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The mid-Cretaceous transition from basement to cover within sedimentary rocks in eastern New Zealand: evidence from detrital zircon age patterns

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Abstract – Detrital zircon U-Pb ages for 30 Late Jurassic and Cretaceous sandstones from the Eastern Province of eastern New Zealand, combined with previously-published geochronological and palaeontological data, constrain the time of deposition in the Pahau and Waioeka terranes of the Cretaceous accretionary margin of Zealandia, and their adjacent cover strata. The zircon age patterns also constrain possible sediment source areas and mid-Cretaceous geodynamic models of the transition from basement accretionary wedge to passive-margin cover successions. Pahau Terrane deposition was mainly Barremian to Aptian but continued locally through to late Albian time, with major source areas in the adjacent Kaweka and Waipapa terranes and minor inputs from the inboard Median Batholith. Waioeka Terrane deposition was mainly Albian, with distinctive and exclusive sediment sources, principally from the Median Batholith but with minor inputs from the Western Province. Alternative tectonic models to deliver such exclusive Median Batholith and Western Province-derived sediment to the mid-Cretaceous Zealandia continental margin are: (1) the creation of a rift depression across Zealandia or (2) sinistral displacement of South Zealandia with respect to North Zealandia, to expose Western Province rocks directly at the Zealandia margin. Detrital zircon age patterns of Cretaceous cover successions of the Eastern Province of eastern New Zealand demonstrate purely local sources in the adjacent Kaweka and Waipapa terranes. Cretaceous zircon components show a decline in successions of late Early Cretaceous age and disappear by late Late Cretaceous time, suggesting the abandonment or loss of access to both the Median Batholith and Western Province as sediment sources.

Keywords: New Zealand, Cretaceous, Torlesse Terrane, Pahau Terrane, Waioeka Terrane, sedimentary basin, U-Pb dating, detrital zircon, provenance.

1. Introduction

In mid-Cretaceous times, between 112 and 85 Ma, the tectonic situation of New Zealand changed dramatically. A long-lived active plate-margin setting with oblique convergent subduction had persisted from Early Permian to late Early Cretaceous time. Accretionary wedges developed at this margin with Permian–Cretaceous marine sedimentary basins, representing fan delta to mid-fan environments having various inputs of terrigenous and redeposited volcaniclastic material (Korsch & Wellman, 1988; Bradshaw, 1989; Mortimer, 1994; Fig. 1). These are mapped as several tectonostratigraphic terranes constituting an Eastern Province (Bishop, Bradshaw & Landis, 1985). Between 112 and 85 Ma, accretion waned and eventually ceased, and during this period was replaced by an extensional regime with development of cover successions of younger Cretaceous sedimentary rocks (Laird & Bradshaw, 2004; Fig. 1). In the west, they were mostly terrestrial–fluviatile sedimentary rocks deposited on stabilized Palaeozoic basement of the *Western Province* of New Zealand, and older, Permian–Triassic terranes of the Eastern Province e.g. Rakaia Terrane. In contrast, the younger terranes of the Eastern Province, e.g. Pahau and Waipapa terranes, were overlain by more varied marine sedimentary successions, both shallow- and deep-water (Laird & Bradshaw, 2004).

In many cases there are stratigraphical and lithological similarities between Cretaceous accretionary basement rocks and their cover successions, and unconformities are not always obvious. Furthermore, New Zealand Cretaceous rocks are sometimes sparsely fossiliferous, so that biostratigraphic age control can be poor. Consequently, the timing and nature of the Cretaceous basement-cover relationship has remained uncertain in some areas, e.g. Wairarapa district, North Island (Fig. 1). To help constrain this relationship, we report here detrital zircon age patterns from sandstones in mid-Cretaceous basement and cover successions of eastern New Zealand, i.e. East Cape (Raukumara), Hawkes Bay, Wairarapa, Marlborough and North Canterbury districts (Fig. 1). These provide maximum ages for the deposition of the Cretaceous

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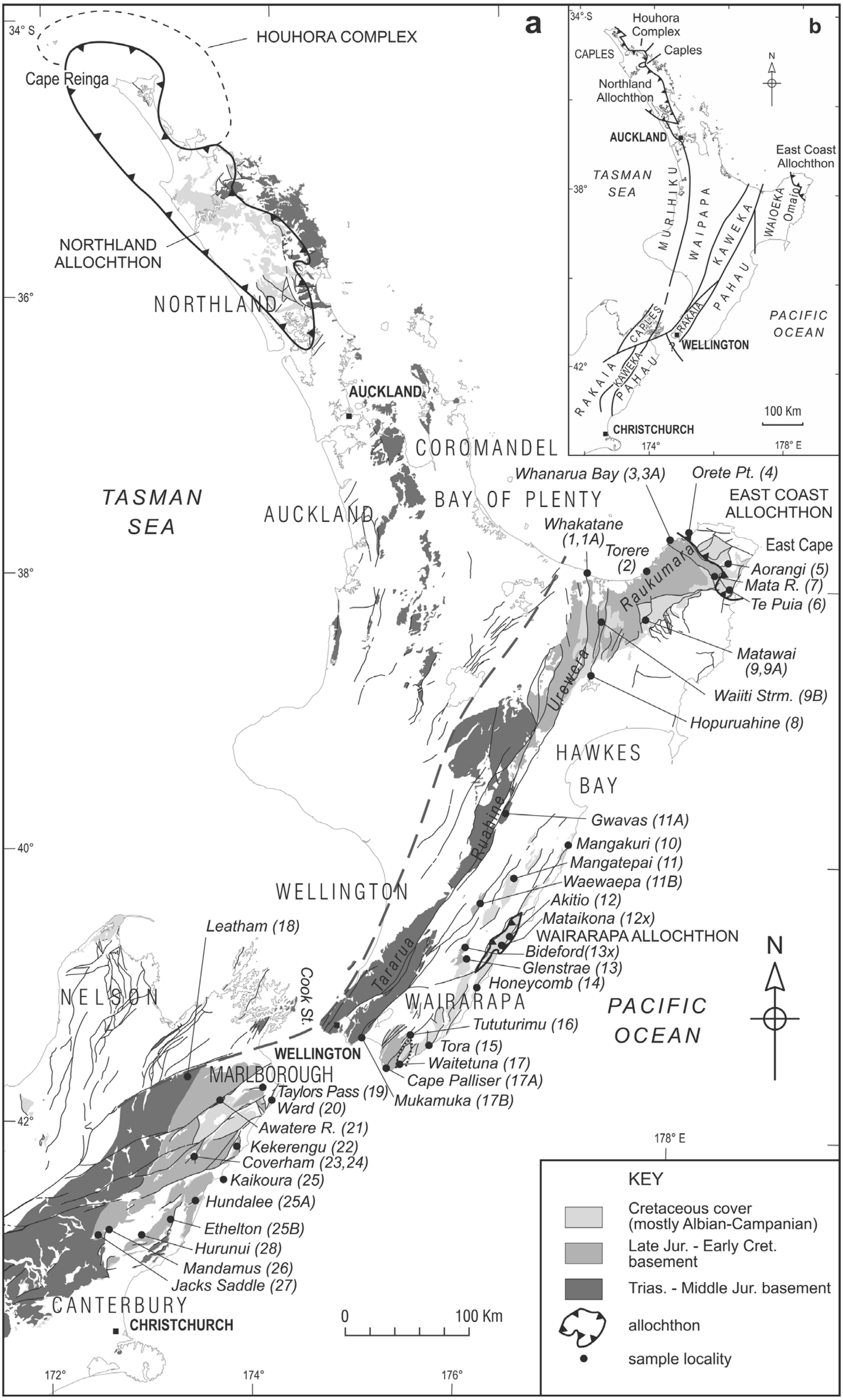


Figure 1. (a) Map of Cretaceous cover sedimentary successions (pale grey) in eastern New Zealand, and Eastern Province basement terranes subdivided as Jurassic–Cretaceous Pahau Terrane and Kaweka Terrane (mid-grey), and combined Permian–Jurassic Waipapa, Caples, Rakaia and Murihiku terranes (dark grey). Closed dots indicate detrital zircon dating localities (with locality number in italics). (b) Basement terrane configuration and Cenozoic allochthons in eastern and northern New Zealand.

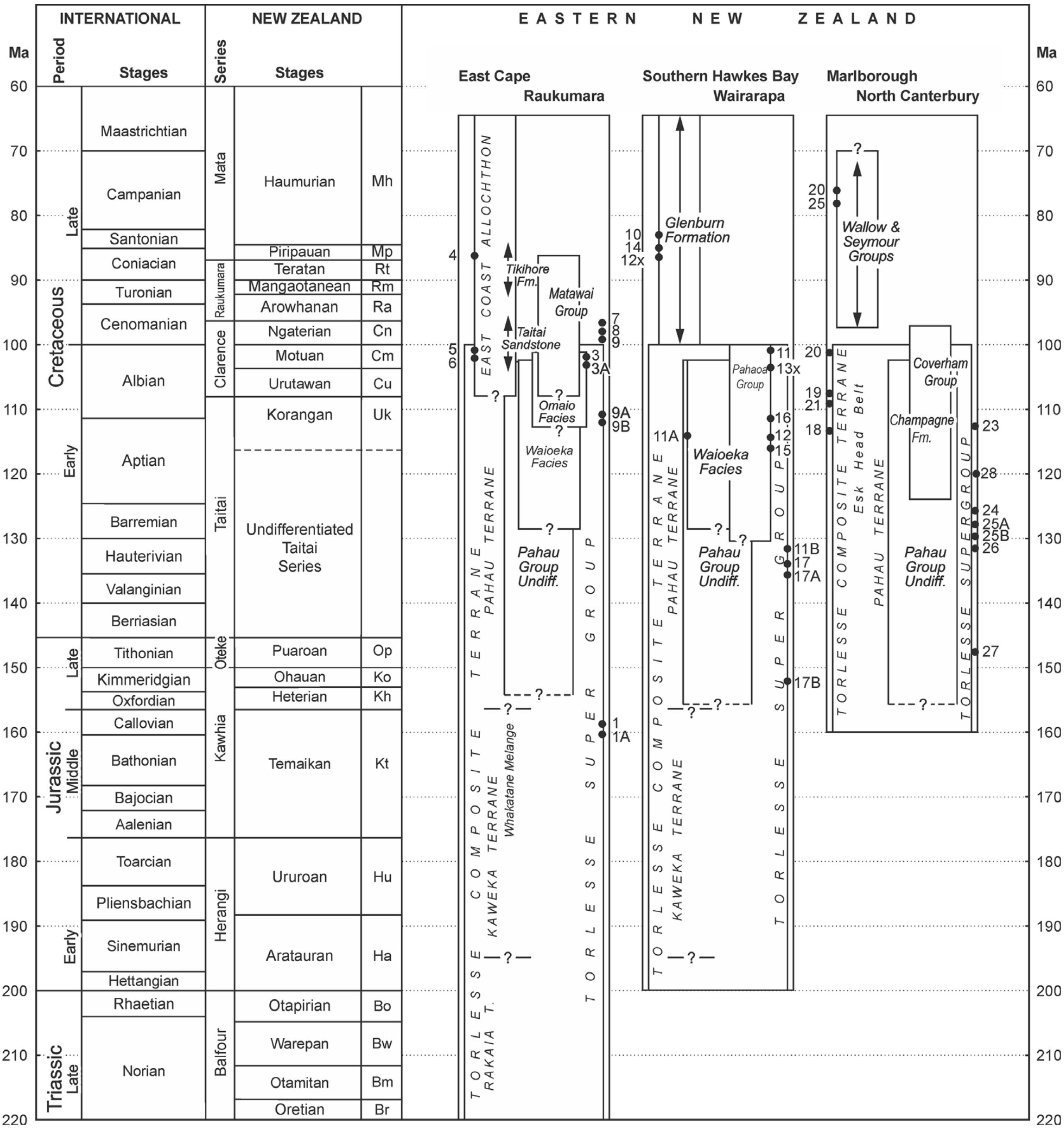


Figure 2. Stratigraphic columns of Jurassic to Cretaceous cover and basement sedimentary rocks in eastern and northern New Zealand, showing New Zealand Stages and Series and International Ages and Stages, as presented in Cooper (2004), thus allowing consistent cross-referencing to previously published zircon age studies on Cretaceous basement in New Zealand. Age differences with the IUGS 2010 timescale are generally <1 Ma. Sampling locations are shown as dots with locality number.

rocks and the timing of the basement–cover transition. The age patterns are further used to investigate the tectonic transition from subduction to extension.

In terms of the New Zealand Local Timescale for Cretaceous time (Cooper, 2004), the Urutawan, Motuan and Ngaterian stages (the Clarence Series) overlap the International Cenomanian and Albian Stages, and thus also the Early–Late Cretaceous boundary. In this study the rocks deposited during this crucial late Early Cretaceous to early Late Cretaceous interval are informally termed ‘mid-Cretaceous’. The exact correlation of the New Zealand and International stages is discussed in Cooper (2004).

2. Geological Outline

Cretaceous sedimentary successions have been studied in considerable detail throughout New Zealand and, despite the variable and sometimes imprecise biostratigraphic control, a robust sequence of local series and stages specific to New Zealand is well established (Cooper, 2004; Fig. 2).

Extensive re-examination and review of the Cretaceous of New Zealand has formed a large part of recent 1:250 000 geological mapping of the classic eastern New Zealand regions; from north to south, the newly published map sheets relevant to this paper are: Raukumara (Mazengarb & Speden, 2000), Rotorua (Leonard, Begg & Wilson, 2010), Hawkes Bay (Lee *et al.* 2011), Wairarapa (Lee & Begg, 2002), Wellington (Begg & Johnston, 2000) and Kaikoura (Rattenbury, Townsend & Johnston 2006). These authors evaluated and incorporated the fission track geochronological studies of Kamp (1999, 2000) where appropriate. Comprehensive descriptions of Cretaceous rocks, evaluation of previous field studies and a standardized stratigraphic nomenclature are found in these works. Their nomenclature is followed here. The descriptions below summarize only those points relevant to the geochronological work and its interpretation.

2.a. Late Jurassic – Cretaceous basement rocks in the accretionary terranes

The Torlesse Composite Terrane constitutes a large proportion of the Eastern Province of New Zealand. Although some lithostratigraphical subdivision has been locally successful (e.g. Pahaoa Group, Lee & Begg, 2002; Pahau River Group, Bassett & Orlowski, 2004), the monotonous character of the rocks, their structural complexity and the paucity of fossils, make conventional stratigraphy very difficult. For this reason, broad high-level tectonostratigraphic subdivisions are more useful: a Late Permian to Late Triassic Rakaia Terrane, a Jurassic Kaweka Terrane and an Early Cretaceous Pahau Terrane (Bishop, Bradshaw & Landis, 1985; Adams, Campbell & Griffin, 2007; Adams *et al.* 2009*b*, 2011; Fig. 1b). Rocks of the Torlesse Composite Terrane are quartzo-feldspathic, sandstone-dominated, turbiditic sedimentary successions deposited in a mid-submarine fan environment (Andrews, Speden & Bradshaw, 1976; MacKinnon, 1983; Korsch & Wellman, 1988; A. D. George, unpub. Ph.D. thesis, Victoria Univ. of Wellington, 1988; Barnes & Korsch, 1991; Roser & Korsch, 1999), although there are important exceptions in the Pahau Terrane where shallower, possible distal fore-arc fan-delta to upper accretionary wedge environments have been suggested (Bassett & Orlowski, 2004).

In eastern North Island, the Waioeka Terrane (Mazengarb & Speden, 2000) occupies much of the Raukumara Peninsula (Fig. 1) and represents an unusual continuation of accretionary wedge environments well into Albian–Cenomanian time (Mazengarb & Harris, 1994). It is fault-bounded to the west against the Whakatane Melange, part of the Esk Head Belt (Kaweka Terrane; Adams *et al.* 2011), but any boundary against the Pahau Terrane is less clear, mostly hidden beneath Cenozoic successions of Hawkes Bay. For this reason, it remains uncertain whether the Waioeka Terrane is independent of or part of the Pahau Terrane. It contains two mid-Cretaceous volcaniclastic petrofacies: a Waioeka Facies of andesitic-dacitic composition, and a more quartzose, dacitic-rhyolitic, Omaio Facies (Mortimer, 1994; Mazengarb & Speden, 2000; Lee & Begg, 2002; Fig. 1b).

The Esk Head Belt (Rattenbury, Townsend & Johnston, 2006) is a major zone of melange and broken formation; in the South Island it incorporates the Esk Head Melange (Bradshaw, 1972), and in the North Island the Rimutaka Melange (Barnes & Korsch, 1990, 1991; Campbell, Grapes & Handler, 1993; Begg & Mazengarb, 1996; Begg & Johnston, 2000; Lee & Begg, 2002), the Pohangina Melange and the Whakatane Melange (Mortimer, 1994; Leonard, Begg & Wilson, 2010; Lee *et al.* 2011). Recently, the melange has been regarded as part of the Kaweka Terrane, intervening between the Pahau and Rakaia terranes throughout both North and South Islands (Adams *et al.* 2011; Fig. 1b). As a tectonic melange, it was originally considered to include blocks of both Rakaia and Pahau terrane origin (Bradshaw, 1972, 1973). However, although Late Triassic – Early Jurassic fossils are known from melange blocks (Campbell & Warren, 1965; Silberling *et al.* 1988) and Late Jurassic fossils are found in broken formation matrix (Campbell & Warren, 1965; Speden, 1976; Foley, Korsch & Orr 1986; Leonard, Begg & Wilson, 2010), Cretaceous fossils (other than broad-ranging dinoflagellate taxa) are absent. The middle Early Cretaceous metamorphic ages (*c.* 130–135 Ma) for the Kaimanawa Schist provide an additional younger (early Early Cretaceous) age constraint (Graham, 1985; Adams *et al.* 2009*b*).

Most of the Pahau Terrane is not lithostratigraphically subdivided but Bassett and Orlowski (2004) proposed the Lochiel Formation (mudstone–sandstone) and the Mt Saul Member (conglomerate) in the Pahau River area, North Canterbury, as type sections for a Pahau River Group. This represents a submarine fan-delta environment at the top of an accretionary wedge, possibly in a distal fore-arc position. Elsewhere, in Marlborough and Wairarapa districts, sandstone-dominated sandstone–mudstone successions are more common and represent a deeper, mid-fan environment (Rattenbury, Townsend & Johnston, 2006). In the Kekerengu, Clarence and Awatere River valleys (Marlborough), rocks of the Pahau Terrane contain late Early Cretaceous (mostly Albian) bivalves, e.g. *Mytiloides, Aucellina* and inoceramids (Campbell & Warren, 1965; Reay, 1993; Crampton *et al.* 2004) but elsewhere they are frequently unfossiliferous, or contain poorly-preserved dinoflagellates of broad-ranging taxa (often Late Jurassic to Early Cretaceous). Those from North Canterbury to Marlborough (Bassett & Orlowski, 2004; Wilson & Helby, 1988; J. I. Raine pers. comm.) have a probable Barremian to early Albian range, but many have less precise Tithonian – early Albian ranges (Rattenbury, Townsend & Johnston, 2006).

In the Wairarapa to southern Hawkes Bay region of the North Island, the Aptian–Albian Pahaoa Group is recognized (Begg & Johnston, 2000; Lee & Begg, 2002; Lee *et al.* 2011). This comprises conglomerate, sandstone, minor mudstone (Mangapokia Formation) and massive channelled sandstones (Taipo Formation), both of which represent submarine fan environments (Moore & Speden, 1984; Moore, 1988; Crampton, 1989, 1997; Lee & Begg, 2002). It has similarities with nearby Cretaceous cover successions and this has introduced uncertainty about its stratigraphic status (basement versus cover) but Lee & Begg (2002) considered that its sedimentary environment and structural complexity (Barnes & Korsch, 1990, 1991) place it within the basement Pahau Terrane nearby.

The relationship of the Pahaoa Group to local Waioeka Facies rocks (Waioeka Terrane) is not clear as it is locally unconformably overlain by a cover sequence (Mangapurupuru Formation) of late Albian (Motuan) age. The Pahaoa Group near Akitio, on the Wairarapa coast, forms a small allochthonous slice (Miocene emplacement; Delteil *et al.* 1996), and a portion near Martinborough might be similar (a leading-edge thrust is seen but the trailing edge is obscured by Recent faulting).

Detrital zircon studies (Cawood *et al.* 1999; Pickard, Adams & Barley, 2000; Wandres *et al.* 2004; Adams, Campbell & Griffin, 2007; Adams *et al.* 2009*b*) have revealed significant proportions of Early Cretaceous zircons (as young as 104 Ma) in undifferentiated Pahau Terrane and Waioeka Terrane (Omaio Facies) sandstones. The zircon age patterns indicate that sediment sources include some contemporary volcanic input, but this is often overwhelmed by major, long-continuing reworked components from Late Permian – Early Triassic plutoniclastic sources, such as a Cordilleran granitoid batholith (Adams, Campbell & Griffin, 2007; Adams *et al.* 2009*b*). It is unlikely that this latter was situated within the New Zealand region ('Zealandia'), and origins in Antarctica and eastern Australia have been considered (Adams & Kelley, 1997; Cawood *et al.* 1999; Pickard, Adams & Barley, 2000; Wandres *et al.* 2004, Adams, Campbell & Griffin, 2007).

Igneous sources for late Early Cretaceous Pahau Terrane sediments have been recognised in the South Island, for example. Wandres *et al.* (2004) plausibly matched granitoid clasts in Pahau Terrane conglomerates with distinctive A-type granites in the Median Batholith.

Kamp (1999, 2000) presented fission track thermochronology studies on zircons from basement rocks in eastern North Island including Torlesse Composite Terrane, Pahau Terrane. Waioeka Terrane, and the East Coast Allochthon. The interpretations drawn provide insight into the age ranges of sediment accumulation within these terranes, cessation of subduction along this part of the Zealandian sector of Gondwanaland and estimates of the required rate of Cretaceous erosion. The results presented herein, based primarily on detrital zircon age data, build on and are in broad general agreement with Kamp (1999, 2000), but refine the terrane categorization and provide additional important perspectives on sediment provenances.

2.b. Cretaceous cover rocks in eastern New Zealand

In eastern New Zealand, Cretaceous cover rocks rest unconformably on the Torlesse Composite Terrane and also occur inside the East Coast Allochthon (Mazengarb & Speden, 2000).

2.b.1. Raukumara

In the Raukumara district, the Aptian–Albian Matawai Group consists of variable sandstone-conglomerate and sandstone-mudstone dominated successions, with some evidence from several formations of an E-W facies change from bathyal to shelf environments (Speden, 1976; Mazengarb & Speden, 2000). Where observed, these formations rest unconformably upon Waioeka Terrane (Omaio Facies) rocks (Feary, 1979), although the unconformities cannot be proved to represent a single event. Indeed, Mazengarb & Harris (1994) showed that subduction-driven deformation and basin formation continued throughout the Early Cretaceous, and well into Late Cretaceous times (to *c.* 85 Ma). The East Coast Allochthon also contains similar mid-Cretaceous sedimentary rocks (Aptian–Albian Ruatoria Group, Field *et al.* 1997; Mazengarb & Speden, 2000).

2.b.2. Hawkes Bay – Wairarapa

The early Late Cretaceous Glenburn Formation (Lee & Begg, 2002; Lee *et al.* 2011) extends along the Wairarapa coastline and has been tentatively considered as a long-distance southern correlative of the allochthonous Ruatoria Group (East Coast Allochthon, Raukumara district). It comprises conglomerates, thin-bedded sandstones and mudstones, probably deposited in a bathyal submarine fan environment.

2.b.3. Marlborough – North Canterbury

Sedimentary and volcanic rocks form a major part of the Cretaceous cover successions of Marlborough and northern Canterbury, and in particular have been well-studied along the Clarence and Awatere River valleys (Crampton *et al.* 2004; Laird & Bradshaw, 2004; Rattenbury, Townsend & Johnston, 2006). Like their North Island counterparts, these sedimentary rocks consist predominantly of thin-bedded sandstone and mudstone, and occasional conglomerate. The oldest unit, the late Early Cretaceous (Albian, Motuan) Coverham Group (Champagne Formation), is quite deformed but rests unconformably upon basement rocks of the Pahau Terrane (Crampton *et al.* 2004). There is no intra-Motuan unconformity similar to that of the Mangapurupuru Formation in the Wairarapa area. Late Cretaceous rocks of the succeeding Seymour and Wallow Groups are similar to the Coverham Group, but are less deformed, and include thick-bedded sandstone and conglomerate. Compared to eastern North Island, the depositional environment of the North Canterbury to Malborough Cretaceous sequences is clearly more shallow-water, both fluvial and marine, and reflects fault-controlled topography.

3. Technical details

Sampling protocols and technical methods relating to the present detrital zircon studies are given in Adams, Campbell & Griffin (2007), and Adams *et al.* (2009*b*). Locations and sample details of present and relevant previously published dating samples are shown in Table 1 and Figure 1. Where cited in the text, location numbers are bracketed in italics e.g. (*11*).

In describing zircon age plots, a peak is the most probable value i.e. the topmost part of the curve (e.g. 130 Ma); it may or may not have statistical validity; a group is an obvious cluster of ages in a given age range, e.g. Late Permian to Late Triassic, but without statistical validity i.e. not Gaussian (the range exceeds $\pm 3\ \sigma$); a component is a cluster of ages with statistical validity (e.g. 125 ± 2 Ma) i.e. it has a Gaussian distribution (the age range is less than about $\pm 3\ \sigma$).

U–Pb zircon ages were determined on Agilent 7500 and 7700 LA-ICPMS instruments at GEMOC, Macquarie University, Sydney, using techniques (calibration, standardization, data treatment) described by Jackson *et al.* (2004). The detrital zircon ages reported here were determined close to crystal terminations, and do not include analyses of crystal cores. Full U–Pb isotopic ratios for new analyses are tabulated in Appendix S1 in the online Supplementary Material available online at http://journals.cambridge.org/geo. Also included in Appendix S1, are combined probability/histogram diagrams generated using the ISOPLOT 3 software (Ludwig, 2003). Significant zircon age components derived from the probability density diagrams have been calculated as simple weighted averages, but where some overlap of components is apparent, the components have been deconvoluted using ISOPLOT 3 ‘Unmix Ages’ subroutines. Individual zircon ages and those of zircon components are listed in Appendix S1, and the latter are further summarized in Table 2. Measured ages are referred to the New Zealand Geological Timescale of Cooper (2004).

The detrital zircon age data are further illustrated in two ways. Firstly, as in Figure 3, they are subdivided in terms of the proportions (as percentages of a total set) of those zircon ages that fall within selected geological periods (see also inset boxes in the Appendix S1 tables).

Secondly, ages are presented only for significant component peaks in the probability density curves (Fig. 4b, d, f, h, j). These are accepted using relatively conservative criteria (Adams, Campbell & Griffin, 2007), namely that any group must: (1) contain as a minimum three, and preferably at least four, zircon grains; (2) comprise at least 4 % of the total dataset; and (3) have $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages that overlap at 95 % confidence limits. These significant age components for individual sample datasets are then stacked in order of maximum stratigraphic age (Fig. 4b, d, f, h, j). The heights of the age component data-boxes are proportional to the percentage of that component in the total dataset. In all diagrams, new and previously-published zircon age data are calculated similarly. The plots of zircon age components are accompanied by all-data histograms from which the components are drawn (Fig. 4a, c, e, g, i).

4. Results

4.1. Broad distribution of detrital zircon age groups

Detrital zircon age data are compiled (Fig. 3) for sandstones from the 27 new localities of this study and 11 previously published datasets. They are presented in four categories including three basement terranes (Kaweka, Pahau and Waioeka) and Cretaceous cover successions. They follow two main patterns:

Firstly there is a common pattern exemplified by the Pahau and Kaweka terrane samples (this is largely inherited by the Cretaceous cover successions) in which there is a dominant group (usually 30–55 %) of Permian and Triassic zircons, and a major (usually 15–40 %) group of Precambrian and early Palaeozoic zircons (Fig. 3). There are relatively few mid-Palaeozoic (Silurian–Carboniferous) zircons. The proportion of inherited to probable contemporary zircons is thus large; in Pahau Terrane samples, Cretaceous zircons are relatively abundant in only 5 of 17 samples (in the 21–64 % range) and minor occurrences (mostly 10–20 %) in 7 of 17 samples, whilst in Kaweka Terrane samples, Jurassic zircons are even rarer, <10 %.

Secondly, the pattern observed in the Waioeka Terrane and the allochthons, is the reverse of the above (Fig. 3). Cretaceous zircons are dominant (usually 35–94 %) whereas Permian–Triassic and Precambrian – early Palaeozoic zircon groups are very much diminished. Additionally, in the Omaio Facies (Waioeka Terrane) and East Coast Allochthon samples, there is an unusual but significant (20–40 %) cluster of Devonian–Carboniferous ages (Fig. 4a, c).

In the great majority of cases, the Cretaceous cover successions inherit zircon distributions from nearby basement in the Pahau or Kaweka terranes (or a mixture of both), but also with slightly higher proportions of Cretaceous (contemporary?) zircons. There are two exceptions: at locality (*9*), the Matawai Group sandstone clearly inherits a zircon age pattern from the Waioeka Terrane basement nearby (*9A*), but in stark contrast, at locality (*4*) the Tikihore Formation sandstone (within the East Coast Allochthon) has a pattern unlike the possible Waioeka Terrane basement nearby, e.g. localities (*5*, *6*), and is more similar to the Pahau Terrane.

4.2. Significant age components of detrital zircon age patterns

The precise distributions of zircon ages within the two patterns above are seen in the 38 individual probability density curves presented in Appendix S1 (available at http://journals.cambridge.org/geo) but these are more

Table 1. Sample localities for Cretaceous cover and Late Jurassic – Cretaceous basement rocks, eastern New Zealand

Locality No.	Sample Acronym	GNS R. No.	Unit/ Terrane	Group (Formation)	Stratigraphic Age	Location	Grid Ref. 1:50 000 (Nzms260)	Data Source
East Cape – Western Bay of Plenty								
1	OHOP1	23122	Kaweka	Esk Head Belt	Late Jurassic	Otarawairere Bay, Whakatane	W15/636532	6
1A	t44	–	Kaweka	Torlesse Supergroup	Late Jur – Early Cret	Kohi Point, Whakatane	W15/628547	1
2	ECAP12	24211	Omaio Facies	Torlesse Supergroup	Late Jur – Early Cret	Torere, beach	X15/050534	6
3	ECAP6	24204	Omaio Facies	Torlesse Supergroup	Late Jur – Early Cret	Whanarua Bay	Y14/329802	6
3A	t420	–	Omaio Facies	Torlesse Supergroup	Late Jur – Early Cret	Whanarua Bay, East Cape	Y14/326802	1
4	ECAP5	24202	East Cape Allochthon	Ruatoria Group (Tikihore F)	Late Cret (Rt)	Orete Pt, Waihau Bay	Y14/436864	6
5	ECAP4	24201	East Cape Allochthon	Ruatoria Group (Taitai Sst)	Early Cret (Cm–Cn)	Aorangi, Ruatoria, E crags	Y15/639534	6
6	ECAP3	24200	East Cape Allochthon	Ruatoria Group (Taitai Sst)	Early Cret (Cm–Cn)	Puketiti, Te Puia, E crags	Z16/707348	6
7	MATA1	24357	Cretaceous Cover	Matawai Group (Waitahaia F)	Early Cret (Cm–Cn)	Mata River, Te Puia	Y15/623452	6
8	URE20	23813	Waioeka Facies (uncert)	Matawai Group ?	Early Cret	Hopuruahine Str., Lake Waikaremoana, rds.	W18/629711	6
9	ECAP8	24206	Cretaceous Cover	Matawai Group	Early Cret (Uk)	Matawai, Waioeka Gorge, Te Kohu quarry	X17/009033	6
9A	WAIOK1	23684	Waioeka Facies	Torlesse Supergroup	Late Jur – Early Cret	Matawai, Waioeka Gorge	X17/992061	5
9B	WAIITI1	23996	Waioeka Facies	Torlesse Supergroup	Late Jur – Early Cret	Waiiti Stream, Urewera Range	W16/713138	5
Hawkes Bay – Wairarapa								
10	MKUR2	24356	Cretaceous Cover	Glenburn Formation	Late Cret (Cn–Mh)	Mangakuri Beach, Elsthorpe	V23/441289	6
11	MGPI1	24354	Pahau Terrane	Pahaoa Group	Early Cret (Uk)	Mangatepai Stream, Ngahape	U23/018070	6
11A	GWA1	23420	Pahau Terrane	Torlesse Supergroup (Pahau Group undiff)	Late Jur – Early Cret	Gwavas Forest track	U22/972573	5
11B	WWP1	23444	Pahau Terrane	Torlesse Supergroup (Pahau Group undiff)	Late Jur – Early Cret	Coonor, Waiwaepa Range	U24/723819	5
12	AKIT1	24305	Pahau Terrane	Pahaoa Group (Mangapokia Formation)	Early Cret (Cu–Cm)	Middle Creek, Akitio Rd, Akitio	U25/987657	6
12x	MTKN1	24596	Cretaceous Cover	Glenburn Formation	Late Cret (Rt)	Mataikona River, south bank	U25/839477	6
13	TAIP1	24558	Pahau Terrane	Pahaoa Group (Taipo Formation)	Early Cret (Cu–Cm)	Gladstone–Glenburn Rd, nr Glenstrae Stn.	T27/442023	6
13x	BID1	24598	Pahau Terrane	Pahaoa Group (Taipo Formation)	Early Cret (Cu–Cm)	Bideford–Ikahaua Rd, quarry	T25/528407	6
14	GLBN1	24457	Cretaceous Cover	Glenburn Formation	Late Cret (Cn)	beach o/c at Honeycomb Light	T28/807469	6
15	TORA1	24307	Pahau Terrane	Pahaoa Group (Mangapokia Formation)	Early Cret (Uk)	Oterei River mouth, Tora	S28/249659	6
16	TORA2	24308	Pahau Terrane	Pahaoa Group (Taipo Formation)	Early Cret (Cu–Cm)	Range Rd, Tuturumiru, wind turbine site	S28/164774	6
17	CPEX2	24402	Pahau Terrane	Torlesse Supergroup (Pahau Group undiff)	Late Jur – Early Cret	Waitetuna Stream, Cape Palliser, beach	S28/040534	6
17A	CPD2	21180	Pahau Terrane	Torlesse Supergroup (Pahau Group undiff)	Late Jur – Early Cret	Cape Palliser, lighthouse access	S28/008525	2
17B	MUKA1	24303	Kaweka Terrane	Esk Head Belt	Late Jurassic	Mukamuka Stream, Palliser Bay	R28/797786	5
Marlborough – North Canterbury								
18	LTHM1	23060	Kaweka Terrane	Esk Head Belt	Late Jur – Early Cret	Leatham River Valley. eastern hillside o/c	N29/278402	6
19	TP1	24551	Pahau Terrane	Torlesse Supergroup (Pahau Group undiff)	Late Jur – Early Cret	Taylors Pass, north side, rds	P28/912548	6
20	WARD1	24550	Cretaceous Cover	Seymour Group (Woolshed Formation)	Late Cret (H)	Ward Beach	P29/086286	6
21	AWX1	23291	Pahau Terrane	Torlesse Supergroup (Pahau Group undiff)	Early Cret (Cu–Cm)	Awatere River, right bank	P29/703291	6
22	KEK1	23298	Pahau Terrane	Torlesse Supergroup (Pahau Group undiff)	Early Cret (Cu–Cm)	Kekerengu River, Kekerengu	P30/913156	6
23	COV1	24528	Cretaceous Cover	Coverham Group (Champagne Formation)	Early Cret (Cu)	Ouse River, Coverham	P30/817164	6
24	COV2	24529	Pahau Terrane	Torlesse Supergroup (Pahau Group undiff)	Late Jur – Early Cret	Ouse R., o/c on R bank	P30/812155	6
25	KKR1	24487	Cretaceous Cover	Bluff Sandstone	early Late Cret (Cn)	South Bay beach, Kaikoura	O31/658652	6

Table 1. Continued.

Locality No.	Sample Acronym	GNS R. No.	Unit/ Terrane	Group (Formation)	Stratigraphic Age	Location	Grid Ref. 1:50 000 (Nzms260)	Data Source
25A	HUN4	21286	Pahau Terrane	Torlesse Supergroup (Pahau Group undiff)	Late Jur – Early Cret	Hundalee, Hwy 1	O32/455487	2
25B	Ethelton	–	Pahau Terrane	Torlesse Supergroup (Pahau Group undiff)	Late Jur – Early Cret	Ethelton, Hurunui River	N33/127150	3
26	MAND1	23305	Pahau Terrane	Torlesse Supergroup (Pahau Group undiff)	Late Jur – Early Cret	Mandamus River, Tekoa Rd.	M33/733625	6
27	JKS10	23303	Kaweka Terrane	Esk Head Belt	Late Jurassic	Jacks Saddle Rd, west side of pass	M33/646173	6
28	HURW1	23069	Pahau Terrane	Torlesse Supergroup (Pahau Group undiff)	Late Jur – Early Cret	Hurunui River, south bank	N33/930155	6
Chatham Islands								
27A	CIX70	23275	Cretaceous Cover	Waihere Bay Group (Tupuangi Formation)	Late Cret (Cm–Rt)	Waihere Bay beach, Pitt Island	CI Sheet2/704213	4

Locality no.: samples in **bold** are from this work; others are from previously published work: 1 – Cawood *et al.* (1999); 2 – Pickard, Adams & Barley, (2000); 3 – Wandres *et al.* (2004); 4 – Adams, Campbell & Griffin (2007); 5 – Adams *et al.* (2009*b*); 6 – this work.

Stratigraphic Age (New Zealand Series and Stages):
H – Mata Series (late Late Cretaceous); Mh – Haumurian (84–65 Ma)
R – Raukumara Series (early Late Cretaceous); Rt – Teratan (86–89 Ma)
C – Clarence Series (mid-Cretaceous); Cu – Urutawan (108–103 Ma); Cm – Motuan (103–100 Ma); Cn – Ngaterian (100–95 Ma)
U – Taitai Series (late Early Cretaceous); Uk – Korangan (118–108 Ma)

Table 2. Detrital zircon age components for Cretaceous cover and Late Jurassic – Early Cretaceous basement sandstones, eastern New Zealand

Zircon group	^{206}Pb/^{238}U zircon age group Age (Ma)	± 2e	n	% Total	Total, N
East Cape – Bay of Plenty					
(*1*) OHOP1 (R23122) OTARAWAIRERE BAY, Whakatane, Grid Ref.: W15/636532					
a	**193**	**7**	**4**	**5**	
b	**223**	± **4**	**4**	**5**	
c	**232**	± **3**	**10**	**13**	
d	**237**	± **3**	**8**	**10**	
e	**247**	± **2**	**13**	**16**	
f	**267**	± **4**	**5**	**6**	**80**
(*1A*) t44 KOHI POINT, Whakatane, Grid Ref.: W15/6285471[1]					
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
(*2*) ECAP12 (R24211) TORERE, beach, Grid Ref.: X15/050534					
a	**112**	± **1**	**7**	**15**	
b	**117**	± **2**	**7**	**15**	
c	**352**	± **8**	**5**	**10**	**48**
(*3*) ECAP6 (R24204) WHANARUA BAY, beach, Grid Ref.: Y14/329802					
a	**102**	± **2**	**8**	**14**	
b	**116**	± **2**	**10**	**18**	
c	**127**	± **3**	**4**	**7**	
d	**355**	± **4**	**8**	**14**	**57**
(*3A*) t420 WHANARUA BAY, beach, Grid Ref.: Y14/329802[1]					
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
(*4*) ECAP5 (R24202) ORETE POINT, Waihau Bay, Grid Ref.: Y14/436864					
a	**243**	± **4**	**7**	**13**	
b	**255**	± **2**	**9**	**17**	
c	**264**	± **3**	**6**	**11**	**54**
(*5*) ECAP4 (R24201) AORANGI, Ruatoria, Grid Ref.: Y15639534					
a	**111**	± **1**	**15**	**27**	
b	**122**	± **3**	**3**	**11**	
c	**160**	± **8**	**4**	**7**	
d	**337**	± **2**	**8**	**14**	
e	**351**	± **3**	**7**	**13**	
f	**360**	± **3**	**7**	**13**	**56**
(*6*) ECAP3 (R24200) PUKETITI, Te Puia, Grid Ref.: Z16/707348					
a	**112**	± **1**	**20**	**29**	
b	**118**	± **1**	**12**	**17**	
c	**125**	± **2**	**7**	**10**	
d	**350**	± **5**	**6**	**9**	
e	**361**	± **1**	**8**	**12**	**69**
(*7*) MATA1 (R24357) MATA RIVER, Te Puia, Grid Ref.: Y15/623452					
a	**244**	± **3**	**4**	**7**	
b	**268**	± **2**	**9**	**15**	
c	**346**	± **5**	**3**	**5**	**59**
(*8*) URE20 (R23813) HOPURUAHINE, Lake Waikaremoana, Grid Ref.: W18/629711					
a	**179**	± **4**	**5**	**8**	
b	**215**	± **5**	**4**	**6**	
c	**238**	± **3**	**4**	**6**	
d	**244**	± **2**	**8**	**13**	
e	**263**	± **4**	**7**	**11**	**63**
(*9*) ECAP8 (R24206) MATAWAI, Waioeka Gorge, Te Kohu quarry, Grid Ref.: X17/009033					
a	**126**	± **1**	**34**	**68**	
b	**135**	± **2**	**5**	**10**	
c	**198**	± **2**	**5**	**10**	**49**
(*9A*) WAIOK1 (R23684) MATAWAI, Wiaoeka Gorge, Grid Ref.: X17/009033[5]					
a	116	± 1	6	12	
b	121	± 1	10	19	

Table 2. Continued.

Zircon group	^{206}Pb/^{238}U zircon age group Age (Ma)	±	2e	n	% Total	Total, N
c	125	±	1	13	25	
d	129	±	2	6	12	
e	132	±	2	5	10	
f	219	±	4	3	6	52
(*9B*) WAIITI(R23996) WAIITI STREAM, Urewera Range, Grid Ref.: W16/713138[5]						
a	118	±	1	11	36	
b	123	±	1	10	32	
c	128	±	1	5	16	
d	138	±	6	3	10	31
Hawkes Bay – Wairarapa						
(*10*) MKUR2 (R24356) MANGAKURI BEACH, Elsthorpe, Grid Ref.: V23/441289						
a	**240**	±	**5**	**3**	**6**	
b	**257**	±	**4**	**8**	**17**	
c	**302**	±	**5**	**3**	**6**	**47**
(*11*) MGPI1 (24354) MANGATEPAI STREAM, Ngahape, Grid Ref.: U23/018070						
a	**112**	±	**2**	**3**	**5**	
b	**129**	±	**2**	**4**	**7**	
c	**169**	±	**2**	**8**	**13**	
d	**240**	±	**4**	**14**	**23**	**61**
(*11A*) GWA1 (R23420) GWAVAS FOREST, Grid Ref.: U22/972573[5]						
a	130	±	4	7	8	
b	176	±	6	5	6	
c	231	±	3	4	5	
d	243	±	5	16	19	
e	254	±	2	6	7	
f	270	±	5	6	7	84
(*11B*) WWP1 (R23444) COONOR, Waewaepa Range, Grid Ref.: U24/723819[5]						
a	126	±	2	6	12	
b	173	±	2	4	8	
c	182	±	2	6	12	
d	240	±	3	3	6	
e	249	±	3	5	10	
f	260	±	4	3	6	52
(*12*) AKIT2 (R24353) AKITIO ROAD, Akitio, Grid Ref.: U25/980669						
a	**105**	±	**1**	**19**	**38**	
b	**112**	±	**2**	**6**	**12**	**50**
(*12x*) MTKN1 (R24596) MATAIKONA RIVER, south bank, Grid Ref.: U25/839477						
a	**230**	±	**2**	**6**	**10**	
b	**242**	±	**3**	**5**	**8**	
c	**259**	±	**3**	**5**	**8**	
d	**444**	±	**5**	**5**	**8**	
e	**484**	±	**5**	**4**	**6**	**60**
(*13*) TAIP1 (R24558) GLENSTRAE, Gladstone – Glenburn Rd, Grid Ref.: T27/442023						
a	**111**	±	**2**	**6**	**8**	
b	**123**	±	**2**	**13**	**18**	
c	**189**	±	**4**	**4**	**6**	
d	**231**	±	**4**	**6**	**8**	**71**
(*13x*) BID1 (R24598) BIDEFORD, Bideford – Ikahaua Road, Grid Ref.: T25/528407						
a	**119**	±	**2**	**14**	**21**	
b	**242**	±	**3**	**6**	**9**	**67**
(*14*) GLBN1 (R24457) HONEYCOMB LIGHT, beach, Grid Ref.: T28/807469						
a	**242**	±	**5**	**4**	**7**	
b	**249**	±	**3**	**9**	**15**	**59**
(*15*) TORA1 (R24307) OTEREI RIVER MOUTH, Tora, Grid Ref.: S28/249659						
a	**182**	±	**#**	**4**	**5**	
b	**224**	±	**3**	**6**	**8**	
c	**234**	±	**3**	**4**	**5**	
d	**245**	±	**3**	**7**	**9**	
e	**256**	±	**3**	**7**	**9**	
f	**267**	±	**3**	**4**	**5**	
g	**317**	±	**4**	**4**	**5**	
h	**480**	±	**6**	**4**	**5**	**76**
(*16*) TORA2 (R24308) TUTURURIMU, Range Rd (wind turbine site), Grid Ref.: S28/164774						
a	**114**	±	**3**	**7**	**14**	
b	**122**	±	**2**	**8**	**37**	
c	**364**	±	**7**	**3**	**6**	**49**
(*17*) CPEX2 (R24402) WAITETUNA STREAM, Cape Palliser, Grid Ref.: S28/040534						
a	**218**	±	**3**	**5**	**6**	
b	**244**	±	**3**	**6**	**8**	
c	**257**	±	**2**	**10**	**13**	
d	**265**	±	**3**	**6**	**8**	**79**
(*17A*) CPD2 (R21180) CAPE PALLISER, beach, Grid Ref.: S28/008525[2]						
a	240	±	4	4	9	
b	250	±	4	4	9	
c	266	±	3	8	19	43
(*17B*) MUKA1 (R24303) MUKAMUKA, Palliser Bay, Grid Ref.: R28/79778[5]						
a	225	±	3	4	7	
b	244	±	2	7	13	
c	254	±	2	9	16	
d	274	±	4	4	13	55
Marlborough – North Canterbury						
(*18*) LHTM1 (R23060) LEATHAM RIVER VALLEY, eastern hills, Grid Ref.: N29/278402						
a	**249**	±	**2**	**7**	**12**	
b	**259**	±	**4**	**3**	**5**	
c	**272**	±	**4**	**4**	**7**	
d	**461**	±	**5**	**4**	**7**	
e	**522**	±	**6**	**4**	**7**	**60**
(*19*) TP1 (R24551) TAYLORS PASS, north side, Grid Ref.: P28/912548						
a	**114**	±	**2**	**4**	**7**	
b	**220**	±	**3**	**6**	**10**	
c	**241**	±	**4**	**5**	**8**	**60**
(*20*) WARD1 (R24550) WARD BEACH, Ward, Grid Ref.: P29/086286						
a	**245**	±	**4**	**4**	**7**	
b	**252**	±	**4**	**4**	**7**	
c	**268**	±	**4**	**5**	**9**	
d	**289**	±	**5**	**4**	**7**	**58**
(*21*) AWX1 (R23291) AWATERE RIVER, right bank, Grid Ref.: P29/703291						
a	**128**	±	**5**	**8**	**15**	
b	**182**	±	**5**	**4**	**7**	
c	**262**	±	**3**	**8**	**15**	
d	**363**	±	**6**	**4**	**7**	
e	**624**	±	**9**	**4**	**7**	**54**
(*22*) KEK1 (R23298) KEKERENGU RIVER, Kekerengu, Grid Ref.: P30/913156						
a	**104**	±	**1**	**3**	**5**	
b	**247**	±	**2**	**9**	**15**	
c	**270**	±	**3**	**6**	**10**	
d	**326**	±	**4**	**4**	**7**	**61**
(*23*) COV1 (R24528) OUSE RIVER, Coverham Station, Grid Ref.: P30/817164						
a	**116**	±	**2**	**4**	**5**	
b	**126**	±	**2**	**6**	**8**	
c	**135**	±	**2**	**4**	**5**	
d	**240**	±	**2**	**3**	**4**	
e	**286**	±	**3**	**8**	**11**	
f	**297**	±	**4**	**4**	**5**	
g	**355**	±	**6**	**3**	**4**	**73**
(*24*) COV2 (R24529) OUSE RIVER, Coverham Station, Grid Ref.: P30/812155						
a	**111**	±	**3**	**6**	**10**	
b	**133**	±	**3**	**5**	**8**	
c	**240**	±	**5**	**16**	**26**	**61**
(*25*) KKR1 (R24487) KAIKOURA, South Bay, Grid Ref.: O31/658652						
a	**115**	±	**1**	**4**	**8**	
b	**122**	±	**2**	**5**	**10**	
c	**142**	±	**5**	**4**	**8**	

Table 2. Continued.

Zircon group	^{206}Pb/^{238}U zircon age group Age (Ma)	±	2e	n	% Total	Total, N
e	**244**	±	**4**	**6**	**12**	
d	**266**	±	**3**	**4**	**8**	**51**
(*25A*) HUN4 (R21286) Hundalee, Hwy 1, Grid ref.: O32/455487[2]						
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
(*25B*) Ethelton, ETHELTON, Hurunui River, Grid Ref.: N33/127150 approx.[3]						
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
(*26*) MAND1 (R23305) MANDAMUS RIVER, Tekoa Rd, Grid Ref.: M33/733625						
a	**119**	±	**4**	**4**	**12**	
b	**128**	±	**5**	**4**	**12**	
c	**138**	±	**2**	**4**	**12**	
d	**256**	±	**4**	**3**	**7**	
e	**531**	±	**6**	**4**	**12**	**42**
(*27*) JKS10 (R23303), JACKS SADDLE, west side of pass, Grid Ref.: M33/646173						
a	**250**	±	**2**	**23**	**32**	
b	**271**	±	**3**	**10**	**14**	
c	**498**	±	**7**	**4**	**5**	
d	**545**	±	**7**	**5**	**7**	**73**
(*28*) HURW1 (R23069) HURUNUI RIVER, Hurunui, south bank, Grid. Ref.: N33/930155						
a	**118**	±	**3**	**4**	**8**	
b	**129**	±	**3**	**3**	**6**	
c	**255**	±	**3**	**7**	**14**	**51**
Chatham Islands						
(*27A*) CIX70 (R23275) WAIHERE BAY, Pitt Island, Grid Ref.: CI/2/704213[4]						
a	101	±	3	5	7	
b	109	±	1	6	9	
c	115	±	1	8	11	
d	120	±	1	6	9	
e	144	±	3	3	4	
f	248	±	3	4	6	
g	270	±	4	3	4	
h	343	±	5	4	6	
j	552	±	7	3	4	70

GNS geochronology sample archive R number given in brackets
Data in **bold** are this work; data not in bold are from previously published work: [1]Cawood *et al.* 1999; [2]Pickard *et al.* 2000; [3]Wandres *et al.* 2004; [4]Adams *et al.* 2007; [5]Adams *et al.* 2009*b*
e – errors are 95 % confidence limits; n – number of grains in age group; N – total population

conveniently summarized in Fig. 4. Using the broad categories shown in Fig. 3, the zircon age data are presented as histograms of all-data totals at the left, and as significant age components to the right. The detail is best revealed by a 0–500 Ma format for all categories. Again, the same two patterns are revealed:

Firstly, within the broad 220–290 Ma age group seen in all Cretaceous Pahau and Kaweka terrane basement and Cretaceous cover samples, it is Late Permian – Middle Triassic (*c.* 255–235 Ma) zircon age components that dominate; these persist over the full Late Jurassic to late Early Cretaceous interval sampled, which embraces a period of about 60 Ma. In the Pahau Terrane, there are also subordinate clusters in both Early–Middle Jurassic (*c.* 185–165 Ma) and late Early Cretaceous (*c.* 125 Ma) intervals (Fig. 4). In the Kaweka Terrane samples (all Late Jurassic), the Early–Middle Jurassic (*c.* 185–165 Ma) age cluster is surprisingly absent.

The Late Permian – Early Triassic zircon groups can be resolved into many significant age components: in the samples from the Pahaoa Group in the Pahau Terrane (probable Albian) these cluster around *c.* 235 Ma (Fig. 4f); in the remaining Pahau Terrane (Barremian–Albian) they cluster at *c.* 245 Ma (Fig. 4f); and in the Kaweka Terrane (Esk Head Belt; Late Jurassic) at *c.* 255 Ma (Fig. 4h). In the late Early Cretaceous groups, the significant age components are always in the range 130–105 Ma (Fig. 4b, d, f) and although difficult to resolve, the main subgroups are 115–110 Ma and 130–120 Ma.

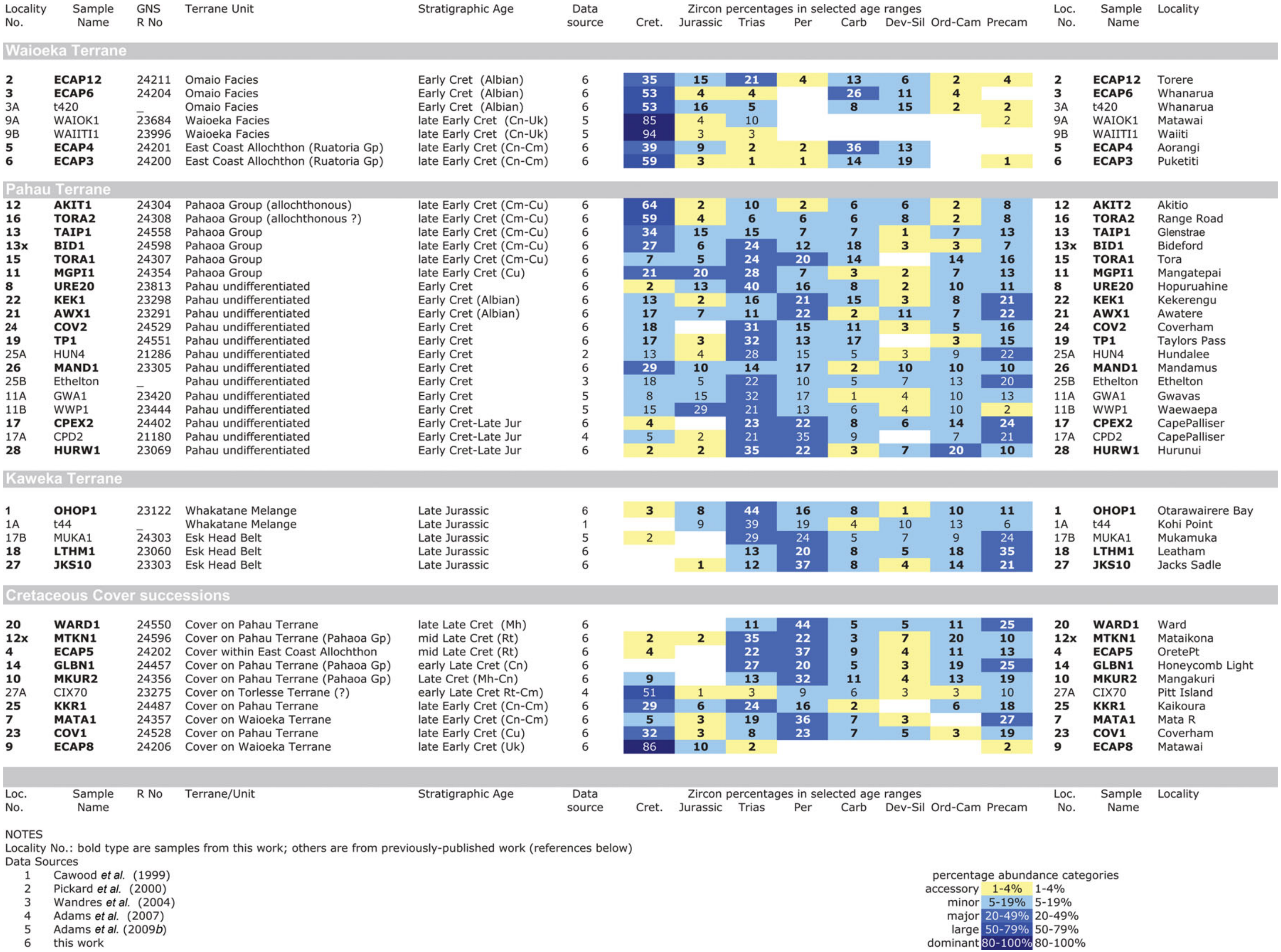
Secondly, in the Waioeka Terrane and allochthon samples, the Late Permian – Early Triassic components are completely absent (Fig. 4b, d), and the dominant groups are late Early Cretaceous (130–110 Ma) and, with the exception of the Waioeka Facies samples, 120–110 Ma. There are also unusual Late Devonian – Early Carboniferous zircon components at *c.* 350 Ma.

With the exception of a sample from the Matawai Group (*9*), which overlies Waioeka Terrane basement (see Section 2.b.1), the Cretaceous cover successions have detrital zircon age components generally similar to those in the Pahau and/or Kaweka terrane basement nearby (Fig. 3). However, the cover successions seem not to have inherited the Late Triassic components (*c.* 230–210 Ma) and few of the Early–Middle Jurassic components (*c.* 185–165 Ma) present in some Pahau Terrane datasets. Whilst there are no significant age components >550 Ma, an all-data zircon diagram demonstrates similar Late Precambrian (1000–550 Ma) detrital zircon patterns for both Cretaceous basement and cover successions.

5. Discussion of results

5.a. Maximum stratigraphic age constraints from detrital zircon ages

Detrital zircon age data provide useful maximum depositional age constraints for basement rocks that are sparsely fossiliferous or unfossiliferous. Whilst individual young ages, isolated from the main groups, are occasionally encountered, for example localities (*1*, *7*, *17*, *23*), we prefer here to take a conservative position and use only youngest significant age components (Table 2) to set maximum depositional ages. In zircon datasets from localities with a known fossil age at the intra-stage level, e.g. Albian localities (*11*, *21*, *22*), the youngest age components always coincide with the fossil age. Where the fossil age control is only within a broader range e.g. Barremian–Aptian localities in Waioeka and Pahau terranes (*9A*, *9B*, *24*, *25*), this remains the case but, interestingly, for the older Kaweka Terrane (Esk Head Belt) localities (*1*, *17B*, *18*, *27*), the



Locality No.	Sample Name	GNS R No	Terrane Unit	Stratigraphic Age	Data source	Cret.	Jurassic	Trias	Per	Carb	Dev-Sil	Ord-Cam	Precam	Loc. No.	Sample Name	Locality
Waioeka Terrane																
2	**ECAP12**	24211	Omaio Facies	Early Cret (Albian)	6	**35**	**15**	**21**	**4**	**13**	**6**	**2**	**4**	**2**	**ECAP12**	Torere
3	**ECAP6**	24204	Omaio Facies	Early Cret (Albian)	6	**53**	**4**	**4**		**26**	**11**	**4**		**3**	**ECAP6**	Whanarua
3A	t420	_	Omaio Facies	Early Cret (Albian)	6	**53**	**16**	**5**		**8**	**15**	**2**	**2**	3A	t420	Whanarua
9A	WAIOK1	23684	Waioeka Facies	late Early Cret (Cn-Uk)	5	85	4	10					2	9A	WAIOK1	Matawai
9B	WAIITI1	23996	Waioeka Facies	late Early Cret (Cn-Uk)	5	94	3	3						9B	WAIITI1	Waiiti
5	**ECAP4**	24201	East Coast Allochthon (Ruatoria Gp)	late Early Cret (Cn-Cm)	6	**39**	**9**	**2**	**2**	**36**	**13**			**5**	**ECAP4**	Aorangi
6	**ECAP3**	24200	East Coast Allochthon (Ruatoria Gp)	late Early Cret (Cn-Cm)	6	**59**	**3**	**1**	**1**	**14**	**19**		**1**	**6**	**ECAP3**	Puketiti
Pahau Terrane																
12	**AKIT1**	24304	Pahaoa Group (allochthonous)	late Early Cret (Cm-Cu)	6	**64**	**2**	**10**	**2**	**6**	**6**	**2**	**8**	**12**	**AKIT2**	Akitio
16	**TORA2**	24308	Pahaoa Group (allochthonous ?)	late Early Cret (Cm-Cu)	6	**59**	**4**	**6**	**6**	**6**	**8**	**2**	**8**	**16**	**TORA2**	Range Road
13	**TAIP1**	24558	Pahaoa Group	late Early Cret (Cm-Cu)	6	**34**	**15**	**15**	**7**	**7**	**1**	**7**	**13**	**13**	**TAIP1**	Glenstrae
13x	**BID1**	24598	Pahaoa Group	late Early Cret (Cm-Cu)	6	**27**	**6**	**24**	**12**	**18**	**3**	**3**	**7**	**13x**	**BID1**	Bideford
15	**TORA1**	24307	Pahaoa Group	late Early Cret (Cm-Cu)	6	**7**	**5**	**24**	**20**	**14**		**14**	**16**	**15**	**TORA1**	Tora
11	**MGPI1**	24354	Pahaoa Group	late Early Cret (Cu)	6	**21**	**20**	**28**	**7**	**3**	**2**	**7**	**13**	**11**	**MGPI1**	Mangatepai
8	**URE20**	23813	Pahau undifferentiated	Early Cret	6	**2**	**13**	**40**	**16**	**8**	**2**	**10**	**11**	**8**	**URE20**	Hopuruahine
22	**KEK1**	23298	Pahau undifferentiated	Early Cret (Albian)	6	**13**	**2**	**16**	**21**	**15**	**3**	**8**	**21**	**22**	**KEK1**	Kekerengu
21	**AWX1**	23291	Pahau undifferentiated	Early Cret (Albian)	6	**17**	**7**	**11**	**22**	**2**	**11**	**7**	**22**	**21**	**AWX1**	Awatere
24	**COV2**	24529	Pahau undifferentiated	Early Cret	6	**18**		**31**	**15**	**11**	**3**	**5**	**16**	**24**	**COV2**	Coverham
19	**TP1**	24551	Pahau undifferentiated	Early Cret	6	**17**	**3**	**32**	**13**	**17**		**3**	**15**	**19**	**TP1**	Taylors Pass
25A	HUN4	21286	Pahau undifferentiated	Early Cret	2	13	4	28	15	5	3	9	22	25A	HUN4	Hundalee
26	**MAND1**	23305	Pahau undifferentiated	Early Cret	6	**29**	**10**	**14**	**17**	**2**	**10**	**10**	**10**	**26**	**MAND1**	Mandamus
25B	Ethelton	_	Pahau undifferentiated	Early Cret	3	18	5	22	10	5	7	13	20	25B	Ethelton	Ethelton
11A	GWA1	23420	Pahau undifferentiated	Early Cret	5	8	15	32	17	1	4	10	13	11A	GWA1	Gwavas
11B	WWP1	23444	Pahau undifferentiated	Early Cret	5	15	29	21	13	6	4	10	2	11B	WWP1	Waewaepa
17	**CPEX2**	24402	Pahau undifferentiated	Early Cret-Late Jur	6	**4**		**23**	**22**	**8**	**6**	**14**	**24**	**17**	**CPEX2**	CapePalliser
17A	CPD2	21180	Pahau undifferentiated	Early Cret-Late Jur	4	5	2	21	35	9		7	21	17A	CPD2	CapePalliser
28	**HURW1**	23069	Pahau undifferentiated	Early Cret-Late Jur	6	**2**	**2**	**35**	**22**	**3**	**7**	**20**	**10**	**28**	**HURW1**	Hurunui
Kaweka Terrane																
1	**OHOP1**	23122	Whakatane Melange	Late Jurassic	6	**3**	**8**	**44**	**16**	**8**	**1**	**10**	**11**	**1**	**OHOP1**	Otarawairere Bay
1A	t44	_	Whakatane Melange	Late Jurassic	1		9	39	19	4	10	13	6	1A	t44	Kohi Point
17B	MUKA1	24303	Esk Head Belt	Late Jurassic	5	2		29	24	5	7	9	24	17B	MUKA1	Mukamuka
18	**LTHM1**	23060	Esk Head Belt	Late Jurassic	6			**13**	**20**	**8**	**5**	**18**	**35**	**18**	**LTHM1**	Leatham
27	**JKS10**	23303	Esk Head Belt	Late Jurassic	6		**1**	**12**	**37**	**8**	**4**	**14**	**21**	**27**	**JKS10**	Jacks Sadle
Cretaceous Cover successions																
20	**WARD1**	24550	Cover on Pahau Terrane	late Late Cret (Mh)	6			**11**	**44**	**5**	**5**	**11**	**25**	**20**	**WARD1**	Ward
12x	**MTKN1**	24596	Cover on Pahau Terrane (Pahaoa Gp)	mid Late Cret (Rt)	6	**2**	**2**	**35**	**22**	**3**	**7**	**20**	**10**	**12x**	**MTKN1**	Mataikona
4	**ECAP5**	24202	Cover within East Coast Allochthon	mid Late Cret (Rt)	6	**4**		**22**	**37**	**9**	**4**	**11**	**13**	**4**	**ECAP5**	OretePt
14	**GLBN1**	24457	Cover on Pahau Terrane (Pahaoa Gp)	early Late Cret (Cn)	6			**27**	**20**	**5**	**3**	**19**	**25**	**14**	**GLBN1**	Honeycomb Light
10	**MKUR2**	24356	Cover on Pahau Terrane (Pahaoa Gp)	Late Cret (Mh-Cn)	6	**9**		**13**	**32**	**11**	**4**	**13**	**19**	**10**	**MKUR2**	Mangakuri
27A	CIX70	23275	Cover on Torlesse Terrane (?)	early Late Cret Rt-Cm)	4	51	1	3	9	6	3	3	10	27A	CIX70	Pitt Island
25	**KKR1**	24487	Cover on Pahau Terrane	late Early Cret (Cn-Cm)	6	**29**	**6**	**24**	**16**	**2**		**6**	**18**	**25**	**KKR1**	Kaikoura
7	**MATA1**	24357	Cover on Waioeka Terrane	late Early Cret (Cn-Cm)	6	**5**	**3**	**19**	**36**	**7**	**3**		**27**	**7**	**MATA1**	Mata R
23	**COV1**	24528	Cover on Pahau Terrane	late Early Cret (Cu)	6	**32**	**3**	**8**	**23**	**7**	**5**	**3**	**19**	**23**	**COV1**	Coverham
9	**ECAP8**	24206	Cover on Waioeka Terrane	late Early Cret (Uk)	6	**86**	**10**	**2**					**2**	**9**	**ECAP8**	Matawai
Loc. No.	Sample Name	R No	Terrane/Unit	Stratigraphic Age	Data source	Cret.	Jurassic	Trias	Per	Carb	Dev-Sil	Ord-Cam	Precam	Loc. No.	Sample Name	Locality

(Columns Cret. to Precam: Zircon percentages in selected age ranges)

NOTES
Locality No.: bold type are samples from this work; others are from previously-published work (references below)
Data Sources
1 Cawood *et al.* (1999)
2 Pickard *et al.* (2000)
3 Wandres *et al.* (2004)
4 Adams *et al.* (2007)
5 Adams *et al.* (2009*b*)
6 this work

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 3. (Colour online) Percentage proportions of detrital zircon $^{238}U/^{206}Pb$ ages (as % of total) occurring within selected geological periods in Pahau, Waioeka and Kaweka terrane basement, Cretaceous cover successions and Cenozoic allochthons. In each group, datasets are stacked from top to bottom in ascending maximum stratigraphic age, or where unknown, their youngest significant zircon age component. Data values in bold type are from the present work, other datasets are taken from previously published work. The percentage proportions are categorized and shown according to a colour-scale (bottom right corner).

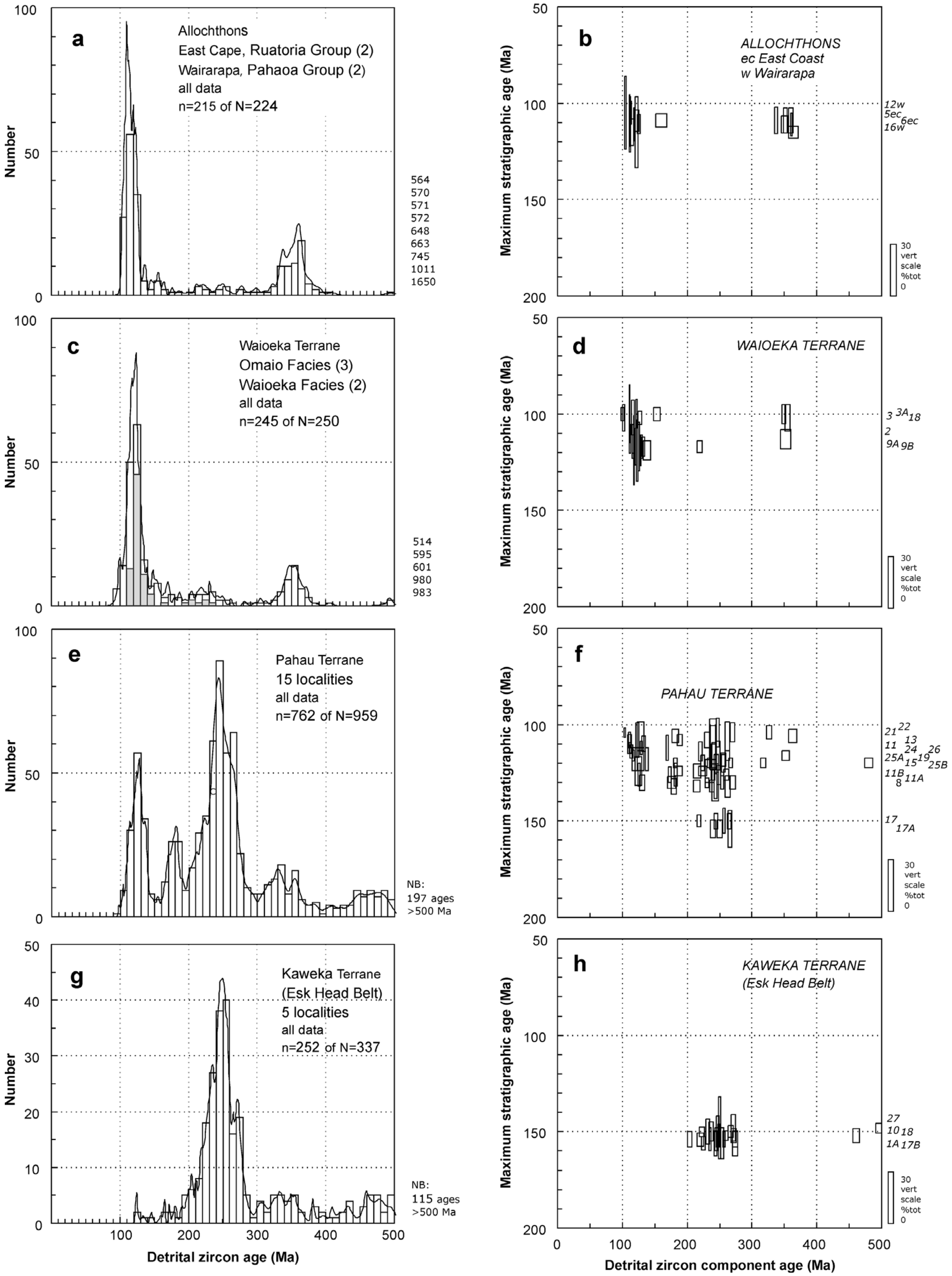


Figure 4. Detrital zircon ages from late Early Cretaceous sandstones in eastern New Zealand combined in major geological units: (a, b) Cenozoic allochthons; (c, d) Waioeka Terrane; (e, f) Pahau Terrane; (g, h) Kaweka Terrane; (i, j) Cretaceous cover successions. (a, c, e, g, i) Individual ^{206}Pb/^{238}U zircon ages are shown as combined all-data probability density/histogram diagrams with a common 0–500 Ma format, and ages >500 Ma stacked at right margin. (b, d, g, h, j) Significant detrital zircon ^{238}U/^{206}Pb age components derived from cumulative probability diagrams (Table 2 and Appendix S1) of the same datasets are shown. Data are stacked

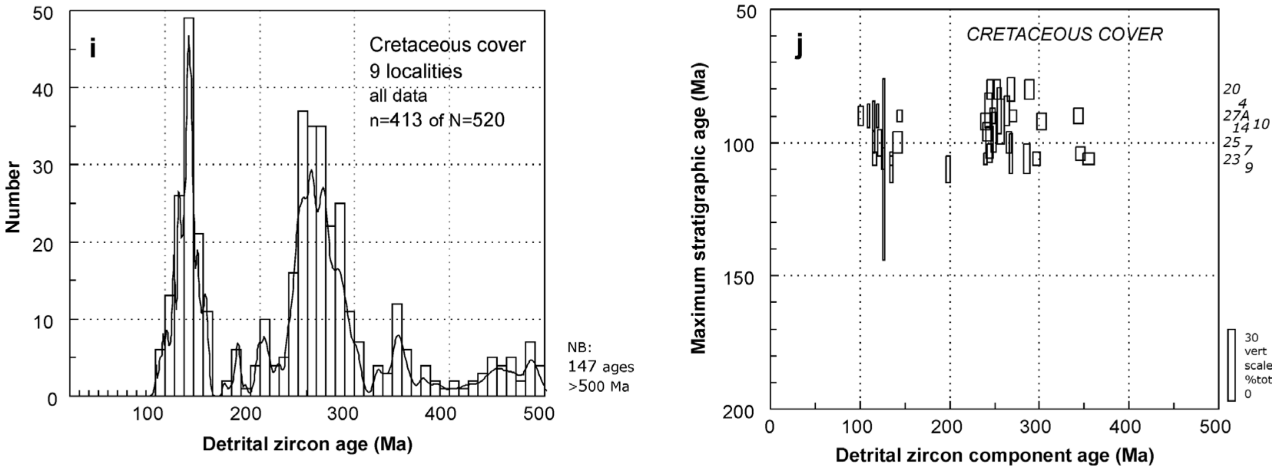


Figure 4. Continued. vertically from top to bottom in order of ascending stratigraphic age or, where unknown, the youngest significant zircon age component. Each data box represents a significant zircon age component of n ≥ 4 analyses and ≥ 4% of total dataset (usually N = 50–100), whose position and width on the horizontal axis represent the component age and error, and whose height on the vertical axis shows the proportion of that component as a percentage of the total dataset (see 0–30 % scale bar at right). Locality numbers of the datasets are shown at right margin.

youngest age components are always much older than their demonstrable Late Jurassic fossil age.

In the Waioeka Terrane, the sandstones of the Omaio Facies (*2*, *3*, *3A*) have the youngest detrital zircon components, 112 ± 1, 102 ± 2, and 100 ± 2 Ma respectively (cf. 108 ± 12 Ma (2σ) weighted mean zircon fission track in Kamp, 1999). These dominate (30–50 %) the set totals and it is reasonable to connect these ages with clear petrographic evidence of first cycle volcaniclastic detritus (Mortimer, 1994) and thus contemporary volcanism as young as late Albian. However, this age estimate overlaps a U–Pb zircon age (101.6 ± 0.2 Ma) from a tuff in local Cretaceous cover rocks at nearby Motu Falls (Crampton *et al.* 2004). Because the single zircon grains dated in the tuff were analysed by solution techniques, there remains the possibility that the analyses include older internal zones of the zircons, making the age spuriously old. The detrital zircon ages reported here, determined close to crystal terminations, minimize this effect. Waioeka Facies age patterns (*9A*, *9B*) are similar to those of the Omaio Facies, but are almost completely dominated by 115–130 Ma zircons. The youngest age components, 116 ± 1 and 118 ± 1 Ma respectively, probably also reflect contemporary late Aptian volcanism and are broadly in agreement with dinoflagellate age estimates (Leonard, Begg & Wilson, 2010) and the youngest zircon fission track ages from the Waioeka Gorge of 127 ± 12 Ma (Kamp, 1999). Basement rocks of uncertain age near Hopuruahine (*8*) have been provisionally placed in the Waioeka Facies (Leonard, Begg & Wilson, 2010) but the zircon age pattern here is unlike nearby Waioeka examples (*9A*, *9B*) and matches the Pahau Terrane datasets in the Wairarapa district (*17*, *17A*) much better. This implies a narrow northward extension of the Pahau Terrane into the Urewera district that intervenes between known Waioeka and Kaweka terrane rocks, a situation which is similar to that further south.

In the Pahau Terrane, the autochthonous Pahaoa Group zircon patterns from localities (*11*, *13*, *15*) resemble those of undifferentiated Pahau Terrane rocks elsewhere, for example, localities (*19*, *21*, *24*), thus supporting its placement within the basement. In sandstones of the Pahau Terrane, the youngest age components, usually late Early Cretaceous, represent a low proportion (<15 %). These are absent in Cape Palliser localities (*17*, *17A*) although Kamp (2000) reported weighted mean zircon fission track ages from Cape Palliser as young as 101 ± 12 Ma (2σ). Most commonly, the youngest age components impose an Aptian or early Albian maximum depositional age, but this range is extended from Barremian to late Albian at a few localities (*11A*, *11B*).

Precise (intra-stage) fossil age control at localities (*11*, *21*, *22*) certainly indicates that there was some contemporary volcanism in the Pahau Terrane hinterland in the Albian (112–100 Ma), but unfortunately, at all other localities there is no independent evidence (fossil age or petrography) to allow us to extend such volcanism back in time (e.g. to the Aptian). If we assume that all the youngest zircon age components do reflect at least some contemporaneous volcanism (and are thus not reworked zircons), then deposition within the Pahau Terrane could have extended from the Barremian to the Albian (130–100 Ma). However, there is neither zircon nor fossil age evidence indicating that deposition started any earlier (Berriasian–Hauterivian).

Kamp (1999) speculated that detrital zircon age peaks in the East Coast Allochthon matched those in the nearby autochthon. A distinctive group of four samples (three allochthonous, one probably so) within Ruatoria Group, East Coast Allochthon (*5*, *6*) and Pahaoa Group, Pahau Terrane (*12*, *16*) have the youngest age components: 111 ± 1, 112 ± 1, 105 ± 12, 114 ± 3 Ma respectively. The full age patterns strongly resemble those of the Omaio Facies examples above (*2*, *3*, *3A*) and like them, they indicate contemporary volcanism within a latest Albian–Aptian maximum age range, broadly in accordance with local Albian fossil occurrences. Accordingly, we maintain that these samples indicate assignment of the East Coast Allochthon Cretaceous rocks, and allochthonous parts of the Pahaoa Group, to the Waioeka Terrane.

5.b. Status of the Pahau Terrane

With incorporation of the Pahaoa Group into the Pahau Terrane it is now evident that the terrane is dominated by late Early Cretaceous (Barremian–Albian) sedimentary rocks. Deposition occurred in an active-margin accretionary environment with some contemporary volcanic zircon inputs, but these were overwhelmed by reworked zircons from Late Permian, Early Triassic and Jurassic hinterlands (Torlesse and Waipapa terranes). Contemporary volcanic rocks are very rare.

Adams *et al.* (2009*b*) originally regarded the Kaweka Terrane in the North Island as an Early–Middle Jurassic sub-unit of the Torlesse Composite Terrane, but subsequent study of its South Island continuation (Adams *et al.* 2011) has suggested that typical Kaweka zircon age characteristics extend to rocks of known Late Jurassic age in the Esk Head Belt. Retrospectively, some similar Late Jurassic detrital zircon localities in the Rimutaka and Whakatane Melanges of the North Island (Cawood *et al.* 1999; Adams, Campbell & Griffin, 2007) and locality (*1*) (this work) which follow this pattern, also are placed in the Esk Head Belt. They are thus regarded as true Kaweka Terrane, rather than parts of a melange solely containing Pahau and Rakaia terrane protoliths. Furthermore, the main axial ranges between Whakatane and Taupo, which were formerly regarded as Pahau Terrane by Mortimer (1994) and Kamp (1999), are now part of the Kaweka Terrane of Adams, Campbell & Griffin (2009*a*) and Adams *et al*. (2009*b*). The Pahau Terrane thus loses some Late Jurassic localities and is restricted (most probably) to a late Early Cretaceous age. The Pahau Terrane extends from the Urewera district in the North Island, to North Canterbury in the South Island and everywhere encompasses successions of Albian (macrofossil) and/or Barremian–Albian (dinoflagellate) ages, all having a common active-margin character. It is possible that the terrane extends eastwards along the north flank of the Chatham Rise, but it is absent in the Chatham Islands (Wood *et al.* 1989; Adams, Campbell & Griffin, 2008).

5.c. Status of the Waioeka Terrane

Terrane nomenclature of the Raukumara and Urewera basement rocks has changed over the years, starting with their inclusion in the Torlesse Supergroup (Suggate *et al.* 1978) and initial placement in a Mata Terrane (Spörli & Ballance, 1988). Mortimer (1994) subsequently re-grouped the newly-defined Waioeka and Omaio ‘petrofacies’ as a Waioeka Subterrane. Mazengarb & Speden (2000), Begg & Johnston (2000) and Lee & Begg (2002) then raised this to full terrane status within a Torlesse Composite Terrane. However, there remained some uncertainty about its relationship to the Pahau Terrane, principally because of the lack of demonstrable fault boundaries between them. For this reason, Adams *et al.* (2009*b*) and Leonard, Begg & Wilson, (2010) tentatively placed the Waioeka and Omaio facies in the Pahau Terrane. However, the present work lends some support for the reinstatement of a Waioeka Terrane possibly outside the Torlesse Composite Terrane. Thus, within such a Waioeka Terrane, both the Omaio and Waioeka facies have very distinctive detrital zircon patterns. They have a more limited depositional range (Aptian–Albian) than that in the Pahau Terrane (Barremian–Albian). Their zircon populations are nearly unimodal and contain high proportions of contemporary zircons. There are also differences in the age patterns of the inherited zircons. Unlike the rocks of the Torlesse Composite Terrane, those in the Waioeka Terrane (1) lack the ever-present component(s), usually major, of reworked Late Permian – Early Triassic zircons and a substantial proportion of Precambrian – early Palaeozoic zircons but (2) do include unusual Devonian–Carboniferous components. Although both Pahau and Waioeka terranes contain Albian rocks, deposition of the rocks of the Waioeka Terrane probably extended to the early Late Cretaceous (Mazengarb & Harris, 1994).

The Waioeka Terrane is now defined following Kamp (1999). It has a major fault boundary along its western margin with the Kaweka Terrane (Esk Head Belt) near Whakatane, but the southern boundary with Pahau Terrane is less certain. If locality (*8*) near Lake Waikaremoana is the northernmost point of the Pahau Terrane, then the Waiotahi Fault immediately to the east (Leonard, Begg & Wilson, 2010) might represent a boundary with Waioeka Terrane. To explore this possibility, further mapping is necessary. We also note here that late Early Cretaceous rocks within the East Coast Allochthon (and allochthonous parts of the Pahaoa Group in the Wairarapa district) have ‘Waioeka’ zircon patterns, and might thus represent detached portions of the Waioeka Terrane itself.

The definitions of the Pahau and Waioeka terrane proposed here thus distinguish two major along-strike sectors of the mid-Cretaceous continental margin, both with typical accretionary wedge sedimentation styles. Despite their present-day close proximity, they have quite different zircon age spectra and therefore appear to have distinct provenances.

5.d. Provenance changes in Pahau and Kaweka terranes

In defining the Kaweka Terrane in the North Island, Adams *et al.* (2009*b*) noted that minor, Jurassic zircon age components probably indicated some inputs of contemporary volcanic zircon (although in the absence of diagnostic fossils this could not be proved). In recognising a continuation of the Kaweka Terrane in the South Island, Adams *et al.* (2011) included the Esk Head Belt localities of Late Jurassic age, previously placed in the Pahau Terrane. In all the Esk Head Belt localities (*1*, *1A*, *7B*, *18*, *27*), contemporary zircons are almost or completely absent. The complete loss of contemporary zircons in the latest depositional stages of the Kaweka Terrane more resembles a pattern expected at a passive-margin. This may have happened as contemporary magmatic arcs stepped outboard of the accretionary front, and then allowed a pronounced increase in the proportion of Precambrian and early Palaeozoic zircons derived from an old hinterland. This transition could also be related to melange formation as well. Although melanges in the Esk Head Belt were originally considered a tectonic amalgamation of rocks from the Triassic Rakaia and Cretaceous Pahau terranes, it is noteworthy that the matrix sandstones only contain zircon components of Late Jurassic age or older. No late Early Cretaceous fossils occur in the Esk Head Belt. Adams *et al.* (2011) thus suggested that it might in fact be a Late Jurassic sedimentary melange, with only minor, tectonic modification.

Within the Pahau Terrane, many microfossil taxa are only broad-ranging (Late Jurassic – Early Cretaceous). There are no taxa recorded that are only diagnostic for the Berriasian–Hauterivian interval (145–130 Ma) and this might indicate an important depositional hiatus. The subsequent development of the accretionary wedge is thus unclear. However, in the main depositional phase (Barremian–Albian), sandstones of the Pahau Terrane always contain significant amounts of reworked zircons of Berriasian–Hauterivian age, suggesting that continental-margin magmatism continued (somewhere) through this time. These reworked zircons persist in significant proportions throughout the deposition of the Pahau Terrane and always represent a larger proportion than the contemporary volcanic (e.g. Aptian–Albian) zircons. Similar to the trend in the Kaweka Terrane, continued Berriasian–Albian deposition in the Pahau Terrane was accompanied by a gradual decline in contemporary volcanism. In Albian time, this was then repositioned to the new outboard environment of the Waioeka Terrane.

5.e. Zircon sources for Pahau Terrane sandstones

The Pahau Terrane occupies a 300 km long accretionary front, yet immediately adjacent magmatic zircon sources for the sandstones seem absent. Within the terrane itself, apart from rare thin tuffs, there are neither Aptian–Albian magmatic volcanic rocks to provide contemporary zircons, nor Berriasian–Hauterivian plutonic rocks that might be exhumed to provide reworked zircons. Although separated from several other Eastern Province terranes, an obvious source for Pahau Cretaceous zircons lies in the Median Batholith. This is a major Carboniferous to Cretaceous magmatic arc that intervenes between the Eastern and Western Provinces (Mortimer *et al.* 1999*a*, *b*). In a 300 km sector through the South Island and Cook Strait region, there are voluminous Early Cretaceous granitoids (Kimbrough *et al.* 1994; Allibone & Tulloch, 1997; Muir *et al.* 1995, 1997; Mortimer, Tulloch & Ireland, 1997; Tulloch & Kimbrough, 2003; Turnbull, Allibone & Jongens, 2010). Late Jurassic – early Early Cretaceous examples are particularly common in its southern extent (Fiordland and Stewart Island), while late Early Cretaceous granitoids now dominate the northern exposures. However, any associated volcanic successions (if formerly present) have mostly been eroded away; Aptian–Albian examples have not been found, but ignimbrites on Stewart Island are Berriasian–Valanginian in age (Kimbrough *et al.* 1994). The present extent of the batholith is comparable to the present extent of the Pahau Terrane, and thus rapid exhumation of the former would provide sediment debris of appropriate age and composition for the latter. However, it should be noted that, in their present relative on-land positions, the granitoid sources as a whole are displaced 300 km sinistrally with respect to Pahau depocentres.

Permian–Triassic zircons in the range 270–230 Ma always form the major part of the reworked zircons in the Pahau Terrane but this period represents a lull in Median Batholith magmatism (Mortimer *et al.* 1999*a*, *b*). With respect to the Cretaceous zircon group, the relative proportion of Permian–Triassic to Cretaceous groups is constant (1.5–2.0 times more abundant along the terrane) but is greater in the northernmost part (*8*, *15*, *16*). A likely source for these Permian–Triassic zircons would be the Torlesse Composite Terrane and/or Waipapa Terrane, or their common source(s). Jurassic zircons form a smaller but distinctive group, also more abundant in the northern localities e.g. (*8*, *11*, *11A*, *11B*), and a source in the Kaweka and/or Waipapa terranes is therefore suggested. The hinterland of the Pahau Terrane would thus seem to include mainly Waipapa and Kaweka terranes in the north, but would include a substantial component of Median Batholith in the south. This is supported by the probable juxtaposition of the Kaweka Terrane along most of its length in Early Cretaceous time and also, in the North Island, the Waipapa Terrane inboard of this. A major problem with this scenario is the intervention of several extensive terranes (Caples, Dun Mountain - Maitai, Murihiku, Brook Street) between the Pahau depocentres and their Median Batholith sediment sources. If these intervening terranes were available for erosion, then they would contribute less quartzose sediment detritus dominated by Triassic (Caples) and Permian (Brook Street) zircons (Adams, Campbell & Griffin, 2007; Adams, Campbell & Griffin, 2009*a*, Adams *et al.* 2009*b*) both with very low proportions of Precambrian – early Palaeozoic zircons. They would thus seem inappropriate as a contributor to Pahau sediments. It is possible that these terranes were entirely buried beneath a continental-margin plain, thus allowing Pahau rivers to flow from the Median Batholith unimpeded and then continue downstream to locally intersect Kaweka and Waipapa terranes. Unfortunately, the Early Cretaceous history of all these terranes remains poorly-known; sedimentary rocks of this age are not recorded, except in the easternmost part of the Waipapa Terrane.

5.f. Zircon sources for Waioeka Terrane sandstones

A provenance area for Waioeka Terrane zircons raises quite different problems. Although the sedimentary deposition of the terrane overlaps with that of the Pahau Terrane, the zircon pattern, with its total lack of Late Permian – Triassic and Precambrian – early Palaeozoic zircon groups, seems to totally exclude any of the sources within the adjacent Eastern Province terranes (or their source areas) which are so characteristic of the Pahau Terrane. The patterns indicate an overwhelming input of late Early Cretaceous zircons (both contemporary and reworked) and a modest but unusual contribution of Late Devonian – Carboniferous zircons. Although there are local thin tuff horizons, there are no late Early Cretaceous volcanic or plutonic rocks within the terrane itself. As for the Pahau Terrane (above), this suggests that the Cretaceous zircons originate from the Median Batholith, whereas the Late Devonian – Carboniferous zircons would derive from the restricted parts of the Western Province where there are extensive late Palaeozoic batholiths (Muir *et al.* 1996; Turnbull & Allibone, 2003; Turnbull, Allibone & Jongens, 2010). This scenario then requires a rather elaborate palaeogeography.

A river transport system for Waioeka Terrane sediments would begin in the Median Batholith and Western Province batholiths and then traverse both Western and Eastern Province terranes but without contributions from either of them, to the most outboard depocentre along the eastern margin of Zealandia. Initially, during deposition of the Waioeka Facies, probably in Barremian–Aptian time, the zircon sources would be exclusively in the Median Batholith but subsequently, during deposition of the Omaio Facies in Albian time, this would be joined by a modest input from Western Province granitoids. However, throughout this period, the Waioeka river systems had to coexist in close proximity to contemporary Pahau rivers that carried sediments dominantly from the Eastern Province terranes (mainly Kaweka and Waipapa). A tectonic repositioning of the Median Batholith (and parts of the Western Province) with respect to the Eastern Province terranes in late Early Cretaceous time might provide a more plausible alternative and is discussed in Section 6.

One other possible interpretation is that the Waioeka Terrane is a part of the Pahau Terrane that has simply been overwhelmed by contemporary Cretaceous zircons, leaving any inherited zircons as a negligible component.

5.g. Zircon sources for Cretaceous cover sandstones

In accord with the conclusions of several workers (Mazengarb & Speden, 2000; Begg & Johnston, 2000; Lee & Begg, 2002; Laird & Bradshaw, 2004), the youngest detrital zircon age components in the Pahau Terrane support sedimentological evidence that indicates a rapid transition at the Zealandia margin, during late Albian time (104–102 Ma), from accretionary-style sedimentation in the basement to passive-margin style in the cover successions. The older cover successions are late Early Cretaceous (mostly New Zealand Clarence Series) such as the late Albian (*c.* 106 Ma) Champagne Formation of North Canterbury (Crampton *et al.* 2004) which rests unconformably on undifferentiated Pahau Terrane basement with youngest detrital zircon age components of 111 ± 3 Ma (*24*) and 104 ± 1 Ma (*22*). The sandstones of the Champagne Formation (*23*) broadly inherited the major features of these patterns, but have not inherited the admittedly small Albian components, and the youngest component is late Aptian, 116 ± 2 Ma. A similar relationship is seen in the oldest North Island Cretaceous cover successions, where the possibly Cenomanian (*c.* 100–94 Ma) sandstone of the Glenburn Formation (*10*) inherits patterns similar to local Pahau Terrane basement (*11*, *11A*) but with a small number of younger zircons with individual ages 92 ± 3 Ma, 96 ± 2 Ma, 101 ± 3 Ma, 104 ± 3 Ma. These might originate from late volcanism (as yet undated) in the Waioeka Terrane, or might originate in local volcanic centres on the passive margin. Near the Waioeka Terrane, there is a strong resemblance between the zircon age pattern of the cover sandstones of the Matawai Group (probable early Albian) (*9*) and nearby basement sandstones (*9A*).

Some examples of zircon patterns in mid-Cretaceous cover sandstones are compared with those from their local basement rocks in Figure 5. In general, the Cretaceous cover datasets have diminished proportions of late Early Cretaceous zircons, suggesting that the cover rocks are not purely derived from recycled local basement (Pahau or Waioeka terrane) but include significant contributions from the adjacent Rakaia and Waipapa terranes, and less from the Median Batholith. A few isolated ages <100 Ma at (*7*) and (*10*) suggest minor zircon inputs from local volcanic centres in the extensional tectonic environment. This trend is emphasized by two late Late Cretaceous zircon patterns, one in North Island (*4*) and one in South Island (*20*), in which both contemporary late Late Cretaceous zircons and reworked late Early Cretaceous zircons are completely absent. The former clearly reflects the much-diminished level of contemporary magmatism (acid-intermediate) in the late Late Cretaceous, whilst the latter feature suggests that Median Batholith sources were definitely inaccessible (and recycling of Pahau Terrane rocks was also much-diminished). It is uncertain whether the loss of these zircon sources was caused by substantial erosion and/or burial of the Median Batholith (and parts of the Eastern Province), or development of some major barrier such as a rift valley during Late Cretaceous continental extension. In general, these zircon patterns best match Triassic sources in the Rakaia and/or Waipapa terranes.

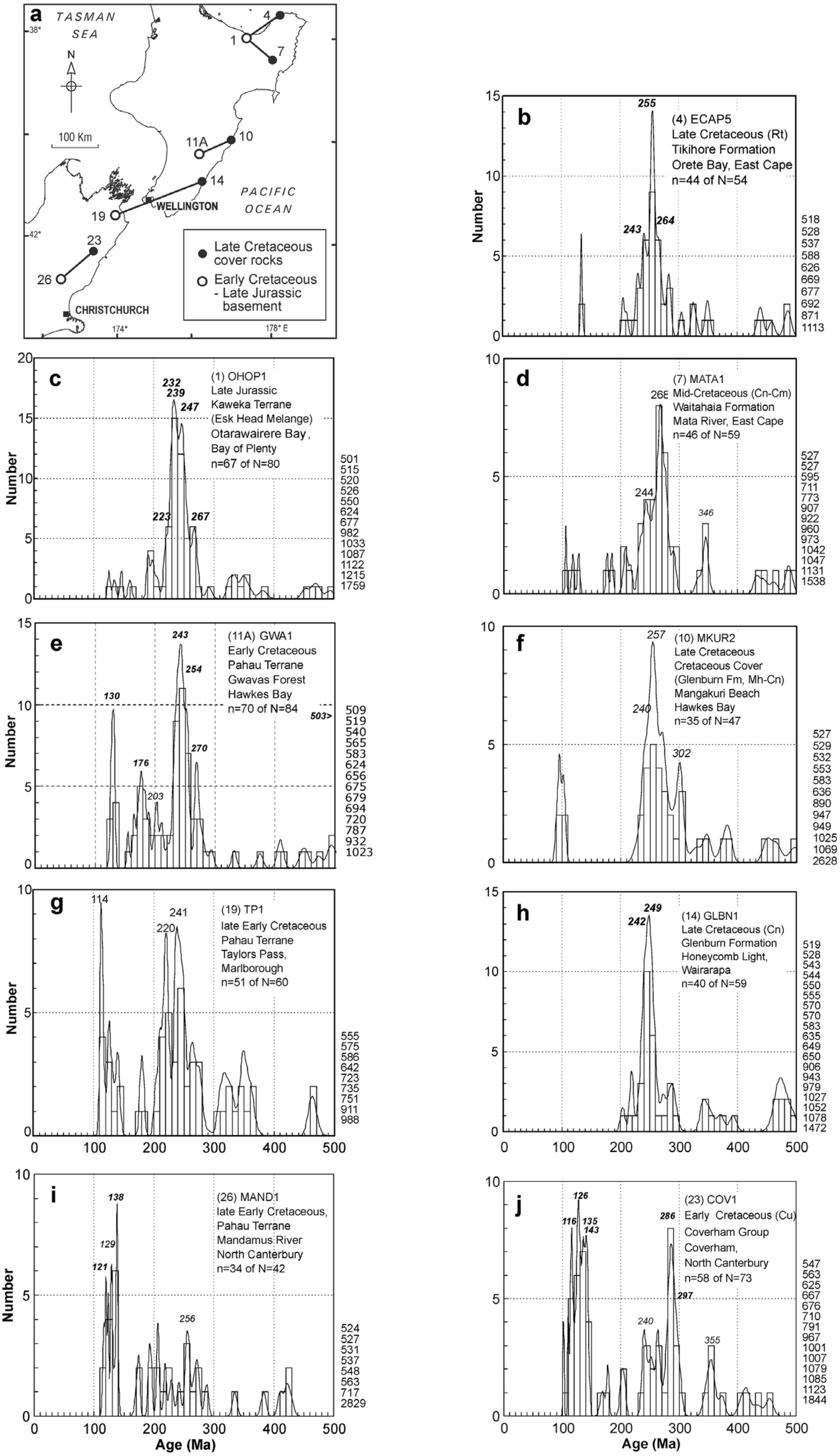


Figure 5. Comparison of detrital zircon ^{206}Pb/^{238}U age datasets as combined probability/histogram plots of selected Cretaceous cover sandstones in eastern New Zealand (b, d, f, h, j) and their nearby basement rocks (c, e, g, i). Ages >500 Ma are stacked at right margins of diagrams. Sample localities are shown on map (a).

6. Optional palaeogeographies for the Cretaceous margin in eastern New Zealand

The Cretaceous Period, as recorded in eastern New Zealand, probably began with the establishment of a chain of major Barremian–Albian Pahau depositional basins along a 300 km portion of an accretionary wedge at the convergent Zealandian Pacific margin sector of Eastern Gondwanaland. The margin was consolidated and uplifted in latest Jurassic (and possibly through to earliest Cretaceous) time, after the Jurassic sedimentation and contemporary volcanism characteristic of the Kaweka Terrane. Speculatively, a final phase of tectonism saw the repositioning of the volcanic arcs outboard (oceanward with respect to Gondwanaland), and formation of melanges inboard, of this margin. The present whereabouts of the former are unknown, but exhumation of the Median Batholith (or volcanic edifices above it, now eroded away) in late Early Cretaceous time provided a minor, but important sediment source. However, the major sediment source for the Pahau terrane was within the adjacent Kaweka and/or Waipapa terranes. In devising a palaeogeography to illustrate a Cretaceous history it is hard to reconcile these major and minor sources. This is complicated by the fact that all the zircon sources are in two terranes considered ‘suspect’ (far-travelled) and a batholith which could be a collage of many units. The timing of their amalgamation remains poorly known; rocks of Late Jurassic to Late Cretaceous age are common to all three, but only Oligocene cover rocks constrain a younger age limit. Another factor is the reassembly of Zealandia as a whole in a mid-Cretaceous configuration: a subject of considerable assumptions and therefore controversy.

In an analysis of detrital zircon age patterns in Eastern Province terranes, Adams, Campbell & Griffin (2007) suggested sediment sources in eastern Queensland and northeast New South Wales for the Rakaia and Waipapa terranes respectively, and deposition at the adjacent Gondwanaland continental margin. For the Pahau Terrane, sources much closer to northern New Zealand were indicated, and by interpolation, the primary sediment sources and deposition of the Kaweka Terrane were assumed to be situated along the Lord Howe Rise. Southeastward translation of these depositional basins during Jurassic and Cretaceous time resulted in their amalgamation, as terranes, in the New Zealand region during Early Cretaceous time. A possible involvement of the Median Batholith rocks was not considered in that study, but the present work could suggest some participation during the later Cretaceous history. Recognition of the continuation of the Median Batholith about 300 km northwards to the west of the Norfolk Ridge (Mortimer, Tulloch & Ireland, 1997; Mortimer *et al.* 1998), places it inboard of the Waipapa and Kaweka terranes, mostly in the North Island and opposite the present extent of Pahau Terrane sedimentary rocks. In this position, transport of sediment inputs from Median Batholith to Pahau depocentres would become shorter because the intervening Caples, Brook Street and Dun Mountain - Maitai terranes in the North Island are only intermittently present or highly attenuated (Adams, Campbell & Griffin, 2007; Adams, Campbell & Griffin, 2009*a*). (However, a broad Murihiku Terrane would still intervene between the Median Batholith and the Waipapa Terrane.) In the mid-Cretaceous, the Median Batholith would then have been displaced sinistrally with respect to the Kaweka and Waipapa terranes, to a new southerly position against the Brook Street, Murihiku and Dun Mountain - Maitai terranes in the South Island.

A profound reorganization of this Early Cretaceous palaeogeography would have occurred with the demise of the accretionary margin during Albian time. Following this, a Late Cretaceous extensional regime saw crustal extension and widespread development of rift depressions throughout both Western and Eastern Provinces (Norvick, Smith & Power, 2001; Norvick *et al.* 2008; Uruski, 2010), no doubt disrupting and diverting the many major W-to-E river transport systems that are implied in our model of the Jurassic – Early Cretaceous, accretionary-margin history.

In mid-Cretaceous time, there could have been an important zone of tectonic dislocation between North and South Zealandia (the boundary being approximately along the line of the present-day Alpine Fault). Continental reconstructions of North and South Zealandia against Australia and Antarctica respectively, are objectively achieved by elimination of post-85 Ma seafloor of the Tasman Sea and Southwest Pacific Ocean (Gaina *et al.* 1998; Eagles, Gohl & Larter, 2004). These give a good geological match to early Palaeozoic orogenic belts (the Australian Lachlan Orogen and its equivalents) between South Zealandia (Western Province) and Marie Byrd Land (West Antarctica), North Victoria Land (East Antarctica) and southeast Australia (Fig. 6). However, there is only a poor match of the Eastern Province terranes across the North–South Zealandia boundary, with many terranes (e.g. Brook Street, Murihiku, Dun Mountain - Maitai) appearing to be substantially displaced at least 300 km sinistrally. This is also implied in mid-Cretaceous reconstructions proposed by Sutherland (1999), Norvick, Smith & Power (2001), Norvick *et al.* (2008), Schellart, Lister & Toy (2006), Tulloch *et al.* (2009) and Uruski (2010). The reconstructions of Gaina *et al.* (1998) and Eagles, Gohl & Larter (2004) assumed rigid continental blocks, and the consequent mismatch is usually accommodated by assumed Cenozoic deformation within the North–South Zealandia boundary zone (or to some extent within Eastern Province terranes themselves); see for example Sutherland (1999) and Mortimer *et al.* (2006). However, an alternative interpretation that must be considered is that terrane offset was indeed a real, longstanding feature in Cretaceous time (e.g. Bradshaw, Weaver & Muir, 1996). There is no evidence that the Waioeka Terrane was similarly displaced, and

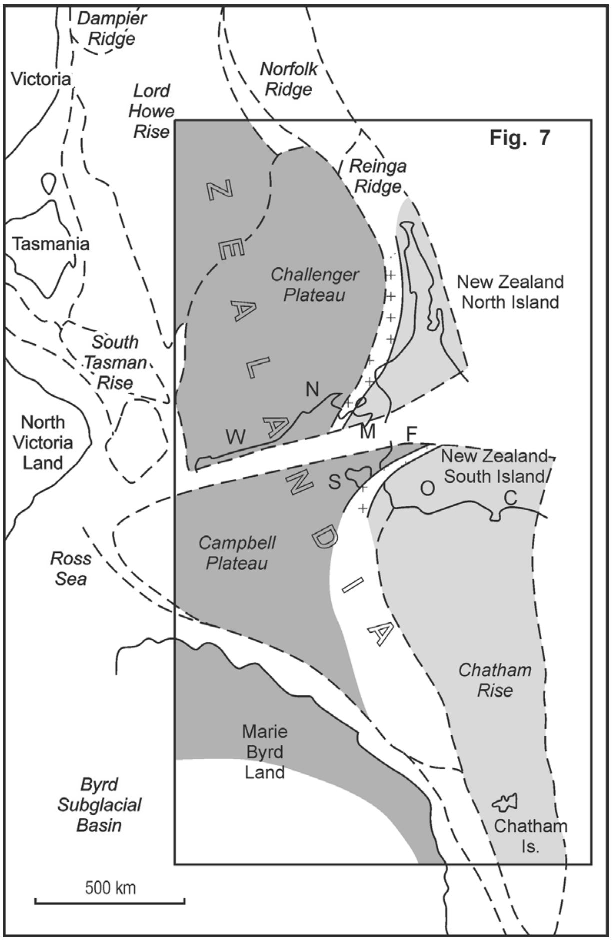


Figure 6. General reconstruction of Zealandia, eastern Australia, East Antarctica and West Antarctica in Late Jurassic to Early Cretaceous time, obtained by reassembly of major subcontinental fragments as rigid blocks only (after Gaina *et al.* 1998 and Eagles, Gohl & Larter, 2004). The Eastern Province (pale grey), Western Province (dark grey) and Median Batholith (crosses) of New Zealand are superimposed upon this.

indeed Albian sedimentary rocks within the Waioeka Terrane may be immediately related to the dislocation process itself.

In Figure 7a, an Early Cretaceous reconstruction (Barremian–Aptian; 130–112 Ma) realigns the Eastern Province terranes and the Median Batholith through Zealandia and in doing so includes, as suggested above, a speculative displacement of *c.* 300 km between them. In this case, the alignment is made holding Zealandia and West Antarctica together as rigid blocks and the required geological reorganization is accommodated arbitrarily by closing the Byrd Subglacial Basin. This results in a sinuous pattern for the terranes, which could be attributed to post-100 Ma deformation. However, there are no precisely dated (Jurassic or Cretaceous) geological markers in either North or South Zealandia that can be used to assess the degree to which this sinuosity might have been original. There is no *a priori* reason why the continental margin, depositional basins, terranes or batholiths should have been originally linear or straight or curved.

The reconstruction of Figure 7a presents a possible model for the origin of the sedimentary rocks of the Pahau Terrane. A major accretionary front occupies a 300 km sector of the Zealandia margin and is backed by an immediate hinterland of Kaweka and Waipapa terranes and beyond that, Median Batholith plutonic rocks. A much-diminished northern extension of this front probably occurs in north-eastern North Island (Coromandel and Great Barrier Island) where there is evidence that sedimentation of the Waipapa Terrane continued into Early Cretaceous time (Adams *et al.* 2009*b*). A southern extension seems less likely; early Early Cretaceous rocks are absent in the South Island but offshore geophysical evidence suggests that an attenuated Early Cretaceous unit (Seismic Unit IIA) might extend along the northern part of the Chatham Rise (Wood *et al.* 1989; Davy, Hoernle & Werner, 2008).

A Zealandia reconstruction for mid-Cretaceous time (Albian; 112–100 Ma) is shown in two versions in Figure 7b, c. In Figure 7b the disposition of the pre-112 Ma geological units (terranes, batholiths) is retained but there is crustal extension normal (NNW–SSE) to the North–South Zealandia boundary zone in its mid-section. This created a wide rift depression acting as a corridor for Waioeka Terrane sediments. In latest Aptian – early Albian time, the Waioeka Facies intersected only Median Batholith rocks, and then in late Albian time the source area of Omaio Facies penetrated further, into the Western Province. This tectonic framework is similar to that envisaged for the development of the Paparoa Metamorphic Complex in North Westland (Tulloch & Kimbrough, 1989), in which Albian crustal extension on NNW–SSE axes led to development of a metamorphic core complex flanked by depressions. As a significant drawback, this model requires the 'Waioeka' sediment corridor to be operating from only Median Batholith and Western Province sources, while close by, to the north in Wairarapa and to the south in Marlborough, contemporaneous Pahau Terrane sediments maintain equally exclusive corridors into Kaweka–Waipapa terrane hinterlands.

In Figure 7c, an alternative mid-Cretaceous terrane reorganization is accomplished by accepting the major sinistral displacement (*c.* 400 km) of South Zealandia with respect to North Zealandia implied by the 90 Ma reconstruction of Sutherland (1999). In this case, the pre-112 Ma Zealandia continental margin (mainly the Pahau and Kaweka terranes) is broken, to be replaced progressively by portions of the Median Batholith in late Aptian – early Albian time and Western Province in late Albian time. This then provides a short Western Province section of the Zealandia continental margin to supply immediately adjacent sediments of the Waioeka Terrane, whilst to the north and south, broader sections of Kaweka–Waipapa terranes continue to supply sediments to the Pahau Terrane. This interpretation requires offset of the Median Batholith in its final stages. The main

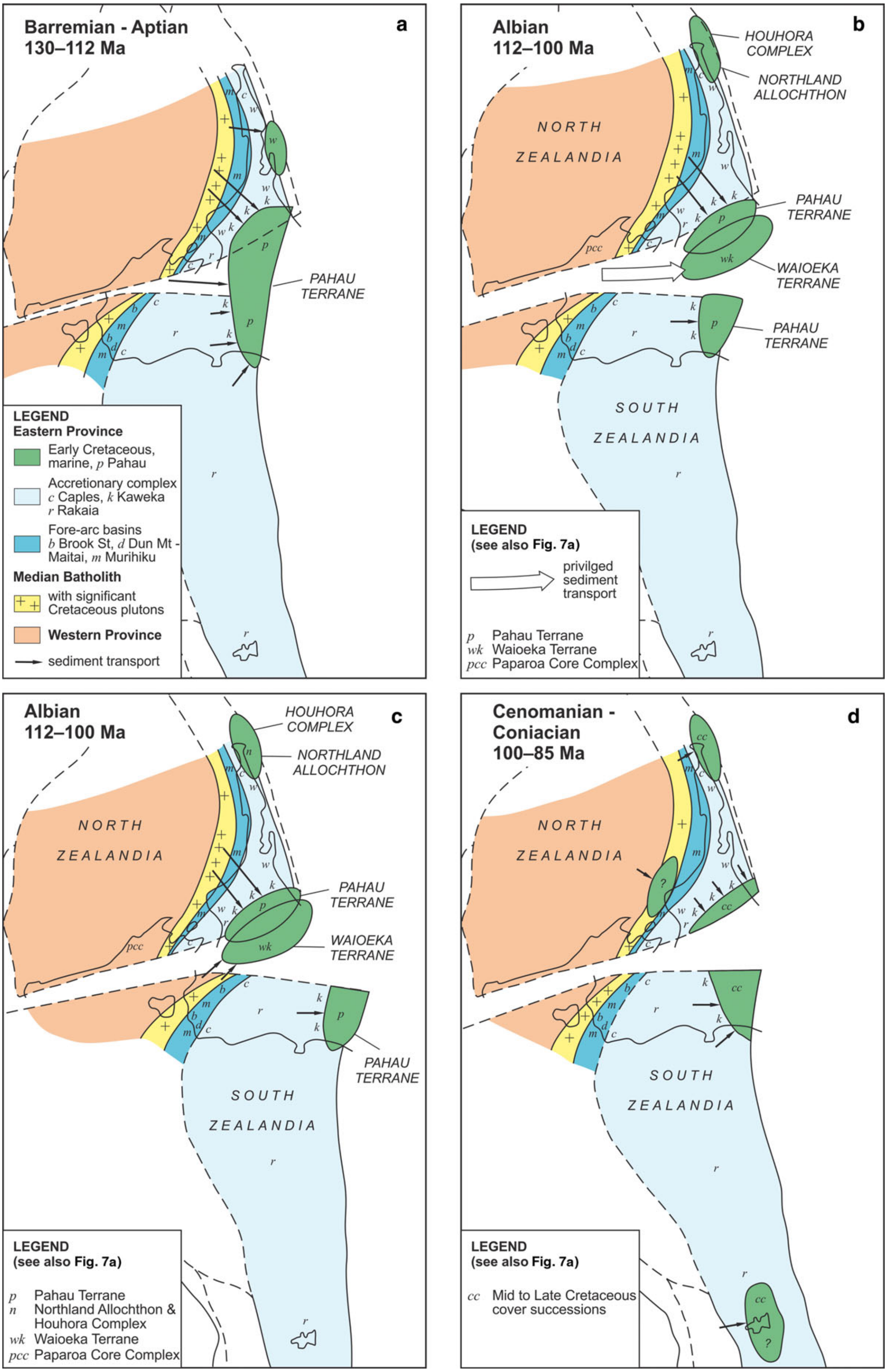


Figure 7. (Colour online) (a) Reassembly of North and South Zealandia in Barremian–Aptian time, 130–112 Ma, by realignment of New Zealand tectonostratigraphic terranes, and contemporary development of the Pahau Terrane sedimentary basins. (b) Reassembly in Albian time, 112–100 Ma, by N-S crustal extension at the North–South Zealandia boundary to create a privileged transport corridor

drawback of this scenario (Fig. 7c) is the absence of high-quality supporting evidence, such as Aptian–Albian palaeopoles for both North and South Zealandia that could confirm their relative positions. However, on the basis of palaeopoles of Marie Byrd Land plutonic rocks with U–Pb zircon ages to *c.* 102 Ma, DiVenere, Kent & Dalziel (1994) proposed substantial mid-Cretaceous extension in the Ross Sea region to displace West Antarctica (including South Zealandia) several hundred kilometres with respect to East Antarctica. It is unfortunate that similar palaeopoles are not available for the Median Batholith.

In general, the Cretaceous cover sedimentary successions, commencing in latest Early Cretaceous times, see a gradual diminishment of Early Cretaceous zircons at the expense of renewed zircon inputs from the older, marginal terranes (Kaweka and Waipapa). This suggests a gradual closing-off of Median Batholith sources, a process that was completed by late Late Cretaceous times (*c.* 85 Ma). The same appears true of the Waioeka Terrane, since the late Late Cretaceous (Coniacian) sandstone (*5*) within the East Coast Allochthon (and here included in Waioeka Terrane) contains virtually no Cretaceous zircons and has a zircon age pattern similar to other Cretaceous cover successions that rest on the Pahau Terrane. A reconstruction for the period 100–85 Ma (Fig. 7d) thus shows the mid-Cretaceous 'Waioeka' corridor to be now abandoned, either by continued widely-spread crustal extension throughout Zealandia to sever it, or dextral movement of North Zealandia with respect to South Zealandia to block it during the earliest phases of opening of the Tasman Sea. This scenario now reduces the sources for Cretaceous cover sediments to just the local Kaweka and Waipapa terranes, although inputs from the Murihiku Terrane in the North Island cannot be excluded.

7. Conclusions

New U–Pb age patterns for detrital zircons from 30 Late Jurassic and Cretaceous sandstones in the Pahau Terrane, Kaweka Terrane (Esk Head Belt) and East Coast Allochthon of eastern New Zealand have been combined with previously-published geochronological and palaeontological data to constrain a mainly late Early Cretaceous (Barremian–Albian) history for the Pahau Terrane. This improves on earlier interpretations of eastern North Island basement geology by Mortimer (1994), Kamp (1999, 2000) and Adams *et al.* (2009*b*).

The Waioeka Terrane is provisionally reinstated to define a geochronologically distinctive group of basement rocks in the Raukumara (East Cape) district, and this includes similar rocks in the East Coast Allochthon and smaller allochthons in the Wairarapa district to the south. Deposition in the Pahau part of the accretionary wedge was mainly during Barremian to Aptian time, but earlier Cretaceous successions cannot be excluded. The youngest stratigraphic unit within the Pahaoa Group includes rocks in the Wairarapa and Pahau Terrane in Marlborough, and extends into the late Albian. Deposition in the Waioeka Terrane part of the accretionary wedge is mainly Aptian to Albian in its component Waioeka Facies, and Albian in its Omaio Facies. Therefore, deposition in the Waioeka Terrane was contemporaneous with that in the younger part of the Pahau Terrane.

The provenance for sediments of the Pahau Terrane is predominantly in a hinterland of the Eastern Province, Kaweka and Waipapa terranes, as characterized by their major components of Late Permian to Early Triassic and Precambrian to early Palaeozoic zircons. However, there is an important minor component of late Early Cretaceous zircons derived from the Median Batholith, of which only a small proportion appear to be of contemporary (volcanic) origin. Zircon age patterns in the Pahau Terrane are characteristic of the Composite Torlesse Terrane.

The provenance of the Waioeka Terrane sediments does not have the above-mentioned 'Torlesse' characteristics but has a major component of Cretaceous zircons, a larger proportion of which may be of contemporary (volcanic) origin. A principal source area in granitoid rocks of the Median Batholith (and possibly associated volcanic edifices now eroded away) is indicated for the Waioeka Facies, while that of the Omaio Facies would also include a small contribution of Devonian–Carboniferous zircons from the batholiths of the Western Province of New Zealand.

The distinctive provenance of the Waioeka Terrane sediments requires the development of an exclusive sediment transport corridor across the mid-Cretaceous Zealandia continental margin. Alternative models to create such a corridor are: (1) crustal extension to form a rift depression at a North–South Zealandia boundary zone (approximately at the present Alpine Fault) delivering Western Province derived sediments across the Eastern Province terranes; or more speculatively, (2) sinistral displacement along the North–South Zealandia boundary zone to expose Median Batholith and Western Province derived rocks directly at the Zealandia continental margin.

New U-Pb detrital zircon age patterns from sandstones in mid-Cretaceous and Late Cretaceous cover successions of eastern New Zealand overwhelmingly demonstrate purely local sources. The contributions of Cretaceous zircons from the Median Batholith are less than in the Pahau and Waioeka terranes, and from the

Figure 7. Continued. for contemporary Waioeka Terrane sediments. (c) An alternative reassembly in Albian time, 112–100 Ma, by sinistral displacement of South Zealandia with respect to North Zealandia, to create Median Batholith and Western Province sediment sources close to the continent margin and Waioeka Terrane sedimentary basins. (d) Reassembly in Cenomanian–Coniacian time, 100–85 Ma, showing formation of contemporary Cretaceous cover successions in relation to basement terranes. Arrows indicate sediment transport directions.

late Early Cretaceous to late Late Cretaceous show a gradual decline and disappearance. This trend indicates a gradual closing-off of the sediment corridors from the Median Batholith and Western Province, and restriction of source areas purely to the Kaweka, Waipapa and (possibly) Murihiku Terranes.

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