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Provenance comparisons of Permian to Jurassic tectonostratigraphic terranes in New Zealand: perspectives from detrital zircon age patterns

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Abstract – U–Pb detrital zircon ages (LAM-ICPMS) are reported for 20 greywackes and sandstones from seven major tectono-stratigraphic terranes of the Eastern Province of New Zealand (Cretaceous to Carboniferous) to constrain sediment provenances. Samples are mainly from three time horizons: Late Permian, Late Triassic and Late Jurassic. Age datasets are analysed as percentages in geological intervals, and in histogram and cumulative probability diagrams. The latter discriminate significant zircon age components in terms of terrane, sample stratigraphic age, component age, precision and percentage (of total set). Zircon age distributions from all samples have persistent, large Triassic–Permian, and very few Devonian–Silurian, populations, features which exclude a sediment provenance from the early Palaeozoic, Lachlan Fold Belt of southeast Australia or continuations in New Zealand and Antarctica. In the accretionary terranes, significant Palaeozoic (and Precambrian) zircon age populations are present in Torlesse and Waipapa terranes, and variably in Caples terrane. In the fore-arc and back-arc terranes, a unimodal character persists in Murihiku and Brook Street terranes, while Dun Mountain–Maitai terrane is more variable, and with Caples terrane, displays a hybrid character. Required extensive Triassic–Permian zircon sources can only be found within the New England Fold Belt and Hodgkinson Province of northeast Australia, and southward continuations to Dampier Ridge, Lord Howe Rise and West Norfolk Ridge (Tasman Sea). Small but significant Palaeozoic (and Precambrian) age components in the accretionary terranes (plus Dun Mountain–Maitai terrane), have sources in hinterlands of the New England Fold Belt, in particular to mid-Palaeozoic granite complexes in NE Queensland, and Carboniferous granite complexes in NE New South Wales. Major and minor components place sources (1) for the older Torlesse (Rakaia) terrane, in NE Queensland, and (2) for Waipapa terrane, in NE New South Wales, with Dun Mountain–Maitai and Caples terrane sources more inshore and offshore, respectively. In Early Jurassic–Late Cretaceous, Torlesse (Pahau) and Waipapa terranes, there is less continental influence, and more isolated, offshore volcanic arc sources are suggested. There is local input of plutonic rock detritus into Pahau depocentres from the Median Batholith in New Zealand, or its northward continuation on Lord Howe Rise. Excepting Murihiku and Brook Street terranes, all others are suspect terranes, with depocentres close to the contemporary Gondwanaland margin in NE Australia, and subsequent margin-parallel, tectonic transport to their present New Zealand position. This is highlighted by a slight southeastward migration of terrane depocentres with time. Murihiku and Brook Street terrane sources are more remote from continental influences and represent isolated offshore volcanic depocentres, perhaps in their present New Zealand position.

Keywords: U–Pb geochronology, detrital zircon, provenance, New Zealand, Palaeozoic terranes, Mesozoic terranes.

1. Introduction

The Eastern Province of New Zealand comprises a mobile belt of Carboniferous to Cretaceous tectono-stratigraphic terranes (Bishop, Bradshaw & Landis, 1985) adjacent to the older Western Province (Fig. 1), which is a southeastward extension of the early Palaeozoic Lachlan Fold Belt of southeastern Australia. Between the provinces there is a dominantly plutonic Median Tectonic Zone (Bradshaw, 1993), or Median Batholith (Mortimer *et al.* 1999*b*), containing mostly Early Cretaceous–Late Jurassic, and fewer Triassic–Permian and Carboniferous plutons.

The Eastern Province terranes (Fig. 2) are characterized by greywacke-dominated accretionary prism environments in the east (Torlesse, Waipapa and Caples terranes) and more volcaniclastic-dominated, fore-arc and/or back-arc environments in the west (Brook Street, Murihiku, and Dun Mountain–Maitai terranes). Petrographic and geochemical features clearly demonstrate

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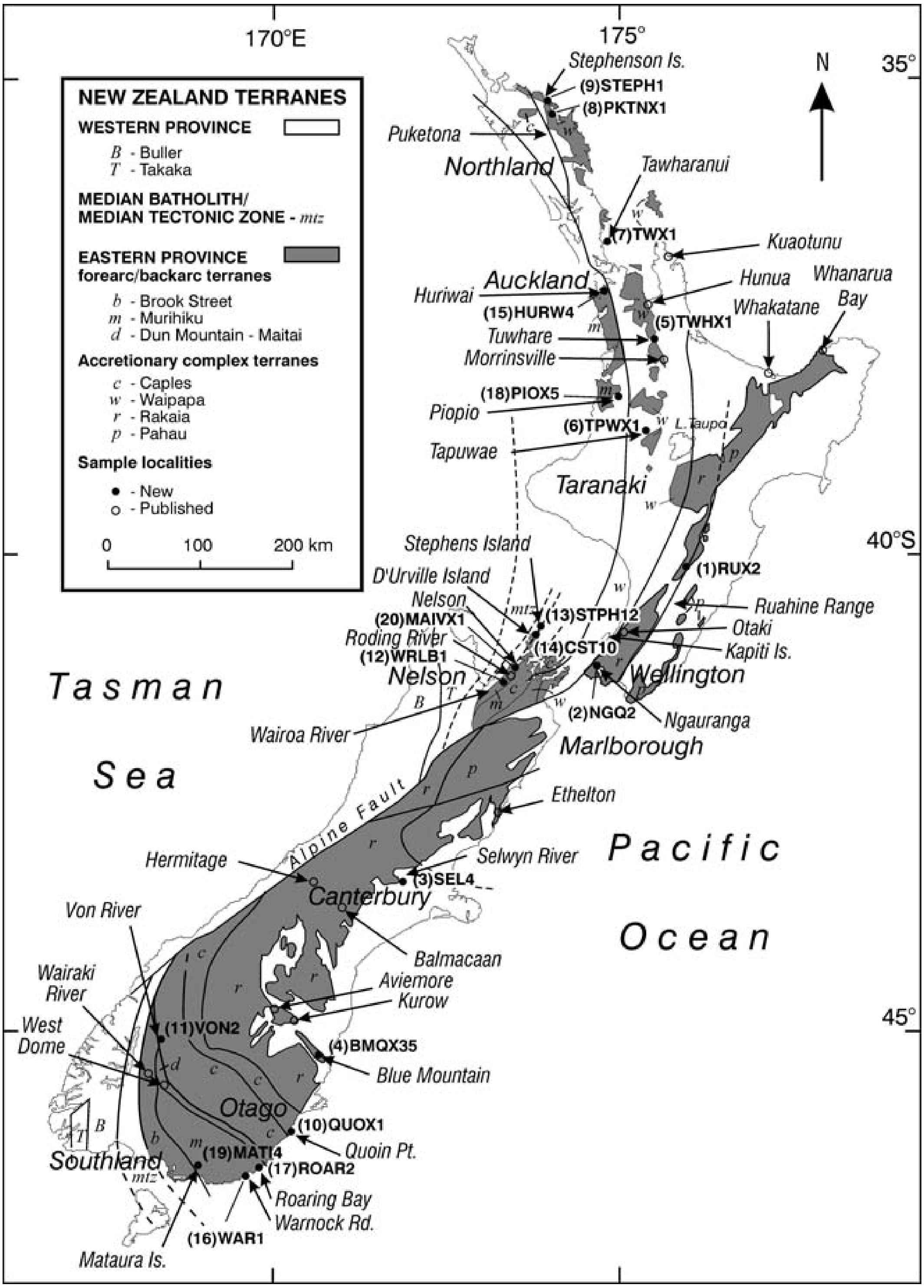


Figure 1. New Zealand, showing the Eastern Province terranes outcrop areas, locations discussed in text, and positions of U–Pb detrital zircon samples used in the present (black dots) and previously published work (open circles).

the importance of continental-derived clastic sediment sources for the former group, but intra-oceanic island-arc environments for the latter (Turnbull, 1979*b*; MacKinnon, 1983; Houghton & Landis, 1989; Roser *et al.* 1993; Roser & Korsch, 1999).

A comparison of radiogenic isotope (Sr and Nd) and detrital zircon and muscovite age patterns of the sediments with possible sources within New Zealand, eastern Australia, and the Pacific margin of Antarctica, suggest that some of the terranes must be 'suspect', that is, far-travelled from their original depositional site. This topic has aroused considerable controversy (Ireland, 1992; Adams & Kelley, 1998; Cawood *et al.* 1999; Pickard, Adams & Barley, 2000; Wandres

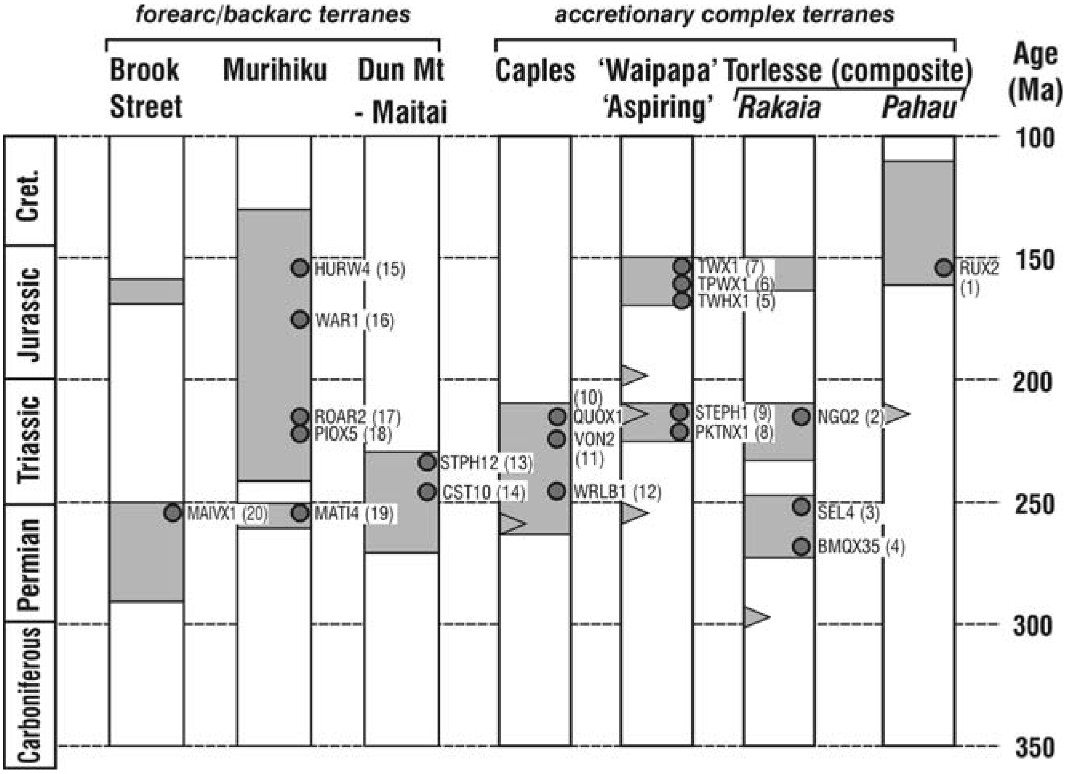


Figure 2. Stratigraphic columns for the Eastern Province tectonostratigraphic terranes of New Zealand, showing ages of 20 sedimentary rock samples chosen for U–Pb detrital zircon dating studies. The triangular shapes represent limited horizons of oceanic, rather than continental, sediment assemblages, which are often tectonically intercalated, but frequently fossiliferous.

et al. 2004*a*,*b*; Wandres, Bradshaw & Ireland, 2005), and detailed studies of individual terranes, such as Torlesse, or a particular time period, such as the Jurassic (Wandres *et al.* 2004*a*), indicate evidence for both local and distant origins. In this study, we take a broader approach, investigating detrital zircon age patterns in greywackes and sandstones from all Eastern Province terranes, at three critical time horizons: Late Permian, Late Triassic and Late Jurassic, in an attempt to reconcile some conflicting interpretations.

2. Geological outline

The Western Province of New Zealand has two terranes (Fig. 1). A more extensive, western, 'Buller' terrane, comprises extensive quartzose turbiditic greywacke-dominated successions of Early Ordovician age, intruded by Carboniferous to Late Devonian (Karamea Batholith) and Cretaceous (Paparoa, Hohonu batholiths) granitoids. The smaller, eastern 'Takaka' terrane comprises more varied quartzites, black shales, greywackes and limestones of Cambrian to Devonian age (Cooper, 1989; Cooper & Tulloch, 1992).

The Median Tectonic Zone or Median Batholith (Bradshaw, 1993; Mortimer *et al.* 1999*b*), as exposed in the South Island (Fig. 1), comprises Early Cretaceous–Late Jurassic (mainly), Late Triassic and Late Permian granite–granodiorite–diorite plutons (Kimbrough *et al.* 1994), which intrude the Brook Street and Takaka terranes (Mortimer *et al.* 1999*a*,*b*). It extends offshore in the Cook Strait region and along the northeast margin of the Lord Howe Rise, to West Norfolk Ridge (Mortimer, Tulloch & Ireland, 1997).

The Eastern Province comprises several tectonostratigraphic terranes (Fig. 1) of principally Permian to Cretaceous, low-grade metasediments (Bishop, Bradshaw & Landis, 1985). In general, the major sedimentation cycles are of Late Permian, Late Triassic and Early Cretaceous–Late Jurassic age (Fig. 2).

The Torlesse composite terrane is the easternmost and most extensive, comprising relatively quartzose, turbidite-dominated greywacke successions (Torlesse Supergroup) in a Triassic–Permian, 'Rakaia' terrane and an Early Cretaceous–Jurassic, 'Pahau' terrane (Andrews, Speden & Bradshaw, 1976; Speden, 1976; MacKinnon, 1983; Mortimer, 1995). Within the former are two Permian–Carboniferous microterranes (Kakahu and Akatarawa) having probable Tethyan faunal provenances (Hitching, 1979; Hada & Landis, 1995). Fossil occurrences, although sparse, establish a biostratigraphy at the Stage level. The Rakaia terrane rocks pass into extensive areas of medium-grade metamorphic rocks (Haast Schist) in the South Island (Mortimer, 1993*a*,*b*), and probably extend along the Chatham Rise eastwards to the Chatham Islands (Adams & Robinson, 1977).

The remaining, narrower, terranes to the west have increasing degrees of volcanic and volcaniclastic input. The overwhelmingly dominant redeposited volcanic detritus of Waipapa and Caples terrane rocks have acid–intermediate igneous sources, whereas Dun Mountain–Maitai, Murihiku and Brook Street terrane rocks are mainly intermediate–basic (Roser & Korsch, 1999).

Waipapa terrane rocks are monotonous, medium-grained greywacke–siltstone successions (Waipapa Group). Rare fossil occurrences indicate extensive Late Jurassic, and more local Triassic, clastic sequences (Black, 1994). These are intercalated with rarer but ubiquitous Early Jurassic, Triassic and Late Permian hemipelagic oceanic horizons (Spörli, 1978; Spörli, Aita & Gibson, 1989; Mortimer, 1995) containing faunas of both Tethyan and Boreal affinities. Waipapa terrane rocks extend through the North Island and pass into the Haast Schist in Marlborough, South Island (Mortimer, 1993*b*).

Caples Terrane rocks are mainly confined to the South Island, where monotonous greywacke-dominated, intermediate-volcaniclastic successions (Caples and Pelorus groups). Rb–Sr (and K–Ar) metamorphic ages (C. J. Adams, unpub. data) indicate a pre-Jurassic stratigraphic age. Although diagnostic fossil localities are exceedingly rare, a Triassic to Permian age is probable, and several lithostratigraphic formations are recognized (Turnbull, 1979*a*,*b*).

The Dun Mountain–Maitai terrane is more variable: Early Permian ophiolites (Dun Mountain Ophiolite Belt: Coombs *et al.* 1976) are overlain by moderately fossiliferous, Middle Triassic to Late Permian, successions (Maitai Group) of volcaniclastic sedimentary rocks and bioclastic calc-turbidite limestones.

The Murihiku terrane consists almost entirely of volcaniclastic sedimentary successions, with some richly fossiliferous horizons (Murihiku Supergroup: Campbell & Coombs, 1966; Ballance & Campbell, 1993; Campbell, Mortimer & Turnbull, 2003), mostly acid to intermediate igneous rock source compositions, and with a few extrusive/intrusive bodies. The terrane forms a long syncline through both North and South islands, without certain extensions to the north or southeast.

Significant volcanic edifices are only present in the Brook Street terrane. These are mainly Middle to Late Permian basalt, andesite and minor dacite–rhyolite, with voluminous gabbro, diorite and rarer granodiorite intrusives, and thick redeposited volcaniclastic sedimentary aprons (Takitimu Group: Houghton, 1981; Houghton & Landis, 1989). A more varied succession of Late Permian siltstones and limestones (Productus Creek Group), and very local Jurassic conglomerates and sandstones, overlie this (Landis *et al.* 1999).

For the Torlesse composite terrane, petrographical, geochemical and detrital mineral age evidence suggests a continental arc-derived sediment supply, principally of Permian and Triassic granitoid materials, into an accretionary prism environment (MacKinnon, 1983; Roser & Korsch, 1999; Adams & Kelley, 1998; Adams *et al.* 1998; Pickard, Adams & Barley, 2000). A similar situation is recognized for the Waipapa and Caples terranes, but with more mafic-intermediate volcanic influences (Spörli, 1978; Turnbull, 1979*a*,*b*). In contrast, more probable back-arc and fore-arc environments are suggested for Murihiku and Dun Mountain–Maitai terranes, respectively (Campbell & Coombs, 1966; Coombs *et al.* 1976; Ballance & Campbell, 1993), with some continent-derived sediment input in the latter. Finally, the Brook Street terrane represents an isolated and dissected, predominantly Permian, volcanic island-arc environment (Houghton, 1981; Houghton & Landis, 1989; Mortimer *et al.* 1999*a*), but with platform sediments (Landis *et al.* 1999).

The relative positions of the Eastern Province terranes, with respect to the Gondwanaland margin, suggest that the Torlesse, Waipapa, and possibly Caples, terranes are ‘suspect’, and must have distant sediment sources (Landis & Bishop, 1972; Bishop, Bradshaw & Landis, 1985). Two possible origins have been suggested: (1) partly in the Lachlan Fold Belt (and continuations in New Zealand and Antarctica), and partly in the Median Tectonic Zone or Batholith (and its continuations in Antarctica) (MacKinnon, 1983; Cawood *et al.* 1999, 2002; Wandres *et al.* 2004*a*,*b*; Wandres, Bradshaw & Ireland, 2005), and (2) partly or completely in the New England Fold Belt of northeast Australia (Pickard, Adams & Barley, 2000; Cawood *et al.* 2002).

3. Previous geochronological studies of detrital zircon sources

Detrital zircon U–Pb (SHRIMP) dating was first applied to Western and Eastern Province basement rocks by Ireland (1992). From the Eastern Province, a Torlesse greywacke (of probable Late Permian age) near Lake Aviemore (Fig. 1) contained zircons of mostly (40 %) Late to Middle Permian age. A local derivation was regarded as less probable than a more distant source along the eastern margin Gondwanaland, in eastern Australia or West Antarctica.

This conclusion was supported by similar age data (Adams *et al.* 1998) from two Late Triassic greywackes in the Rakaia terrane from the Hermitage and Otaki River (Fig. 1). The predominance of Late Triassic to Late Permian zircon age groups, the poverty of Devonian–Carboniferous zircons, and a surprisingly high proportion of early Palaeozoic and Precambrian zircons again made a local source less likely than a more distant one, most probably in the New England Fold Belt of northeastern Australia.

Cawood *et al.* (1999) extended detrital zircon age studies into the Waipapa terrane Early Cretaceous–Late Jurassic greywackes from the basement of central and northern North Island (Fig. 1). Abundant Jurassic zircons, often close in age to the time of sedimentation, favoured local derivations, but the sources of significant Triassic and Late Permian age groups were more problematical. It was concluded that more distant sources might occur in Triassic–Permian arcs along the eastern margin of Gondwanaland, although south and east of New Zealand, there is little evidence for these.

Subsequently, broader detrital age studies of Rakaia, Pahau and Waipapa terrane greywackes (Pickard, Adams & Barley, 2000; Cawood *et al.* 2002) have all demonstrated the persistence of Triassic and Permian zircon groups throughout all terranes. This suggests a long-lived active continental margin environment, in which older zircon sources (Early Palaeozoic and Precambrian) are also an important contributor. Most of these Cretaceous to Permian samples contain significant zircon age groups close to (< 10 Ma), or within their sample stratigraphic age range, again reflecting the active nature of both sediment source and depocentre. These age data characteristics were considered best met by derivation of Torlesse and Waipapa terrane sediments from sources in northeastern Australia during Triassic and Permian times, but derivation from sources closer to New Zealand in the Cretaceous and Jurassic.

Adams *et al.* (2002) concluded that detrital zircon age patterns in Maitai Group (Dun Mountain–Maitai terrane) sandstones also indicated a provenance in northeast Australia (probably in the southern sector of the New England Fold Belt). However, Jurassic sandstones in the Brook Street terrane (Barretts Formation) were more problematical, since they showed no diagnostic provenance markers.

From U–Pb zircon age, geochemical and Sr- and Nd-isotopic characteristics of Pahau terrane conglomerate clasts and their host sandstones, Wandres *et al.* (2004*a*) showed clear similarities with several Early Cretaceous–Jurassic granitoid sources, mostly in the Median Batholith to the west, but possibly also in the Bounty Islands to the east. Thus a local derivation of Pahau terrane rocks was strongly supported.

Similar studies in the Rakaia terrane (Wandres *et al.* 2004*b*) indicated that granitoid (and related volcanic) sources for older Torlesse Supergroup sediments formed two main age groups: (1) Middle Triassic–Permian, probably divided into two subordinate groups, Middle Triassic–Middle Permian, and Early Permian, and (2) Carboniferous. A broad correlation with, and derivation from, plutons and volcanic rocks of similar age in Amundsen Sea region (Marie Byrd Land) was suggested.

4. Technical details

Samples for detrital zircon studies were collected from representative stratigraphic horizons where coarse-medium greywacke and sandstone predominate, preferably with established biostratigraphic age control, and most frequently at the Stage level. The exception is samples from the Caples terrane, where no suitable fossiliferous sample locations were available. Twenty greywacke/sandstone samples (Table 1, Figs 1, 2) were mostly chosen from three critical time horizons, Late Permian, Late Triassic and Late Jurassic, since these are representative of the major episodes of sedimentation common to the maximum number of terranes. Since most localities are in lower metamorphic grades (typically zeolite to lower pumpellyite–actinolite mineral facies), they are essentially unfoliated rocks and free of metamorphic zircon.

To minimize sample handling steps for zircon recovery, a 2–3 kg sample was collected at the field outcrop as a 5 mm size gravel, removing all weathered rinds, blemishes, inclusions and joint faces. This enabled direct crushing in a tungsten carbide swingmill, 2–3 times, for 5–10 seconds, sieving at each stage through only a 250 μm mesh sieve. The sieved material was washed and decanted several times in water, to remove mud-size fractions, thus retaining a 200–300 g sample in a $\sim$30–250 μm size range, which was then dried. A heavy mineral concentrate was removed from a 100 g portion in sodium polytungstate liquid, adjusted to a specific gravity 2.95–2.98. Where substantial amounts of magnetic minerals (e.g. biotite, chlorite, epidote) were present, they were removed at minimum magnetic conditions (0.5 Å magnet current, 10° side slope) on a Frantz magnetic separator. From the remaining non-magnetic component, about 500 zircon grains were hand-picked as randomly as possible, that is, taking all grains within a 1 mm microscope stage field of view, either definite or probable zircons, and whether euhdral, subhedral or anhedral. Of these, 50–100 grains were mounted in resin to be polished for BSE (back-scattered electron) imaging and LA-ICPMS (laser-ablation inductively coupled plasma-source mass spectrometry) analysis.

Analytical protocols relating to ablation procedures, mass spectrometric analysis and data treatment are discussed in detail in Jackson *et al.* (2004). These authors' preferred procedures were followed in this work. A few analyses early in the study used a pulsed argon-ion laser operating at 266 nm, and an Agilent 4500-ICP-quadropole mass spectrometer. The majority of the later analyses used a Merchantek pulsed Nd-YAG laser, frequency-quintupled to operate at 213 nm and the same ICPMS.

In all cases, the ablated spot size was in the range 30–50 μm, with the ablation time about 60 seconds, preceded by 60 seconds background measurement, and followed by 60–120 seconds washout. Groups of 10–12 zircon sample grain analyses were preceded and followed by duplicate analyses of firstly, the in-house zircon standard GJ-1, and secondly, 1–2 analyses each of the international zircon standards, MT-1 and 91500. The GLITTER data interpretation software package (www.els.mq.edu.au/GEMOC/) enabled analysis of U, Pb and Th absolute count rates and all relevant isotopic

Table 1. Eastern Province of New Zealand, sandstone/greywacke samples for detrital zircon U–Pb dating

Dataset	Sample acronym	GNS R. No.	Sample type	Stratigraphic unit	Stratigraphic age (and stage, where known)	Location	Grid ref. 1:50 000 (NZMS 260)
Torlesse terrane							
1	RUX2	23433	c gw	Pahau Group	Late Jurassic (Tithonian)	Waipawa River, Hawkes Bay	U22/253513
2	NGQ2	17017	c gw	Torlesse Supergroup	Late Triassic (Norian)	Ngauranga, Wellington	R27/617956
3	SEL4	23241	c gw	Torlesse Supergroup	Late Permian (Wuchiapingian)	Lower Selwyn River, Canterbury	L35/193526
4	BMQX35	22966	c gw	Torlesse Supergroup	Uncertain	Blue Mountain, Otago	I42/286337
Waipapa terrane							
5	TWHX1	21156	c gw	Waipapa Group	Late Jurassic (Kimmeridgian)	Tuwhare, Waikato	S14/278780
6	TPWX1	21171	c gw	Waipapa Group	Late Jurassic (Kimmeridgian)	Tapuwae, King Country	S17/148908
7	TWX1	19943	c gw	Waipapa Group	Late Jurassic (Kimmeridgian)	Tawharanui Peninsula, North Auckland	R09/758354
8	PKTNX1	22459	c gw	Waipapa Group	Uncertain	Puketona, Northland	P05/002549
9	STEPH1	22822	c gw	Waipapa Group	Late Triassic (Norian)	Stephenson Island, Northland	P04/820934
Caples terrane							
10	QUOX1	23030	c gw	Tuapeka Group	Late Triassic (Norian)	Quoin Point, Otago	I45/913465
11	VON2	22766	c gw	Caples Group	Uncertain	Von River, Southland	E42/463548
12	WRLB1	22722	c gw	Pelorus Group	Uncertain	Wairoa River, Left Branch, Nelson	N28/187645
Dun Mountain–Maitai terrane							
13	STPH12	22884	sst	Stephens Subgroup	Early Triassic (Olenekian)	Stephens Island, Nelson	P25/948588
14	CST10	22875	sst	Maitai Group	Early Triassic (Olenekian)	D'Urville Island, Nelson	P25/913554
Murihiku terrane							
15	HURW4	22530	sst	Murihiku Supergroup	Late Jurassic (Tithonian)	Port Waikato, South Auckland	R13/673210
16	ROAR2	23017	sst	Murihiku Supergroup	Late Triassc (Norian)	Roaring Bay, Otago	H46/673210
17	PIOX5	22500	sst	Murihiku Supergroup	Late Triassic (Norian)	Pio Pio, King Country	R17/845804
18	MATI4	21235	c gw	Murihiku Supergroup	Late Permian (Changhsingian)	Mataura Island, Southland	F46/848107

c gw – coarse greywacke, sst – sandstone; NZMS 260 is the standard New Zealand topographic map series.

ratios during the run cycle, and the elimination of unstable beam intervals, and rejection of data where zircon core regions were inadvertently encountered.

In the greywacke samples studied here, detrital zircon is a relatively common accessory mineral in the more quartzose Torlesse and Waipapa terrane examples, but much scarcer in the more volcaniclastic greywackes of the Caples, Dun Mountain–Maitai and Murihiku terranes, and extremely rare in the Brook Street terrane greywackes. Zircons occur most commonly (> 95 %) in the 40–200 μm size range, as euhedral or subhedral grains, occurring as both equant, pink, barrel-shaped and thin, clear prismatic types. Rounded grains (often dark pink) are rare (2 %), reflecting the relative immaturity of the sediments. Anhedral, clear grains (< 2 %) are presumably fragments of rare (< 1 %) larger grains. BSE images of the grain mounts indicate that, in general, the majority (> 80 %) of the zircons are pristine with simple concentric zoning, whereas fewer than 20 % show some evidence for older cores.

Using the laser spot size of 30–50 μm enabled age measurements to be made adjacent to crystal edges, and preferably, at face terminations as defined by two crystal edges. Isotopic data were continually monitored during ablation to check that zircon cores were not being intersected. Measurement of substantially older grain cores could unduly distort zircon age patterns being acquired principally for their provenance implications. Efficient use of the instrument time dictated that strongly unimodal patterns were investigated only to analysis totals of $N = 33$–50, bimodal patterns to $N = 50$–70, and strongly polymodal patterns to $N = 100$ (NB: throughout this work 'N' and 'n' refer to dataset totals and subgroups, respectively). This allowed significant age groups (n) at the 10 % level to be revealed by three or more analyses (Andersen, 2005). Since the rock samples are all of low metamorphic grade (zeolite to prehnite–pumpellyite mineral facies), there is no metamorphic zircon present, and Pb-loss from detrital zircon is unlikely.

Full ^{207}Pb–^{206}Pb, ^{206}Pb–^{238}U, ^{207}Pb–^{235}U and ^{208}Pb–^{232}Th age, and common ^{206}Pb data (and 1σ errors) have been lodged in PETLAB, the New Zealand Rock Catalogue and Analytical Database, accessible at http://pet.gns.cri.nz/.

Following the published Australasian U–Pb (SHRIMP) zircon age studies relevant to this work, all ages used here are ^{206}Pb–^{238}U zircon ages where < 1000 Ma, and ^{207}Pb–^{206}Pb ages where > 1000 Ma. An expanded version of the data presented in Tables 2 and 3, with relevant zircon U–Th–Pb raw counts and

Table 2. Detrital zircon population age components: New Zealand Eastern Province sedimentary rocks (new data, this work)

Zircon group	^{206}Pb/^{238}U zircon age group Age (Ma) ± 2e	*n*	% total	Total, *N*
Torlesse composite terrane				
(1) RUX2 (R23433) Pahau Group, Ruahine Range (Late Jur.)				
a	183 ± 6	7	9	
b	235 ± 4	4	5	
c	245 ± 5	17	22	
d	263 ± 3	10	13	
e	272 ± 6	6	8	
f	332 ± 5	4	5	
g	496 ± 7	4	5	77
(2) NGQ2 (R17017) Torlesse Supergroup, Ngauranga (Late Trias.)				
a	223 ± 3	7	7	
b	233 ± 4	14	15	
c	243 ± 3	5	5	
d	252 ± 2	6	6	
e	263 ± 3	4	4	
f	287 ± 3	5	5	
g	456 ± 5	4	4	
h	543 ± 8	5	5	
j	602 ± 11	7	8	93
(3) SELXX (R23241) Torlesse Supergroup, Selwyn River (Late Perm.)				
a	253 ± 3	6	11	
b	264 ± 3	14	26	
c	287 ± 5	8	15	54
(4) BMQX35 (R22966) Torlesse Supergroup, Blue Mountain				
a	270 ± 4	16	18	
b	311 ± 4	4	4	
c	341 ± 4	8	8	
d	350 ± 1	4	4	
e	383 ± 6	6	7	
f	464 ± 5	5	5	
g	489 ± 4	7	8	91
Waipapa terrane				
(5) TWHX1 (R21156), Waipapa Group, Tauwhare (Late Jur.)				
a	154 ± 2	5	7	
b	162 ± 2	5	7	
c	173 ± 1	11	16	
d	185 ± 4	5	7	
e	207 ± 2	5	7	
f	228 ± 3	5	7	
g	243 ± 3	4	6	
h	253 ± 2	3	4	70
(6) TPWX1 (R21171) Waipapa Group, Tapuwae (Late Jur.)				
a	162 ± 3	5	8	
b	168 ± 2	15	25	
c	182 ± 3	11	18	
d	199 ± 5	7	12	
e	218 ± 6	4	7	60
(7) TWX1 (R19943) Waipapa Group, Tawharanui Peninsula (Late Jur.)				
a	152 ± 1	9	16	
b	158 ± 2	5	9	
c	234 ± 3	4	7	
d	242 ± 3	4	7	
e	250 ± 2	5	9	
f	262 ± 3	4	7	55
(8) PKTNX1 (R22459) Waipapa Group, Puketona				
a	241 ± 2	15	88	17
(9) STEPH1 (R22822) Waipapa Group, Stephenson Island (Late Jur.)				
a	207 ± 5	5	9	
b	216 ± 2	13	22	
c	227 ± 5	9	16	
d	235 ± 2	11	20	
e	249 ± 4	6	11	
f	304 ± 9	4	7	55
Caples terrane				
(10) QUOX1 (R23030) Tuapeka Group, Quoin Point (Late Trias.)				
a	221 ± 2	4	9	
b	230 ± 2	11	25	
c	240 ± 2	7	16	
d	248 ± 2	11	25	44
(11) VON2 (R22766) Caples Group, Von River				
a	235 ± 2	18	6	
b	248 ± 3	8	29	28
(12) WRLB1 (R22722) Pelorus Group, Wairoa River Left Branch				
a	251 ± 2	25	39	
b	260 ± 2	19	30	
c	319 ± 5	3	5	
d	334 ± 5	3	5	
e	347 ± 4	4	6	64
Dun Mountain–Maitai terrane				
(13) STPH12 (R22884) Maitai Group, Stephens Island (Early Trias.)				
a	248 ± 3	6	15	
b	256 ± 2	14	35	
c	323 ± 5	6	15	
d	335 ± 4	4	10	40
(14) CST10 (R21325) Maitai Group, D'Urville Island (Early Trias.)				
a	248 ± 2	15	47	
b	255 ± 3	6	19	
c	262 ± 3	4	13	
d	272 ± 3	4	13	32
Murihiku terrane				
(15) HURW4 (R22530) Murihiku Supergroup, Port Waikato (Late Jur.)				
a	141 ± 2	15	23	
b	156 ± 1	22	34	
c	165 ± 2	6	9	
d	258 ± 6	4	6	
e	272 ± 3	4	6	66
(16) WAR1 (23319) Murihiku Supergroup, Warnock Road (Middle Jur.)				
a	176 ± 2	4	6	
b	191 ± 2	5	7	
c	200 ± 2	6	8	
d	236 ± 3	5	7	
e	250 ± 2	14	20	
f	262 ± 2	8	11	
g	339 ± 4	4	6	
h	361 ± 4	5	7	71
(17) ROAR2 (23017) Murihiku Supergroup, Roaring Bay (Late Trias.)				
a	220 ± 3	5	19	
b	233 ± 3	3	11	
c	256 ± 6	9	33	
d	264 ± 4	3	11	27
(18) PIOX5 (R22500) Murihiku Supergroup, Pio Pio (Late Trias.)				
a	218 ± 2	7	14	
b	226 ± 2	14	28	
c	250 ± 3	7	14	
d	303 ± 5	6	12	
e	320 ± 4	3	6	50
(19) MATI4 (R21325) Murihiku Supergroup, Mataura Island (Late Perm.)				
a	244 ± 2	30	83	
b	251 ± 1	3	8	
c	263 ± 1	3	8	36
Brook Street terrane				
(20) MAIVX1 (R23846) Grampian Formation, Nelson (Late Perm.)				
a	256 ± 1	38	49	
b	265 ± 2	21	27	
c	302 ± 3	4	5	77

Sample information – GNS geochronology sample archive R number given in brackets.
e – errors are 95% confidence limits.
n – number of grains in age group, *N* – total population.

Table 3. Detrital zircon population age components: New Zealand Eastern Province sedimentary rocks (previously published work)

Zircon group*	^{206}Pb/^{238}U zircon age group Age (Ma) ± 2e	*n*	% total	Total, *N*
Torlesse composite terrane				
(1A) T420 Torlesse Supergroup, Whanarua Bay (Early Cret.)[3]				
a	100 ± 2	4	7	
b	111 ± 1	18	30	
c	122 ± 1	9	15	
d	153 ± 5	4	7	
e	349 ± 3	6	10	61
(1B) Pahau Group, Ethelton (Late Jur.–Early Cret.)[7]				
a	125 ± 5	9	15	
b	186 ± 6	3	5	
c	215 ± 6	4	7	
d	224 ± 6	3	5	
e	235 ± 7	7	12	60
(1C) HUN4, Pahau Group, Hundalee (Late Jur.–Early Cret.)[7]				
a	117 ± 2	6	6	
b	241 ± 3	12	13	
c	247 ± 3	14	15	
d	262 ± 3	5	5	
e	352 ± 6	5	5	95
(1D) CPD2 Pahau Group, Cape Palliser[5]				
a	240 ± 4	4	9	
b	250 ± 4	4	9	
c	266 ± 3	8	19	43
(2A) RBW1 Torlesse Supergroup, Rainbow River (Late Trias.)[5]				
a	214 ± 2	9	11	
b	224 ± 2	9	11	
c	241 ± 4	6	7	
d	260 ± 3	11	13	
e	319 ± 4	4	5	
f	462 ± 6	6	7	
g	533 ± 7	4	5	83
(2B) OTQ1 Torlesse Supergroup, Otaki River (Late Trias.)[3]				
a	237 ± 2	14	21	
b	246 ± 6	4	6	
c	281 ± 4	5	7	
d	295 ± 5	3	4	
e	326 ± 4	6	9	
f	506 ± 6	5	7	67
(2C) HERM2 Torlesse Supergroup, Hermitage (Late Trias.)[2]				
a	221 ± 11	4	6	
b	246 ± 3	15	23	
c	256 ± 4	7	11	
d	299 ± 4	3	5	
e	434 ± 9	3	5	66
(2D) NGQ2X Torlesse Supergroup, Ngauranga (Late Trias.)[5]				
a	225 ± 4	11	14	
b	238 ± 3	17	21	
c	254 ± 3	6	8	
d	517 ± 6	7	9	80
(2E) PUD1 Torlesse Supergroup, Pudding Hill Str. (Late Trias.)[5]				
a	239 ± 3	9	12	
b	249 ± 3	14	19	
c	268 ± 3	8	11	
d	454 ± 4	4	5	73
(2F) BAL, Torlesse Supergroup, Balmacaan Stream (Middle Trias.)[8]				
a	236 ± 7	4	6	
b	250 ± 4	8	13	
c	265 ± 4	9	14	
d	285 ± 5	5	8	
e	305 ± 7	4	6	
f	496 ± 8	4	6	
g	1019 ± 21	5	8	64
(3A) PAR2 Torlesse Supergroup, Pareora Gorge (Late Perm)[5]				
a	267 ± 3	44	55	
b	282 ± 3	6	8	
c	431 ± 6	4	5	
d	465 ± 7	4	5	80
(3B) KAK35 Torlesse Supergroup, Kakahu Gorge (Late Perm.)[5]				
a	274 ± 3	30	52	
b	301 ± 6	5	9	
c	331 ± 14	4	7	58
(3C) Kurow Torlesse Supergroup, Kurow (Late Perm.)[8]				
a	261 ± 7	5	8	
b	273 ± 4	14	23	
c	305 ± 6	5	8	
d	333 ± 6	5	8	
e	349 ± 9	3	5	
f	507 ± 11	3	5	60
(3D) Aviemore Torlesse Supergroup, Lake Aviemore (Late Perm.?)[1]				
a	257 ± 4	8	32	25
b	523 ± 1	3	12	
(4A) TAKA10 Torlesse Supergroup, Akatarawa Stream (Late Perm.)[5]				
a	106 ± 5	4	6	
b	269 ± 3	6	8	
c	279 ± 2	7	10	
d	317 ± 5	5	7	
e	332 ± 4	7	10	
f	352 ± 5	6	8	
g	409 ± 6	5	7	72
(4B) 94te Torlesse Supergroup, Akatarawa Stream (Late Perm.)[4]				
a	263 ± 3	7	14	
b	284 ± 3	7	14	
c	297 ± 10	4	8	
d	319 ± 5	5	10	
e	352 ± 5	8	16	
f	378 ± 4	5	10	51
Waipapa terrane				
(5A) t44 Waipapa Group, Whakatane (Late Jur.–Early Cret.)[3]				
a	204 ± 3	5	8	
b	220 ± 5	4	7	
c	235 ± 2	7	12	
d	245 ± 2	7	12	
e	257 ± 2	5	8	
f	274 ± 4	5	8	60
(5B) W4 Waipapa Group, Kuaotunu (Late Jur.–Early Cret.)[3]				
a	148 ± 2	7	10	
b	198 ± 5	4	6	
c	220 ± 2	7	10	
d	237 ± 2	8	12	
e	253 ± 2	6	9	
f	262 ± 2	13	19	
g	363 ± 7	5	7	69
(5C) W1 Waipapa Group, Morrinsville (Late Jur.)[3]				
a	156 ± 6	3	11	
b	185 ± 6	4	14	
c	223 ± 2	4	14	
d	250 ± 4	5	18	
e	265 ± 7	3	11	28
(5D) W5 Waipapa Group, Steens Quarry (Late Jur.)[3]				
a	148 ± 1	44	50	
b	157 ± 1	23	26	
c	176 ± 5	4	5	88
(5E) SPE1 Marlborough Schist, Speeds Road[5]				
a	172 ± 2	15	18	
b	193 ± 2	9	11	
c	203 ± 2	9	11	
d	235 ± 3	10	12	
e	245 ± 2	14	17	
f	361 ± 3	6	7	
g	503 ± 8	4	5	83
(5F) BLU8A Marlborough Schist, Blumine Island[5]				
a	175 ± 4	7	7	
b	188 ± 3	8	9	
c	199 ± 4	4	4	

Table 3. *(Contd.)*

Zircon group*	$^{206}Pb/^{238}U$ zircon age group Age (Ma) ± 2e	*n*	% total	Total, *N*
***Waipapa terrane** (Contd.)*				
d	227 ± 3	4	4	
e	241 ± 3	7	7	
f	251 ± 2	13	14	
g	272 ± 4	5	5	
h	363 ± 4	6	6	94
(9A) BOIX31 Waipapa Group, Bay of Islands [5]				
a	225 ± 1	38	40	
b	234 ± 1	38	40	
c	246 ± 2	10	11	94
(9B) ADMX2 Waipapa Group, Administration Bay [5]				
a	226 ± 1	25	28	
b	238 ± 2	54	61	
c	248 ± 4	6	7	88
Dun Mountain–Maitai terrane				
(14A) RODG17 Maitai Group, Roding River (Late Perm.) [6]				
a	251 ± 6	4	6	
b	263 ± 4	11	16	
c	289 ± 6	4	6	
d	345 ± 6	7	10	
e	359 ± 7	6	9	67
(14B) WDX1 Maitai Group, West Dome (Late Perm.) [6]				
a	253 ± 2	9	33	
b	264 ± 3	4	15	
c	364 ± 11	4	15	27
Brook Street terrane				
(19) BAR2A Barretts Formation, Wairaki Downs (Middle Jur.) [6]				
a	172 ± 2	5	8	
b	183 ± 2	14	24	
c	193 ± 2	7	12	
d	202 ± 2	16	27	
e	230 ± 3	4	7	59

e – errors are 95% confidence limits.
n – number of grains in age group, *N* = total population.
*Data sources:
1 – Ireland (1992)
2 – Adams *et al.* (1998)
3 – Cawood *et al.* (1999)
4 – Cawood *et al.* (2002)
5 – Pickard, Adams & Barley (2000)
6 – Adams *et al.* (2002)
7 – Wandres *et al.* (2004*a*)
8 – Wandres *et al.* (2004*b*)

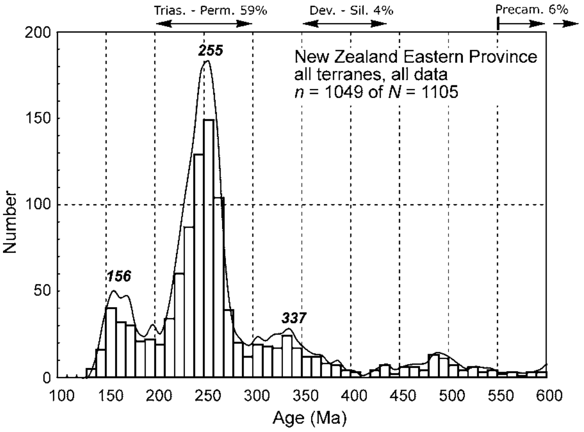


Figure 3. Histogram and cumulative probability diagram of all detrital zircon $^{238}U–^{206}Pb$ ages, < 600 Ma, from Eastern Province sedimentary rocks sampled in this study with, at top, percentages occurring in selected intervals. Major peaks are noted in millions of years.

isotopic ratio data, is lodged in PETLAB (accessible at http://pet.gns.cri.nz/). A small minority (13 %) of the analyses have common Pb corrections (Andersen, 2002). This is achieved by iterative removal of small amounts of common Pb of known composition from the observed composition, to achieve an optimal comparison of theoretical values expected of a common Pb-free zircon, whose age is the corrected $^{207}Pb/^{206}Pb$ value in single-stage Pb loss. Percentage common ^{206}Pb corrections were usually low, < 2 % in 93 % of cases, and only exceeding 8 % in one case. Application or non-application of the common Pb correction in no case altered the recognition a zircon group, or significantly affected its peak value. With the exception of 11 discordant analyses (noted in the data lodged in PETLAB), detrital zircon $^{206}Pb–^{238}U$ and $^{207}Pb–^{235}U$ age data for the remaining 1094 analyses are concordant at 99 % confidence limits. Inclusion or non-inclusion of the discordant analyses in probability curve datasets in no case influenced the recognition a zircon group or its peak value.

Age groupings were then determined by visual inspection using deconvolution (and weighted average) algorithms in the ISOPLOT-Ex (version 3.0) software (kindly provided by K. Ludwig, United States Geological Survey). These groups are noted in the PETLAB data, with their appropriate ages and 2σ errors. Zircon component ages, their errors and frequencies for the 20 samples are summarized in Table 2. Similar treatment of all previously published data is tabulated separately in Table 3. To confine the interpretation of the large age dataset ($N > 1000$ analyses) to manageable proportions, and to focus on groups that could be confidently regarded as significant (Vermeesch, 2004), two conservative criteria were imposed to define 'reasonable' significant age groups, namely, those with $n > 3$ concordant $^{206}Pb–^{238}U$ and $^{207}Pb–^{235}U$ ages, and comprising > 4 % of the total population (*N*). This was relaxed to $n \geq 3$ for a few data sets with $N < 30$. Following Andersen (2005), the age groups are discussed using five categories using the names 'dominant' > 80 %, 'large' 50–79 %, 'major' 20–49 %, 'minor' 5–19 %, and 'accessory' < 5 %, of the total. The Australian and New Zealand timescales used are Young & Laurie (1996) and Cooper (2005), respectively.

5. Detrital zircon age results and interpretation

The total detrital zircon age dataset ($N = 1105$) for the 20 new samples from all the Eastern Province terranes are combined in Figure 3. This is still not large enough to represent all sedimentary horizons in the province in their correct volumetric proportions, but none the less, the very large dataset brings out two important features. Firstly, the overwhelming dominance of Triassic–Permian zircons (60 %) is striking, and contrasts with the relative paucity of potential sources of coeval plutonic and volcanic rocks in the adjacent Median Batholith and Western Province of New Zealand. Secondly, the paucity of Devonian–Silurian zircons (4 %) is equally striking, since extensive granitoid terranes of this age do occur in the Western Province and Lachlan Fold Belt of southeast Australia (and Antarctica), representing an available and potentially enormous source. Unconformably overlying Devonian successions suggest that large areas of the Lachlan Fold Belt granitoid complexes were available for erosion by that time.

5.a. Detrital zircon age proportions expressed in terms of geological periods

The 20 zircon age datasets of the present work are displayed in more detail in Figure 4, where percentage age distributions for individual samples are grouped in terrane and stratigraphic order, and then subdivided into geological periods. Although the latter vary in duration, they provide a simple visual connection to the well-known geological history of the sedimentary successions in each terrane. Data from the present work are highlighted in bold type, and in addition, comparable age data from 26 samples (dataset numbers terminating with a capital letter; locations shown in Fig. 1) of previous studies are inserted in the table at their appropriate positions. Clearly, this presentation has the virtue of displaying the total age dataset without any discrimination, and accords each zircon age equal weight. However, this also introduces the shortcoming, in the Precambrian at least, of combining single, isolated ages that individually might be either highly significant or, for some unknown reason, highly spurious. For this reason, zircon proportions in the 'dominant' to 'minor' categories, as seen in the Torlesse composite terrane datasets, are given the greatest significance, and the 'accessory' category less significance, except where very persistent, as in the Waipapa terrane.

In general, this presentation confirms the dominance and persistence of Triassic and Permian zircon sources throughout the Eastern Province terranes. These age components are invariably close to their sample stratigraphic age ranges, suggesting that the terranes represent a long-continued active margin environment. Importantly, those terranes of accretionary prism character (Torlesse, Waipapa and Caples) are also characterized by substantial (> 20 %), but rather dispersed, early Palaeozoic–Precambrian zircon sources.

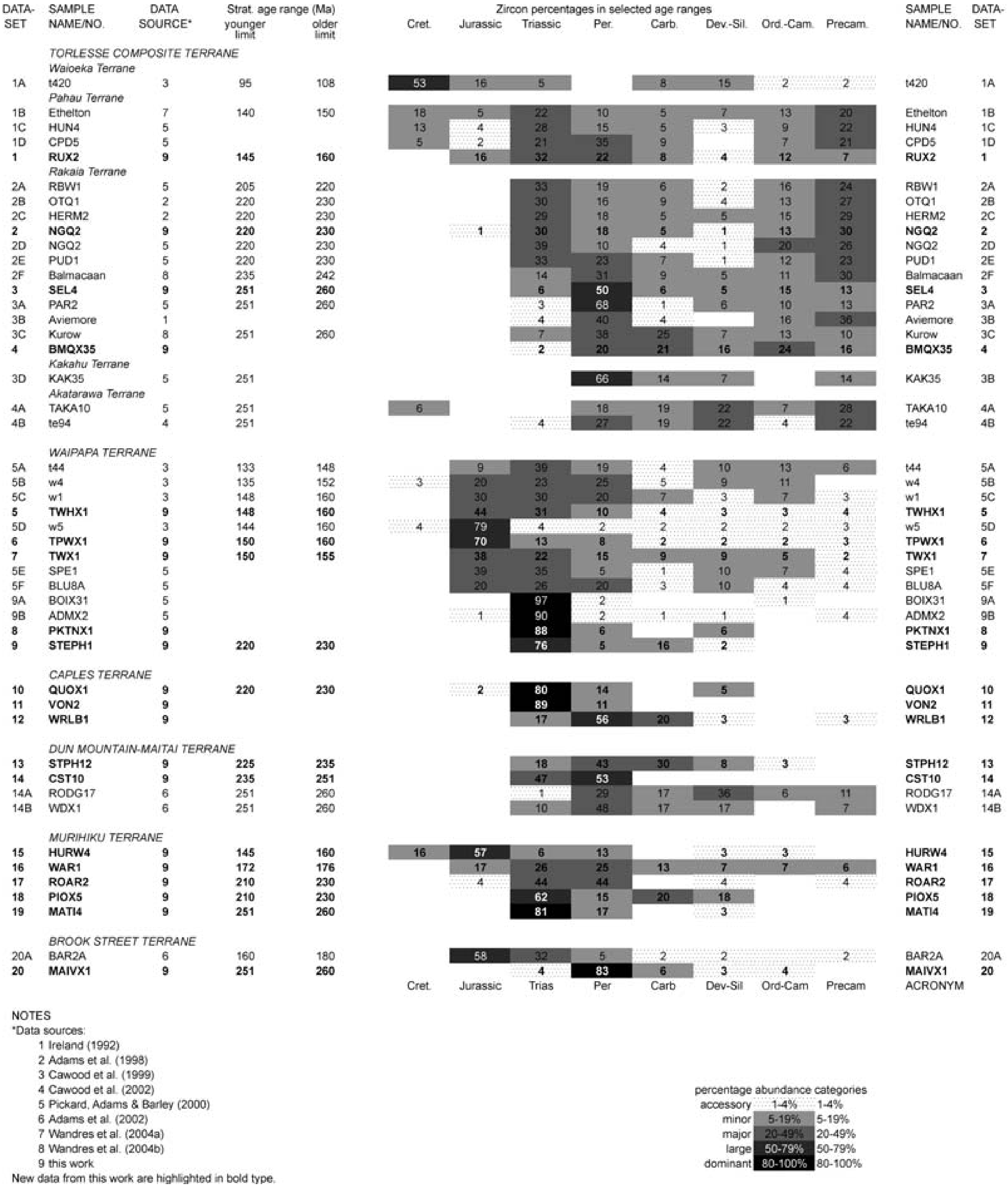
The Precambrian ages ($n = 69$) are difficult to treat statistically, with no significant groups evident. However, it is important to note the substantial proportions in the Neoproterozoic ($n = 51$, 5 % total dataset), and for which there is no obvious local source. This is particularly striking in the Torlesse composite terrane datasets, where the proportions increase to 8–20 % in individual datasets. In general, this group is always larger than that of Mesoproterozoic ($n = 13$), Palaeoproterozoic ($n = 2$) and Archaean ($n = 1$) intervals. The broad dispersal of Precambrian ages (without significant groups) suggests a much-diluted (and probably much-reworked) sediment supply from numerous sources, with no single source dominant.

The Torlesse composite terrane (datasets 1–4) clearly has a distinctive pattern, with its zircon populations probably complex in detail, but having two broad segments: Triassic–Permian and Ordovician–Cambrian–Precambrian. The former becomes younger and diminishes slightly with stratigraphic age, from a large Permian component in the Permian samples, to a major Triassic one in the Triassic samples. The proportion of the latter segment increases slightly with stratigraphic age, and in particular, abundant Precambrian zircons (up to 29 %) seem a distinctive feature of the Torlesse composite terrane, (cf. only 6 % Precambrian zircons in the total dataset; Fig. 3). The Waipapa terrane (datasets 5–9) also displays complex character in detail, but lacks the two segments of the Torlesse data. Like the latter, there is a Triassic–Permian younger segment (but more pronounced) that also becomes younger and diminishes with stratigraphic age, from dominant in the Permian, to major in the Jurassic. Unlike the Torlesse datasets, Precambrian zircons are scarce (< 6 %), and a minor early Palaeozoic segment only becomes apparent in the latest Jurassic. However, Palaeozoic components in the accessory to minor categories occur persistently throughout the Waipapa terrane at all stratigraphic levels.

The Caples, Murihiku and Brook Street terranes show age trends similar to the Waipapa terrane (see above), but with lower percentages of early Palaeozoic and Precambrian zircons. In the Caples terrane (datasets 10–12), the depositional age of all the samples is probably Triassic, and they show greater proportions of Triassic–Permian components than their Waipapa terrane time-correlates. Similarly, in the Murihiku and Brook Street terranes (datasets 15–20), the Permian (–Early Triassic) group is dominant to large at all stratigraphic levels. Early Palaeozoic and Precambrian zircons are here much fewer, and mostly absent.

The Dun Mountain–Maitai terrane data (datasets 13–14) are a small exception to the above trend, anomalous with respect to its immediate neighbours. Rather, it is a hybrid of Caples and Torlesse terrane characteristics; a large Triassic–Permian population resembles the former, while significant minor to major, early Palaeozoic–Precambrian components resemble the latter.

Most Brook Street terrane rocks have volcanic origins, and except for limited rhyolite–dacite formations in the Takitimu Group, these are overwhelmingly of basaltic–andesitic compositions. This is further



DATA-SET	SAMPLE NAME/NO.	DATA SOURCE*	Strat. age range (Ma) younger limit	Strat. age range (Ma) older limit	Cret.	Jurassic	Triassic	Per.	Carb.	Dev.-Sil.	Ord.-Cam.	Precam.	SAMPLE NAME/NO.	DATA-SET
	TORLESSE COMPOSITE TERRANE													
	Waioeka Terrane													
1A	t420	3	95	108	53	16	5		8	15	2	2	t420	1A
	Pahau Terrane													
1B	Ethelton	7	140	150	18	5	22	10	5	7	13	20	Ethelton	1B
1C	HUN4	5			13	4	28	15	5	3	9	22	HUN4	1C
1D	CPD5	5			5	2	21	35	9		7	21	CPD5	1D
1	**RUX2**	**9**	**145**	**160**		**16**	**32**	**22**	**8**	**4**	**12**	**7**	**RUX2**	**1**
	Rakaia Terrane													
2A	RBW1	5	205	220			33	19	6	2	16	24	RBW1	2A
2B	OTQ1	2	220	230			30	16	9	4	13	27	OTQ1	2B
2C	HERM2	2	220	230			29	18	5	5	15	29	HERM2	2C
2	**NGQ2**	**9**	**220**	**230**		**1**	**30**	**18**	**5**	**1**	**13**	**30**	**NGQ2**	**2**
2D	NGQ2	5	220	230			39	10	4	1	20	26	NGQ2	2D
2E	PUD1	5	220	230			33	23	7	1	12	23	PUD1	2E
2F	Balmacaan	8	235	242			14	31	9	5	11	30	Balmacaan	2F
3	**SEL4**	**9**	**251**	**260**			**6**	**50**	**6**	**5**	**15**	**13**	**SEL4**	**3**
3A	PAR2	5	251	260			3	68	1	6	10	13	PAR2	3A
3B	Aviemore	1					4	40	4		16	36	Aviemore	3B
3C	Kurow	8	251	260			7	38	25	7	13	10	Kurow	3C
4	**BMQX35**	**9**					**2**	**20**	**21**	**16**	**24**	**16**	**BMQX35**	**4**
	Kakahu Terrane													
3D	KAK35	5	251					66	14	7		14	KAK35	3B
	Akatarawa Terrane													
4A	TAKA10	5	251		6			18	19	22	7	28	TAKA10	4A
4B	te94	4	251				4	27	19	22	4	22	te94	4B
	WAIPAPA TERRANE													
5A	t44	3	133	148		9	39	19	4	10	13	6	t44	5A
5B	w4	3	135	152	3	20	23	25	5	9	11		w4	5B
5C	w1	3	148	160		30	30	20	7	3	7	3	w1	5C
5	**TWHX1**	**9**	**148**	**160**		**44**	**31**	**10**	**4**	**3**	**3**	**4**	**TWHX1**	**5**
5D	w5	3	144	160	4	79	4	2	2	2	2	3	w5	5D
6	**TPWX1**	**9**	**150**	**160**		**70**	**13**	**8**	**2**	**2**	**2**	**3**	**TPWX1**	**6**
7	**TWX1**	**9**	**150**	**155**		**38**	**22**	**15**	**9**	**9**	**5**	**2**	**TWX1**	**7**
5E	SPE1	5				39	35	5	1	10	7	4	SPE1	5E
5F	BLU8A	5				20	26	20	3	10	4	4	BLU8A	5F
9A	BOIX31	5					97	2			1		BOIX31	9A
9B	ADMX2	5				1	90	2	1	1		4	ADMX2	9B
8	**PKTNX1**	**9**					**88**	**6**		**6**			**PKTNX1**	**8**
9	**STEPH1**	**9**	**220**	**230**			**76**	**5**	**16**	**2**			**STEPH1**	**9**
	CAPLES TERRANE													
10	**QUOX1**	**9**	**220**	**230**		**2**	**80**	**14**		**5**			**QUOX1**	**10**
11	**VON2**	**9**					**89**	**11**					**VON2**	**11**
12	**WRLB1**	**9**					**17**	**56**	**20**	**3**		**3**	**WRLB1**	**12**
	DUN MOUNTAIN-MAITAI TERRANE													
13	**STPH12**	**9**	**225**	**235**			**18**	**43**	**30**	**8**	**3**		**STPH12**	**13**
14	**CST10**	**9**	**235**	**251**			**47**	**53**					**CST10**	**14**
14A	RODG17	6	251	260			1	29	17	36	6	11	RODG17	14A
14B	WDX1	6	251	260			10	48	17	17		7	WDX1	14B
	MURIHIKU TERRANE													
15	**HURW4**	**9**	**145**	**160**	**16**	**57**	**6**	**13**		**3**	**3**		**HURW4**	**15**
16	**WAR1**	**9**	**172**	**176**		**17**	**26**	**25**	**13**	**7**	**7**	**6**	**WAR1**	**16**
17	**ROAR2**	**9**	**210**	**230**		**4**	**44**	**44**		**4**		**4**	**ROAR2**	**17**
18	**PIOX5**	**9**	**210**	**230**			**62**	**15**	**20**	**18**			**PIOX5**	**18**
19	**MATI4**	**9**	**251**	**260**			**81**	**17**		**3**			**MATI4**	**19**
	BROOK STREET TERRANE													
20A	BAR2A	6	160	180		58	32	5	2	2		2	BAR2A	20A
20	**MAIVX1**	**9**	**251**	**260**			**4**	**83**	**6**	**3**	**4**		**MAIVX1**	**20**
					Cret.	Jurassic	Trias	Per	Carb	Dev-Sil	Ord-Cam	Precam	ACRONYM	

NOTES

*Data sources:

1 Ireland (1992)
2 Adams et al. (1998)
3 Cawood et al. (1999)
4 Cawood et al. (2002)
5 Pickard, Adams & Barley (2000)
6 Adams et al. (2002)
7 Wandres et al. (2004a)
8 Wandres et al. (2004b)
9 this work

New data from this work are highlighted in bold type.

percentage abundance categories

accessory	1-4%	1-4%
minor	5-19%	5-19%
major	20-49%	20-49%
large	50-79%	50-79%
dominant	80-100%	80-100%

Figure 4. Proportions of detrital zircon ^{238}U–^{206}Pb ages occurring in selected geological periods from all Eastern Province terranes in New Zealand. Data from the present work (sample dataset numbers) are in bold type, all other data (dataset numbers ending with a capital letter) are recalculated from previously published work. The proportions are categorized, following recommendations of Andersen (2005).

reflected in primitive Sr and Nd isotopic compositions (Adams *et al.* 2005). It is therefore not surprising that zircons are usually absent in the widespread redeposited Permian sedimentary successions, but a single exception occurs in (some) greywackes in the Late Permian, Grampian Formation (Nelson), which itself has more evolved Sr- and Nd-isotopic compositions (Adams *et al.* 2005). A typical greywacke

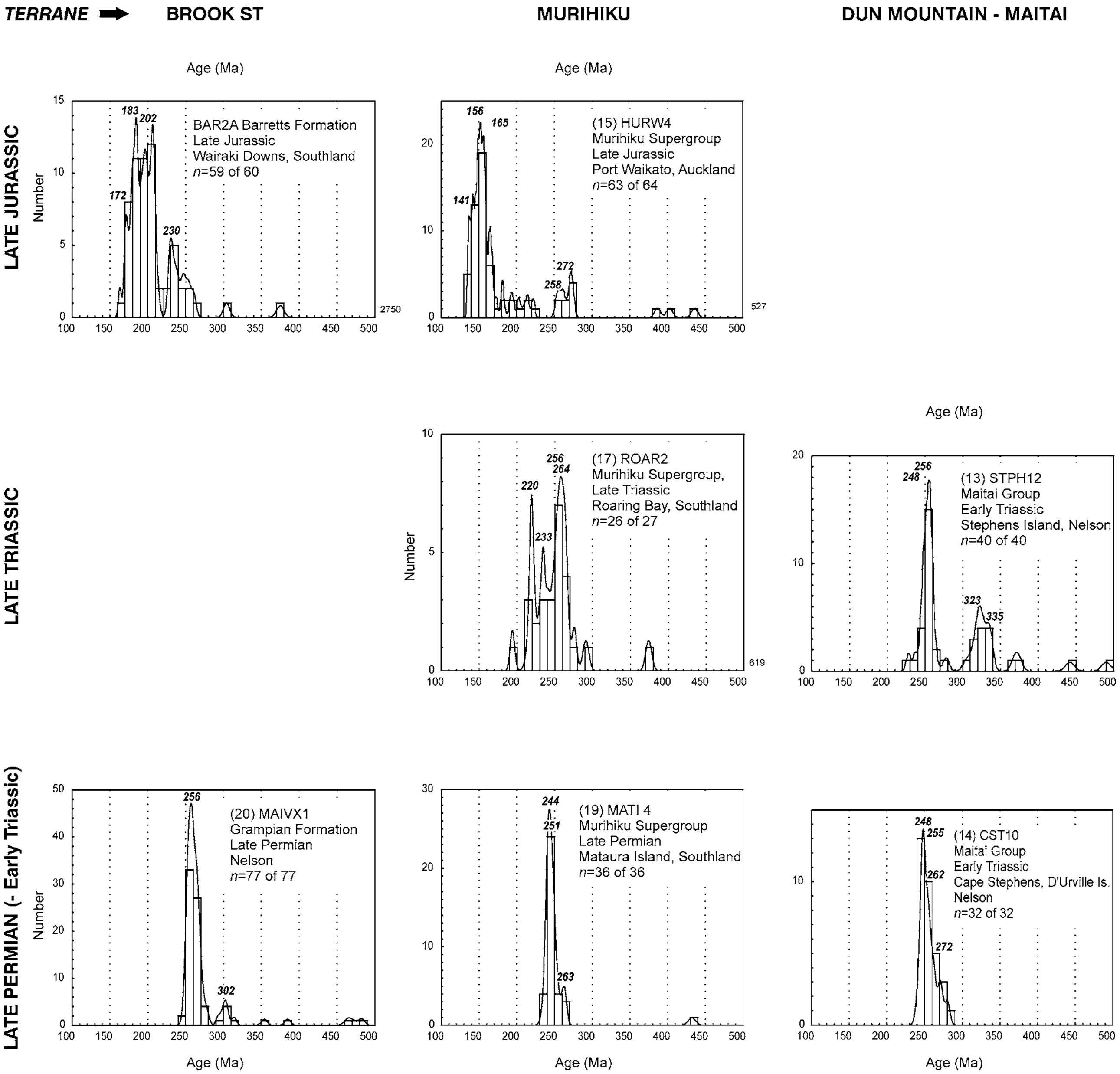


Figure 5. A time-space display of histogram/cumulative probability diagrams of detrital zircon ^{238}U–^{206}Pb age data from 14 Eastern Province greywackes and sandstones selected from this study, and one (BAR2A) from Adams *et al.* (2002), to represent Late Permian, Late Triassic, Late Jurassic time horizons, in west to east terrane order from left to right. Significant age components (expressed in millions of years) are shown in bold italics; other, less significant components, in normal italics. Ages > 500 Ma are stacked at right side.

(MAIVX1) has a zircon population (dataset 20, Table 2) dominated by contemporaneous, Late Permian volcanic zircons, 256 ± 1 Ma, but significantly, also has subordinate recycled populations at 265 ± 2 Ma (Middle Permian) and 302 ± 3 Ma (latest Carboniferous). These latter are probably associated with those provenance components, such as granitoids, imparting the unusual radiogenic character to the Grampian Formation.

5.b. Detrital zircon age components

The new zircon age data presented here are analysed in more detail using histograms/cumulative probability diagrams and constituent age component plots (Figs 5–12). Although relatively cautious criteria for significance are used here to discuss the particular zircon age components, it must be recognized that, inevitably, more general individual age distributions, although important, may fail these criteria and be unfortunately overlooked. However, interpretation of detrital zircon age patterns are very vulnerable to subjective selection of individual data points, and their discussion would be lengthy and ultimately probably yield only ambiguous conclusions.

A time–terrane presentation of 15 selected histograms (Fig. 5) again demonstrates the overwhelming

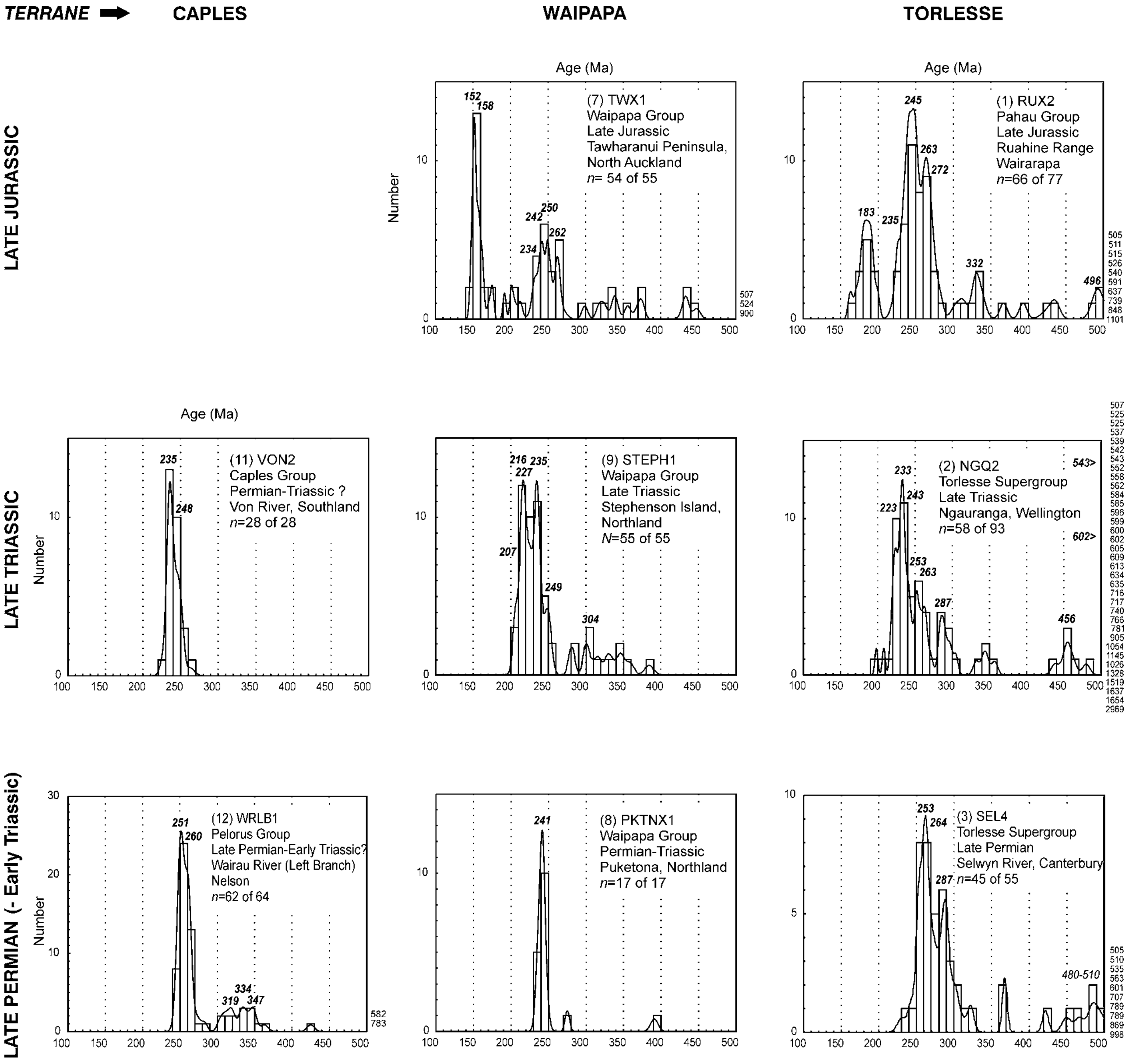


Figure 5. *(Contd.)*

Triassic–Permian age components throughout the Eastern Province. It also displays, more clearly than Figure 4, the increasing degree of polymodality of zircon age components, both in terms of time (top to bottom, Late Jurassic to Late Permian), and space (left to right representing west to east, from Brook Street to Torlesse terranes). Although the Caples terrane samples appear to be an exception, it should be noted that these samples are poorly constrained stratigraphically.

In Figure 6, the zircon age component data of Table 2 are used to provide a more rigorous presentation of the significant age components and their percentages, that is, $n \geq 4$ and comprising $> 4\%$ of total N. Age groups are determined by deconvolution of the total datasets, and their members are designated in the main data repository (PETLAB; the New Zealand Rock Catalogue and Analytical Database, accessible at http://pet.gns.cri.nz/), with lower-case letters. These are reproduced in the age component summary (Table 2), and in the text, following the dataset number, for example, component 4g is from BMQX35, with data: 489 ± 4 Ma, $n = 7$ grains, 8 % of total, $N = 91$. Analogous zircon age data from previously published work, calculated in a similar way, are summarized in Table 3. In general, the curve deconvolution procedures are most secure where two component peaks overlap by $< 50\%$, and they are within the peak size ratio range 0.3–3.0. In Figure 6, a uniform, 100–600 Ma, horizontal axis format accommodates all but one (Precambrian, 1019 Ma) of the 313 significant age components found in the combined present and

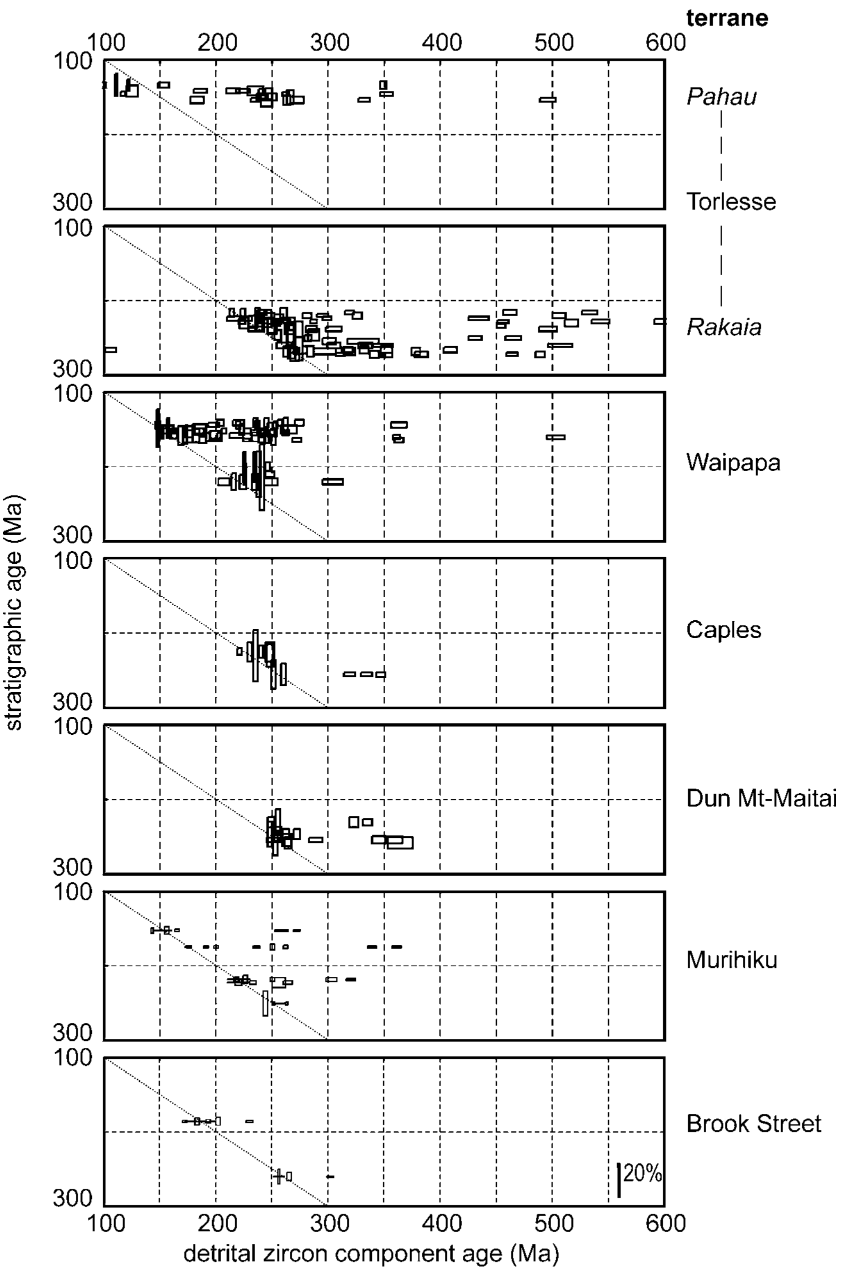


Figure 6. Detrital zircon ^{238}U–^{206}Pb age components derived from cumulative probability diagrams of greywackes and sandstones from all the Eastern Province terranes of New Zealand. Data are from 20 samples of this study, and 26 previously published samples. Samples are stacked from top to bottom in their present-day, east to west, terrane order (listed at right), and within each, in stratigraphic age order. In some cases, small adjustments have been made to avoid overlap of important data, and in the case of the unfossiliferous Caples terrane samples, these are placed only in probable Triassic, and probable Late Permian, groups. The height of each data box indicates the component proportion of total (see % scale bar) and the width is the component age error (2 sigma). The diagonal lines show the theoretical younger limit for detrital mineral ages.

previously published datasets. Individual sample data are assembled on the vertical axis, firstly in terrane order, secondly in stratigraphic order. The individual age component data are shown along the horizontal axis as data boxes whose widths reflect their age component analytical error (2σ) and whose heights (centred about stratigraphic age position) reflect the component's percentage of the total population. Thus, the tall, thin vertical data boxes represent more tightly constrained and more substantial zircon sources than the broad, thin horizontal ones.

5.b.1. *Total dataset*

The zircon age component-percentage variations in Figure 6 allow refinement of the conclusions drawn from Figure 5. For example, although complex in detail, the diagram demonstrates the dramatically diminished

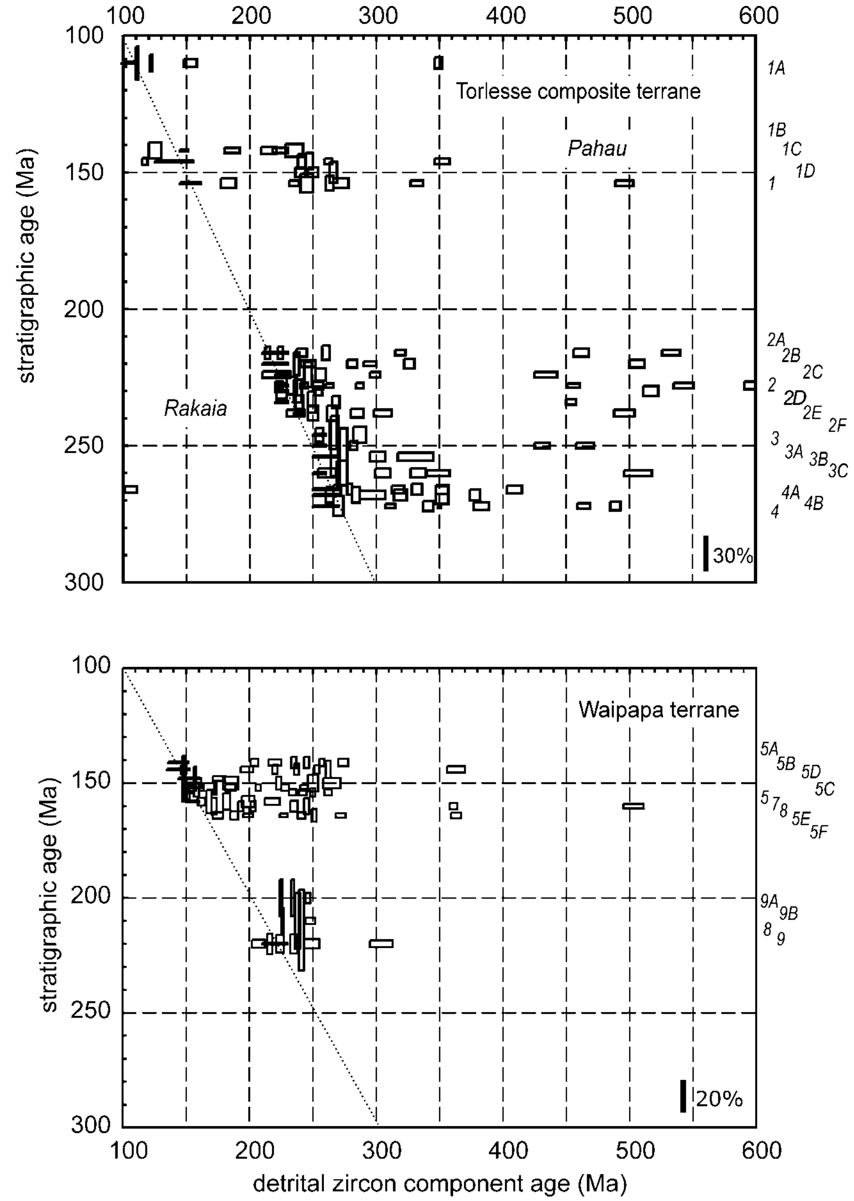


Figure 7. Detrital zircon ^{238}U–^{206}Pb age components derived from cumulative probability diagrams of Torlesse and Waipapa terrane greywackes. In upper diagram, 19 Torlessse composite terrane greywackes (four from this study and 15 from previously published work) are shown subdivided into Pahau and Rakaia terranes. In the lower diagram, similar datasets for 12 Waipapa terrane greywackes are shown (two from this work and ten from previously published work). In each case, datasets (sample numbers in italics at right) are assembled in stratigraphic order. In some cases small adjustments have been made to avoid overlap of important data. The height of each data box indicates the component age proportion of total (see % scale bar) and the width the component age error (2 sigma). The diagonal lines show the theoretical younger limit for detrital mineral ages.

importance for early Palaeozoic–Precambrian zircon age groups, and a lesser degree of polymodality in all but the Rakaia terrane. No significant Precambrian zircon age groups were found in the present study, and only one was found in previously published datasets: 1019 ± 21 in a Middle Triassic greywacke, from Torlesse Supergroup at Balmacaan Stream, Canterbury (Wandres *et al.* 2004*b*, corresponding to data set 2F in Fig. 7). This suggests that Precambrian sediment sources are distant or extremely diluted. On the other hand, Figure 7 convincingly confirms that the total Triassic–Permian age concentrations of Figure 4 are indeed underpinned by frequent and closely constrained age components of Early Triassic and Late Permian age, at the major to dominant levels.

More detailed enlargements of Figure 6 are shown for the Torlesse and Waipapa terranes in Figure 7, including comparable data assembled from previously published work, and for the Caples, Dun Mountain–Maitai, Murihiku and Brook Street terranes in Figure 9. To demonstrate the proximity of the youngest detrital zircon age components to estimated sample stratigraphic age, each dataset line has the sample stratigraphic age estimate (where known) indicated as a narrow solid horizontal bar.

5.b.2. *Rakaia terrane (Torlesse composite terrane)*

Detrital zircon distributions have been most intensively studied in Rakaia terrane greywackes (Ireland, 1992; Adams *et al.* 1998, and this work; Pickard, Adams & Barley, 2000; Cawood *et al.* 2002; Wandres *et al.* 2004*b*), and these provide an excellent starting point for detailed age component analysis. In Figure 7 (upper), the age components for 14 Rakaia samples are strongly crowded close to the stratigraphic age limit (diagonal line), with most dominant and major components located in a diachronous band (from Late Triassic to Early Permian) about 40 million years older. In 80 % of cases, the youngest age component is within the age range of sedimentation, and this strongly suggests that these zircons are formed coincident with deposition, and originate from a volcanic source. Although Torlesse Supergroup turbiditic greywackes in the Rakaia terrane contain some volcanic lithic debris (MacKinnon, 1983), they are not strongly volcaniclastic, and tuffs are absent. Silicic volcanics would provide ample zircon sources, and although central volcanic complexes are not extensive (hundreds of km^2), their associated airfall deposits could be extremely extensive (millions of km^2). However, although laterally extensive, they are rarely very thick (say < 100 m), and they would not necessarily provide dominant or major zircon components over a long erosion period. Significantly, the youngest age components are frequently not the largest. The latter are often 20–50 million years older, perhaps reflecting the delayed exhumation of more deep-seated plutonic equivalents to those volcanic sources; for example, granitoid batholiths have greater depth available for erosion (say, > 5 km) and, locally, could easily constitute a dominant, long-lasting, fluvially transported zircon source. Despite the general diachronous pattern, the most closely constrained, major to dominant, component ages (thin vertical data boxes in Fig. 7) fall persistently in the 260–270 Ma interval in the Permian, and 240–250 Ma in the Triassic. More dispersed age components between 280 and 330 Ma might extend this diachronous age pattern out to 100 million years older than the stratigraphic age limit, but if so, its significance is not understood. Within this zone, a 290–310 Ma component appears the most significant. It seems equally possible that these Carboniferous data are just part of the more dispersed age pattern of older Palaeozoic components. The latter are overwhelmingly Ordovician to Cambrian, show no diachronous behaviour, and have only a single significant grouping at 450–470 Ma. Overall, this pattern seems more referable to a mature, stable cratonic environment providing a mixture of zircon sources with few changes over time.

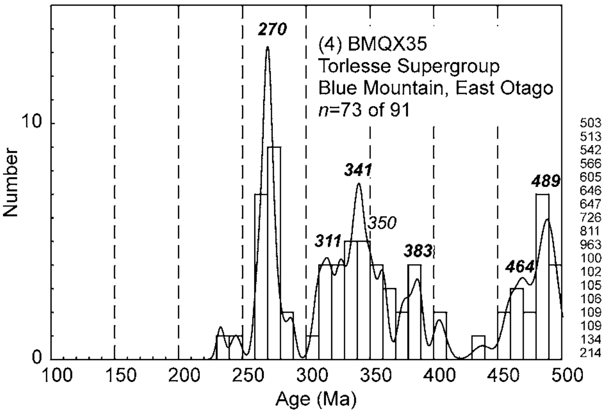


Figure 8. Histogram and cumulative probability diagram of ^{238}U–^{206}Pb age data in a possible Middle Permian greywacke in the Rakaia terrane (dataset (4) BMQX35, Blue Mountain, Otago). Significant age components (expressed in millions of years, Ma) are noted in bold italics. Ages > 500 Ma are stacked at right side.

A rare glimpse of the earliest Torlesse Supergroup sedimentation (Rakaia terrane) is shown by zircon age data (Fig. 8) from a greywacke at Blue Mountain, Otago (dataset 4). Although greywackes at this location are unfossiliferous, unusual limestones in the vicinity (possibly tectonic intercalations) are of Late Carboniferous age. The principal, *c.* 270 Ma, age component in the greywackes would exclude a Carboniferous stratigraphic age, but it and the unusual poverty of *c.* 250 Ma (Late Permian to earliest Triassic) ages, would suggest that a late Early Permian age is more likely. In addition to the abundance (40 % of total) of older, pre-450 Ma, ages that are characteristic of the older Torlesse Supergroup, this sample also reveals a very uncharacteristic pattern of Carboniferous and Middle Devonian age components. Comprising > 30 % of the total, these latter must represent significant zircon sources that disappeared before younger, Permian and Triassic Torlesse sedimentation ensued. However, surprisingly, this change did not affect older, > 450 Ma, zircon supplies.

5.b.3. *Pahau terrane (Torlesse composite terrane)*

Unlike all other Eastern Province terranes, the Pahau samples show no strong concentration of detrital zircon ages at their inferred sample stratigraphic age limit (Fig. 7, top). For samples 1B and 1C, this age limit, although poorly defined, is older than the small, but significant, youngest zircon age components, and thus a late Early Cretaceous stratigraphic age seems more probable. Although the datasets comprise more than 250 analyses, Jurassic age components (only three) are surprisingly few, (cf. the Early Cretaceous–Jurassic Waipapa terrane samples; 15, Fig. 7, bottom). These features may indicate a less active tectonic setting for the Pahau terrane, tending towards a passive margin environment in which older zircons are frequently recycled. However, the Pahau data do show the dominance of Early Triassic and Late Permian ages that is characteristic of all other Eastern Province terranes, particularly in the intervals 230–250 Ma and 270–275 Ma. On the basis of detailed petrographic, geochemical and geochronological studies of Rakaia and Pahau terrane conglomerate clasts, and their host sandstones (Table 3; datasets 1B and 2F), MacKinnon (1983), Wandres *et al.* (2004*a*,*b*) and Wandres, Bradshaw & Ireland (2005) concluded that older Torlesse detritus from the Rakaia terrane is recycled into younger Torlesse sediments of the Pahau terrane. While the general similarity of Triassic–Permian zircon age components in both terranes would seem to support this recycling model, a closer analysis reveals crucial difficulties. There is a drastic diminution in Palaeozoic (> 300 Ma) and Precambrian zircon age components in the Pahau terrane, compared to their characteristic abundance in the older Torlesse of the Rakaia terrane. However, there is no corresponding diminution in percentages of the mostly Triassic–Late Permian age components in the Pahau datasets. It is thus hard to see how recycling of Rakaia terrane Torlesse detritus into Pahau terrane sediments, involving substantial dilution, could remove the Palaeozoic age components (usually 5–10 % of total) without a similar effect on the Triassic–Late Permian ones. Without some unusual grain discrimination, the zircon age groups in the source materials must be conserved in their original proportions during any recycling. Thus the pre-Jurassic greywacke detritus in the Pahau terrane better originates from a Waipapa terrane source, to which then contemporary Jurassic volcanic detritus is contributed.

5.b.4. *Waipapa terrane*

Detrital zircon component ages in the Waipapa terrane reveal clear differences from the Torlesse composite terrane time-correlates (Fig. 7). Firstly, and unlike the Torlesse terrane, the sparse but persistent Waipapa terrane Palaeozoic–Precambrian zircons of Figure 4 are reduced to only five significant pre-Permian components (Fig. 7, bottom) with none Precambrian. Secondly, and unlike the Pahau terrane, the Waipapa greywackes of Jurassic age do have minor to major age components close to their stratigraphic age limits. Both the Jurassic and Triassic Waipapa greywackes (datasets 9A, 9B) have the ubiquitous Early Triassic, 235–250 Ma, components, which become major to dominant in the Triassic samples. Thirdly, and unlike the Torlesse terrane, the Late Permian age components, mainly 260–275 Ma, are diminished overall. The zircon age pattern of the Triassic samples suggests that Pahau terrane sediments may be derived from recycled Waipapa, rather than Rakaia, detritus. Permian and Early Palaeozoic–Precambrian zircon age components would be minor or absent, while the strong 235–250 Ma components in the Pahau sediments would be conserved.

Triassic successions in the Waipapa terrane might be more extensive than apparent from the very few fossil occurrences. Apart from the localities mentioned above, it is probable that a central block in Northland, for example, Puketona (Table 2; dataset 8) is Triassic. Mortimer (1993*b*) designated a central block (of unknown age) of Haast Schist in Marlborough as having Waipapa terrane protolith. Late Triassic greywackes on Kapiti Island, near Wellington (Fig. 1) may be a northeast continuation of this, and Adams & Graham (1996), on Rb–Sr age and Sr-isotope characteristics, suggested a Waipapa rather than Torlesse parentage. These authors draw a similar conclusion (Adams & Graham, 1997) for anomalous Caples terrane rocks on the East Otago coast, such as Quoin Point (Table 2; dataset 10).

5.b.5. *Caples, Dun Mountain–Maitai, Murihiku and Brook Street terranes*

The Caples and Dun Mountain–Maitai terrane patterns (Fig. 9, top) continue the trend, from Torlesse to Waipapa terranes, of diminishing, early Palaeozoic–Precambrian components. K–Ar metamorphic ages and a single fossil occurrence (sample locality 10) only poorly constrain Caples terrane sample stratigraphic ages (datasets 10–12), but with the better-dated Dun Mountain–Maitai terrane samples (datasets 13, 14, 14A, B), their detrital zircon component ages indicate predominantly primary zircon inputs at the time of deposition, with much-diminished recycled zircon populations. Similarities in component age patterns suggest that Caples and Dun Mountain–Maitai terranes might have a common provenance, with the Dun Mountain–Maitai terrane representing a stable shallow shelf, adjacent to a Caples terrane accretionary trench-slope environment. Both terrane datasets contain a few significant older age components and uniquely, these are all Carboniferous and Late Devonian. Thus, these zircon components presumably have older, continental sources, but ones that are subtly different from their Torlesse and Waipapa terrane time-correlates.

The Murihiku and Brook Street datasets (Fig. 9, bottom; datasets 15–20) represent a final stage in a westward trend through the Eastern Province. They could reflect a completely self-contained depositional environment, with samples at each stratigraphic level carrying predominantly primary zircon inputs, but also including a small degree of local zircon reworking from older levels. With the exception of WAR1 (dataset 16), the paucity of Early Palaeozoic and Precambrian age components suggests isolation from continental zircon sources, and this may indicate an offshore island-arc depositional environment.

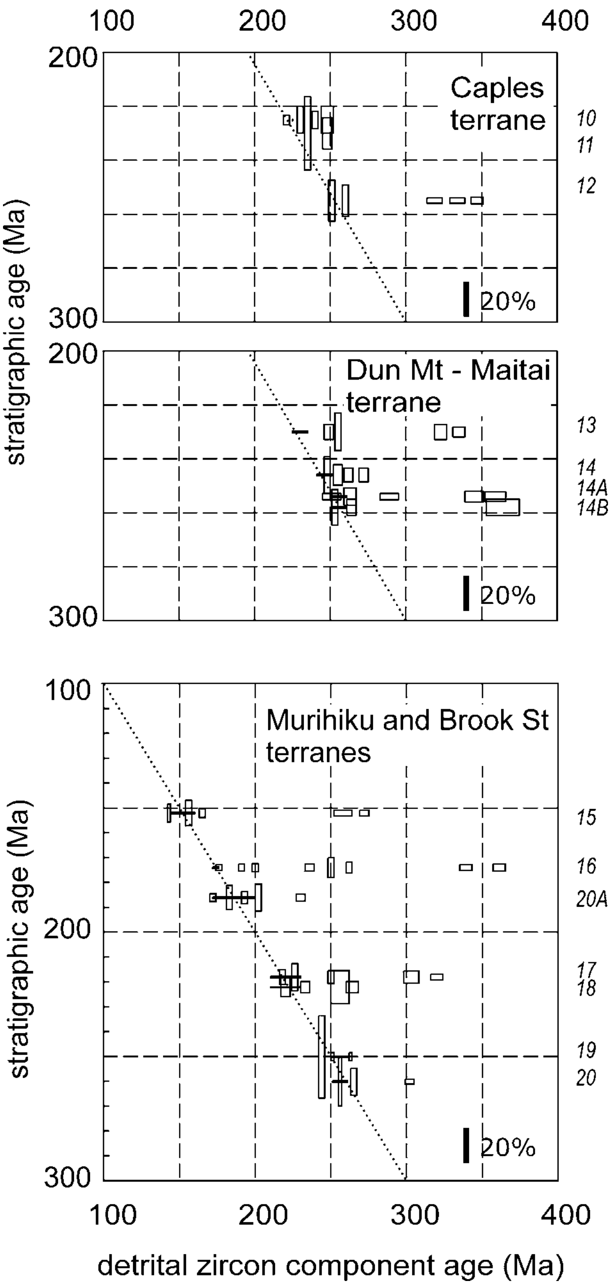


Figure 9. Detrital zircon ^{238}U–^{206}Pb age components derived from cumulative probability diagrams in 14 greywackes (ten from this study, four from previously published work) of the Eastern Province of New Zealand (sample numbers in italics at right). In top and middle diagrams, data are combined from three Caples, and four Dun Mountain–Maitai samples, while in the lower diagram, data are combined from five Murihiku, and two Brook Street terrane samples. Except for Caples terrane, datasets are assembled in stratigraphic order. The unfossiliferous Caples terrane samples are positioned only in probable Triassic and probable Late Permian groups. The height of each data box indicates component age proportion of total set (see % scale bar) and the width the component age error (2 sigma). The diagonal lines show the theoretical younger limit for detrital mineral ages.

5.c. Intra-terrane variations in detrital zircon patterns

While individual terranes generally show distinctive detrital zircon age characteristics, the intra-terrane variation is considerable, sufficiently so to make clear terrane assignment impossible on these criteria alone. Jurassic and Triassic horizons are sufficiently well dated to allow regional comparisons of these patterns.

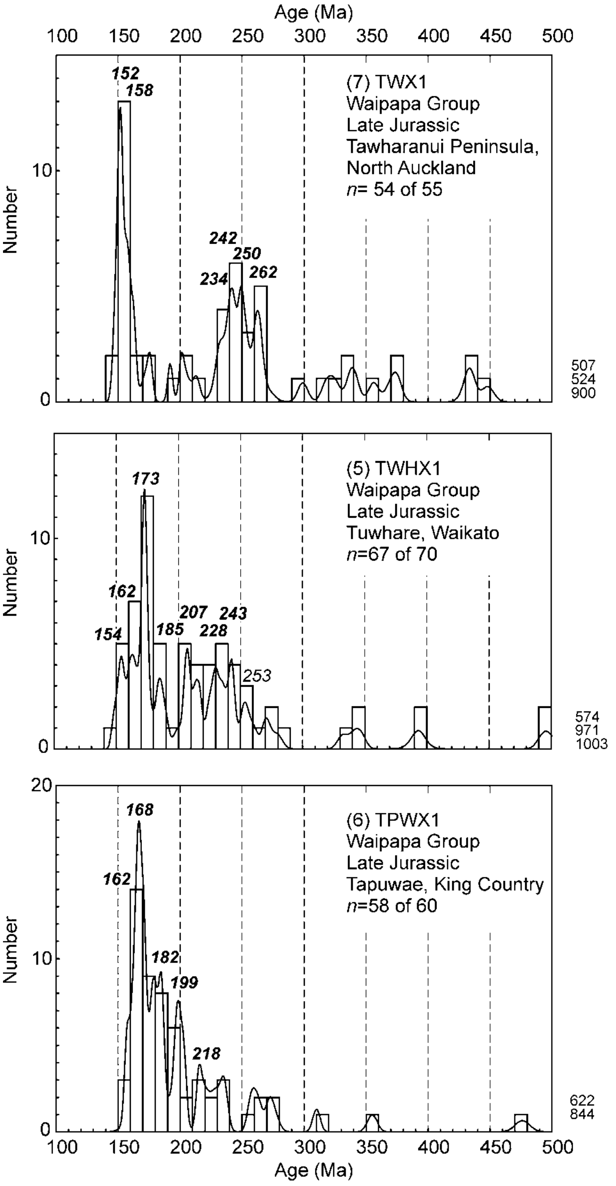


Figure 10. An intra-terrane comparison of histogram/cumulative probability diagrams of detrital zircon ^{238}U–^{206}Pb age data for three greywackes of Late Jurassic (Kimmeridgian) age in the Waipapa terrane of the three North Island datasets: (7) TWX1 Tawharanui, (5) TWHX1 Tuwhare, (6) TPWX1 Tapuwae. Significant age components (Ma) are shown in bold italics; other, less significant components, in normal italics. Ages > 500 Ma are stacked at right.

In Figure 10, age histograms are compared for three Waipapa terrane samples from Late Jurassic (Kimmeridgian) fossil localities. These are arranged from north (Tawharanui) to south (Tapuwae), encompassing a 300 km segment of the terrane. While Jurassic zircons are clearly dominant in all samples, Early, Middle, and Late Jurassic components do change, with Early Jurassic ages (*c.* 180–185 Ma) increasing

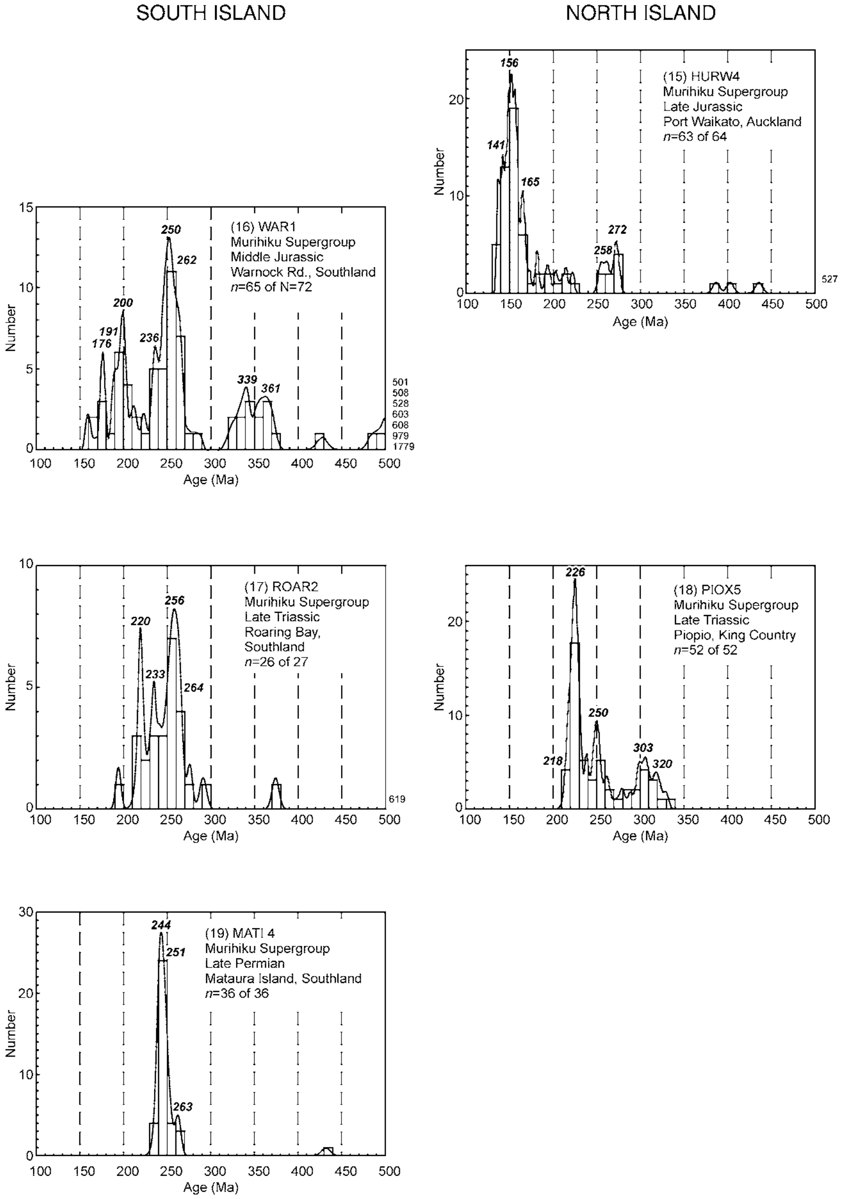


Figure 11. An intra-terrane comparison of histogram/cumulative probability diagrams of detrital zircon ^{238}U–^{206}Pb age data for Permian, Triassic and Jurassic greywackes and sandstones in the Murihiku terrane, divided into South and North Island sectors. Significant age components (Ma) are shown in bold italics. Ages > 500 Ma are stacked at right.

southwards, and Late Jurassic ages northwards (*c.* 150–155 Ma). Similarly, Triassic–Permian ages form a second group in all three, becoming more abundant northwards, and accompanied by a higher proportion of older (> 300 Ma) zircons.

In Figure 11, age histograms are compared for five Murihiku terrane samples of Permian, Triassic and Jurassic age, divided into South and North Island sectors. Note that the two Late Triassic samples are about 1000 km apart, in the Kawhia Syncline in the North Island at Pio Pio, and the Southland Syncline in the South Island at Roaring Bay (Fig. 1), but are from horizons of very similar early Norian age. While Late Triassic (*c.* 220 Ma) and Permian (*c.* 250–260 Ma) ages are significant components in both samples, their ratios are reversed. A small, Late Carboniferous group (< 10 % at 300–320 Ma) occurs only in the Pio Pio dataset. In the South Island sector, from the Permian to Middle Jurassic, there are increasingly polymodal zircon patterns, but in the North Island sector, from Triassic to Late Jurassic, this trend is scarcely discernable.

5.d. Inter-terrane transitions in detrital zircon patterns

In Figure 12, zircon age data are shown for an uncertain Caples terrane sample from a Late Triassic fossil locality at Quoin Point, Otago (Fig. 1). Although apparently within the general trend of the Caples terrane, the rocks here have unusual petrological and geochemical characteristics, more of Torlesse terrane affinity (Mortimer, 1993*a*). On Rb–Sr age and initial

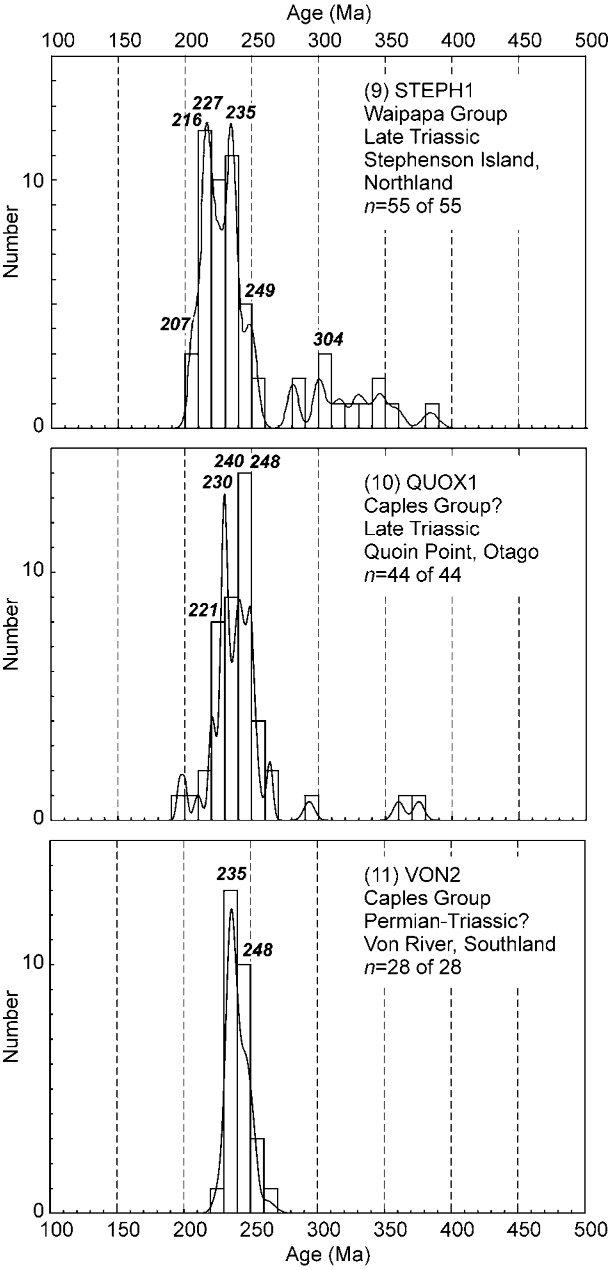


Figure 12. Histogram and cumulative probability diagrams of detrital zircon ^{238}U–^{206}Pb ages for dataset (10) QUOX1 (centre), a Late Triassic greywacke from East Otago, occurring within an extension of the Caples terrane, but which is geochemically and/or isotopically of Torlesse or Waipapa terrane affinity. This is compared with Late Triassic datasets from greywackes of true Waipapa (9) STEPH1 (above), and true Caples (11) VON2 (below), terrane affinities. Significant age components (Ma) are shown in bold italics; other, less significant components, in normal italics.

Sr-isotopic evidence, Adams & Graham (1997) suggested that they were neither, but more closely matched correlative Triassic rocks in the Waipapa terrane of the North Island. The Quoin Point data in Figure 12 are compared with Late Triassic samples from the Waipapa terrane *sensu stricto* in Northland (dataset 9), and the Caples terrane *sensu stricto* at a type Caples Group locality in western Southland (dataset 11). Rb–Sr metamorphic ages here suggest a minimum, Late Triassic, stratigraphic age (C. J. Adams, unpub. data). The latter sample (11) is unsupported by fossil ages, and its youngest zircon ages, *c.* 230 Ma, only provide a late Middle Triassic older age limit. All three samples show similar Middle (*c.* 235 Ma) and Early (*c.* 245 Ma) Triassic age components, but an additional Late Triassic (*c.* 220 Ma) age component is absent from the Caples *s.s.* dataset. The close match better supports the assignment of Quoin Point sample (10) into the Waipapa terrane.

6. Provenance of detrital zircons in eastern province sediments

6.a. Zircon sources in New Zealand

Previous studies of the turbiditic, greywacke-dominated Torlesse composite terrane have all concluded that its position, as the most outboard Eastern Province terrane at the Gondwanaland continental margin, indicates a suspect terrane origin (Coombs *et al.* 1976; MacKinnon, 1983). Relying upon detrital zircon age evidence alone, the same conclusion was also reached for the Waipapa (Pickard, Adams & Barley, 2000; Cawood *et al.* 2002), and Dun Mountain–Maitai and Brook Street (Adams *et al.* 2002) terranes. In all cases, the inboard terranes and the adjacent continental margin terranes are (1) of quite dissimilar character, (2) lack source rocks of appropriate age (or they are too restricted) and (3) contain source rocks of inappropriate age (Fig. 13a, b). Although Wandres *et al.* (2004*a*) demonstrated clear comparisons of Pahau conglomerate clasts with Cretaceous granitoids in the Median Batholith, these latter are small plutons insufficient to provide the total younger Torlesse sediment supply. Of course, the original extent of these plutons could now have been drastically reduced by tectonic modification, but recent recognition of these (and other) plutons as part of a batholith (Median Batholith), with Permian components overlapping ('stitching') the Brook Street Terrane, and Cretaceous components the Takaka/Buller terranes, perhaps diminishes the potential for this. There is also a complication of conflicting zircon sources. Late Jurassic and Early Cretaceous granitoids do dominate throughout the Median Batholith and the adjacent Takaka/Buller terranes, but they are often intimately mixed (Fig. 13a, b) with older Early Carboniferous to Late Devonian granitoids, for example, in southwest Fiordland (Muir *et al.* 1994, 1996*a*,*b*, 1997, 1998). While the former do represent an appropriate zircon source, they cannot be divorced from inappropriate zircon sources of the latter. More seriously, in the older, Triassic–Permian parts, appropriate zircon sources (required to be the dominant ones) are extremely restricted in the Median Batholith (and almost absent

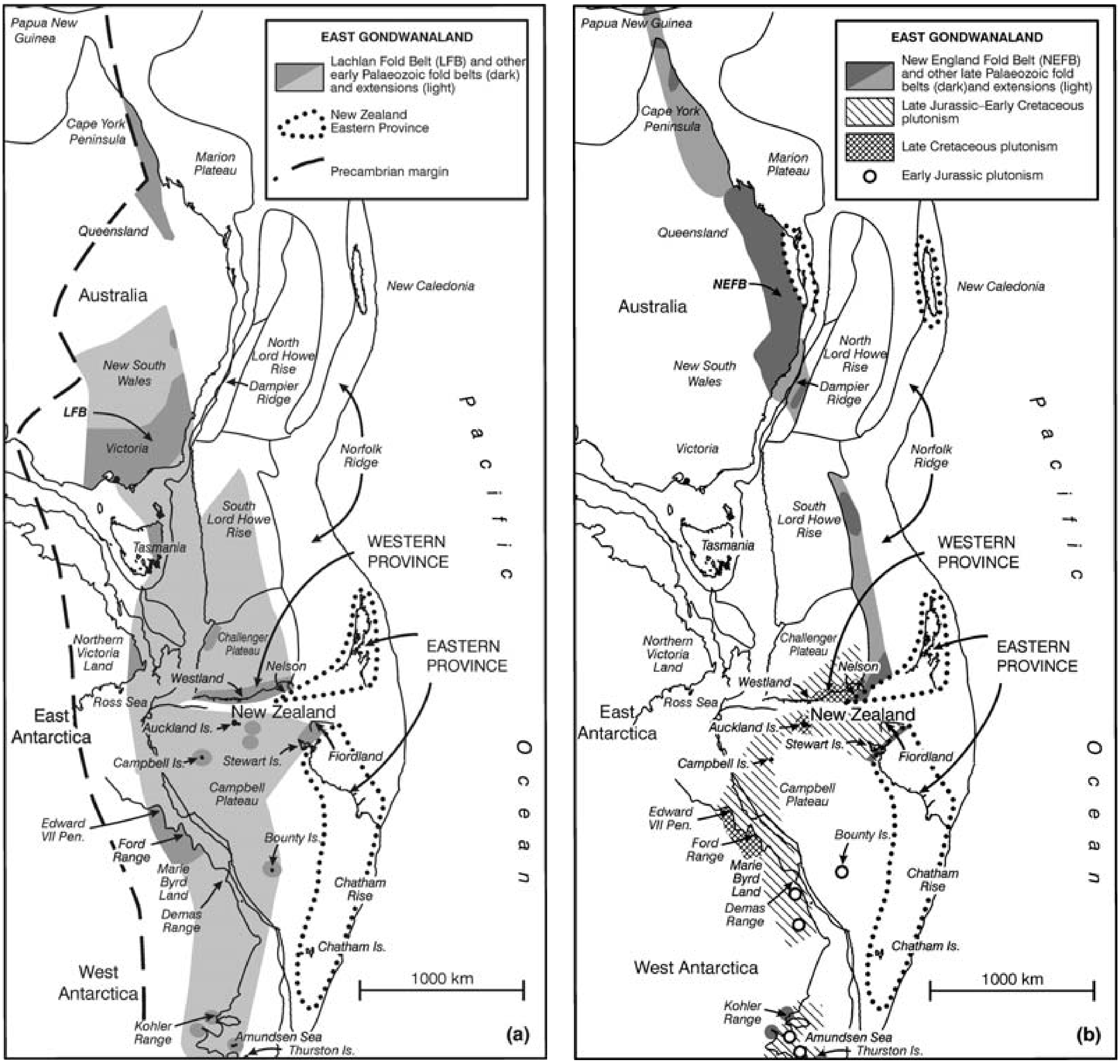


Figure 13. The Eastern Gondwanaland margin (in Late Triassic time) showing principal geological elements: (a) the Lachlan Fold Belt of Australia and continuations in New Zealand and Antarctica, and its possible full extent and (b) the New England Fold Belt and Hodgkinson Province of Australia and possible continuations in New Zealand, Antarctica, New Caledonia and northernmost Australia, and their possible full extent. Pattern denotes areas of Cretaceous plutonism; small open circles denote areas of Early Jurassic plutonism. The present extent of the Eastern Province of New Zealand is shown as a dotted envelope.

in the adjacent terranes), since plutonism there is more basic-intermediate, and granitoids are rare and local.

6.b. Zircon sources in West Antarctica and on the Campbell Plateau

The Campbell Plateau and the formerly contiguous Marie Byrd Land sector of West Antarctica are major continental crustal fragments and potentially could provide voluminous sediment sources for Eastern Province suspect terranes (Fig. 13a). However, their geophysical characteristics tell us nothing of the age of the continental basement. On the Campbell Plateau, basement is only seen on a few subantarctic islands (Adams, Morris & Beggs, 1979), sea-floor dredge sites and oil exploration drill-holes (Beggs, Challis & Cook, 1990). In West Antarctica, basement is restricted to the Ford Range and isolated ranges of nunataks to the east. Age control is poor and fossil localities extremely rare. Thus, the geological makeup of this region, comparable in size to Europe, rests on very patchy evidence. Only 2 % of these regions are above sea- or ice-level, and it is dangerous to speculate on major continental geology from such small available outcrop. Even setting aside these reservations, there is little or no evidence from the tiny available outcrop for basement complexes of appropriate size (10^6 km^3), rock type (granitoids or similar), and age mixtures (dominantly Permian–Triassic, and with no Devonian) that might provide a source for New Zealand Eastern Province sediments. Petrographic, geochemical and geochronological (mostly Rb–Sr isochron, but some U–Pb zircon ages) evidence suggests that Mesozoic (mostly Cretaceous and Jurassic) plutonic and volcanic complexes, although scattered and local, occur along the length of the Marie Byrd Land coast, from the Ross Sea to the Amundsen Sea (Bradshaw *et al.* 1997; Pankhurst *et al.* 1993, 1998). In the Amundsen Sea area (Pine Island Bay, Thurston Island, Kohler Range), Early Cretaceous and Jurassic plutonic rocks are frequent. The local basement is Late Carboniferous orthogneiss on Thurston Island and Silurian–Devonian orthogneiss at Mt Wilbanks (Kohler Range). Triassic and Permian granitoids are not known in western Marie Land, but Early Permian granitoids occur at Mt Wilbanks, Kohler Range (Mukasa & Dalziel, 2000), and Triassic granitoid at Mt Murphy. In central Marie Byrd Land, metasediments at Patton Bluff and Mt Petras are dominated by Devonian–Carboniferous detrital zircon ages suggesting a local derivation (see below). More generally, for example, in the Demas Range, Early Cretaceous complex granitoid suites and mid-Cretaceous granodiorites are dominant. The magmatism in these areas is regarded as a convergent margin type (Pankhurst *et al.* 1998).

In contrast, in western Marie Byrd Land (Edward VII Peninsula and Ford Ranges), mid-Cretaceous A-type granitoid plutonism (Adams, 1987) is related to continental break-up. There, the more extensive basement outcrop is similar to the Buller terrane of New Zealand: a mixture of Early Palaeozoic metasediments and Early Carboniferous and Late Devonian granitoids. Early Silurian–Late Ordovician metamorphism in the former (Adams, 1986) can be correlated with plutonism of similar age in the eastern Marie Byrd Land, and this suggests that an extension of the Lachlan Fold Belt *sensu lato* extends along the entire Marie Byrd Land coast (Fig. 13a). Bradshaw *et al.* (1997) thus interpreted the broader features of Marie Byrd Land geology as a continuation of the Buller (and more speculatively) Takaka terranes in the west, and the New Zealand Median Tectonic Zone/Median Batholith in the east. These authors further attempted to trace the connection across the Campbell Plateau, but there are few features that confirm this. Apart from a short southeast continuation of magnetic anomalies associated with the Dun Mountain–Maitai terrane (Fig. 13b), there are no geological or geophysical features, such as magnetic anomalies (Sutherland, 1999), that might be attributable to the Median Tectonic Zone. No Permian or Triassic plutonic rocks are known on the Campbell Plateau, and only the Early Jurassic granites of the Bounty Islands might be candidates. These do have eastern Marie Byrd Land correlates, but uniquely (on the Bounty Platform), they intrude Palaeozoic metasediments correlated with the Greenland Group of the Buller terrane (Adams & Cullen, 1978). Mid-Cretaceous granites on Auckland and Snares islands are better correlated with western Marie Byrd Land suites in Antarctica (above), and the Paparoa and Hohonu batholiths in New Zealand (Cooper & Tulloch, 1992), all also within the Buller terrane or its extensions. The magnetically ‘quiet’ pattern (Sutherland, 1999) in this belt (Fig. 13a, b) may reflect these granites. It is probable that the Buller, and possibly Takaka, terranes extend over much of the Campbell Plateau, particularly from Campbell Island to Bounty Island (as reflected by its ‘noisier’ magnetic pattern that seems characteristic of most of the Western Province). This could drastically reduce any potential extension of the Median Tectonic Zone to the Bounty Trough area. Of course, Jurassic granitoids, as part of the Median Batholith, might be more extensive than apparent within the Buller terrane on the Campbell Plateau, and provide appropriate zircon source components for Waipapa and Pahau terrane sediments. However, any Eastern Province sediments (from Cretaceous to Permian) derived from this region would also have to carry a substantial Buller terrane inheritance. This would be signalled by its characteristic detrital zircon age patterns having two predominant components: Early Carboniferous–Late Devonian and Cambrian–late Neoproterozoic, as the Patton Bluff and Mt Petras examples noted above. Since zircons in these two age ranges are rare and sometimes absent in Eastern Province sedimentary rocks, a source for the latter most probably does not lie in West Antarctica or the Campbell Plateau.

6.c. Zircon sources in southeastern Australia and East Antarctica

The Lachlan Fold Belt of southeast Australia, from southern New South Wales, through Victoria and Tasmania, extends southwards into northern Victoria Land, East Antarctica (Tessensohn *et al.* 1981). Throughout, it comprises voluminous granitoid complexes, of mainly Early Carboniferous–Devonian age (Veevers, 2000, fig. 192), emplaced into extensive early Palaeozoic greywacke-dominated sedimentary terranes (Veevers, 2000, figs 182–184). Australian references to regional geology and geochronological studies are too numerous to cite fully, and reliance is placed on summary data compilations and extensive reviews in Veevers, Conaghan & Powell (1994) and Veevers (2000) and references cited therein. More recent studies are cited here. Triassic and Permian plutonic rocks are essentially absent, and like counterparts in New Zealand and Marie Byrd Land, these regions would be unsuitable as zircon sources for New Zealand Eastern Province sediments.

6.d. Zircon sources in northeastern Australia and on Lord Howe Rise

In comparison to the Campbell Plateau and Antarctic regions, northeastern Australia provides a wealth of potential source rocks for New Zealand Eastern Province sediments. From northeastern New South Wales, through Queensland to Papua New Guinea, comprehensive mapping, good biostratigraphic control, and extensive geochronological studies provide opportunities for many general scenarios that can be rigorously checked in detail. Unfortunately, the sequence of submerged continental fragments linking Australia to New Zealand, that is, the Chesterfield Plateau, Dampier Ridge, Lord Howe Rise, Norfolk Ridge and Challenger Plateau, all have no pre-Cenozoic outcrop, except a few sea-floor dredge sites (McDougall & Van der Lingen, 1974; McDougall *et al.* 1994; Tulloch, Kimbrough & Wood, 1991).

In easternmost Australia, the single important basement feature is the New England Fold Belt (1500 km × ∼200 km), along the coast of northeast New South Wales and southeast Queensland, and backed by the Permian–Cretaceous (Sydney–Surat–Bowen Basins) sedimentary basins (Veevers, Conaghan & Powell, 1994). To the west is a meridional belt of Early Palaeozoic orogens: (1) Lachlan Fold Belt of southeastern New South Wales, Victoria and Tasmania, (2) Thomson Fold Belt of central Queensland, and (3) Hodgkinson–Broken River provinces of northeast Queensland.

The New England Fold belt is a collage of tectonic blocks, containing various mixtures of Devonian to Triassic sedimentary and volcanic rock sequences, and voluminous Carboniferous to Triassic granitoid plutonic complexes. The tectonic associations of these are mainly convergent plate margin, subduction-related (Veevers, Conaghan & Powell, 1994; Veevers, 2000).

Early Permian to Carboniferous rocks, *c.* 270–345 Ma, are the most widespread, with both acid-intermediate volcanic successions and calc-alkaline granitoid plutons (particularly in the interval 270–310 Ma) occurring throughout the New England Fold Belt. They form the major part at the northern end (Allen *et al.* 1998), and continue northwards into the Hodgkinson Province as far as Papua New Guinea, a distance of more than 2000 km (Veevers, 2000, figs 202, 220). Permian granodiorite and diorite on the Dampier Ridge (McDougall *et al.* 1994) are a possible southeastward extension (Fig. 13b).

Triassic–Late Permian rocks, *c.* 220–260 Ma, are the next in importance (Veevers, 2000, figs 203, 204, 221, 222); these are more restricted to the New England Fold Belt itself, but in this case, the extensive granitoid complexes and acid-intermediate volcanics are concentrated in 1000 km of the south-central sector (Veevers, 2000, fig. 221).

Western and northern hinterlands of the New England Fold Belt contain important elements relevant to sediment provenances, in particular their detrital zircon patterns. Firstly, mainly on Cape York Peninsula, Precambrian (Proterozoic) rocks come closest to the Gondwanaland margin, and occur as metamorphic complexes (Coen, Yambo, Georgetown and Anakie inliers) extending southwards over 1000 km (Veevers, 2000, fig. 178). Secondly, also in the north, there is mid- to late Palaeozoic plutonism in several areas: (1) on Cape York Peninsula and in the Georgetown Inlier as Early Devonian granite plutons (Veevers, 2000, fig. 209), (2) further south in the Charters Towers area as Silurian– Late Ordovician granitoids (Ravenswood Batholith) emplaced in Ordovician metasediments and Cambrian acid volcanics (Veevers, 2000, figs 207, 208), (3) in southeast Queensland, as smaller and more isolated Late Devonian granite plutons at Retreat Hills and Mt Morgan (and volcanics at Silver Hills), and as Early Carboniferous granites, 330–355 Ma, subsurface near Roma (Veevers, 2000, fig. 211). Thirdly, near Bathurst, New South Wales, where Lachlan and New England fold belts are closest, there are Carboniferous granites, 315–330 Ma, at the northwest boundary of the former (Veevers, 2000, fig. 201). These are similar to granitoids, 335 ± 7 Ma, on the Challenger Plateau (Tulloch, Kimbrough & Wood, 1991), and in Westland, New Zealand, for example, the Cape Foulwind Granite (Muir *et al.* 1996*a*,*b*).

In summary, the New England Fold Belt and its hinterland do provide very extensive terranes with source rock materials of the correct age and composition to supply the New Zealand Eastern Province sedimentary depocentres. Crucially, Permian and Triassic source rocks are far more abundant in this region than in New Zealand and Antarctica. They are voluminous and extensive over 2000 km of the eastern Gondwanaland margin, and were available for erosion throughout Mesozoic time. Sufficient detail is available to match the supply of source zircons of appropriate age with detrital zircon ages in New Zealand sediments.

7. Tracing New Zealand sediment sources in northeast Australia

7.a. Permian and Triassic

In the Torlesse composite terrane, the broad division into Triassic–Permian and Early Palaeozoic–Precambrian zircon age groups inevitably places sediment sources in north Queensland where, uniquely, the Australian Precambrian craton (here mostly Palaeoproterozoic metasediments and Mesoproterozoic igneous rocks) is close to the eastern margin of Gondwanaland (Pickard, Adams & Barley, 2000; Cawood *et al.* 2002). For the Permian Torlesse Supergroup (Rakaia terrane, and Akatarawa and Kakahu microterranes), the predominant Permian zircons could

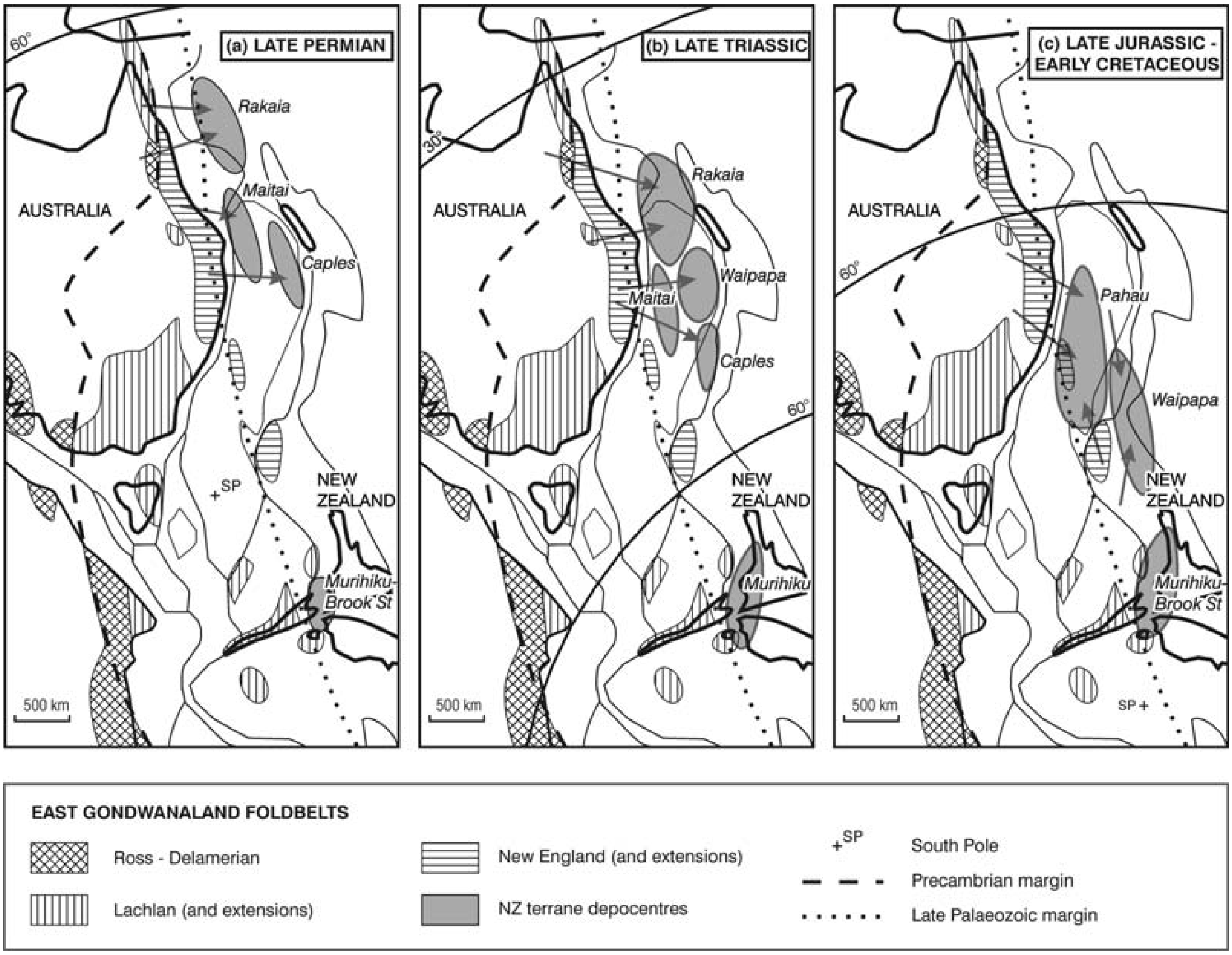


Figure 14. The reassembled Eastern Gondwanaland continental margin showing major geological elements: late Neoproterozoic–early Palaeozoic, Ross–Delamerian, early Palaeozoic Lachlan, and Carboniferous–Triassic, New England fold belts and principal transport directions (arrows) from these possible sources to depocentres of New Zealand Eastern Province sediments in (a) Late Permian, (b) Late Triassic and (c) Late Jurassic (and Early Cretaceous) times. Contemporary South Poles (SP), and 30° and 60° meridians are shown.

be derived from the extensive Permian granitoids and volcanics in the Hodgkinson Province, with a subordinate Precambrian (mostly Mesoproterozoic) component derived from the adjacent Georgetown Inlier (Fig. 14a). To this must also be added the significant proportion of Silurian–Ordovician and Early Carboniferous–Devonian zircons, perhaps also derived from Hodgkinson hinterland, that is, granitoids on Cape York Peninsula, in the Georgetown Inlier, and Charter Towers area, and volcanic formations in the Yarrol terrane. For the Triassic Torlesse Supergroup, the predominant Triassic zircon components could only be derived from a region much further south, within the New England Fold Belt of southeast Queensland (Fig. 14b). (An exception might be less extensive and local volcanic and plutonic sources in Papua New Guinea.) In doing this, Permian and Carboniferous zircon sources would also be appropriately diminished, but the region would now be more remote from the cratonic sources that are required to supply the increased percentage of Precambrian zircons so characteristic of the Triassic Torlesse greywackes. This may suggest that Precambrian zircons are not supplied directly, but recycled through closer Palaeozoic sedimentary basins, such as Drummond Basin, or drawn from lower crustal sources during formation of the Triassic–Permian granitoids and volcanic rocks themselves, a large proportion of which are indeed S-type, (Veevers, 2000, fig. 192). However, this is not clearly apparent from zircon morphology; Precambrian zircon sets contain as many euhedral as rounded types.

In the Waipapa terrane, possible Early Triassic (sample 8), and Late Triassic (sample 9) examples would follow the Late Permian to Late Triassic sediment pathways of the Torlesse (above), but require a more dominant contemporary Triassic zircon source, with a diminished contribution from Palaeozoic and Precambrian zircon age components. Following the conclusions of Pickard, Adams & Barley (2000), the southern New England Fold Belt granitoid complexes fulfil these criteria (Fig. 14b) with their various suites: Hillgrove and Bundarra, 290–310 Ma; New England Supersuite, 240–265 Ma; Post-orogenic, 235 Ma (Hensel, McCulloch & Chappell, 1985), nicely matching individual detrital zircon age components.

In Caples terrane rocks, their more marked volcaniclastic nature is reflected in very high proportions of probably contemporary zircon sources. This, and the absence of early Palaeozoic and Precambrian zircons, indicates a more isolated position with respect to the continental margin, perhaps within an offshore volcanic island arc. This is particularly marked in those samples with major Triassic components, such as dataset 11. In these cases it is impossible to relate their original depocentre position with respect to those of time-correlatives in other terranes. However, a possibly older, Early Triassic–Late Permian, sample (dataset 12) has a significant Carboniferous zircon percentage, similar to Triassic greywackes of the Waipapa terrane (e.g. sample 9), and this might suggest a partial, but common link back to southern New England Fold Belt sources (Fig. 14a, b).

Dun Mountain–Maitai terrane rocks are regarded as back-arc analogues to the accretionary terranes described above (Coombs *et al.* 1976) Reflecting this, their proportions of Palaeozoic and Precambrian zircons (> 300 Ma) are higher than in Late Triassic and Late Permian correlates in the accretionary Caples terrane, and more closely resemble that of Torlesse and Waipapa terrane counterparts. Attempting to resolve these features, Adams *et al.* (2002) suggested that detrital zircon sources for Late Permian Maitai Group sandstones (samples 14A, 14B) could be drawn from the southern end of the New England Fold Belt (mainly Permian components), and the northeast margin of the Lachlan Fold Belt (the older Palaeozoic, > 300 Ma, components). We recognize here that more northerly provenances are equally practical, the Permian components being drawn from the mid-sections of the New England Fold Belt (granitoids and volcanic rocks of southeast Queensland) and the Palaeozoic components from its western hinterland (Fig. 14a). For Triassic Maitai Group sandstones (samples 13, 14), the more dominant Late Triassic–Late Permian, and much-diminished older (> 440 Ma) zircon components, suggest sources similar to their Caples terrane time-correlatives (Fig. 14b).

Finally, in the Murihiku and Brook Street terranes, the Permian to Triassic successions have strongly contemporary zircon patterns, with a small degree of intra-terrane reworking. The simplicity of these patterns strongly suggests an isolated and long-lived environment of island-arc volcanoes with surrounding volcaniclastic sediment aprons, having no access to older, ‘continental’ zircon sources. For this reason, the original terrane position, whether well offshore in the New Zealand region, or far-travelled as a suspect terrane, cannot be decided. Since there is no compelling evidence for a suspect terrane, the depocentres are placed in their present New Zealand positions in Figure 14a, b.

7.b. Jurassic and Cretaceous

The significant influence of volcaniclastic sediment sources in Early Cretaceous–Jurassic Torlesse and Waipapa terrane rocks is clearly reflected in their crowded mixtures of contemporary or quasi-contemporary zircon age components, which must indicate a relatively local, and long-lived volcanic environment as the primary zircon source. In addition, the Median Batholith (Wandres *et al.* 2004*a*), particularly extending north of New Zealand to the West Norfolk Ridge (Mortimer *et al.* 1998), could contribute Early Cretaceous–Late Jurassic (and Late Permian) zircons. As a persistent background, Palaeozoic and Precambrian ages are rather scattered, but reach 40 % of total in Pahau, and 30 % in Waipapa terrane greywackes. Lack of any clear grouping suggests these zircons are predominantly reworked from plutonic and/or volcanic sources, and from Rakaia terrane greywackes as preferred by Wandres, Bradshaw & Ireland (2005) or, as preferred in this work, from older Waipapa terrane greywackes. Precambrian zircons are far less abundant in Waipapa greywackes (< 5 %), than Pahau terrane counterparts (10–30 %), perhaps suggesting a position more distant from these influences. The high proportion (20–70 %) of Jurassic zircon ages in the Waipapa terrane greywackes, many contemporaneous with deposition, suggests a more isolated, offshore, volcanic environment. To reconcile all these zircon sources, a general depocentre south and east of the New England Fold Belt is indicated, perhaps adjacent to the mid-section of the Lord Howe Rise (Fig. 14c). This would allow contributions from sources similar to those of the Waipapa terrane, or recycled Waipapa terrane rocks themselves. To these could be added Permian plutonic sources from the Dampier Ridge and Norfolk Ridge, Jurassic–Cretaceous plutonic and volcanic contributions from a northern Median Batholith extension and finally, substantial contemporary contributions from primary volcanic sources, perhaps on the Lord Howe Rise itself.

Jurassic horizons in the Murihiku terrane have detrital zircon age patterns that closely follow those seen in the Permian and Triassic, perhaps suggesting a degree of zircon reworking. An isolated volcanic environment is indicated in their position (Fig. 14c). However, in the Middle Jurassic sample (16), there is a small, but significant (13 % of total), contribution early Palaeozoic and Precambrian additional, whose origin is unknown.

The summaries of zircon sources for Eastern Province sediments at Late Permian (and Early Triassic), Late Triassic, and Early Cretaceous–Late Jurassic time intervals, amplify the conclusions of

Adams & Kelley (1998), Pickard, Adams & Barley (2000) and Adams *et al.* (2002). These authors argued that Torlesse, Waipapa and Dun Mountain–Maitai sediments originated in northeast Australia, with their original depocentres closer to the Australian, rather than the New Zealand, margin of Gondwanaland. This implied relatively short (500–1000 km) fluvial/hydraulic sedimentary transport distances and subsequent large margin-parallel tectonic transport, rather than major long-distance (about 3000 km) transport on river, delta or sea-floor systems, to arrive at their present New Zealand position. The present summaries follow this preference, and in Figure 14a–c it can be seen that the suggested depocentres would have been in the mid-latitudes (magnetic South Poles for the Permian, Triassic and Jurassic are in the southern greater New Zealand and West Antarctic region). The depocentres are drawn approximately to their estimated present New Zealand sizes (representing a minimum), and these can be matched with the appropriate sizes of source regions. To a first order approximation, for clastic sedimentary rocks of this type (with a very small biogenic component), the sizes of sediment rock sources and their depocentres should be similar. There is a general tendency for the depocentres to be displaced southwards with time, following the general southeastwards movement of plate margin convergence at the Gondwanaland margin throughout Late Palaeozoic and Mesozoic times. This migration clearly dictates the zone of maximum plutonic and volcanic activity and its tectonic association, which in turn influences the associated orogenic effects of uplift, erosion and development of sedimentary basins (Holcombe *et al.* 1997*a*,*b*). A transition from convergent- to extension-related tectonism/plutonism is seen in the Late Mesozoic in the New Zealand region (Bradshaw, 1989), and then continues, in late Cenozoic times, along the Pacific margin of Antarctica into the Antarctic Peninsula (Weaver *et al.* 1994).

8. Summary of conclusions

U–Pb detrital zircon age patterns in greywackes and sandstones, at three time horizons (Early Cretaceous–Jurassic, Late Triassic and Late Permian), in several tectonostratigraphic terranes of the Eastern Province of New Zealand, place important constraints on sediment provenance:

(1) Zircon age populations from all terranes have large Triassic–Permian components, and only a few Devonian–Silurian ages, thus excluding significant sediment provenances from the Lachlan Fold Belt of southeast Australia, and its continuations in New Zealand and Antarctica.

(2) In the accretionary prism Torlesse and Waipapa terranes (and less so in the Caples terrane), significant Palaeozoic and Precambrian zircon components are present. These reflect a former proximity to the Precambrian and early Palaeozoic continental margin, the Rakaia terrane of the Torlesse composite terrane being closest to a continental margin.

(3) In the fore-arc/back-arc, Murihiku and Brook Street terranes, more unimodal patterns are prevalent, suggesting volcanic island-arc environments, isolated from continental input. The fore-arc Dun Mountain–Maitai terrane is more variable, and (with the accretionary Caples terrane) has a character transitional to the Torlesse/Waipapa terranes.

(4) Persistent Triassic–Permian zircon supplies require very extensive, long-lived sources, which are suggested in the New England Fold Belt and Hodgkinson Province of northeast Australia, and speculatively, their southward continuations into the Tasman Sea.

(5) Reconciling both major and minor zircon age components in Permian and Triassic sediments constrains sources for (a) Torlesse (Rakaia) depocentres to northeast Queensland and (b) Waipapa terrane depocentres to northeast New South Wales (with the Dun Mountain–Maitai and Caples terrane depocentres more inshore and offshore respectively).

(6) Older Palaeozoic and Precambrian zircon age components in the accretionary terranes (plus the Dun Mountain–Maitai terrane) originated in the New England Fold Belt hinterland, that is, mid-Palaeozoic granite complexes in northeast Queensland (Georgetown Inlier, Charter Towers Province, Anakie Inlier) and Carboniferous granite complexes in northeast New South Wales.

(7) In Early Cretaceous–Late Jurassic successions of the Torlesse (Pahau) and Waipapa terranes, there is significantly less continental influence, and more offshore volcanic arc environments are probable. Following the conclusions of Wandres *et al.* (2004*a*), a large proportion of Pahau terrane sediments can be locally sourced in the Median Tectonic Zone/Median Batholith, possibly in New Zealand, but also probably in its northward continuation on to the Lord Howe Rise. Unlike Wandres *et al.* (2004*b*) and Wandres, Bradshaw & Ireland (2005), Late Triassic Waipapa (rather than Rakaia) terrane rocks are regarded a more likely source for the recycled component of Pahau terrane sediments.

(8) Inferred southeastward migration of some terrane depocentres, from Permian to Jurassic times, is consistent with margin-parallel tectonic transport of the terranes to their present New Zealand position.

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