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Provenance history of a Late Triassic–Jurassic Gondwana margin forearc basin, Murihiku Terrane, North Island, New Zealand: petrographic and geochemical constraints

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Abstract The Murihiku Terrane in the North Island was a forearc basin adjacent to a volcanic arc along the eastern margin of Gondwana during the Mesozoic. The rocks that infill the basin are mainly volcaniclastic sandstones and mudstones, often turbiditic, with sparse shellbeds, rhyolitic tuffs, carbonaceous sandstones, plant beds, concretionary horizons, and rare thick granitoid-rich conglomerates. Petrographic studies of the rock fragments in the sandstones show that andesites are the dominant lithic type, but there is a wide range of other lithologies, including dacites, rhyolites, ignimbrites, granitoids, quartzofeldspathic mica schists, rare amphibolites, and reworked mudstones and sandstones. The sandstones are texturally and mineralogically immature and suggest deposition relatively close to a source of high relief, undergoing physical rather than chemical weathering in cool- to cold-temperate conditions. Geochemical analyses of 67 whole-rock volcaniclastic sandstones and siltstones indicate that they were derived from an active and dissected volcanic arc in a convergent margin setting built upon relatively thin continental crust. Modal petrographic data and whole-rock geochemistry both confirm that there were systematic variations with time in the composition of clastic material being supplied to the basin. From the Late Triassic to Middle Jurassic, there was a decrease in silicic volcanic material, plutonics, and metamorphics, and an increase in the supply of andesitic detritus. This was followed in the Late Jurassic by a broader range of volcanic detritus, varying from basaltic andesite to rhyolite, which may have been caused by progressive extension of the volcanic arc and thinning of the crust, a precursor to the breakup of Gondwana in the Early–Middle Cretaceous. Comparison with the Southland segment of the Murihiku Terrane in the South Island suggests that there were significant along-arc source variations, with relatively less silicic but greater andesitic and continental crust contributions in the North Island than in Southland. This may be analogous to the modern Taupo-Kermadec arc where there is a south–north along-arc transition from a continental to an oceanic arc.

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INTRODUCTION

The history and geologic record of ancient eroded and dissected continental magmatic arcs along plate margins is best expressed and elucidated by studies of the adjacent sedimentary basins. This paper describes the Murihiku Terrane in western North Island, New Zealand, which is considered by most previous authors to be a forearc basin adjacent to a volcanic arc, above a westward-dipping subduction zone, along the eastern margin of Gondwana during the Mesozoic (Fig. 1) (Campbell & Coombs 1966; Ballance & Campbell 1993; Grant-Mackie et al. 2000). The basin is filled predominantly with volcaniclastic sediments. The purpose of this paper is to describe the provenance of these sediments

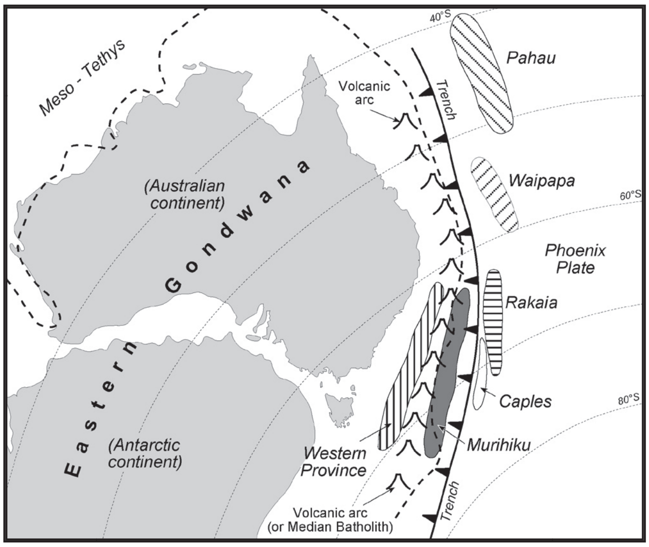

Fig. 1 Paleogeographic map of eastern Gondwana during the early Middle Jurassic including inferred positions of several basement terranes of New Zealand at the time, prior to final amalgamation in the Late Cretaceous (modified from Grant-Mackie et al. 2000). The Murihiku Terrane is shown occupying a position off the eastern continental margin of Gondwana, and east of a volcanic arc (the Median Batholith, marked by cones) and above a westward-dipping subduction zone (marked by heavy line with saw-teeth on down-dip side). The Brook Street and Dun Mountain–Maitai Terranes had already accreted on to the Median Batholith by the Middle Jurassic. This map by Grant-Mackie et al. (2000) is the first published attempt to place these terranes in their individual configuration, and is based on paleobiogeographic evidence, geochronology, mineralogic and sedimentologic criteria, and their present geologic relations. The dashed line marks the coastline of the time with local terrestrial environments extending eastwards from the continent at western North Island and parts of Southland.

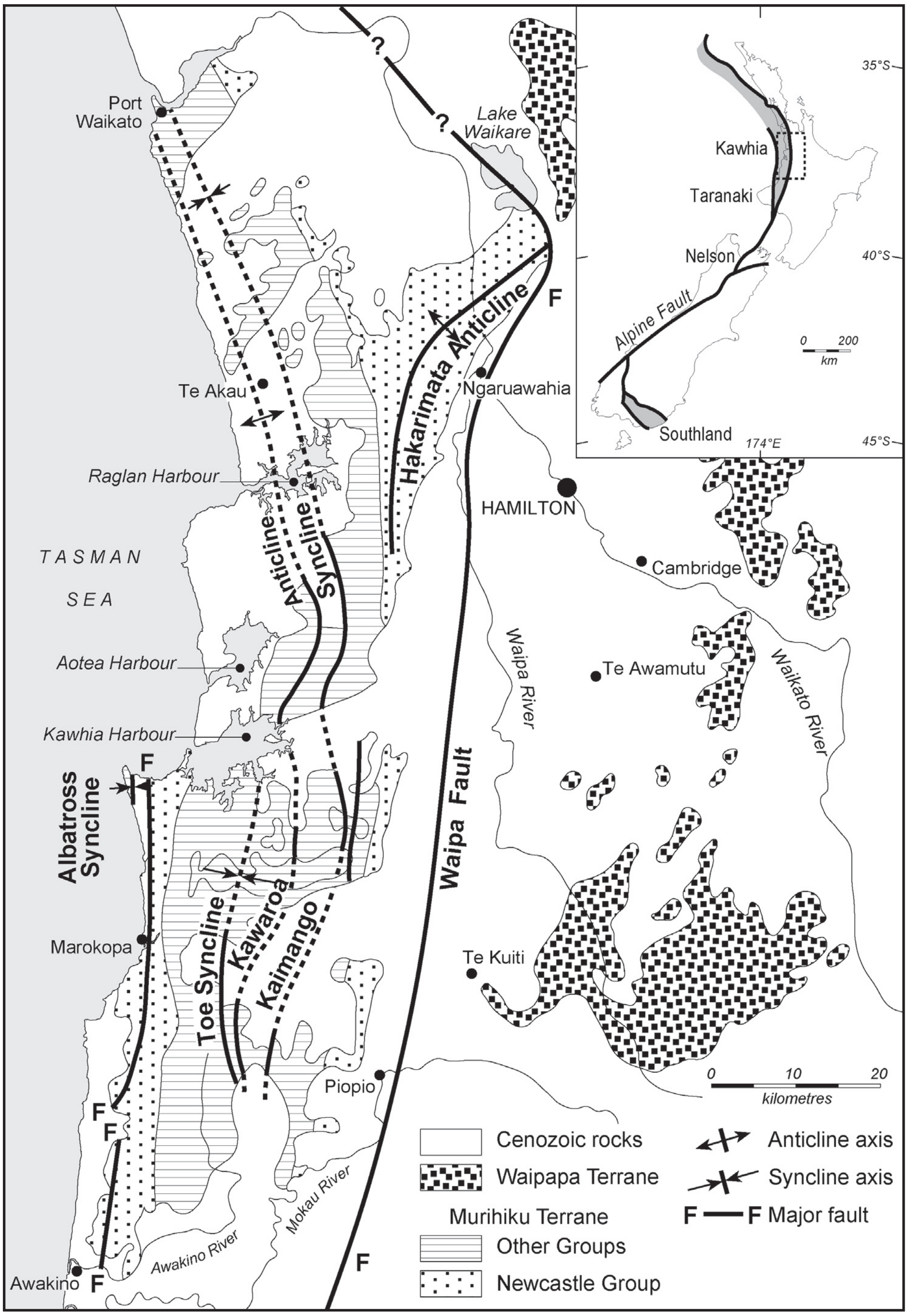

Fig. 2 Map of western North Island showing the distribution of the Murihiku Terrane and main structural features (modified from Kear 1978). Inset map indicates the present distribution (shaded) of the Murihiku Terrane in New Zealand (after Campbell et al. 2003), and the location of the figure (dotted).

from petrographic and geochemical studies, and to examine the changes in composition and evolution through time of the Murihiku rocks in the North Island. Some comparisons are also made with the Murihiku Terrane in the South Island.

GEOLOGIC SETTING

The Murihiku Terrane is one of several tectonostratigraphic basement terranes in New Zealand (e.g., Coombs et al. 1976; Bishop et al. 1985). Murihiku rocks outcrop in Southland and Nelson in the South Island, and in western North Island where they extend from Port Waikato in the north to Awakino in the south (Fig. 2). The boundaries of the Murihiku Terrane are faulted, but the terrane is characterised by broad open folds that are remarkably intact (Ballance & Campbell 1993). The adjacent volcanic arc is considered to be represented by the Median Batholith of Mortimer et al. (1999), but primary, *in situ* lavas and ignimbrites are absent from the Murihiku Basin, so it must have been distant from the arc.

The Murihiku Supergroup was initially defined by Campbell & Coombs (1966), and has been recently amended by Campbell et al. (2003) to include Late Permian carbonate sequences in the Kuriwao Group in eastern Southland (Campbell et al. 2001). The Murihiku Supergroup (or terrane) in the western North Island comprises five groups of rocks and ranges in age from Late Triassic (Oretian Stage) to at least

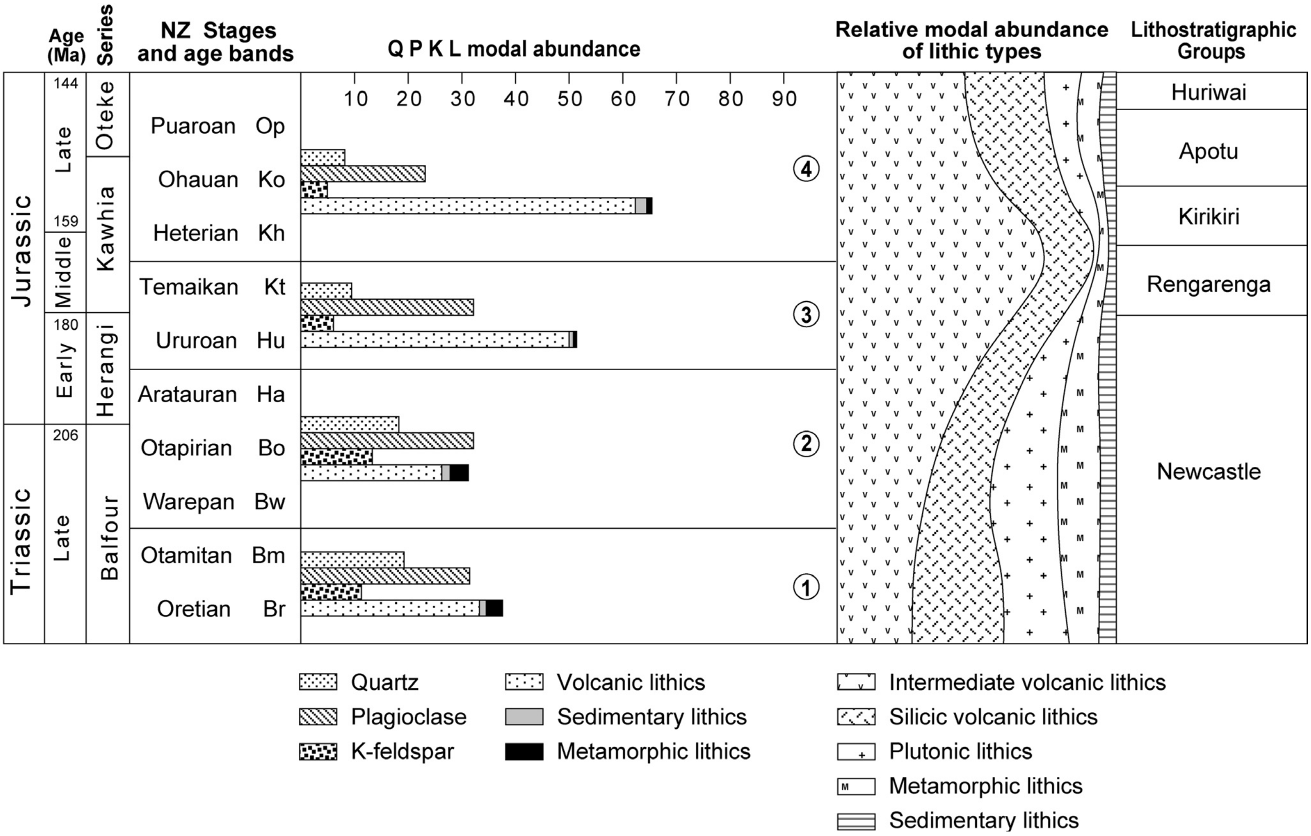

Fig. 3 Plots of variations in modal abundance of quartz (Q), plagioclase (P), K-feldspar (K), and lithic fragments (L) with time from early Late Triassic to Late Jurassic for Murihiku rocks in western North Island. New Zealand series and stage names and symbols are shown, together with the formally recognised lithostratigraphic groups in the North Island (at right). Histograms depict modal% variations in total quartz, plagioclase, K-feldspar, and total lithic fragments (subdivided into relative proportions of volcanic, sedimentary, and metamorphic lithics) for four age bands (see text): Br–Bm; Bw–Ha; Hu–Kt; and Kh–Op. The relative modal abundances of intermediate volcanic rocks (andesites), silicic volcanics and pyroclastics (rhyolites, dacites, ignimbrites), plutonics, metamorphics, and reworked sedimentary rocks as a proportion of total lithic types in each stage are also shown.

Late Jurassic (Puaroan Stage) (Fig. 3). Most recently, Kear & Mortimer (2003) have proposed a new Waipa Supergroup that overlies the Murihiku Supergroup west of the Waipa Fault, possibly unconformably, which would place an upper age of the Murihiku Terrane as middle Late Jurassic. However, we consider that the proposed new Waipa Supergroup requires further confirmation, at least west of the Waipa Fault, and hence for this paper we have retained the Late Jurassic Apotu and Huriwai Groups within the Murihiku Supergroup.

The Murihiku Terrane is richly fossiliferous (Grant-Mackie et al. 2000), and the macrofossils, which are mainly bivalves, brachiopods, belemnites, gastropods, and ammonoids, have allowed the Murihiku sequence to be subdivided into 16 biostratigraphic stages, spanning from Late Permian to Late Jurassic (Campbell et al. 2001). Only 10 of these stages, from Late Triassic to Late Jurassic, are present in the North Island (Kear 1964) (Fig. 3). The Murihiku Terrane is at least 10.5 km thick (Kear & Mortimer 2003), but may have been much thicker because the entire sequence has undergone burial metamorphism in the zeolite facies, which requires burial of the youngest Jurassic rocks by a younger cover (Coombs 1954; Boles 1974; Boles & Coombs 1975; Black et al. 1993) before amalgamation of the basement terranes in the Middle Cretaceous (Bradshaw 1989). Apatite fission-track thermochronologic studies by Kamp & Liddell (2000) suggested burial by a further c. 3 km of section, probably of Early Cretaceous age, overlying the youngest Jurassic beds. Hence, Murihiku sedimentation may have continued into the Middle Cretaceous (Ballance et al. 1980).

Murihiku rocks are mainly volcaniclastic sandstones and siltstones, with occasional shellbeds, rhyolitic tuff horizons, carbonaceous sandstones, concretionary horizons, plant beds, coal seams, and rare thick (up to 1000 m) granitoid-rich conglomerates in the southwest near Marokopa. Alternating sandstones and mudstones are generally well bedded and graded, and show features typical of turbidite deposition (Ballance & Campbell 1993). Turbidite facies range from conglomerate dominated (e.g., the Moeatoa Conglomerate; Keane 1986; Graham & Korsch 1990) to mud dominated (e.g., at Port Waikato; Ballance 1988). Some facies contain fining-upward, coarsening-upward, and coarsening-to-fining-upward cycles, compatible with submarine fan deposition (Boggs 2001).

The rocks of the Murihiku Terrane have been broadly folded forming the Kawhia Syncline, a north–northwest-trending asymmetric open fold with Late Jurassic beds in the core (Kear 1964; Edbrooke 2001) extending for 150 km from Taranaki to Port Waikato. Towards the south, this broad synclinal structure has transformed into north–south striking, subparallel, asymmetric folds (Fig. 2): Albatross Syncline, Toe Syncline, Kawaroa Anticline, and Kaimango Syncline (Waterhouse & White 1994). Murihiku rocks in the North Island have undergone very low grade metamorphism, and the sequence has been described by Clark (1982) and Black et al. (1993).

METHODOLOGY

Two hundred and eight samples were collected from exposures throughout the Murihiku Terrane in western North Island that cover the full range in ages. Details of sample locations are given in Middleton (1993). Petrographic data are based on 92 thin sections of volcaniclastic fine sandstones to fine conglomerates, and a selection of photomicrographs of representative sandstones and lithic fragments is shown in Middleton (1993). Modal analyses (500 points counted per section) were determined in 47 of the medium to coarse sandstones by the standard Gazzi-Dickinson method (Ingersoll et al. 1984) using unstained thin sections. Identification of felsic minerals and specifically quartz:feldspar ratios was confirmed by routine XRD analysis of 137 samples, using calibrated peak intensity versus mineral abundance charts of Hume & Nelson (1982), following the procedure of Nelson & Cochrane (1970). Sixty-seven samples were selected for XRF analysis of major and trace element compositions at the Analytical Facility, Victoria University of Wellington. All major element concentrations have been normalised and reported to 100 wt% volatile free. All laboratory data, including modal, XRD, and XRF analyses are available on request.

PETROGRAPHY

For purposes of petrographic and geochemical description, and to track variations in composition with time, the rocks of the Murihiku Terrane in the North Island have been subdivided into four stratigraphic provenance groups, or age bands, using the format of New Zealand stage names and symbols (Fig. 3):
(1) Late Triassic: Oretian–Otamitan (Br–Bm);
(2) Latest Triassic to Early Jurassic: Warepan–Aratauran (Bw–Ha);
(3) Early–Middle Jurassic: Ururoan–Temaikan (Hu–Kt);
(4) Late Jurassic: Heterian–Puaroan (Kh–Op).

These age bands are similar to those used by Roser et al. (2002), except their stratigraphic provenance groups extend back to the Late Permian for the Southland sequence, and their Late Triassic age band extends from the Kaihikuan (early Late Triassic) to the Warepan. Emphasis is placed in this paper on the petrography of the sandstones which are classified as feldspathic arenites and lithic arenites (Boggs 2001), and are texturally and mineralogically immature. The rocks are composed of four main constituents, quartz, feldspar, lithics, and a minor matrix, and are described below and summarised in Table 1.

(1) Quartz

Quartz is ubiquitous, averages 12 modal%, ranges from 2 to 35%, and shows a general trend from highest (18%) in the oldest rocks to 7% in the youngest rocks of the basin (Table 1; Fig. 3). Quartz typically occurs as monocrystalline subhedral to anhedral crystals, but may be undulose and occasionally occurs as polycrystalline aggregates.

(2) Feldspars

Feldspars are the most common mineral constituent in Murihiku rocks (Fig. 3), averaging between 27 and 44 modal%, and ranging from 2 to 50%. Feldspars vary in habit from euhedral, particularly in coarse-grained sandstones, to anhedral and angular to subangular in fine-grained sandstones. Plagioclase is the most common feldspar, averaging 22–32 modal% (ranges 1–50%), and compositions range from albite to labradorite. Orthoclase is less common (5–12%), but may reach 20% in medium to coarse-grained plutonic-rich lithic arenites. Microcline and perthitic feldspars are rare (<1 modal%) and occur in association with plutonic lithics. Feldspars are often replaced by laumontite (Black et al. 1993).

(3) Other detrital minerals

Other detrital minerals, ranging from rare to some (<1–5 modal%), include biotite, muscovite, augite, orthopyroxene, green-brown hornblende, and chlorite. Rare (<1%) quantities of zircon, apatite, garnet, and Fe-Ti oxides were also identified.

(4) Lithics (rock fragments)

The percentage of rock fragments ranges from 0% to as high as 80 modal%, with most rocks containing between 20 and 70%, and an overall average of 46% (Table 1; Fig. 3). Their abundance is strongly related to grain size with coarser sandstones generally having a higher lithic abundance. Rock fragments are usually more well rounded than detrital mineral grains, which are generally angular to subangular. Andesites are the dominant lithic type (Fig. 3), and their low abundance of ferromagnesian phenocrysts suggests that they are mainly high-SiO_2 andesites. Many of the volcanic lithics have been extensively hydrothermally altered, which makes their identification difficult. No volcanic or plutonic lithics of basic composition have been observed, suggesting that if basic volcanism or plutonism had occurred in the source area, it was very minor in volume and distribution, and not in sufficient volumes to be eroded, transported, and preserved in the basin in detectable amounts.

The following is a brief summary of the petrography of the lithic types, subdivided into volcanic, plutonic, metamorphic, and sedimentary. Further detailed petrographic descriptions and mineralogical and XRD data are given in Middleton (1993).

Volcanic lithic fragments

Andesites: Andesites are typically porphyritic with phenocrysts dominated by euhedral to subhedral plagioclase, with minor hornblende, augite, orthopyroxene, Fe-Ti oxides, and biotite, set in a trachytic to felted groundmass of plagioclase laths and devitrified glass. Some lithics appear to be aphyric, but are most likely fragments of groundmass only. Hydrothermal alteration of the andesite lithics is common, shown by alteration of phenocrysts and groundmass to chlorite, epidote, calcite, and leucoxene, and in some cases veins of polycrystalline quartz cut the fragments.

Dacites: Dacites are porphyritic and contain phenocrysts of plagioclase (dominant), quartz ± sanidine ± biotite, set in a felsic to hyalopilitic groundmass.

Rhyolites: Rhyolite lithics display variable textures, are generally porphyritic or vitrophyric, and may be flow banded

Table 1 Mean and standard deviations (SD, values in italic) of modal petrographic data (percentages, counted parameters, and recalculated values) of Murihiku rocks in western North Island for each age band, and the entire age range.

Age bands		Qm	Qp	Qtz	P	K	F	A	Dc	R	Luv	Lv	Lm	Ls	L	Lt	M	D	Misc.	P/F	LmLvLs %Lm	LmLvLs %Lv	LmLvLs %Ls
Kh-Op	mean	5.9	1.2	7.1	22.2	5.3	27.5	42.3	2.2	3.9	12.7	61.2	0.6	1.9	63.7	64.8	0.2	1	0.5	0.82	1.1	95.7	3.2
	SD	*5.4*	*1.1*	*6.2*	*6*	*3.4*	*8.7*	*15.6*	*1.6*	*2.6*	*5.2*	*14.8*	*0.9*	*2*	*13.8*	*13.3*	*0.5*	*1.7*	*0.7*	*0.1*	*1.8*	*4.4*	*3.6*
Hu-Kt	mean	8.4	0.9	9.3	31.5	6.5	38.0	30.5	3	4.3	11.4	49.1	0.5	0.3	49.9	50.8	0.8	1.4	0.4	0.84	0.9	98.5	0.6
	SD	*6.2*	*1.1*	*6.5*	*11.6*	*3.9*	*14.5*	*17.4*	*5.8*	*7.7*	*6.8*	*16.2*	*0.9*	*0.6*	*16.5*	*15.9*	*0.8*	*1.5*	*0.4*	*0.07*	*1.4*	*2.2*	*1.1*
Bw-Ha	mean	15.5	2.1	17.6	31.4	12.4	43.8	10.2	3.2	4.2	8.6	26.2	3.5	0.9	30.6	32.6	5.4	0.8	0.9	0.71	10.8	85.9	3.3
	SD	*7.3*	*1.2*	*7.8*	*12*	*4*	*13.1*	*6.6*	*4.8*	*5.5*	*5*	*12.1*	*6.6*	*0.7*	*13.2*	*13.2*	*4.8*	*1.1*	*1.6*	*0.07*	*14.2*	*14.7*	*3.6*
Br-Bm	mean	15.4	3.1	18.5	30.6	10.9	41.5	19.7	2.3	2.7	9.2	33.9	1.7	0.8	36.4	39.5	3.1	0.4	0.1	0.74	6.9	90.8	2.3
	SD	*9.8*	*1.5*	*10.6*	*12.4*	*5*	*15.7*	*22.8*	*4.1*	*1.9*	*4.9*	*23.9*	*2.4*	*0.9*	*23.4*	*23.2*	*3*	*0.5*	*0.1*	*0.07*	*8.6*	*9.9*	*1.9*
Total ($n = 47$)	mean	10.9	1.7	12.6	29.1	8.4	37.5	26.3	2.7	3.9	10.6	43.5	1.5	0.9	45.9	47.6	2.2	1	0.5	0.78	4.5	93.3	2.2
Br-Op	SD	*8*	*1.5*	*8.9*	*11.2*	*4.91*	*14.3*	*19.8*	*4.4*	*5.3*	*5.7*	*21*	*3.5*	*1.3*	*26.5*	*19.9*	*3.3*	*1.3*	*6.9*	*0.1*	*8.8*	*9.8*	*2.9*

Qm = monocrystalline quartz
Qp = polycrystalline quartz
Qtz = total quartzose grains (Qm + Qp)
P = plagioclase feldspar
K = K-feldspar
F = total feldspar (P + K)

A = andesitic lithic
Dc = dacitic lithic
R = rhyolitic lithic
Luv = unidentified volcanic lithic
Lv = total volcanic lithic
Lm = metamorphic lithic

Ls = sedimentary lithic
L = total lithics (Lm + Lv + Ls)
Lt = L + Qp
M = phyllosilicates
D = dense (heavy) minerals
Misc. = miscellaneous and unidentified grains

P/F = plagioclase/total feldspar
LmLvLs%Lm = 100*Lm/(Lm + Lv + Ls)
LmLvLs%Lv = 100*Lv/(Lm + Lv + Ls)
LmLvLs%Ls = 100*Ls/(Lm + Lv + Ls)

or spherulitic. Phenocrysts are quartz, sanidine, plagioclase, and biotite, and the groundmass varies from fine-grained felted with cryptocrystalline quartz and feldspar to completely devitrified glass.

Ignimbrites: Ignimbrite lithics are uncommon and typically comprise anhedral crystals of quartz and plagioclase in a vitroclastic devitrified matrix of Y-shaped and cuspate glass shards. Some ignimbrites appear densely welded and have lenticular textures and flattened tuning-fork-shaped shards.

Plutonic lithic fragments

All plutonic lithics are granitoids and are hypidiomorphic-granular, medium to coarse grained, and the main crystals are quartz, orthoclase, plagioclase, and minor biotite. Accessory minerals are titanite, zircon, and apatite. Graphic, myrmekitic, and perthitic intergrowth textures are common. Some granitoids are dominated by plagioclase, others by orthoclase, and biotite may be partially altered to chlorite.

Metamorphic lithic fragments

The most common metamorphic rock fragments are quartzofeldspathic mica schists which contain metamorphic assemblages of quartz-muscovite ± biotite-chlorite-titanite-Fe-Ti-oxides. Other metamorphic lithics include amphibolites (green hornblende-plagioclase-quartz-titanite-Fe-Ti-oxides ± epidote), and hornfelses (quartz-albite-muscovite-chlorite-titanite ± pale green actinolite).

Sedimentary lithic fragments

Sedimentary lithics are most commonly found in coarse-grained sandstones and conglomerates, and comprise mainly mudstones and sandstones. Mudstone lithics are the most common and are dominated by a clay-sized matrix with fine-grained detrital quartz. Many have weathered brown rims. Sandstone lithics are quartz poor, immature, poorly sorted with angular clasts, and are feldspathic arenites and lithic arenites. Some sandstone lithics have a mylonitic texture, probably as a result of shearing and faulting.

(5) Matrix

Matrix varies from <1 to 75 modal%, and is generally highest in the finer grained mudstones. Conglomerates generally contain <15% matrix, consisting of fine detrital quartz and feldspar, chlorite, and small flakes of muscovite and biotite.

(6) Diagenetic and very low grade metamorphic minerals

Calcite is a common diagenetic product as a cement and often occurs in irregular patches that replace matrix, detrital quartz and feldspar grains, and lithic fragments. Black et al. (1993) noted that calcite was a more common cement on the eastern limb of the Kawhia Syncline, and possibly played a role in inhibiting zeolitisation. Quartz also forms a cement replacing the matrix, particularly in the more deeply buried Triassic rocks, and occurs as veins and stringers of polycrystalline habit.

Chlorite is common as a product of hydrothermal alteration, replacing pyroxene and amphibole phenocrysts in volcanic lithic fragments and in the groundmass. In these cases the hydrothermal alteration only occurs in certain lithic clasts, and hence the alteration is clearly pre-depositional. Chlorite and illite are also common clay minerals throughout the sequence, and chlorite occurs as a very low grade metamorphic mineral replacing ferromagnesian minerals, feldspar, quartz, volcanic glass, and the matrix. Clark (1982) and Black et al. (1993) described the clay mineral distribution in Murihiku sandstones and showed that there was a consistent relationship with stratigraphy. Vermiculite and vermiculite/chlorite mixed-layer clays occur in Late Triassic and Early Jurassic rocks, while smectite and smectite/chlorite interlayered minerals are confined to Jurassic sandstones. Kaolinite, halloysite, and celadonite were also recorded by Ballance et al. (1980) in the Late Jurassic Huriwai Group rocks at Port Waikato. Other non-detrital grains include titanite, irregular patches of epidote, pyrite, glauconite, sericite, Fe-Ti oxides, and albitised and partially replaced feldspars.

A number of zeolites have been identified in this study (confirmed by XRD), and were found in volcaniclastic sandstones, mudstones, fine conglomerates, and tuffs. The youngest parts of the stratigraphic sequence contain chlorite, illite, smectite, and variable amounts of the zeolites laumontite and heulandite, plus analcime and calcite. Laumontite is the most common zeolite, and clinoptilolite was found in only two samples in the younger and stratigraphically uppermost Late Jurassic (Heterian–Puaroan) age rocks. Ballance et al. (1980) also recorded stilbite occurring with heulandite and analcime in Late Jurassic Huriwai Group volcaniclastic sandstones, and Black et al. (1993) found phillipsite-analcime-celadonite in Huriwai Group vitric tuffs. Prehnite and pumpellyite have been found in the oldest Late Triassic (Oretian) parts of the Murihiku sequence at Awakino and Marokopa. Black et al. (1993) noted that there is a broad correlation between zeolite species and stratigraphic position along the length of the Kawhia Syncline but across the synclinal structure the mineral distribution is more complicated and not simply related to depth of burial. They recorded that zeolites are most common on the western limb but are rare on the eastern limb. Black et al. (1993) also considered that the metamorphic mineral zones are superimposed on known structural, lithological, and age trends, and so are clearly a thermal overprint, and that the metamorphic crystallisation is coincident with open folding, hydraulic fracturing, and veining.

(7) Other components

Bivalve shell fragments are common at certain stratigraphic levels (e.g., *Monotis*) but foraminifera are very rare and generally have been infilled by matrix or devitrified glassy material. Rare Y-shaped glass shards are found and were probably derived from fall deposits that have been subsequently reworked. Carbonaceous material occurs in certain horizons (e.g., in the Puaroan Huriwai Group), and is described by Clark (1982) and Black et al. (1993).

TEMPORAL VARIATIONS IN MODAL ABUNDANCE

There are significant variations in modal abundance of mineral and lithic components with time in Murihiku rocks, tracked here in terms of the four age bands, and summarised in Fig. 3 and Table 1.

In general, the abundance of all the mineral components (quartz and feldspar) is highest in the oldest Late Triassic sandstones and lowest in the youngest Late Jurassic rocks, and is opposite to the lithic component abundance. For example, quartz is 19 modal% in the Late Triassic rocks (Br–Bm), but decreases progressively with time to 7% in the Late Jurassic (Kh–Op). Similarly, plagioclase and orthoclase decrease from 31 and 11%, respectively, in the late Triassic, to 22 and 5%, respectively, in the Late Jurassic. Conversely, the lithic abundance is 36% in the Late Triassic, decreases to 31% in the latest Triassic and Early Jurassic, and then steadily increases to 64% in the Late Jurassic. Furthermore, there is a progressive relative increase in volcanic lithics with time (Fig. 3).

The plagioclase:feldspar (P:F) ratio is high (0.78) and ranges from 0.71 in the latest Triassic to Early Jurassic age band to 0.84 in the Early–Middle Jurassic. The lowest value of P:F during the latest Triassic to Early Jurassic suggests a relatively larger component of plutonic material was being uplifted and eroded during this period.

In the LvLmLs diagram (Fig. 4A), useful for determining variations in the supply of lithic material to the basin, there is a dominance of volcanic lithics, a minor contribution from metamorphic lithics, and sedimentary lithics contributed the least amount of detritus to the basin. The two older groups received a relatively greater input of metamorphic detritus than the two younger groups (Fig. 3; 4A).

Triangular QFL diagrams are useful for providing information on the variations in provenance and tectonic environment with time (e.g., Dickinson et al. 1983; Ingersoll 1990; Marsaglia & Ingersoll 1992). Most Murihiku rocks plot within the magmatic arc field (i.e., dissected arc–transitional arc–undissected arc, Fig. 4B), and some Early–Middle Jurassic (Hu–Kt) and Late Jurassic (Kh–Op) rocks plot within the continental arc and intraoceanic arc field of Marsaglia & Ingersoll (1992). This suggests that the source for the Jurassic rock groups was a continental arc which had a volcanic arc component and only a minor exposed plutonic/basement component. There is also a general trend from plutonic-rich to more volcanic-rich-derived material with time.

Figure 3 summarises the relative abundances of source material that was deposited into the Murihiku Basin with time, and illustrates that andesitic detritus was most dominant in the Middle Jurassic (Temaikan). This has been previously recorded by Hudson (1983) in the Rengarenga Group in the Kawhia district, who suggested this group was deposited in a terrestrial to shallow marine environment that was closer to source. The Huriwai Group rocks in the latest Jurassic also contain a large volume of andesitic lithics. The relative dominance of andesitic lithics in the Late Jurassic is at the expense of plutonic and metamorphic lithics.

Silicic volcanism was active throughout the development of the basin, especially during the Late Triassic (Br–Bm) and Late Jurassic (Kh–Op). Ignimbrites that are partially or weakly welded, or unwelded, are generally easily broken down by transport processes, and their volume in the source may be underestimated.

Plutonic lithics have been found in rocks of all ages, but are most notable in the Late Triassic Moeatoa Conglomerate (Oretian Stage). Plutonic lithics are also very common in the coarse-grained arenites of Warepan age in the Piopio and Marokopa districts (see locations in Fig. 2). Plutonic lithics are relatively least abundant in the Temaikan.

Hydrothermal alteration of igneous and sedimentary rocks took place on the arc massif. This is supported by Keane (1986) and Graham & Korsch (1990) who noted that some clasts in the Moeatoa Conglomerate were hydrothermally altered.

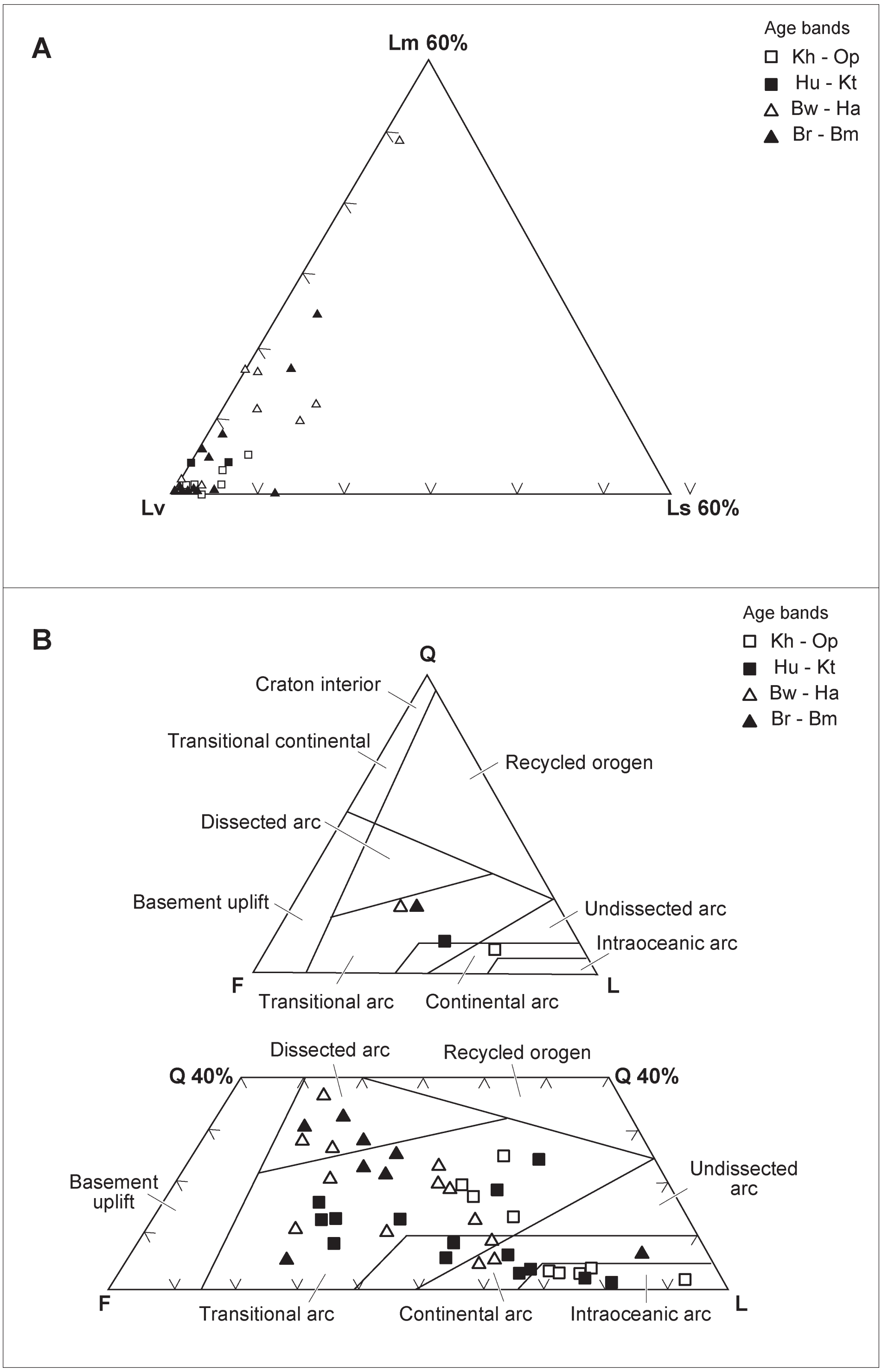

Fig. 4 Suggested provenance fields based on modal abundance of lithic fragments and minerals, plotted according to age bands. **A**, LvLmLs plot: Lv, volcanic lithic fragments; Lm, metamorphic lithics; Ls, sedimentary lithics. **B**, QFL plot with provenance fields after Dickinson & Suczek (1979), Dickinson et al. (1983), and Marsaglia & Ingersoll (1992). Q, total monocrystalline and polycrystalline quartz; F, total feldspar; L, lithic fragments. A plot of means of age band data is also given (upper triangle).

Metamorphic lithics are dominated by low-grade quartzofeldspathic mica schists and rare medium-grade amphibolites, and are most abundant in Late Triassic to Early Jurassic rocks. The Middle Jurassic (Temaikan) and latest Jurassic (Puaroan) rocks contained the least amount. Metamorphic lithics are very rare in the Port Waikato district (Purser 1961), and Ballance et al. (1980) found only one sample of sandstone in the Huriwai Group with fragments of mica schist.

Only a small number of sedimentary lithics and pebbles were identified. Some sedimentary lithics show evidence of recycling of older volcanic rocks (e.g., in Puaroan rocks at Port Waikato; Ballance et al. 1980), and others have a mylonitic texture indicative of shearing in the arc massif. MacDonald (1954) reported the only known limestone pebble in the Murihiku rocks of the North Island from the Ohana Point Conglomerate of Ohauan age.

GEOCHEMISTRY

Many studies have shown that the major and trace element geochemistry of sandstones reflects provenance differences that depend upon tectonic setting (e.g., Bhatia & Crook 1986; Roser & Korsch 1986, 1988; Skilbeck & Cawood 1994). Trace elements are particularly useful in this regard, especially those that are relatively immobile like La, Y, Th, Zr, Hf, Nb, Ti, and Sc. These elements behave geochemically with relatively low mobility during sedimentary processes of weathering, transportation, and burial (McLennan et al. 1983), and also during diagenetic and very low grade metamorphic reconstitution (Roser et al. 2002). Hence, the abundances of immobile trace elements in the sandstones can be used as reliable signatures inherited from the parent material, and sandstones are more reliable than siltstones or mudstones as they contain less matrix and more detrital components, and represent near-source deposition (Roser et al. 2002).

Sixty-seven XRF geochemical analyses have been done on selected North Island Murihiku sandstones and a few mudstones, and representative analyses are given in Table 2. The whole-rock chemical composition of the sandstones and mudstones shows a wide range of 56–74 wt% SiO_2 and 0.29–3.80 wt% K_2O. Whole-rock geochemical analyses of sedimentary rocks are an average of all components within the rock, including the matrix, and even in volcaniclastic sandstones the analyses only approximate the composition of the igneous rock types from the source. Given this restriction, the source was likely to be calc-alkaline in character, and most volcanic rocks in the source supplying detritus to the Murihiku Basin in western North Island were probably medium-K andesites and medium to high-K dacites. The high-K signature may be enhanced by the presence of micaceous minerals in the matrix, rather than a true indicator of the source composition. Furthermore, the rocks with low K_2O contents (<0.8 wt%) have been incipiently hydrothermally altered, and contain veins of quartz and calcite.

The average chemical compositions (Table 3) show little variation with time from the Late Triassic (Br–Bm) to the Late Jurassic (Kh–Op). The Early–Middle Jurassic (Hu–Kt) sandstones have slightly lower SiO_2 wt% (62 ± 4) contents and higher ($Fe_2O_3 + FeO$) and MgO. There is also a small decrease in K_2O abundance in sandstones with time from 2.64 to 1.90 wt%. The overall average major element composition of the mudstones has slightly higher abundances of K_2O and Al_2O_3, and lower CaO, compared with the sandstones, and probably reflects the higher proportion of matrix in the mudstones.

Roser & Korsch (1986) constructed SiO_2 versus K_2O/Na_2O diagrams to distinguish between different tectonic settings. Western North Island Murihiku rocks plot in the active continental margin (ACM) and oceanic island arc (ARC) tectonic settings (Fig. 5A), and indicate that Murihiku rocks were derived from a subduction-related magmatic provenance. Most of the oldest Late Triassic group (Br–Bm) cluster together in the lower part of the ACM field, and there is an overall trend with time to a wider scatter of data that straddle both the ACM and ARC fields. This suggests a change from continental silicic volcanism to a broader range of andesitic to rhyolitic volcanism. Mudstones within the Late Jurassic group (Kh–Op) plot together within the ACM field.

Bhatia & Crook (1986) used the immobile trace elements Th, La, and Sc to discriminate between tectonic settings. Th and La are typically higher in rhyolites, and Sc is typically higher in basic igneous rocks. Hence, rocks that plot in the A field (oceanic island arc) in Fig. 5B are generally more basic (and andesitic) than those in the B field (continental arc), which are generally more silicic. In the Th-La-Sc plot, the general trend is confirmed for older North Island Murihiku Terrane rocks which plot mainly in the continental arc (B) field, but there is an overall trend towards a broader range that includes oceanic island arc (or andesitic) characteristics.

Bhatia & Crook (1986), Roser (1987), and Roser et al. (2002) determined differences between groups of sedimentary rocks based on trace element ratios of contrasting element pairs, and Roser (1987) used Ti/Zr, Th/Sc, Ce/Sc, and V/La. Ti/Zr and V/La both increase with more basic detritus, and in western North Island Murihiku rocks (Table 4), Ti/Zr shows an increase from the oldest to the youngest rocks. V/La is highest in the Early–Middle Jurassic (Hu–Kt), reflecting the dominance of andesitic detritus at this stage. Th/Sc and Ce/Sc ratios increase with greater felsic components, and are both lowest in the Early–Middle Jurassic. Furthermore, the Late Jurassic rocks (Kh–Op) show the greatest variability in their ratios, indicating a wider range of volcanic detrital material eroded into the basin during this time.

Roser et al. (2002) used average major and trace element abundances and normalised multi-element diagrams to estimate proportions of three model end-member source constituents for all the Southland, Nelson, and western North Island Murihiku Terrane. Their three end-members were an average upper continental crust component, a felsic, and a mafic component. Their modelling results for western North Island show that the Late Triassic rocks had the greatest silicic volcanic component, but it progressively declined through the Jurassic. The mafic or basaltic andesite component increases from the Late Triassic to the Middle and Late Jurassic (Temaikan–Puaroan sandstones). The upper continental crust component becomes significant in the Late Triassic and increases through to the Late Jurassic. These trends are broadly similar to our data determined by a combination of petrographic and geochemical criteria, and confirm the trend of a progressively greater andesitic or mafic component with time from the Late Triassic to the Late Jurassic, with a peak in the Temaikan and Middle Jurassic. However, our petrographic data indicate that there was a relative decrease in basement material (plutonics and metamorphics) being supplied to the Murihiku Basin from the Late Triassic to the Late Jurassic, opposite to the trend suggested by the geochemical modelling of Roser et al. (2002). The geochemical modelling of source proportions by Roser et al. (2002) also show that for Southland there are similar trends to western North Island, but that they differ in end-member proportions, with Southland in the Middle Triassic to Middle Jurassic having a much greater silicic component, a smaller mafic or basaltic andesite component, and a smaller upper continental crust and basement component than western North Island. Also, the Southland segment commenced in Late Permian to early Middle Triassic time (not found in western North Island) with a predominant mafic source of basaltic andesite and no upper continental crust component (Roser et al. 2002).

DISCUSSION AND CONCLUSIONS

The rocks of the Murihiku Terrane in western North Island are mainly volcaniclastic sandstones and mudstones, with occasional shellbeds, rhyolitic tuffs, carbonaceous sandstones, plant beds, concretionary horizons, and rare thick granitoid-

Table 2 Whole-rock XRF analyses (major elements normalised to 100 wt% volatile free; trace elements in ppm) of representative Murihiku rocks in western North Island from each of the four age bands. Sst, sandstone; Mst, mudstone.

Age bands:	Br–Bm				Bw–Ha				Hu–Kt				Kh–Op			
Sample	Sst W95	Sst W97	Sst W127	Sst W117	Sst W177	Sst W119	Sst W191	Sst W202	Sst W160	Sst W200	Sst W190	Sst W114	Sst W197	Sst W153	Mst W205	Mst W90
SiO_2	66.71	65.45	65.01	66.55	66.56	67.84	67.99	64.57	58.16	63.82	61.05	56	63.55	66.11	64.75	64.3
TiO_2	0.72	0.9	0.86	0.77	1.06	0.64	0.59	0.81	1.21	0.84	0.99	1.03	0.8	0.79	0.87	0.9
Al_2O_3	16.53	16.7	16.43	16.28	15.73	15.81	15.86	16.98	16.73	17.28	17.64	18.25	18.48	17.31	18.53	18.87
Fe_2O_3	1.06	1.18	1.28	1.06	1.16	0.9	0.82	1.14	2.13	1.2	1.68	1.97	1.39	1.15	1.41	1.33
FeO	3.83	4.26	4.6	3.82	4.19	3.24	2.95	4.09	7.68	4.32	6.04	7.09	5.02	4.13	5.08	4.8
MnO	0.08	0.08	0.07	0.07	0.09	0.06	0.06	0.09	0.21	0.09	0.15	0.13	0.07	0.06	0.05	0.08
MgO	2.06	2.38	2.64	2.42	2.38	1.98	1.97	2.22	4.19	2.63	3.09	4.17	2.23	2.01	2.07	2.34
CaO	1.78	1.83	1.33	1.61	2.06	3.46	2.05	2.98	2.99	2.85	3.68	3.88	1.89	1.62	1.11	1.64
Na_2O	4.2	4.87	5.1	4.35	4.63	3.2	4.1	4.37	5.92	4.1	3.07	3.51	3.02	3.4	2.73	2.6
K_2O	2.86	2.18	2.54	2.89	1.96	2.76	3.45	2.6	0.53	2.68	2.41	3.75	3.09	3.23	3.22	2.98
P_2O_5	0.17	0.15	0.13	0.17	0.15	0.12	0.14	0.15	0.25	0.2	0.2	0.22	0.44	0.18	0.16	0.17
LOI*	3.01	2.94	3.54	3.49	3.06	5.1	2.7	3.84	4.93	4.72	6.25	6.23	5.41	4.36	6.11	11.39
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Sc	15	17	14	15	17	11	10	16	27	16	23	24	17	16	15	17
V	110	144	123	135	151	94	87	137	242	133	173	202	149	133	147	134
Cr	35	48	43	54	49	34	27	58	33	39	18	24	48	40	46	42
Ni	13	17	15	20	17	14	14	22	23	19	11	16	19	16	22	26
Cu	21	22	14	23	14	17	12	27	73	25	67	52	27	25	34	40
Zn	84	85	80	88	97	79	62	101	106	96	93	100	95	89	112	114
Ga	21	20	21	20	19	19	19	23	22	21	21	23	24	22	23	23
As	12	9	4	6	7	8	6	10	3	8	10	9	6	8	16	13
Rb	101	55	54	110	58	88	104	91	7	85	63	59	120	120	124	108
Sr	213	218	168	157	176	987	403	240	57	372	791	143	161	188	165	238
Y	31	28	21	28	28	26	22	28	26	27	29	28	37	31	28	27
Zr	185	186	200	179	275	229	151	187	114	173	148	138	187	199	172	178
Nb	7	7	8	8	8	8	6	9	3	8	4	5	11	8	10	10
Ba	442	424	525	470	410	797	543	474	63	417	658	505	338	479	481	437
La	25	25	21	24	26	21	21	24	15	23	20	19	31	28	24	21
Ce	54	54	45	51	55	45	44	51	34	48	42	43	64	58	51	45
Pb	18	16	16	17	16	21	18	19	11	18	16	16	20	22	23	22
Th	10	8	8	12	8	11	8	10	2	10	5	5	13	11	11	13
U	3	2	3	3	3	3	2	4	1	3	3	2	4	3	4	2

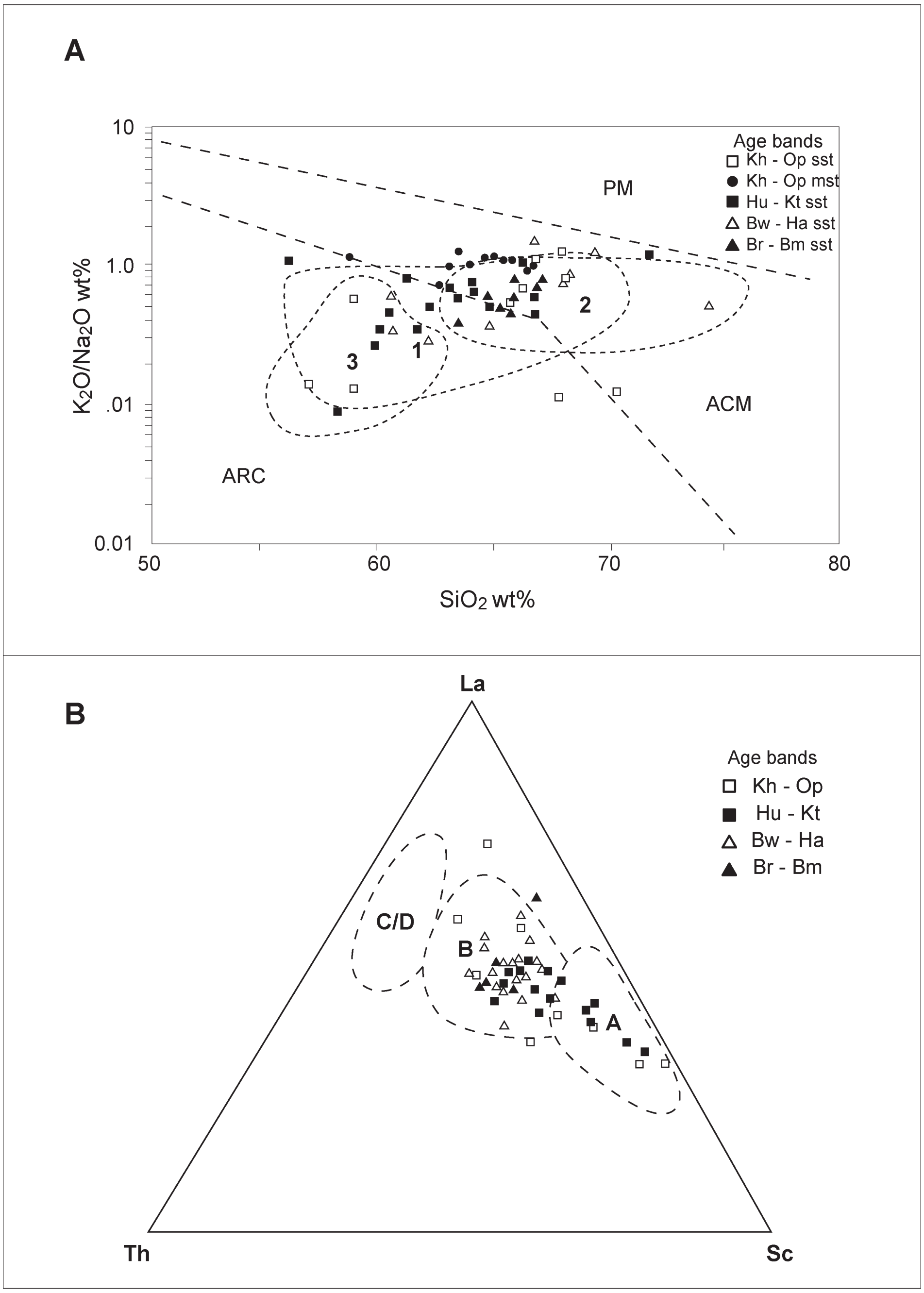

Fig. 5 Suggested sample provenance based on whole-rock geochemical composition of Murihiku rocks in the North Island. **A**, SiO_2 versus K_2O/Na_2O diagram, plotted according to age bands. Provenance fields after Roser & Korsch (1986). ARC, oceanic island arc; ACM, active continental margin; PM, passive margin. Compositional fields of Southland Syncline Murihiku rocks after Roser & Korsch (1986) are also shown (dotted envelopes): 1, Middle Triassic; 2, Late Triassic; 3, all Jurassic. sst, sandstone; mst, mudstone. **B**, Th-La-Sc diagram, plotted according to age bands. Provenance fields after Bhatia & Crook (1986). A, oceanic island arc; B, continental island arc; C, active continental margin; D, passive margin.

Table 3 Average major element compositions of representative Murihiku rocks in western North Island for each of the four age bands, and the entire age range (Br–Op). Sst, sandstone; Mst, mudstone; SD, standard deviation, values in italic.

Age bands		SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
Kh–Op	mean	64.04	0.92	19.18	1.36	4.89	0.07	2.13	1.43	2.82	2.98	0.18
Mst	SD	*2.08*	*0.22*	*1.47*	*0.34*	*1.24*	*0.04*	*0.21*	*0.50*	*0.51*	*0.48*	*0.08*
Kh–Op	mean	64.19	0.92	17.06	1.45	5.22	0.10	2.16	2.56	4.21	1.90	0.24
Sst	SD	*4.74*	*0.30*	*1.24*	*0.70*	*2.50*	*0.06*	*0.88*	*1.69*	*1.60*	*1.34*	*0.17*
Hu–Kt	mean	62.41	0.97	17.16	1.46	5.27	0.12	2.86	3.14	4.14	2.26	0.21
Sst	SD	*4.09*	*0.15*	*1.18*	*0.38*	*1.37*	*0.05*	*0.80*	*0.95*	*1.04*	*0.93*	*0.05*
Bw–Ha	mean	65.06	0.90	16.79	1.10	3.95	0.08	2.16	2.86	4.31	2.60	0.30
Sst	SD	*3.73*	*0.26*	*1.17*	*0.29*	*1.06*	*0.03*	*0.45*	*1.53*	*1.06*	*0.70*	*0.07*
Br–Bm	mean	65.52	0.78	16.62	1.07	3.86	0.08	2.20	2.64	4.43	2.64	0.16
Sst	SD	*1.16*	*0.07*	*0.38*	*0.13*	*0.47*	*0.02*	*0.32*	*1.54*	*0.53*	*0.42*	*0.02*
Br–Op	mean	64.25	0.90	16.91	1.26	4.54	0.09	2.36	2.84	4.27	2.38	0.20
all Sst	SD	*3.81*	*0.22*	*1.07*	*0.43*	*1.56*	*0.04*	*0.70*	*1.40*	*1.07*	*0.90*	*0.09*
Br–Op	mean	64.2	0.91	17.40	1.28	4.62	0.09	2.31	2.53	3.95	2.51	0.20
Sst + mst	SD	*3.49*	*0.22*	*1.49*	*0.41*	*1.49*	*0.04*	*0.63*	*1.39*	*1.15*	*0.86*	*0.09*

rich conglomerates. The rocks are well bedded with alternating sandstone-mudstone sequences that often show grading and other features typical of turbidites. Lithic fragments are the dominant component of the sandstones, comprising an average of 46 modal%, but ranging generally from 20 to 70%. Andesites are the main lithic type, but a wide range of other lithologies occurs, including dacites, rhyolites, ignimbrites, granitoids, quartzofeldspathic mica schists, rare amphibolites, and reworked mudstones and sandstones.

The highly volcaniclastic nature of the sandstones and the dominance of andesitic lithic fragments imply that the Murihiku rocks were deposited in a sedimentary basin that was close to a continental magmatic arc. The continental margin is assumed to be the eastern margin of Gondwana (Fig. 1), and sedimentological evidence suggests that the sediment was derived from the western, Gondwanan, side of the Murihiku Basin (Keane 1986; Ballance & Campbell 1993). However, there are no *in situ* lavas or thick ignimbrites interbedded within the sedimentary rocks of the Murihiku Basin in western North Island, only thin (20–50 mm thick) rhyolitic tuff horizons, and hence the basin must have been distal to the volcanic arc. The dominance of turbidite sequences also suggests that deposition within the Murihiku Basin was distant from the continental arc in the outer shelf and slope regions, associated with a submarine fan environment (Carter et al. 1978; Keane 1986; Ballance & Campbell 1993). There are two main regressive periods of deposition leading to shallow marine and eventually non-marine facies in the Murihiku Basin in western North Island, one occurring in the Early–Middle Jurassic (Hu–Kt) at Kawhia (Hudson 1983), and the other in the latest Jurassic Huriwai Group at Port Waikato. Both represent the outbuilding of a large delta plain over shelf and slope sequences (Ballance 1988).

The sandstones are texturally and mineralogically immature. Quartz and feldspar are mainly subangular to angular, feldspars are fresh or only slightly altered (allowing for diagenetic or very low grade metamorphic overprint), and there is an abundance of unstable lithic components. These kinds of properties suggest either deposition relatively close to a primary source of high relief, or else rapid transportation and sedimentation with little reworking from an arc massif experiencing limited chemical weathering (Boggs 2001). Despite differences of opinion in detail about paleoclimates off the paleo-Pacific coast of Gondwana during the Late Triassic–Jurassic (Grant-Mackie et al. 2000), wet, cool- to cold-temperate conditions appear to have characterised the high-latitude (60–70°S) "Murihiku portion" of this margin for much of the time (e.g., Stevens 1980; Retallack 1987; Frakes et al. 1992; Parrish 1993), even perhaps involving local ice production and melting (e.g., Ballance 1988; Parrish 1993). Such a climatic regime favoured physical weathering of source rocks and the production of texturally and mineralogically immature sediments.

Table 4 Comparison of trace element ratios Ti/Zr, Th/Sc, Ce/Sc, and V/La between each of the four age bands of Murihiku rocks in western North Island. SD, standard deviation, values in italic.

Age bands		Ti/Zr	Th/Sc	Ce/Sc	V/La
Kh–Op	mean	36.96	0.5	3.3	6.8
	SD	*21.61*	*0.4*	*2.5*	*4.5*
Hu–Kt	mean	36.42	0.4	2.4	8.2
	SD	*12.8*	*0.2*	*0.8*	*3.2*
Bw–Ha	mean	26.72	0.6	3.4	5.6
	SD	*5.72*	*0.2*	*0.7*	*1.2*
Br–Bm	mean	24.85	0.6	3.4	5.3
	SD	*3.73*	*0.2*	*0.4*	*0.8*

Most previous authors have proposed that the Murihiku sequence was deposited in a forearc basin, above a westward-dipping subduction zone (Fig. 1). An alternative possibility has been suggested by Coombs et al. (1996) that the Murihiku Terrane was deposited in a backarc setting above an eastward-dipping subduction zone, based on minor coeval high-K volcanic suites (the Park Volcanics Group; Coombs et al. 1992) that crop out in the Southland and Nelson segments, but not in the North Island. High-K suites are typically found in backarc environments and hence are unlikely to be the source of sediments in a forearc basin. Coombs et al. (1996) also pointed out that the broad open synclinal folding of the thick pile of Murihiku sediments in Southland and Kawhia is remarkably intact and little deformed for a long-lived (at least 80 m.y.) forearc basin, which would have been expected to have undergone complex folding, thrusting, and imbrication during active plate convergence. However, with this model it is difficult to incorporate accretion of the other tectonostratigraphic terranes in New Zealand, for example, the Caples, Waipapa, and Torlesse (Pahau and Rakaia) Terranes on to the eastern side of the Murihiku Terrane, and a westward-dipping subduction model is preferred (Fig. 1). A further suggestion is that the Southland segment of the Murihiku Terrane could be a backarc basin, while the North Island segment is a forearc, so that in fact they are different basins. The Nelson segment could thus occupy a critical position.

Whole-rock geochemical compositions of western North Island Murihiku volcaniclastic sandstones confirm that they were derived from an active and dissected volcanic arc in a convergent margin setting, built upon relatively thin continental crust rather than a thick uplifted Andean-type continental crust (cf. Bhatia & Crook 1986; Skilbeck & Cawood 1994). The granitoids and metamorphic rocks suggest derivation from a plutonic and low- to medium-grade regionally metamorphosed terrane from a continental interior. The plutonic rocks were supplied in only minor amounts and were most common in the latest Triassic Moeatoa Conglomerate, in which Keane (1986) and Graham & Korsch (1990) described a variety of granitoids (granites, granodiorites, tonalites, quartz monzodiorites, and hypabyssal equivalents). Furthermore, some rocks have been hydrothermally altered, probably in conjunction with intermediate to silicic volcanism.

Modal petrographic data and whole-rock geochemistry both confirm that there were systematic variations in time in the nature of the clastic material being supplied to the Murihiku Basin. These changes in western North Island were an overall general shift towards a wider range of volcanic detritus from the Late Triassic to the Late Jurassic (Fig. 6). Between the Late Triassic and latest Triassic to Early Jurassic, there was an increase in the supply of silicic material, plutonics, and metamorphic rocks, and a decrease in the P:F ratio because of the greater input of orthoclase from a plutonic source. Later in the Early–Middle Jurassic, there is an increase in the supply of andesitic detritus, followed in the Late Jurassic by a broader range of basaltic andesite to rhyolitic volcanism, with a wide scatter that straddles the active continental margin to oceanic island arc fields.

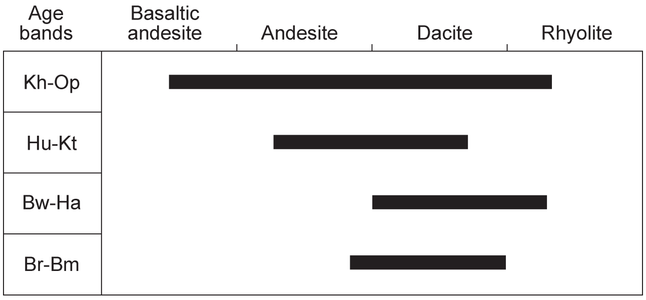

Fig. 6 Variation in provenance with time, plotted according to age bands. The compositions are broad fields based on the discriminant function analysis method of Roser & Korsch (1988) using major elements.

The geochemical approach of Roser et al. (2002) shows that there are important variations within the Murihiku Basin with different trends in the abundance of source components, both with time from the Late Permian to Late Jurassic, and also with location along the arc from Southland to western North Island. The lowermost Murihiku sediments in Southland indicate derivation from a relatively immature basaltic andesite to andesite volcanic arc, without evidence for any continental crust component (Roser et al. 2002). Later, in the Middle Triassic in Southland, there was a substantial influx of silicic volcanic detritus, dominant over the andesitic component, and continental crust was exposed. Then, through to the Middle Jurassic in Southland, there was a decrease in silicic detritus and a progressive increase in mafic detritus and in the proportion of material derived from continental crust (Roser et al. 2002). By comparison, the western North Island has a much higher proportion of andesitic detritus from the Late Triassic to the Late Jurassic compared with Southland, and there is relatively less silicic material and a relatively larger component of upper continental crust detritus.

The changes in the composition of the volcanic arc with time along the Gondwana margin may be due to a number of factors. Some volcanic arcs situated on thicker crust are characterised by more silicic and differentiated magmas, and lesser volumes of andesites (e.g., Gill 1981). Hence, the change from andesitic volcanism to a wide range of volcanic compositions from rhyolites to basaltic andesite may reflect a thickening of the crust with time. However, in contrast, within the Taupo Volcanic Zone there is a change in composition along the arc, with bimodal rhyolitic and basic volcanism occurring in the central segment where there is thinner attenuated crust, higher extension rates, and higher heat flow (Hochstein et al. 1993) than in the southern or northern segments which are dominated by andesites. Also, on a larger scale, in the Tonga-Kermadec to Taupo arcs, there is an along-arc variation from an intraoceanic island arc (the Tonga-Kermadec arc) to a continental arc (the Taupo arc) built on relatively thin continental crust (not thick Andean-type crust). Furthermore, in the Coromandel Volcanic Zone of New Zealand, precursor to the Taupo Volcanic Zone, there is a trend from andesitic to bimodal rhyolitic/basic volcanism with time (Adams et al. 1994), which may also be due to increasing extension and rifting of the arc, thinning of the crust, and higher heat flow. In the case of the Triassic–Jurassic Gondwana margin arc, the Taupo-Kermadec arc type situation is preferred where it is considered that the arc may have been undergoing progressive rifting and extension, and thinning of the crust, that ultimately led to the breakup of Gondwana. This is supported by some rock fragments in the Murihiku sandstones which have a mylonitic texture, indicating shearing and faulting within the arc.

Hence, the variation in provenance of Murihiku sediments in time and space probably reflects the evolution of an arc which commenced in the Late Permian as an intraoceanic arc in the south, and extended laterally during the Triassic and Jurassic both in the south and in the north to an arc built on continental crust. The arc generally became more andesitic and less silicic with time, and finally in the Late Jurassic there was extension of the arc and thinning of the crust that introduced a broader range of andesitic and rhyolitic detritus into the Murihiku Basin.

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