19/ s2 McKee-3A 2134.8m	100	-	-	-	E-eO
Sst	[Q19/ s3 McKee-3A 2151.5m	97	-	-	2	E-eO
Sst	[Q19/ s4 McKee-3A 2168m	99	-	-1	2	E-eO
Sst	[Q19/ s5 McKee-3A 2184.3m	98	-	-1	4	E-eO
Sst	[Q19/ s6 McKee-3A 2202.6m	92	-	-1	8	E-eO
Sst	[Q19/ s7 McKee-3A 2217.8m	72	-	-	27	E-eO
Mst (choc)	[Q19/ s8 McKee-3A 2221.5m	101	-	-	-1	E-eO
Sst	[Q19/ s9 McKee-4 2356m	98	-	-	2	E-eO
Sst	[Q19/s10 McKee-4 2458.6m	97	-	-	3	E-eO
Sst	[Q19/s11 McKee-5A 2292.3m	99	-	-	-	E-eO
Sst	[Q19/s12 McKee-5A 2328m	100	-	-	-	E-eO
Sst	[Q19/s13 Onaero-1 3027.5m	77	20	-1	5	E-eO
	Average overthrust slab	95	2	-	4	

/ - interbedded (lithology)   * - samples with >70% pyrite

Table 3: Proportions of "end-members" in samples, arranged in approximate stratigraphic order within geographic areas.

In addition to these groups, there are three small clusters, comprising eight samples containing elements of three or all four factors. Seven of these samples are Miocene or younger, indicating that during this time all recorded provenance areas provided sediment, especially to the Western Platform. This is confirmed in Table 3.

Stratigraphic and geographic distribution

At the top of the Giant Foresets in Ariki-1 and Tangaroa-1 the influence of volcanics (factor 2) is very strong (in this case the proportion of magnetite is particularly high), and could be from either the west Auckland or Taranaki volcanoes. Only in these two drillholes were samples taken that were young enough to show the influence of Taranaki or Taupo volcanoes. The high proportion of factor 2 in older (Miocene) sediments in Kaimiro-1 could be from west Auckland volcanoes, but in view of earlier influence of factor 2, such as that in the Eocene of Tangaroa-1, it could also reflect a Maitai-type source. Though it appears not to reflect a Murihiku assemblage, because of the proximity of Murihiku rocks in the Kawhia area these should be checked as a potential source - the data are lacking at present. In the western wells Tane-1 and Kiwa-1 the influence of factor 2 is low, with the exception of Cretaceous material in Kiwa-1 (at 3700 m). It is absent from Ariki-1 at 4500 m. In the South Taranaki Graben the influence of volcanics is generally low, except in the Kapuni Group (at 425 m) in Fresne-1. In onshore wells it is generally high in the west (though there is none in New Plymouth-2) and more erratic in the east.

The north-west Nelson or Rotoroa influence (factor 4) on the Western Platform in the Cretaceous is evident in Tane-1 and to a lesser extent in Kiwa-1, and in the Pliocene it is strong in Tane-1, and moderate in Kiwa-1 and Taimana-1. In the remaining drillholes in the Western Platform its influence is weak. It is of more general influence in the South Taranaki Graben. It is less evident in onshore wells, because of intrastratal solution, but it is in fact the only influence still recognizable in the Kapuni Group (Smale and Morton 1987). Where the sediments have not been so deeply buried, or where pore-fluid circulation has been restricted, even in the Cretaceous and Eocene, a greater influence of factor 2 and/or 4 is present (as in the Tangaroa Sandstone, the Kapuni Group in Fresne-1, and below the Kapuni Group in Tane-1, Kiwa-1, and Kupe-1).

The very impoverished suite in the Kapuni Group, consisting largely of factor 1, is one of the most striking features in Table 1. On land only in Onaero-1 does the Kapuni Group show influence of another factor (2). While this may be due to intrastratal solution, sediments of this age also reflect the end of a period of stable tectonics and passive margin development, with deep weathering conspicuous in many places. The intrastratal solution could thus have taken place at the source of the sediments.

A Murihiku/Torlesse influence (factor 3) is present in cuttings from shallow depths in Fresne-1 and various other wells. However, epidote minerals, which are the main indicators of this source, may have been dissolved from relatively deeply buried sediments in the Taranaki Basin, as they have in, e.g. Texas Gulf Plio-Pleistocene sediments below 3500 m (Milliken 1988), and from North Sea sediments below 1100 m (Morton 1984). The Murihiku/Torlesse has had a strong influence in the South Taranaki Graben, and distinctly less in the Western Platform (Table 3), even taking into account solution of the characteristic Torlesse minerals in the Cretaceous sediments.

Geological history indicated by heavy minerals

Most of the Cretaceous-Cenozoic sediment in the Taranaki Basin has been derived from Murihiku/Torlesse and north-west Nelson sources, and some volcanogenic provenance of Caples character. Heavy minerals in the south Kawhia area must be checked before the significance of a Murihiku source can be properly assessed. The influences have varied, however, even when the effects of solution are taken into account. In the South Taranaki Graben the north-west Nelson and Murihiku/Torlesse influences have been stronger than in the Western Platform.

A Maitai- or Caples-like source provided sediment in the Cretaceous-Paleocene in the areas of Kiwa-1, Te Kiri-1, and to a lesser extent in Kupe-1 and Fresne-1, but the influences were small in Ariki-1 and Maui. The sediments in Tane-1 had a mixed source in the earlier Cretaceous, but in the late Cretaceous were strongly influenced by north-west Nelson. It is possible that sources continued to be mixed, but evidence of them has been leached from Eocene to early Oliogocene sediments.

The abrupt change to a greater variety of heavy minerals and lack of progressive reintroduction of more soluble minerals, shown in the Miocene, probably represents more than a cessation of solution effects. It is presumably related to the onset of compression and overthrusting close to the Taranaki Fault, and coincident uplift in the hinterland to the south and east, ultimately causing increased sand deposition within the Taranaki Basin (King and Robinson 1988).

Andesitic volcanoes were active in the north-east of the basin in the mid to late Miocene (Hatherton *et al.* 1979, Hayward 1979, King and Thrasher in press). The effects of volcanic sources in the Miocene and Pleistocene are detected in factor 2, though they cannot easily be differentiated either from each other or from Caples-like sources. The striking influence of the Pleistocene volcanics in the Wanganui area (Smale 1991) would probably be more apparent in the Taranaki Basin if more Pleistocene samples had been studied. Nevertheless, it is clearly shown in Tangaroa-1 and Ariki-1.

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