Detrital zircon provenance of the Cretaceous–Neogene East Coast Basin reveals changing tectonic conditions and drainage reorganization along the Pacific margin of Zealandia

Jared T. Gooley1,* and Nora M. Nieminski2,*

1Geology, Energy & Minerals Science Center, U.S. Geological Survey, Reston, Virginia 20192, USA
2Pacific Coastal and Marine Science Center, U.S. Geological Survey, Santa Cruz, California 95060, USA

ABSTRACT

The Upper Cretaceous–Pliocene strata of New Zealand record ~100 m.y. of Zealandia’s evolution, including development of the Hikurangi convergent margin and Alpine transform plate boundary. A comprehensive, new detrital zircon U-Pb data set (8315 analyses from 61 samples) was generated along a ~700 km transect of the East Coast Basin of New Zealand. Age distributions were analyzed and interpreted in terms of published data available for Cambrian–Cretaceous igneous and metasedimentary source terranes using a Monte Carlo mixture modeling approach. Results indicate a widespread Early Cretaceous transition in sediment source from the Gondwana interior to the Median Batholith magmatic arc prior to Late Cretaceous rifting from Antarctica. Submergence of Zealandia during a Late Cretaceous–Paleogene drift phase led to major drainage reorganization and the influx of Eastern Province sediment to the East Coast Basin. A long-lived sediment conduit that transported extraregional Western Province detritus to the south-central East Coast Basin may have developed along a structural precursor to the Alpine Fault. Marked Neogene increase of Upper Jurassic–Lower Cretaceous Torlesse Composite Terrane sediment to the central East Coast Basin resulted from exhumation of the Axial Ranges, convergence along the Hikurangi subduction margin, and concurrent development of the Alpine Fault. Concurrent influx of contemporaneous Neogene zircon in the northern East Coast Basin indicated the onset of subduction-related volcanism of the Northland–Coromandel Volcanic Arc. Middle Miocene–Pliocene exhumation and dextral translation of the Nelson region along the Alpine Fault resulted in the eastward routing of Western Province sediment to the central East Coast Basin. Finally, topography developed across the plate boundary and ultimately partitioned continental drainage of Zealandia, such that sediment from the Murihiku, Caples, and Rakaia Terranes in the Otago region was routed to the southern extent of the East Coast Basin. These results illuminate the evolution of the Zealandia continental drainage divide in response to the initiation of the Pacific-Australian plate boundary and demonstrate the power of mixture modeling and large data sets for deciphering sediment routing in dynamic tectonic environments.

INTRODUCTION

Over the past 100 m.y., Zealandia experienced profound change as it separated from Antarctica and ultimately Australia (King, 2000; Mortimer, 2004) (Fig. 1). Evidence of the Cretaceous evolution and superposed Neogene initiation of the Hikurangi subduction zone and development of the Alpine continental transform boundary are preserved in the sedimentary basins of Zealandia (Prebble, 1980; Van der Lingen and Pettinga, 1980; Browne, 1995; Barnes et al., 2005; Shane et al., 1998; Foster and Goscombe, 2013; Mortimer et al., 2014; Bland et al., 2015; Kamp et al., 2015; Adams et al., 2016). The Upper Cambrian–Lower Cretaceous metasedimentary basement of Zealandia shared a common source of sediment derived from the continental interior of Gondwana, albeit with successively younger additions from contemporaneous magmatic arc sources (e.g., Foster and Goscombe, 2013). Furthermore, Neogene exhumation and erosion associated with plate convergence has repeatedly remobilized sediment with similar composition and provenance characteristics. Consequently, provenance analysis to extract key details of the geologic evolution of Zealandia, such as the timing and topographic response to the developing plate boundary and location of the continental paleodrainage divide, requires advanced interpretative methods to constrain sediment recycling and contributions from different source terranes.

Fortunately, study of the Gondwana-derived Cambrian to Early Cretaceous basement terranes of Zealandia has been a major focus of investigation over the last several decades (Howell, 1980; Mortimer, 1994; Cawood et al., 1999; Kamp, 2001; Wandres et al., 2004; Adams et al., 2007; Adams et al., 1998, 2009a, 2009b, 2011, 2015). In particular, three successive detrital zircon U-Pb age studies have provided a framework for understanding the changes in Cretaceous provenance and paleogeography during the demise of the Mesozoic subduction zone (Adams et al., 2013a, 2013b; Adams et al., 2016). However, the evolution of the sediment source of Cenozoic basin sediments that record the...
progressive tectonic transformation of Zealandia to present-day New Zealand remains poorly constrained, despite abundant quantitative petrologic data from western Zealandia (e.g., Martin, 1990; Smale, 1996; Sutherland, 1996; Browne et al., 2005; Rotzien et al., 2018; Sloss et al., 2021; Qadri et al., 2021) and limited data from eastern Zealandia (e.g., Watters, 1990; Rivera, 2010; Strogen, 2011; Collier, 2015). Furthermore, the only published U-Pb detrital zircon ages for Neogene or younger sediments in Zealandia are spatially and temporally limited to the western-central North Island of New Zealand (e.g., Hopcroft, 2009; Shumaker, 2016; Rotzien et al., 2018).

This study focuses on the East Coast Basin system of New Zealand that crops out on both the North Island and northeastern South Island and directly overlies the metasedimentary terranes of the Torlesse Composite Terrane (Figs. 1–2). Important details of the evolution of the East Coast Basin are elusive because the Neogene deformational history of Zealandia complicates the assessment of sediment sources and routing (e.g., Rait et al., 1991; Ballance, 1993; Buret et al., 1997; Chanier et al., 1999; Kamp, 1999; King, 2000). For example, the rapidly changing tectonic regime and associated segmentation of the East Coast Basin into smaller sub-basins during Cretaceous to Neogene time (e.g., Van der Lingen, 1982) are expected to have had a major impact on sediment supply, sediment dispersal patterns, and basin geometries. Specifically, we hypothesize that identifying the basement terranes that are the primary contributors of sediment along the Pacific margin of Zealandia will provide insight into the exhumation of the Cretaceous Gondwanan magmatic arc, the spatial extent of emergent landmass during Paleogene flooding of the continent, the timing and extent of Neogene arc volcanism, and the topographic effects of the developing convergent-to-transform plate boundary on eastward sediment routing.

New detrital zircon U-Pb age distributions measured from 61 samples acquired from a 700 km latitudinal transect across the East Coast Basin of New Zealand are presented in this study. Results are compiled with existing detrital age distributions from metasedimentary basement and crystallization ages of Cretaceous magmatic rocks to produce a comprehensive database...
to interpret the late Mesozoic to Cenozoic evolution of Zealandia. We interpret this database with geologic data and by applying a mixture modeling approach (DZMix; Sundell and Saylor, 2017) to evaluate Late Cretaceous to present-day changes in sediment source and delivery routes that resulted from the disassembly of Gondwana and the subsequent Neogene development of the Hikurangi subduction margin, associated volcanic arc, and Alpine transform fault system.

**GEOLOGIC SETTING**

Modern New Zealand is the emergent portion of the Zealandia continent that rifted from Gondwana in Late Cretaceous time (King, 2000; Mortimer, 2004). Zealandia is currently situated between the westward-dipping Hikurangi subduction zone to the south and the eastward-dipping Puysegur subduction zone to the north (Fig. 1). These opposing subduction zones are kinematically linked by the dextral-slipping Alpine transform fault system. The Neogene convergent margin formed in response to southward-propagating subduction of the Pacific Plate beneath the Australian Plate and led to the subsidence that formed the East Coast Basin (Ballance, 1976; Spörli, 1978; Rait et al., 1991; Kamp, 1999; Stern et al., 2006).

**Tectonic History**

The history of Zealandia can be summarized in terms of four main tectonic stages: (1) a Permian–Cretaceous convergent margin phase during which Zealandia was positioned along the Gondwana accretionary margin; (2) a Cretaceous to early Cenozoic rift phase during the break-up of Gondwana as Zealandia rifted away from western Antarctica; (3) an early Cenozoic passive margin, drift phase during which Zealandia was largely submerged beneath the Paleo-Pacific Ocean; and (4) a second convergent margin phase that initiated in the early Neogene (ca. 23 Ma) and resulted in the development of the Hikurangi subduction zone and Alpine intracontinental transform fault (Kamp, 1986; Ballance, 1993; King, 2000; Laird and Bradshaw, 2004; Nicol et al., 2007).

The formative portion of Zealandia’s history relates primarily to stage 1. All Upper Cambrian–middle Cretaceous metasedimentary and igneous basement rocks are collectively grouped within the “Austral Superprovince” (Mortimer et al., 2014). Metasedimentary terranes were predominantly sourced from contemporaneous arc-related Upper Cambrian to middle Cretaceous rocks prior to being accreted onto the eastern margin of Gondwana beginning during the Late Devonian (Borg and DePaolo, 1991; Fig. 2). During Middle Jurassic to late Early Cretaceous time, the Gondwana convergent margin extended from New Zealand, through West Antarctica and the Antarctic Peninsula, to southern South America (Dalziel et al., 1987). Rifting of Zealandia from Antarctica ultimately occurred during the early Late Cretaceous between 100 Ma and 82 Ma (Richard et al., 1994; Spell et al., 2000; Kula et al., 2007). The “Zealandia Megasequence” incorporates all Upper Cretaceous through modern sedimentary and volcanic rocks that accumulated in a few dozen basins throughout Zealandia during and after Late Cretaceous rifting from Gondwana (Mortimer, 2004; Adams et al., 2016) (Figs. 1–2).

**Basement Rocks**

Rocks of the Austral Superprovince are contained within a series of north–south–trending metasedimentary, volcanic, and intrusive units that either formed or were accreted along the Gondwana convergent margin (Fig. 1). This assemblage is subdivided into two geologic provinces (Fig. 2). The Eastern Province is the younger and more extensive of the two and consists of pre–Cenozoic metasedimentary rocks. The Western Province is composed of lower Paleozoic terranes and includes plutonic basement rocks of Zealandia (Figs. 1–2).

**Western Province**

The Cambrian–Devonian Takaka and Ordovician–Devonian Buller Terranes are the westernmost components of the Western Province and are the oldest metasedimentary units of Zealandia (Fig. 1; Mortimer, 2004). Although they are compositionally different, both terranes received sediment carrying detrital zircon recycled from the upper Neoproterozoic–Silurian interior of Gondwana.
and the Archean–Paleoproterozoic and meso–lower Neoproterozoic rocks of Rodinia (Fig. 3; Table S2; Nebel-Johnson et al., 2011; Adams et al., 2015).

The Tuhua Intrusives are primarily exposed in the Fiordland and Nelson areas of the South Island (Mortimer et al., 2014) and consist of the Karamea and Median Batholith plutonic assemblages (Fig. 2). The Karamea Batholith is part of an extensive Middle–Late Devonian belt of magmatic activity along, or close to, the Paleo-Pacific margin of Gondwana. The Median Batholith is the primary unit of the Tuhua Intrusives discussed in this study and comprises the easternmost Western Province (Mortimer et al., 1999). Notable intrusive units include the Triassic–Jurassic Darran Suite and Lower Cretaceous Separation Point Suite, which likely supplied sediment to the younger units of the Torlesse Composite Terrane (Adams et al., 2016).

**Eastern Province**

The Permian–Cretaceous Brook Street, Murihiku, and Dun Mountain–Maitai are the oldest units of the Eastern Province of Zealandia (Figs. 1 and 2). Individually, each terrane was originally located at different latitudes along the Gondwana margin and translated to its current position during accretion (Adams et al., 2002; Adams et al., 2009a). Collectively, the Brook Street, Murihiku, and Dun Mountain–Maitai Terranes are regarded to represent different elements of an arc-to-trench setting (Adams et al., 2002; Campbell et al., 2020). The Permian–Triassic Caples Terrane is composed of highly imbricated, deep-water, andesitic sandstone that is interpreted to represent a trench-slope basin adjacent to an island arc that was incorporated into the accretionary wedge (Mortimer, 2004). Conversely, the Permian–Jurassic Waipapa Terrane is composed of mostly volcaniclastic sediments that accumulated in the complex accretionary wedge on the Gondwana margin outboard of the Murihiku Terrane (Black et al., 1993).

---

1Supplemental Material. Table S1: Data sources for composite basement terranes. Table S2: Relative proportions of age fractions for composite basement terranes. Table S3: U-Th-Pb isotopic composition of detrital zircon analyzed at the University of Arizona LaserChron Center. Table S4: U-Th-Pb isotopic composition of detrital zircon analyzed at the University California, Santa Cruz. Table S5: Relative proportions of age fractions for Cenozoic East Coast Basin cover stratigraphy. Table S6: Relative proportions of age fractions for Cretaceous East Coast Basin cover stratigraphy. Table S7: Mixture modeling results of detrital zircon samples. Figure S1: Map of all samples from the basement terrane and cover stratigraphy with detrital zircon U–Pb ages. File S1: Systematic analysis of mixture modeling results. Please visit https://doi.org/10.1130/GEOS.S.17290643 to access the supplemental material, and contact editing@geosociety.org with any questions.
Finally, the Torlesse Composite Terrane was deposited in deep-water submarine fans outboard of the Gondwana trench-slope basin that were subsequently accreted onto the margin (Mortimer, 2004). The Torlesse Composite Terrane underpins the East Coast basin and is divided into three tectonostratigraphic domains: the Permian–Triassic Rakaia Terrane, Jurassic Kaweka Terrane, and Lower Cretaceous Pahau Terrane. The Rakaia Terrane was dominantly derived from Permian granitoids, with additional Precambrian recycled sediment from the New England Orogen of northeastern Australia (Adams et al., 2002, 2007). The Kaweka Terrane shares a similar source history as the Rakaia Terrane with the addition of contemporaneous Jurassic input from the Median Batholith (Fig. 1; Adams et al., 2009b, 2011). Similarly, the Pahau Terrane (includes both Omaio and Waioeka petrofacies; see Adams et al., 2013b) received additional contemporaneous Early Cretaceous sedimentary input from the Separation Point plutonic suite of the Median Batholith.

**East Coast Basin**

The East Coast Basin presently extends along the full 700 km length of the eastern margin of the North Island. In the west it depositionally overlies Torlesse Composite Terrane metasediments exposed within the Axial Ranges (Figs. 1 and 4). The active Hikurangi subduction trench forms the eastern boundary of the basin (Fig. 1). Most of the basin resides offshore in an active forearc setting. A series of discrete, weakly to moderately confined, fault-bounded sub basins can be distinguished throughout the East Coast Basin. These elongate trench-slope features tend to be ca. 30 km long and are separated by thrust-fault controlled ridges that developed parallel to the subduction margin (Neef, 1992).

The northeastern portion of the South Island of New Zealand is considered to be the southern limit of the East Coast Basin (Fig. 1). This area evolved rapidly during development of the Neogene Alpine transform faults that link the eastward-dipping Puysegur subduction zone to the south with the Hikurangi subduction zone in the north. The Marlborough Fault System (Fig. 1) consists of four primary faults that bound uplifted blocks of Upper Jurassic–Lower Cretaceous Torlesse Composite Terrane (Van Dissen and Yeats, 1991). These faults initiated through thrusting during early Miocene plate convergence and were subsequently rotated through oblique dextral-slip into their current positions (Knuepfer, 1992; Holt and Haines, 1995; Randall et al., 2011). Presently, the Upper Cretaceous through upper Neogene cover succession is preserved primarily within fault-bounding valleys and along the northeast and eastern coastal areas of South Island. Several studies have addressed detailed variations of the non-marine to deep-water lithofacies in Cretaceous (e.g., Gardiner and Hall, 2021) and local Neogene depocenters (e.g., Lewis et al., 1980; Maxwell, 1990; Browne, 1995).

High sediment accumulation throughout the East Coast Basin preserves a record of the Neogene tectonic evolution as sediment sources west of the Alpine Fault have been displaced northeastward over time. Interpretations of this history are complicated, however, by several factors. Neogene dextral shearing, tectonic uplift, and erosion have stripped away much of the late Mesozoic through Cenozoic sedimentological record across the interior of New Zealand. The resulting shearing has produced moderate to extreme (>90°) Neogene clockwise rotation within both the East Coast Basin and the major fault blocks of the Marlborough Fault System (Roberts, 1992; Little and Roberts, 1997; King, 2000; Hall et al., 2004; Randall et al., 2011). These complications have greatly hindered efforts to palinspastically restore the East Coast region (e.g., Walcott, 1987; Ballance, 1993; King, 2000).

**METHODS**

**Sampling**

To best characterize variations in provenance along the continental margin of the East Coast Basin, the area was divided into 12 geographic segments from north to south to isolate documented Neogene trench-slope basins similar to those presently observed within the modern offshore East Coast Basin (Fig. 4). These include three sub-basins in the Raukumara region (Field and Urvuski et al., 1997; Burgreen and Graham, 2014); two sub-basins in the Hawke Bay region (Van der Lingen and Pettinga, 1980; Nieminski and Graham, 2017); two in the Wairarapa region (Field and Urvuski et al., 1997; Bailleul et al., 2007, 2013); and one in the Wellington area (Fig. 4).

The South Island portion of the East Coast Basin comprises four segments that are subdivided by the three major faults (Fig. 4). While these fault-bounded segments were presumed to have shared depositional histories, the significant late Neogene rotations experienced by the Marlborough Fault System may have obscured original depositional relationships (Randall et al., 2011). In general, upper Miocene through Pliocene stratigraphy is contiguous throughout the North Marlborough segment (upper Wairau and Awatere valleys). Upper Oligocene through middle Miocene stratigraphy is preserved exclusively within the South Marlborough segment, which lies primarily east of the Clarence Fault. Conversely, most of the entire Cretaceous–Pliocene sedimentary succession is preserved throughout the northern Canterbury region.

In each segment, an effort was made to collect sandstone samples for detrital zircon U-Pb geochronology from four depositional age divisions: (1) lower Miocene (23–16 Ma); (2) middle Miocene (16–11.6 Ma); (3) upper Miocene (11.6–5.3 Ma); and (4) Pliocene (5.3–2.6 Ma). In total, 50 Neogene samples were collected along the margin. These were supplemented by two Paleogene samples collected in the North Hawke Bay segment and four Paleogene samples acquired throughout the South Island study area. Four modern sediment samples were collected at the outlets of major river catchments throughout the Marlborough and Canterbury regions. Finally, one new sample was included from the Kaweka Terrane in the Hawke Bay region of the North Island. Published U-Pb data of Upper Cretaceous (13 samples; Adams et al., 2013b, 2016) and Paleogene stratigraphy (one sample; Hopcroft, 2009) were also included in this study.
Published detrital zircon U-Pb data were compiled from Paleozoic–Mesozoic basement terranes throughout New Zealand (Fig. 3) to understand their potential relevance as sediment source areas. The database includes 54 detrital samples from the North Island and 62 samples from the South Island from dominantly metasedimentary basement (Cawood et al., 1999; Pickard et al., 2000; Wandres et al., 2004; Adams et al., 2007, 2009b, 2011, 2013b, 2015; Shumaker, 2016). In addition, igneous zircon U-Pb crystallization ages were compiled from the Median Batholith and associated igneous suites (i.e., Tuhua Intrusives) (Kimbrough et al., 1994; Muir et al., 1994, 1997; Waight et al., 1997; Tulloch and Kimbrough, 2003; Sagar et al., 2016). Tables 1 and 2 provide the location and stratigraphic age of Cenozoic and Cretaceous samples, respectively, and Table S1 (see footnote 1) presents a comprehensive list of all basement terrane samples compiled for this study.

Detrital Zircon U-Pb Geochronology

Detrital zircon grains were concentrated from 2 kg to 5 kg of sandstone per sample at the Stanford University Earth Materials Laboratory, Stanford, California, USA, following standard crushing, sizing, hydrodynamic, magnetic,
| Sample | Age | Segment | Formation (Map Unit) | Latitude (°S) | Longitude (°E) | Source |
|--------|-----|---------|---------------------|--------------|---------------|--------|
| NN-TB11 | L. Miocene | N. Raukumara | Tokomaru Stt. (Mmk) | 38.24214 | 178.16093 | This Study |
| NN-TB13 | L. Miocene | N. Raukumara | Tokomaru Stt. (Mmk) | 38.28600 | 178.15971 | This Study |
| NN-TB14 | L. Miocene | N. Raukumara | Tokomaru Stt. (Mmk) | 38.34721 | 178.24320 | This Study |
| NN-TB10 | E. Pliocene | N. Raukumara | Mangaiheia Grp. undiff. sst. (Pms) | 38.30949 | 178.08536 | This Study |
| NN-TK12 | L. Miocene | N. Raukumara | Areoma Stt. (Mlr) | 38.29069 | 177.99787 | This Study |
| NN-NG09 | E. Pliocene | Gisborne | Mangaiheia Grp. undiff. sst. (Pms) | 38.60492 | 177.80782 | This Study |
| NN-NG07 | M. Miocene | Gisborne | TunauFs. (Mu) | 38.56575 | 177.61688 | This Study |
| NN-NG03 | E. Miocene | Gisborne | Tolaga Grp. undiff. (Mia/Ml) | 38.53023 | 177.54515 | This Study |
| NN-NG05 | L. Miocene | Gisborne | Tolaga Group undifferentd (Mia/Ml) | 38.59053 | 177.64501 | This Study |
| NN-NU19 | M. Miocene | S. Raukumara | TunauFs. (Mu) | 38.82949 | 177.72022 | This Study |
| NN-NU18 | L. Miocene | S. Raukumara | Makaretu Fs. (Mia) | 38.83530 | 177.67599 | This Study |
| NN-NU24 | E. Pliocene | S. Raukumara | Mangaiheia Grp. undiff. sst. (Pms) | 38.66665 | 177.76878 | This Study |
| NN-NU16 | M. Miocene | S. Raukumara | TunauFs. (Mu) | 38.97305 | 177.68712 | This Study |
| NN-NU39 | M. Miocene | S. Raukumara | TunauFs. (Mu) | 39.07329 | 177.82830 | This Study |
| NN-MP82 | E. Miocene | N. Hawke's Bay | Tolaga Grp. undiff. sst. (Ml) | 39.14520 | 177.95221 | This Study |
| NN-MP31 | Eocene–Oligocene | N. Hawke's Bay | Weber/Wanstead Fs. (Egw–Ogw) | 39.14963 | 177.94783 | This Study |
| NN-MP33 | Paleocene–Eocene | N. Hawke's Bay | Whangai/Wanstead Fs. (Kw–Egw) | 39.15886 | 177.94194 | This Study |
| NN-MP79 | L. Miocene | N. Hawke's Bay | Tolaga Grp. undiff. (Ml) | 39.19520 | 177.92126 | This Study |
| NN-TH36 | L. Miocene | S. Hawke's Bay | TunauFs. (Mu) | 39.13218 | 176.60733 | This Study |
| NN-TP37 | E. Pliocene | S. Hawke's Bay | lower Mangaiheia Grp. (Pmz) | 39.25529 | 176.69536 | This Study |
| NN-HA43 | L. Miocene | S. Hawke's Bay | Tolaga Grp. undiff. (Ml) | 39.74548 | 176.94624 | This Study |
| NN-HA42 | E. Pliocene | S. Hawke's Bay | lower Mangaiheia Grp. (Pmz) | 39.74891 | 176.93471 | This Study |
| NN-WE51 | L. Miocene | N. Wairarapa | Palliser Grp. undiff. (Ml) | 40.42584 | 176.41741 | This Study |
| NN-WE54 | M. Miocene | N. Wairarapa | Palliser Grp. undiff. (Ml) | 40.33241 | 176.41891 | This Study |
| NN-CP41 | E. Miocene | N. Wairarapa | Whakataki Fs. (Ml) | 40.86506 | 176.23288 | This Study |
| NN-BF52 | E. Pliocene | S. Wairarapa | Oonke Fs. (Pea) | 41.06481 | 176.03597 | This Study |
| NN-CP56 | E. Miocene | S. Wairarapa | Whakataki Fs. (Mw) | 40.95927 | 175.82411 | This Study |
| NN-BF54 | L. Miocene | S. Wairarapa | Palliser Grp. undiff. (Ml) | 41.03986 | 175.83062 | This Study |
| NN-BF53 | M. Miocene | S. Wairarapa | Palliser Grp. undiff. (Ml) | 41.07536 | 175.87657 | This Study |
| NN-PA86 | L. Miocene | Wellington | Palliser and Soren Grp. (Msb) | 41.31349 | 175.47276 | This Study |
| NN-PA85 | E. Pliocene | Wellington | Oonke Fs. (Pea) | 41.56642 | 175.37878 | This Study |
| BSH-15 | Eocene–Eocene | Wellington | Otaihanga Outlier | 40.91386 | 175.03899 | Hopcroft, 2009 |
| JG-MB3 | Paleocene–Eocene | Cape Campbell | Amuri Fs. (KP2) | 41.72488 | 174.22133 | This Study |
| JG-LP6 | L. Miocene | Cape Campbell | Awarere Grp. equivalent (Mam) | 41.01811 | 174.20494 | This Study |
| JG-WR49 | Modern | N. Marlborough | Wairau River sediment | 41.45850 | 173.97304 | This Study |
| JG-AW55 | Modern | N. Marlborough | Awarere River sediment | 41.62568 | 174.12695 | This Study |
| JG-WB50 | L. Miocene | N. Marlborough | Upton Conglomerate (Mau) | 41.52002 | 174.13128 | This Study |
| JG-AW4 | E. Pliocene | N. Marlborough | Starborough Fs. (Pas) | 41.60357 | 174.08022 | This Study |
| JG-WD23 | E. Pliocene | N. Marlborough | Pliocene unnamed | 41.83423 | 174.08285 | This Study |
| JG-AW58 | M. Miocene | N. Marlborough | Medway Fs. (Mam) | 41.75833 | 173.92650 | This Study |
| JG-AW27 | L. Miocene | N. Marlborough | Upton Fs.---Graded Beds (Mau) | 41.76217 | 173.86730 | This Study |
| JG-AW29 | M. Miocene | N. Marlborough | Medway Fs. (Mam) | 41.80985 | 173.85680 | This Study |
| JG-AW32 | L. Miocene | N. Marlborough | Upton Fs. (Mau) | 41.81343 | 173.75222 | This Study |
| JG-AW31 | L. Miocene | N. Marlborough | Upton Fs. (Mau) | 41.81197 | 173.74853 | This Study |
| JG-CL40 | Modern | S. Marlborough | Clarence River sediment | 42.15997 | 173.90815 | This Study |
| JG-WR48 | Pliocene–Pleistocene | S. Marlborough | Hillderson Gravel (Ph) | 41.53468 | 173.64617 | This Study |
| JG-WR46 | L. Miocene | S. Marlborough | Undifferentiated | 41.62990 | 173.66097 | This Study |
| JG-DM15 | M. Miocene | S. Marlborough | Waima Fs.---Erica Burns Beds (Mnw) | 42.04303 | 173.94962 | This Study |
| JG-DM11 | E. Miocene | S. Marlborough | Waima Grp.---Great Marlborough Congl. (Mnw) | 42.04784 | 173.95151 | This Study |
| JG-CL90 | Oligocene–E. Miocene | S. Marlborough | Waima Fs.---Basal Calcareous Stt. (Mnw) | 41.95864 | 173.78737 | This Study |
| JG-CL21 | E. Miocene | S. Marlborough | Waima Fs.---Great Marlborough Congl. (Mnw) | 42.02488 | 173.70290 | This Study |
| JG-CL22 | E. Miocene | S. Marlborough | Waima Fs.---Stlstone (Mnw) | 42.02540 | 173.70308 | This Study |
| JG-CL39 | E. Miocene | S. Marlborough | Pliocene Unnamed | 42.16040 | 173.90760 | This Study |

(continued)
TABLE 1. CENOZOIC DETRITAL ZIRCON SAMPLE LOCATIONS AND SOURCES (continued)

| Sample | Age         | Segment | Formation (Map Unit) | Latitude ('S) | Longitude ('E) | Source                  |
|--------|-------------|---------|----------------------|---------------|----------------|-------------------------|
| JG-KA19| Oligocene–E. Miocene | S. Marlborough | Waiau-Uwha River sediment | 42.8628 | 173.68803 | This Study               |
| JG-CB38| E. Miocene  | S. Marlborough | Waipara Greensand (E) | 42.38144 | 173.50429 | This Study               |
| JG-WU82| Modern      | N. Canterbury | Mt. Brown Fm. (Mn) | 42.77020 | 173.35905 | This Study               |
| JG-LT88| E. Miocene  | N. Canterbury | Mt. Brown Fm. (Mn) | 42.77020 | 173.35905 | This Study               |
| JG-GW98| L. Miocene  | N. Canterbury | Mt. Brown Fm. (Mn) | 42.86555 | 173.30880 | This Study               |
| JG-GB70| M. Miocene  | N. Canterbury | Mt. Brown Fm. (Mn) | 42.86555 | 173.30880 | This Study               |
| JG-GB71| E. Miocene  | N. Canterbury | Mt. Brown Fm. (Mn) | 42.86442 | 173.30933 | This Study               |
| JG-GB75| Eocene      | N. Canterbury | Waipara Greensand (E) | 42.87412 | 173.30988 | This Study               |

Note: Coordinates are in WGS84. E.—early; L.—late; Cret.—Cretaceous; Jur.—Jurassic; Tri.—Triassic; Grp.—Group; Fm.—Formation; Sst.—Sandstone; Silt.—Siltstone; Congl.—Conglomerate. Geologic map units are from the QMAP series (Mazengetar and Soeden, 2000; Lee and Begg, 2002a, 2002b; Rattenbury et al., 2006; Forsyth et al., 2008; Leonard et al., 2010; Lee et al., 2011).
and density separation techniques. Recovered zircon tended to be fine-grained (<150 µm) and were characterized with backscatter electron (BSE) images. About 100–300 grains were analyzed per sample with a 15–30 µm beam, depending on average grain size, using single-collector laser ablation–inductively coupled plasma–mass spectrometry (LA–ICP–MS). In selecting candidate grains for analysis, an effort was made to avoid bias related to grain size and morphology. Where discernable in BSE images, potentially xenocrystic cores were avoided. About two-thirds of the samples were analyzed at the University of Arizona LaserChron Center, Tucson, Arizona, USA, while the other third were analyzed at the University of California, Santa Cruz, USA (Tables S3 and S4; see footnote 1).

Zircon grains analyzed at the University of California, Santa Cruz, were potted in epoxy at Stanford University with fragments of primary zircon standards R33 and/or Temora2 (419.3 Ma; 416.8 Ma; Black et al., 2004) and secondary standard Plesovice (337.1 Ma; Síláma et al., 2008) to calibrate downhole fractionation and instrument drift. Mounts were sectioned with 1600 grit paper and polished with 1 µm poly crystalline diamond. Samples run at the University of Arizona LaserChron Center were mounted on location with fragments of primary FC–Z5 (1099 Ma; Paces and Miller, 1993), Sri Lanka SL-Mix and SL-F (563.5 Ma; Gehrels et al., 2008), and secondary R33 (419.3 Ma; Black et al., 2004) standard zircon.

Analyses conducted at the University of Arizona LaserChron Center were reduced following standard methods (after Gehrels et al., 2008). The measured U-Pb ages were filtered using the following criteria: $^{206}_{238}$Pb$^{206}$Pb >200, U-Pb discordance <20%, and maximum reverse discordance <5%. U concentration and U/Th ratio were calibrated relative to the Sri Lanka zircon standard. Data reduction for analyses from the University of California, Santa Cruz, Lab was performed using iolite v2.5 with the U_Pb_Geochronology3 data reduction scheme (Nieminski, 2017). Age results were filtered based on age precision (>10%), with discordance (>30%), reverse discordance (>5%), and common $^{206}$Pb content (>200 counts per second). For both data sets, ages are based on common $^{206}$Pb-corrected $^{207}$Pb/$^{206}$Pb if older than 800 Ma or common $^{206}$Pb-corrected $^{207}$Pb/$^{206}$U ages if younger than 800 Ma or common $^{206}$Pb-corrected $^{207}$Pb/$^{206}$Pb if older than 800 Ma.

All interpretations of age maxima in the measured U-Pb age distributions are based on features defined by two or more grains (Dickinson and Gehrels, 2009). Probability density plots (PDPs) of the U-Pb age distributions were calculated using Isoplot 3.7 in Microsoft Excel (Ludwig, 2008). Cumulative distribution plots (CDPs) were calculated using open-source Excel programs available from the University of Arizona LaserChron Center.

Mixture Modeling

A mixing model (DZmix; Sundell and Saylor, 2017) was used to quantitatively compare the compiled detrital zircon U-Pb age data from the basement terranes and igneous rocks to those of East Coast Basin samples (Fig. 5A). In this method, an inverse Monte Carlo approach is used to scale each input source age distribution using a random set of percent contributions that sum to 100% to give a single mixed distribution. The simulation was repeated 100,000 times for each basin sample to statistically ensure that all of the possible mixtures were tested. These mixtures were then compared to the individual basin sample using the Kuiper-V statistic, Kolmogorov–Smirnov (KS) D statistic, and cross-correlation coefficient ($R^2$) independently (Fig. 5B). The top 0.1% best fit trials (100 mixtures) from each statistical method of comparison were then used to calculate the mean relative contribution with 1 uncertainty of each potential source terrane (Fig. 5C). We report the relative contributions of each source using all three statistical methods of inter-sample comparison in Table S7 (see footnote 1). The use of these statistics resulted in varying relative contributions of provenance groups but consistently discriminated between major contributing and non-contributing source areas. In this study, we relied upon the cross-correlation coefficient as the principle basis for source area interpretations because this metric is the most sensitive to the degree of similarity between data sets with a large range of sample sizes (Saylor and Sundell, 2016).

Because it is unknown a priori where the continental drainage divide was located as a function of geologic time, both Western and Eastern Province Terranes were generally considered as candidates in the mixing model process for all time intervals. The full compilation of basement age distributions was used for mixture modeling sources situated west of the East Coast Basin (Fig. 1). However, we used subsets of North and South Island data in cases where basement source candidates locally underlie the basin (i.e., the North Island Caples and Torlesse Composite Terranes were used in modeling North Island samples). We did so because the basement sources tend to exhibit latitudinal variation in U-Pb age distributions (Fig. 6), and we consider that the above strategy allowed for better characterization of local sources. Cenozoic (65–0 Ma) U-Pb zircon ages from basin samples were not considered in the mixing model because all basement age distributions in the database were measured from rocks that formed during Cambrian–Cretaceous time.

RESULTS

Detrital Zircon U-Pb Age Distributions

Figure 6 presents a compilation of normalized probability and cumulative detrital zircon U-Pb age distributions from previously published results of potential sediment sources (Adams et al., 2007, 2009a, 2009b, 2011, 2013b, 2016; Cawood et al., 1999; Pickard et al., 2000; Wandres et al., 2004). Figure 7 displays equivalent results for the newly generated Cenozoic–modern detrital zircon age distributions presented in this study (8315 total analyses from 61 samples). The age distributions in Figures 6 and 7 are binned into 11 age bands that are intended to correspond to geologically significant episodes of plutonic, volcanic, and/or sedimentary source activity (Fig. 3; Tables S5 and S6; see footnote 1). From most to least abundant, these include seven age bands that...
reflect age maxima yielded by batholithic and/or metasedimentary terranes: Permian–Triassic (299–201 Ma), Devonian–Carboniferous (419–299 Ma), Early Cretaceous (145–100 Ma), Early Jurassic (201–174 Ma), Late–Middle Jurassic (174–145 Ma), minor Late Cretaceous–early Paleogene (100–34 Ma), and late Paleogene–Neogene (34–2.6 Ma) in select regions. The additional four age bands representing older time intervals that were significant in the assembly of Gondwana or Rodinia include: late Neoproterozoic–Silurian (720–419 Ma), Mesoproterozoic (1600–1000 Ma), early Neoproterozoic (1000–720 Ma), and Archean–Paleoproterozoic (4500–1600 Ma).

Figure 8 summarizes the percentage of zircon in different age bins both spatially and in time (Cretaceous–Pliocene) along the 700 km of the eastern Zealandia margin that was the focus of this study. Detrital zircon U-Pb age distributions measured from Cenozoic East Coast Basin sediments show that all samples share a common attribute in that they all tend to be dominated by Permian–Triassic zircon (299–201 Ma; 31–59%; mean 44%; Fig. 7). Lower Cretaceous (145–100 Ma; 0–32%; mean 9%) zircon are well-represented in most samples but are entirely absent in seven samples. Lower Jurassic (201–174 Ma; 1–19%; mean 7%) and Middle–Upper Jurassic (174–145 Ma; 0–11%; mean 3%)
Figure 6. Cumulative and normalized probability distributions of detrital zircon U-Pb ages were compiled from previously published data sets for local Permian–Lower Cretaceous accreted metasedimentary terranes and Upper Cretaceous cover stratigraphy within margin-parallel geographic segments. Cumulative distributions are colored based on the north-south arrangement of segments along the East Coast Basin. Number of grains (n) analyzed is displayed below sample names. Samples are compiled from previously published data sets of Adams et al. (2007, 2009b, 2011, 2013b, 2016); Cawood et al. (1999); Pickard et al. (2000); and Wandres et al. (2004). Gray vertical bars indicate the general depositional age range of the samples.
Figure 7. Cumulative and normalized probability distributions of detrital zircon U-Pb ages for Cenozoic stratigraphy within margin-parallel segments are shown. Cumulative distributions are colored based on the north-south arrangement of segments along the East Coast Basin. Number of grains (n) analyzed is displayed below sample names, which have prefixes that indicate the source of data: BSH—Hopcroft (2009); JG—this study, South Island; and NN—this study, North Island. Gray vertical bars indicate the general depositional age range of the samples.
Figure 8. Spatial distribution of relative detrital zircon age fractions in sandstone samples from Permian–Cretaceous Torlesse Composite Terrane (Austral Superprovince) and Upper Cretaceous–Pliocene cover stratigraphy (Zealandia Megasequence) of the East Coast Basin is shown. Margin-parallel distances (y-axis) are measured south-to-north and parallel to the modern margin (see Fig. 4). Sample locations are indicated by a gray line and sample name (see Figs. 6–7 for probability density plots). Gray, italicized sample labels for Pahau Terrane denote later stage units (displayed separately in Fig. 9). Age fractions are binned by geologic periods with distinct magmatic and volcanic events and are interpolated among data locations. White areas indicate where there is a gap in data or the stratigraphy is not exposed along that segment of the margin. Regional abbreviations: R—Raukumara, HB—Hawke Bay, WR—Wairarapa, W—Wellington, CC—Cape Campbell, M—Marlborough, and C—Canterbury.
Ubiquitous U-Pb Detrital Zircon Age Fractions and Their Origins

As shown in Figure 8, Permian–Triassic (259–201 Ma) zircon represents the most abundant age fraction (20–80%; mean 33%) shared by all basement terranes of the Eastern Province. The only exceptions are the arc-sourced Brook Street and Dun Mountain Terranes (Fig. 3). Permian–Triassic zircon is thought to have been ultimately derived from batholiths in the New England Orogen of northeastern Australia (Adams et al., 2009b), although plutons of this age also occur in the formerly adjacent Ford Ranges of western Antarctica (Richard et al., 1994). Regardless of its primary source, Permian–Triassic zircon appears to have been extensively recycled into progressively younger, latest Mesozoic and Cenozoic sedimentary basins. Thus, it also represents a prominent and relatively uniform component throughout the East Coast Basin stratigraphy (Figs. 3 and 7). Similarly, the Devonian–Carboniferous (419–299 Ma) age fraction is ubiquitous in moderate amounts (8–15%) in data compiled for all arc-derived Eastern Province metasedimentary terranes (Fig. 3). Cenozoic samples do not exceed 16% on the North Island and 20% on the South Island (mean 11%) in Devonian–Carboniferous age zircon.

Upper Neoproterozoic–Silurian (720–419 Ma) zircon was created during the assembly of Gondwana. Zircon of this age is the primary constituent within age distributions from the Buller (45%) and Takaka (48%) Terranes (Fig. 3) of the Western Province (Fig. 4; Adams et al., 2015). Upper Neoproterozoic–Silurian zircon is present in variable to trace amounts in younger metasedimentary rocks (Adams et al., 2013b). Note that the mean relative abundance of Upper Neoproterozoic–Silurian zircon in the Torlesse Composite Terrane (13–24%) is substantial relative to the mean composition of most other basement terranes (1–9% excluding CROM1 of the Caples Terrane). In comparison, the abundance of Upper Neoproterozoic–Silurian zircon in Cenozoic samples ranges from 8% to 25% (33% in the lower Miocene sample AW27 of northern Marlborough).

Distinctive U-Pb Detrital Zircon Age Fractions

More distinctive age fractions in Cenozoic basin sediments that are useful for differentiating among otherwise similar potential source terranes span Jurassic to Neogene time. These include the Lower Cretaceous (145–100 Ma) zircon fraction that is present in prominent quantities (mean 27%) only in the Pahau Terrane (Fig. 3). Lower Cretaceous zircon present in Cenozoic East Coast Basin strata must therefore have been derived directly from erosion of the Western Province Median Batholith (i.e., Separation Point Suite; Mortimer et al., 1999) and/or recycled from the contemporaneous Eastern Province Pahau Terrane (Fig. 1). Consequently, the Early Cretaceous age fraction provides the most leverage for determining the provenance of East Coast Basin samples. Specifically, the presence or absence of 145–100 Ma zircon in Cenozoic detrital age fractions either confirms or precludes these sediment sources.

Lower Jurassic (201–174 Ma) detrital zircon occurs most prominently in the Murihiku (mean 15%), Waipapa (mean 10%), and Kaweka (mean 9%; max 21%) Terranes but is also present in the Pahau Terranes at lower quantities (mean 3–5%). Middle–Upper Jurassic (174–145 Ma) zircon that may have been initially sourced from the Darran Suite of the Median Batholith (Muir et al., 1998) is most prominent in the Waipapa (mean 21%) and Murihiku (mean 15%) Terranes. Alternatively, it is only a minor component of the Kaweka (2.8%) and Pahau (3.6%) Terranes. The significant abundance of Lower and Middle–Upper Jurassic zircon fractions in East Coast Basin samples can thus be attributed to erosion of the Waipapa and Murihiku Terranes.

The oldest Archean–lower Proterozoic (4500–1600 Ma) and Mesoproterozoic (1600–1000 Ma) detrital zircon is prominently detected only in age distributions from the Buller and Takaka Terranes (cumulative mean 36%). The Caples and Torlesse Composite Terranes yield only minor proportions of Archean–early Proterozoic (5%) and Mesoproterozoic (2%) zircon. Therefore, these oldest age fractions provide leverage in identifying Buller-Takaka contribution to Cenozoic strata for samples that have any significant (>5%) proportion of Archean–lower Proterozoic and Mesoproterozoic grains.

Finally, contemporaneous middle to late Cenozoic (34–2.6 Ma) zircon provides the most distinguishable age fraction that indicates derivation from the Ruakumoko Volcanic Group on the North Island (Mortimer et al., 2014). In particular, the appearance of 34–2.6 Ma zircon likely records the initiation and migration of the Northland–Coromandel Volcanic Arc, which has subalkaline arc-related rocks as old as 23 Ma (Mortimer et al., 2018) and produced rhyolitic volcanism beginning at ca. 12 Ma (Carter et al., 2003).

Mixture Modeling

Figure 9 illustrates the spatial and temporal variations in the best-fit proportions of candidate source terranes obtained when modeling sediment sources of the East Coast Basin. Note that samples of the Pahau Terrane of the Torlesse Composite Terrane are also modeled. When a cross-correlation coefficient of
Figure 9. Spatial distribution of relative contribution of source terranes modeled using the method of Sundell and Saylor (2017) is shown. Margin-parallel distances (y-axis) are measured south-to-north and parallel to the modern margin (see Fig. 4). Sample locations are indicated by a gray line and sample name (see Figs. 6–7 for probability density plots). White areas indicate where there is a gap in data or the stratigraphy is not exposed along that segment of the margin. Regional abbreviations: R—Raukumara, HB—Hawke Bay, WR—Wairarapa, W—Wellington, CC—Cape Campbell, M—Marlborough, and C—Canterbury.

Western Province
- Buller & Takaka
- Median Batholith

Eastern Province
- Brook Street
- Munihiku
- Waipapa
- Caples
- Rakaia
- Kaweka
- Pahau

Torlesse Composite
- no data
unity is calculated for the mixture model and the measured age distribution, the modeled mixture completely reproduces the sample age distribution. Most of the mixture models calculated for Cenozoic strata yield a cross-correlation coefficient >0.7 (mean 0.87) for the top 0.1% of attempted model fits. This outcome indicates that, in general, the age distribution of the East Coast Basin sample is being adequately reproduced by mixture modeling. The mixing model calculations most powerfully indicate which potential source regions are unlikely to have contributed to the observed age distribution. Similarly, when the potential source of one age dominates all others, it should be considered a necessary contributor to the measured age distribution. However, given the degrees of freedom available, model results that indicate that many potential sources contributed in sub-equal proportions reduces the confidence that any one of these potential sources was necessarily a contributor to the age distribution measured.

The only Cenozoic samples that yield anomalously low correlation coefficients are two Paleogene samples from the South Island \( (R^2 = 0.63 \) and 0.69). The mean cross-correlation coefficient of the Upper Cretaceous models is 0.70, with a third of the samples less than 0.7, and the mean value for the Pahau Terrane models is 0.62 with over half of the models having poor fits. Poor model fits for the Cretaceous stratigraphy and underlying Pahau Terrane accretionary complex likely indicate that at least one important source terrane is missing from the model, such as unidentified sources within the Gondwanan interior that remained on the western side of the rifted margin. However, the poor cross-correlation coefficients for Cretaceous rocks could partly be due to under-sampling of the age distribution in previous studies \( (n = 31–95 \) grains; Fig. 6).

The mixture models of East Coast Basin samples successfully identify sediment sources that can be qualitatively predicted on the basis of the unique attributes of the age distributions. For example, samples with abundant Lower Cretaceous zircon are modeled to have Median Batholith or Pahau Terrane contributions, and samples with elevated oldest age fractions are modeled to have contributions from the Buller-Takaka Terranes (compare Figs. 8 and 9). Remarkably, the model additionally discerns contributions from source terranes that share generally similar age fractions but with varying proportions or subtle age peaks that are otherwise difficult to compare visually \( \text{[e.g., Kaweka, Waipapa, and Murihiku Terranes; Fig. 3]}. Furthermore, source terranes that are geographically located adjacent to one another \( \text{[e.g., Western Province versus Eastern Province terranes; Fig. 1]}) and would likely have been exhumed at similar times tend to be modeled in relative abundance together \( \text{(Fig. 9)\text{. These modeled results are geologically consistent even though no spatial considerations were included in the Monte Carlo simulations. A complete systematic analysis of mixture modeling results can be found in Gooley (2020) and is included in File S1 (see footnote 1).}

### Modern River Tests of Mixture Modeling

The mixture modeling approach for provenance interpretation was further evaluated by comparing modeled percent contributions of source terrane contributions for modern river sediment to the distribution of basement terranes exposed within the river catchments \( \text{(Fig. 10)\text{. The four river samples from the South Island (Fig. 4) have catchments that are controlled by topography associated with the Marlborough Fault System and Alpine Fault. The Cretaceous through Pliocene stratigraphy has been mostly removed from the underlying Torlesse Composite Terrane and is preferentially preserved within the fault-bound river valleys and along the coastal regions.}

The Wairau River runs along the northern extent of the Alpine Fault \( \text{(locally the Wairau Fault), and its catchment covers both sides of the plate boundary. As a result, the catchment contains the most diverse basement assemblage, including all units of the Torlesse Composite Terrane to the south and the Waipapa, Caples, Rakaia, and Dun Mountain Terranes to the north. In contrast, the Awatere and Clarence Rivers follow faults of the same name, and their catchments almost entirely sample the Pahau Terrane, although the Kaweka and Rakaia Terranes are exposed in the uppermost reaches of the Clarence catchment. Additionally, middle to Upper Cretaceous intrusive (Tapuaenuku Plutonic Complex) and volcanic rocks are locally present within these drainages \( \text{(Fig. 10A)\text{. The crystallization ages of these igneous rocks overlap with the youngest pulse of magmatism in the Tuhua Intrusives of the Western Province \( \text{(ca. 101–90 Ma; Baker and Seward, 1996). The Waiau Uwha River of northern Canterbury runs across the Rakaia, Kaweka, and Pahau Terranes, and its catchment has a nearly equal spatial distribution of each. Additionally, the lower reaches of each drainage dissect Cretaceous through Pliocene basin stratigraphy.}

Mixture modeling results for the modern river sand agree remarkably well with geologic expectations \( \text{(Fig. 10C)\text{. For example, the Pahau Terrane is confirmed as the dominant source of sediment in the Clarence and Awatere catchments \( \text{(~68% and 51%) while the Kaweka and Rakaia Terranes contribute ~50% of the modeled mixtures for the Wairau and Waiau Uwha Rivers. Additionally, the Caples Terrane \( \text{(~14%) that underlies most of the Wairau catchment west of the Alpine Fault is represented in the model. Source terranes that are not present within the river catchments \( \text{(e.g., Western Province terranes) were modeled to contribute an appreciable portion of zircon ages to the mixture \( \text{(mean 33%\text{)}\text{. While the goodness of fit for the Awatere River mixture was relatively low \( (R^2 = 0.66) \text{and may explain the high (~49%) modeled contribution of extraregional sources, the models for the other three modern samples had R^2 values between 0.83 and 0.91, which suggests that the sources were well represented.}

### Potential Complications Due to Reworking of East Coast Basin Strata

In the case studies described above, it is significant that Cretaceous–Pliocene sedimentary strata crop out along each river course, particularly in the lower reaches of the catchments \( \text{(Fig. 10C)\text{. Because sediment recycling is likely, the discrepancy in basement sources extraregional to the river catchment may reflect contamination from East Coast Basin strata within the watershed. For example, mixture modeling of basin samples from the northern...}
Figure 10. (A) Geologic map shows four modern river catchments in the Marlborough and northern Canterbury region of the South Island of New Zealand. River catchments are controlled by topography associated with the Marlborough Fault System. (B) Probability density plots of detrital zircon U-Pb age distributions of sediment sampled upstream from the river outlets. (C) Basement terrane and East Coast Basin (ECB) cover stratigraphy located within river catchments is compared to the detrital zircon U-Pb distribution mixture modeling results using the method outlined by Sundell and Saylor (2017). Note that source areas that contribute to the mixture but are not located in the catchment area are likely due to the recycling of Cretaceous–Cenozoic stratigraphy derived from more extraregional sources. $R^2$—cross-correlation coefficient, where 1.0 is a perfect fit.
Marlborough and Canterbury areas indicated episodic contributions from the Western Province terranes (e.g., Buller-Takaka and Murihiku) during early and late Miocene time (Fig. 9). Late Miocene strata are actively being exhumed and reincorporated into the modern river drainages. As a result, best-fit mixture models of the Wairau and Waiau Uwha Rivers include minor to moderate proportions of recycled western sources, despite these rocks not outcropping within these watersheds (Fig. 10C).

Similarly, Cretaceous and Oligocene samples from the East Coast Basin in the southern Marlborough and Canterbury regions have anomalously high proportions of Cretaceous zircon relative to the proximal Pahau Terrane (Figs. 7–8). Modeling results indicate significant contributions from the Median Batholith (Fig. 9), but it is possible that sediment recycling propagated this source into the Clarence and Awatere River models (Fig. 10). However, we consider the high modeled Median Batholith source to be falsely caused by the presence of 100–90 Ma zircon found exclusively in the Awatere and Clarence River samples (Fig 10B). These ages were derived from the Tapuaenuku Plutonic Complex and associated volcanic rocks that are locally present within the two watersheds (Fig. 10C). Fortunately, 100–90 Ma zircon are almost entirely absent in the East Coast Basin samples. The example above highlights that interpretations of mixture models assume that source areas have been appropriately characterized and that unknown local age anomalies in source areas can influence model results.

While application of the mixing model (DZMIX) employed in these calculations has been demonstrated to be capable of identifying non-contributing sources (i.e., 0%; Sundell and Saylor, 2017), this paper conservatively employs a >10% threshold to reach conclusions regarding sediment sources. The necessity of such a threshold is due to the fact that we introduce additional freedom in the calculations by allowing all basement terranes to serve as sources in each mixture model without a priori knowledge that they could have been contributing sediment (e.g., Fig. 10).

## DISCUSSION

### Paleogeographic Implications

Figure 11 shows generalized tectonic reconstructions of the New Zealand basement terranes (modified from King, 2000) during Early Cretaceous through Pliocene time. Paleo-coastline and paleo-shelf edges are depicted from King (2000) and were modified to honor paleoenvironments of outcrop locations in the paleoenvironments with maps (PMAP) database compiled by Kamp et al. (2015). Potential sediment dispersal pathways from modeled dominant source terranes (e.g., Fig. 9) are displayed in Figure 11. In general, modeling results demonstrate a systematic basin-wide shift from extraregional to progressively locally derived sources throughout the Upper Cretaceous to Pliocene (Figs. 9 and 12). This overall trend, as well as spatial and temporal exceptions along the margin, are discussed below.

### Early Cretaceous (150–110 Ma)

We interpret the dominant Median Batholith source in the Lower Cretaceous strata of the northern Pahau Terrane to reflect early-stage exhumation of the magmatic arc (Fig. 11A). Our results indicate that a topographic barrier may have prevented western sources from contributing to the northern part of the margin. Furthermore, basement terranes east of the Median Batholith were likely submerged (Fig. 11A) or covered by sediment due to subsidence in the forearc. The dominant Waipapa Terrane source in the central part of the basin suggests similar margin-parallel sediment transport distances (~320 km) and indicates that exhumation of the Cretaceous batholith was not fully established along the margin. This is highlighted by the diverse array of southern sediment sources that suggest a long-distance drainage extended beyond the magmatic arc to the Buller and Takaka Terranes (>600 km) or further into the Gondwanan interior. The drainage system integrated sediment from younger basement terranes within the downstream areas of the catchment (Fig. 11A). Contributions from local basement sources (i.e., Kaweka Terrane) are interpreted to reflect local deformation of the active accretionary wedge.

### Late–Early Cretaceous (110–100 Ma)

The abrupt shift toward Median Batholith and reduced contributions of Eastern Terrane sources during the late stages of Pahau deposition is interpreted to reflect regional exhumation of Cretaceous magmatic arc in the lead up to rifting of Zealandia from Antarctica. Rapid exhumation to the north inundated the Raukumara region with arc detritus. A paleodrainage divide was likely established along the magmatic arc such that sediment from the Gondwanan interior (e.g., Buller-Takaka Terrane) was no longer contributing to the southern Pahau Terrane (Fig. 11B). Much of the Zealandia basement east of the magmatic arc was covered by sediment and not contributing as sources to the accretionary wedge, with the exception of upland sourcing from the Murihiku and Waipapa Terranes to the Wairarapa region (Fig. 11B). Contributions of local Kaweka Terrane sediment into the Pahau Terrane in the south-central East Coast Basin likely reflect offshore thrusting and the exhumation of Jurassic stratigraphy and incorporation of sediment into the Early Cretaceous accretionary wedge.

### Late Cretaceous (100–66 Ma)

Our results indicate that the Upper Cretaceous sedimentary strata of the East Coast Basin record a major transition from convergent to passive margin sedimentation along the eastern coast of Zealandia (Figs. 11B–11C). The oldest cover stratigraphy in the Marlborough region demonstrates that Cretaceous regional exhumation of the Median Batholith, which delivered detritus to the
Inferred Sediment Source Pathways (arrows)

- Raukumoko Volcanic Region (Neogene contemporaneous)
- Buller-Takaka Terranes
- Median Batholith/Separation Point Suite
- Brook Street Terrane
- Murihiku Terrane
- Waipapa Terrane
- Caples Terrane
- Rakaia Terrane
- Kaweka Terrane
- Pahau Terrane
- Inferred Sediment Source Pathways (arrows)
- Rakaia Terrane
- Caples Terrane
- Kaweka Terrane
- Pahau Terrane
- Median Batholith/Separation Point Suite

Contemporaneous volcanic arc
Gondwana Interior undiff.
Oceanic crust

Figure 11. Generalized tectonic reconstructions of New Zealand basement terranes (modified from King, 2000) with inferred location of paleodrainage divide during (A) Early Cretaceous through (I) present time are shown. Refer to Figure 1 for current configuration of basement terranes (Mortimer, 2004). Paleo-coastline and paleo-shelf edge are modified from King (2000) and were drawn to honor paleoenvironments of outcrop locations compiled in the paleoenvironments with maps (Pmap) database (Kamp et al., 2015). Detrital zircon U-Pb age distribution mixture modeling results for Cenozoic stratigraphy are displayed as pie diagrams (see Fig. 9 for color code). Hypothetical sediment dispersal pathways from inferred source terranes are displayed with colored arrows that correspond to Figure 9. Dashed dispersal pathways are more speculative or alternative routes. Eastern region abbreviations: R—Raukumara, HB—Hawke Bay, WR—Wairarapa, W—Wellington, CC—Cape Campbell, M—Marlborough, and CB—Canterbury. Western region abbreviations: T—Taranaki, N—Nelson, WC—West Coast, and O—Otago. (Continued on following page.)
Early Miocene ca. 21 Ma

Middle Miocene ca. 14 Ma

Late Miocene ca. 10 Ma

Pliocene ca. 5 Ma

Figure 11 (continued).
This reorganization was inherently related to the termination of the magmatic Kaweka Terrane exposure within the northern East Coast Basin with zonation occurred during the Late Cretaceous. The increase in Eastern Province arc, rifting of Zealandia from western Antarctica, and subsequent Late Cretaceous wasting of the local Pahau Terrane in Marlborough has been attributed to the exhumation of the Median Batholith source contributions to the Upper Cretaceous (Fig. 8). Adams et al. (2013b, 2016) postulated that (1) an antecedent river bypassed the Median Batholith and provided a route for western sediment to be delivered to the East Coast Basin; (2) Western Province detritus was delivered via southward longshore drift along margin; or (3) Western Province equivalent rocks were previously present between the eastern and western segments of New Zealand and were exhumed during middle Late Cretaceous time. Considering the new results from Cenozoic stratigraphy discussed below that suggest protracted long-distance transport across the continent, we consider bypass of the magmatic arc as a preferred scenario for the Late Cretaceous delivery of Western Province detritus to the basin.

**Paleogene (66–23 Ma)**

We interpret the provenance record of Paleogene strata within the northern East Coast Basin to demonstrate an eastward shift from Late Cretaceous fluvial drainage of the Western Province terranes toward a more local drainage with headwaters within the Kaweka Terrane (Fig. 11D). Locally in North Hawke Bay, the loss of Median Batholith source across the Eocene–Oligocene transition (MP33 to MP31) was due to the rapid submergence of northwestern Zealandia during Paleogene time (King, 2000). During Eocene time, a regional eastward-flowing drainage likely existed. In contrast, by late Oligocene time (ca. 25 Ma), maximum marine inundation of Zealandia resulted in the drowning of most of the Western Province. This greatly diminished siliciclastic sediment supply to the northern East Coast Basin and resulted in widespread carbonate deposition across much of Zealandia.

The height of marine transgression of Zealandia is considered to have occurred during the late Oligocene–early Miocene (Landis et al., 2008). Mortimer and Strong (2014) investigated the soluble carbonate content of Paleogene limestone throughout New Zealand and found an appreciable proportion of siliciclastic detritus in Oligocene–Early Miocene limestones. They interpreted this finding to indicate that an emergent landmass likely supplied terrigenous material to the offshore basins. We infer that a portion of theMedian Batholith was emergent during Paleogene time (Fig. 11D) and was the source of abundant Early Cretaceous zircon in the Marlborough region. This interpretation is supported by the occurrence of rare Paleogene nonmarine deposits in the northern Nelson region (Kamp et al., 2015; see paleoshoreline in Fig. 11D). Delivery of Median Batholith sediment to the Marlborough region is problematic, however, in that it required long distance transport (>550 km) across the flooded Zealandia interior (Fig. 11D).
Early Miocene (23–16 Ma)

The early Miocene return to Eastern Province sources, specifically terranes that compose the Zealandia interior (i.e., Waipapa and Rakaia), is evidence of the re-emergence of the continent following the late Oligocene sea-level highstand (Fig. 11E). Westward-dipping subduction was re-established along the Hikurangi margin, and initiation of the Alpine transform boundary occurred by ca. 23 Ma (Kamp, 1986). In the northern East Coast Basin, Neogene-age zircon appeared in the Gisborne segment (sample NG03; Fig. 8). This timing is concurrent with early subduction-related arc activity in northern Zealandia (Adams et al., 1994; Fig. 11E). It is conceivable that volcanic ash transported by wind was deposited into the East Coast Basin by air fall. However, no tuffs were sampled in this study, and most sandstones sampled from the North Island are from sediment gravity flow deposits (e.g., turbidites). Furthermore, Median Batholith and Waipapa sources support a fluvial to marine transport system that routed sediment from northcentral New Zealand to the Raucumara region (Fig. 11E).

In the central East Coast Basin, the sediment transport corridor that delivered Median Batholith detritus across the broad epeiric Paleogene shelf was shut off by early Miocene time. We interpret local Rakaia and Kaweka Terrane sources to the Wairarapa and Wellington region to suggest that a significant reduction in sediment transport distances (~250 km) occurred during the transition from passive to convergent margin setting (Fig. 11E). This confirms the timing of early exhumation of the central proto-Axial Ranges around 27–17 Ma (Jiao et al., 2014). Uplift that produced the Axial Ranges is believed to have been a result of deformation that attended the initiation of the Hikurangi
subduction margin. Meanwhile, we interpret that a latitudinal provenance shift occurred across the trace of the developing transform plate boundary (Fig. 11E) to a predominantly Murihiku Terrane source in the southern East Coast Basin. The influx of modeled Murihiku Terrane sediment is supported by elevated Middle to Late Jurassic zircon (174–145 Ma; Figs. 3 and 8), and we infer a southwestward expansion of the drainage area to southernmost Zealandia (i.e., Otago region; ~500–550 km). The exhumation of the Murihiku Terrane during early Miocene time likely explains why the terrane narrows in thickness and is partly missing between the Otago and Taranaki regions in the modern geologic map (Fig. 1). While the greater Canterbury region was submerged, sedimentological evidence indicates that strong, north-directed littoral currents appeared in lower Miocene time (i.e., Bluecliffs Formation drift deposits; Carter, 2007). Sediment from the Otago region was thus likely transported northeastward, parallel to the coastline and across the continental shelf, to the northern Canterbury region (Fig. 11E).

**Middle Miocene (16–11.6 Ma)**

During middle Miocene time, the contemporaneous Neogene volcanic arc began to shift southwestward across the Coromandel Peninsula (Fig. 11F). We interpret the increase in Neogene zircon and the higher proportions of western basement sources (Murihiku and Waipapa Terranes) to the northeasternmost East Coast Basin (Raukumara region) to have been sourced from an emerging landmass coincident with the volcanic arc. Sediment eroded from the exhumed Murihiku Terrane circumvented the emerging northern Zealandia landmass, possibly via an embayment or narrow epeiric seaway, analogous to the modern current-swept Cook Strait that separates the modern North and South Islands, and created a corridor into the northern East Coast Basin (~200 km transport distance). In the Wairarapa region, we interpret the switch from Rakaia and western terrane sources to a nearly exclusive Kaweka Terrane source to indicate an eastward shift in the middle Miocene drainage divide that separated the central East Coast Basin from the Zealandia interior. This eastward shift is likely related to the continued trenchward propagation of the uplifting Axial Ranges due to shortening of the forearc upper plate (Jiao et al., 2015).

The addition of locally derived Pahau Terrane sediment to the South Raukumara segment reflects complex topography and local basement exhumation due to compressional structures that developed within the early forearc wedge (e.g., Bailleul et al., 2007). Similarly, the abrupt introduction of Pahau sediment to the northern South Island (Fig. 11F) was due to local exhumation of the Kaikoura Ranges, which were associated with early reverse faulting within the Marlborough Fault System (Fig. 1; Browne, 1995; Collett et al., 2019). However, the abundant Western Province detritus modeled in the North Marlborough and Cape Campbell segments demonstrates that the local exhumation was insufficient to preclude extraregional sources. Non-marine deposition (Kamp et al., 2015) and modeled basement exhumation occurred during middle Miocene time in the Nelson region (Jiao et al., 2017). Topography created as a result of transpression caused by middle Miocene right-lateral slip on the Alpine Fault may have facilitated eastward transport of sediment across the Zealandia continent (400–450 km) (Fig. 11F).

In comparison, North Canterbury continued to receive detritus from southern Zealandia, south of the Alpine Fault (Fig. 11E). The adjustment from the Murihiku Terrane source that was prevalent in much of the southern East Coast Basin during early Miocene time to Caples and Rakaia Terrane sediment implies a reduction in drainage area and sediment transport distance to the North Canterbury segment (~300 km; see plausible source locations in Fig. 11F).

**Late Miocene (11.6–5.3 Ma)**

During late Miocene time, contemporaneous volcanism persisted in the Coromandel Peninsula. An eastward-trending drainage with headwaters in this region continued to deliver Neogene volcanic zircon with Murihiku Terrane detritus to the western East Coast Basin (Figs. 8 and 11G). Our conclusion that contemporaneous local volcanic sources contributed detrital zircon to the East Coast Basin is supported by evidence of extensive rhyolitic volcanic units within the North Hawke Bay segment during late Miocene time (Shane et al., 1998). Exhumation associated with the fore-arc wedge deformation continued to supply Pahau Terrane detritus to a localized basin in the Raukumara region. In contrast, the northern and central East Coast Basin received widespread Kaweka Terrane sediment from an emergent hinterland (~100 km to the west). This dispersal pattern was due to increased exhumation in the southern Axial Ranges around 10–7 Ma (Jiao et al., 2015; Fig. 11G). Similarly, the exhumation of uplifted basement blocks within the Marlborough Fault System supplied abundant local Pahau Terrane sediment to South Marlborough and North Canterbury (Fig. 11G). Consequently, the lengthy sediment route that had previously connected southern Zealandia with the Canterbury region during the Late Cretaceous through middle Miocene time (Fig. 12) was abruptly cut off.

We infer that a regional drainage divide generally trended parallel to the tectonically active late Miocene margin of the entire East Coast Basin. However, the local occurrence of Western Province detritus in the Hawke Bay, Wellington, and North Marlborough regions suggests that this drainage divide was continually modified by Alpine Fault-related deformation that permitted it to be locally breached. The continued occurrence of zircon derived from Western Province sources in the East Coast Basin is consistent with the timing of prominent basement exhumation in the West Coast and Nelson regions of South Island (ca. 11–10 Ma; Kamp et al., 1996; Seward and Tulloch, 1991; Seward and White, 1992). We interpret that these terranes were exhumed during late Miocene time, a drainage system was established parallel to the developing Alpine transform fault boundary (~375–450 km), and that this drainage distributed sediment to the central and southern East Coast Basin (Fig. 11G).
Pliocene (5.3–2.6 Ma)

As the East Coast forearc basin and accretionary wedge continued to develop during the Pliocene, the drainage divide approached the northern East Coast Basin such that sediment was almost entirely locally derived from the Kaweka Terrane over a latitudinal extent of 350 km (Fig. 11H). Miocene drainages that had once extended into the interior of Zealandia where the Murihiku and Waipapa Terranes were exposed (Fig. 9) were reduced in Pliocene time to apparent transport distances of ~50–100 km. The single sample in the South Raukumara segment provides an exception (Fig. 9). Although local recycling from the Miocene stratigraphy is possible, the combination of western sources with contemporaneous Neogene zircon (Fig. 8) from the volcanic arc suggests that it had continued communication through the Pliocene with a drainage that extended into the Zealandia interior (Fig. 11H).

The configuration of the southern East Coast Basin rapidly changed during the Pliocene as east-west convergence intensified along the southern extent of the Hikurangi subduction zone and right-lateral displacement accelerated along the Alpine and subsidiary faults of the Marlborough Fault System (Nicol et al., 2007). This plate motion displaced Western Province terranes of western Zealandia to within ~300 km of the southern East Coast Basin (Fig. 11H). Regional drainages extending as far west as the Nelson region continued to provide a diverse mixture of sediment to the Wellington segment. The continuity of these transport systems would eventually be terminated as Zealandia reached its present configuration (Fig. 11I). In the Marlborough region, local Pliocene exhumation of fault-bound Pahau Terrane basement blocks (e.g., Kaikoura Ranges; Collett et al., 2019) appears to have provided the dominant source of sediment to the rapidly subsiding Marlborough region. Specifically, sediment derived from the Murihiku and adjacent terranes was routed 200 km to the northeast, parallel to the Alpine Fault, and then into the North Marlborough regions (modern Wairau valley). Similarly, Median Batholith detritus was transported ~250 km eastward into the Marlborough region (modern Awatere valley; Fig. 11H).

Temporal Controls on Sediment Provenance

Figure 12 summarizes stratigraphic changes in relative source terrane contributions throughout the East Coast Basin and demonstrates major temporal shifts in sediment provenance throughout the evolution of the basin. From the Early Cretaceous to Pliocene time, the entirety of the East Coast Basin generally exhibits a trend from western (Median Batholith and Buller-Takaka Terranes) to central (Brook Street, Murihiku, and Waipapa Terranes) to eastern (Torlesse Composite Terrane) sources (Fig. 2). The Kaweka and Pahau Terranes ultimately become the most important sediment sources in the northern and southern extents of the East Coast Basin, respectively, in upper Miocene–Pliocene stratigraphy (Fig. 12). Whereas post-Lower Cretaceous strata in these regions are mostly devoid of western sources, the central East Coast Basin contains Median Batholith and Buller-Takaka Terrane-sourced detritus throughout the entirety of the stratigraphic record (Fig. 12). In fact, in the northern South Island (Cape Campbell and North Marlborough regions), divergent proportions of extraregional and local sources (i.e., Western Province and Pahau Terrane, respectively) are consistently present throughout Cenozoic stratigraphy.

Temporal Controls on Sediment Transport Distance

Figure 13 portrays apparent sediment transport distances as inferred from the palinspastic reconstructions of Figure 11. Distances do not reflect the hypothetical sediment route but rather the line-of-sight proximity of basement sources to the basin segment. Temporal trends in transport distances correlate broadly with changes in the tectonic setting of Zealandia (e.g., convergent margin to passive margin) over the past 150 m.y. and more directly with the Neogene evolution of the Hikurangi-Alpine plate boundary. Comparison of these along-strike trends of the margin provides a proxy for the relative variations in drainage size and alignment of the continental divide in response to regional tectonic events. Overall, there is a long-term decrease in apparent transport distances from hundreds of kilometers in the Cretaceous to tens of kilometers in the present day (Fig. 13). Long-distance transport (~600–700 km) requires drainages that extended into the Early Cretaceous Gondwanan interior (Fig. 11A). Reduction of transport distances by middle Cretaceous time (~300–500 km) reflects development of a north-south regional drainage divide during uplift and exhumation of the Cretaceous magmatic arc (Fig. 11B). The timing of this regional exhumation event generally corresponds to the collision of the Hikurangi oceanic plateau into the southern portion of the Cretaceous subduction zone at ca. 110 Ma (Reyners et al., 2017; Gardiner et al., 2021). This event terminated subduction across the Gondwanan margin by 100 Ma (Crampton et al., 2019; Mortimer et al., 2019). Zealandia subsequently rifted away from western Antarctica between 100 Ma and 80 Ma (Richard et al., 1994; Spell et al., 2000; Kula et al., 2007). This development correlated with a decrease in sediment transport distances across most of the margin (<300 km) (Fig. 13). Rifting of Zealandia from Gondwana led to an eastward-shifting paleodivide and submergence of the Western Province terranes (Fig. 11C).

The long-term gradual decrease in sediment transport distances that occurred throughout the Late Cretaceous and Paleogene began to accelerate on the North Island of New Zealand during the early Miocene in response to the initiation of the Hikurangi subduction zone (Fig. 13). The subsequent eastward shift (from ~200 km to ~20 km) of the northern Zealandia drainage divide is interpreted to reflect the uplift and propagation of faulting along the Axial Ranges. Notable outliers (i.e., >300 km transport) to this trend occurred locally in Hawke Bay and the Wairarapa–Wellington segments during late Miocene and Pliocene time. These occurrences are interpreted as indicating that drainages locally breached the Axial Ranges.

On the South Island, a more pronounced decrease in apparent transport distances (from 500 km to <150 km) occurred throughout the Neogene (Fig. 13).
Figure 13. Time versus apparent transport distance is plotted for margin-parallel segments along the East Coast Basin (see Fig. 4 for locations) during Early Cretaceous through modern time. Tectonic setting and major events causing drainage reorganization of eastern Zealandia are labeled. Distances reflect the proximity of the farthest significant source terrane, not the distance along the hypothetical sediment route, and are dependent on the accuracy of paleogeographic reconstructions (Fig. 11). Modern distances are estimated from the length of the longest drainage basin at that location.
The later stages of this drainage reduction can be attributed to dextral translation of western source areas along the Alpine Fault to more proximal locations with respect to the East Coast Basin but are also interpreted to reflect uplift of the Southern Alps and Kaikoura Ranges.

**Extent of Neogene Arc Volcanism**

The Northland Volcanic Arc and Coromandel Volcanic Zone represent the Neogene precursors to the Quaternary Taupo Volcanic Zone and volcanic arc of the present-day convergent margin (Fig. 2; Carter et al., 2003; Mortimer et al., 2018). Two Oligocene and early Miocene zircon grains (ca. 27 Ma and 20 Ma) were analyzed in lower Miocene stratigraphy of the Gisborne region (sample NG03; Fig. 7). These analyses suggest that the Northland Volcanic Arc initiated as early as the late Oligocene (ca. 27 Ma). It should be noted that the Oligocene detrital zircon was also found in samples from North Canterbury and South Marlborough (Fig. 7), where limited outcrops of Oligocene volcanic rocks are known to be present. However, it is clear that arc-derived Neogene zircon are most abundant in middle Miocene and Pliocene strata and most geographically dispersed throughout upper Miocene strata of the northern East Coast Basin.

The appearance of these contemporaneous volcanic grains in the East Coast Basin confirms the initiation of Coromandel Volcanic Zone activity during the earliest Neogene (ca. 18 Ma) with a flare-up around 10 Ma (Ballance, 1976; Adams et al., 1994). The geographic distribution of contemporaneous Neogene zircon throughout the East Coast Basin is attributed to the reworking of tephra beds of the same age and origin on the coast of the Mahia Peninsula in the North Hawke Bay segment (Shane et al., 1998). The temporal increase in abundance and general distribution of Neogene zircon records the general eastward migration and development of the volcanic arc (Ballance, 1976).

**Uplift of the Axial Ranges**

Throughout the Cenozoic, the Eastern Province terranes, specifically the Torlesse Composite Terrane, have been the most widespread contributor of sediment to the East Coast Basin (Fig. 9). In the northern East Coast Basin, the Kaweka Terrane is the dominant source of sediment and chiefly composes the modern-day Axial Ranges (Fig. 1), which suggests that uplift had a significant impact on sediment sourcing to the basin. Cenozoic detrital zircon U-Pb age data and provenance modeling match previously reported episodes of uplift in the ranges and largely track the evolution of denudation through Neogene time.

For example, sediment contribution from the Rakaia Terrane, which is inferred predominantly in the southernmost segments of the East Coast Basin, corresponds well with preferential exposure of the Rakaia Terrane in the southeast Axial Ranges (Adams et al., 2011). The inferred Pahau and additional, but subordinate, Rakaia Terrane contributions in late Miocene to Pliocene time (Fig. 9) are concurrent with increased exhumation recorded in the southern region of the Axial Ranges (Jiao et al., 2015). Furthermore, the onset of Pahau Terrane sources to the northern region of the East Coast Basin in early Miocene time confirms the onset of exhumation in the central Axial Ranges around 27–20 Ma (Jiao et al., 2015).

In addition to providing local basement sources to the East Coast Basin, it is likely that the uplift of the Axial Ranges also created a sediment barrier between western sources and some parts of the basin. The persistent mismatch of dominant sources to the northern, central, and southern North Island throughout the Cenozoic (Fig. 12) suggest the likelihood of long-lived partitioning of sediment sources to the basin. The distribution of contemporaneous volcanic detritus, for instance, was likely controlled by such sediment barriers. Neogene-age zircon, which are only observed in the northern regions of the basin, could have been blocked from reaching any further south in the basin by the emergence of the Axial Ranges, which was concurrent with eastern migration of the arc.

**Delivery of Western-Derived Sediment to the East Coast Basin**

Evidence for the contribution of sediment from the Buller and Takaka Terranes to the upper Miocene strata of the South Hawke Bay and Marlborough segments has significant implications for regional drainage networks and the tectonic configuration of Zealandia. During this time, the Western Province terranes of the North Island were regionally submerged, whereas much of the South Island was emergent (King, 2000; Fig. 11). The most viable option for delivering Buller and Takaka Terrane-derived detritus to the East Coast Basin is via the southwestern Nelson region. The latter has exhibited a record of non-marine deposition since the middle Miocene (Kamp et al., 2015, and references therein). Jiao et al. (2017) compiled low-temperature thermochronology data throughout Zealandia and reported a transition from slow exhumation of the Nelson region around 11 Ma to accelerated exhumation beginning at ca. 6 Ma. The Nelson region is currently located >400 km southwest of South Hawke Bay. Palinspastic reconstructions generally show pre-Cenozoic distances of >575 km (King, 2000; Kamp et al., 2015). This configuration would have required a regional drainage network that had its headwaters in the Nelson region to have transported sediment northwest to reach the northern East Coast Basin (Figs. 11G–11H). Uplift of the Axial Ranges would have likely acted as a sediment barrier that segregated the central East Coast Basin from the western half of the North Island. Delivery of Western Province sediment to the central East Coast Basin would thus have required either (1) a paleo-drainage that dissected the central Axial Ranges, or (2) a sediment transport pathway that circumvented the Axial Ranges to the south and ran axially along the forearc to Hawke Bay.

**Antiquity of the Transform Boundary**

The modern Alpine strike-slip fault is widely accepted to have initiated around 23 Ma in conjunction with the late Oligocene–early Miocene southward...
propagation of subduction along the Hikurangi margin (Kamp, 1986). The transform boundary has been inferred to be a subduction-transform edge propagator (STEP) fault (Govers and Wortel, 2005) that was aligned with the northwestern edge of the Hikurangi Plateau (Reynier, 2013). However, some researchers have speculated that the location and orientation of the Alpine Fault was controlled by a pre-existing structural feature in the continental crust that originally formed during the Paleozoic when Zealandia was part of Gondwana (Barnes et al., 2005; Sutherland et al., 2000). Other recent studies have considered differences in the curvature of individual basement terranes within the orocline bend (Fig. 1) and have hypothesized that between 320 km and 400 km of sinistral displacement along a predecessor fault prior to Eocene time is required to reconcile observed relationships (Mortimer, 2014; Lamb et al., 2016). In this scenario, the Neogene Alpine Fault would have been required to reverse this pre-Eocene movement prior to accommodating the 450–480 km displacement it has accumulated since the Miocene.

While the antiquity of a “Proto-Alpine fault” remains uncertain, this hypothesis is intriguing in light of the anomalous provenance trends that we model in the south-central East Coast basin. Specifically, the Late Cretaceous delivery of western Zealandia Buller-Takaka Terrane sediment to the East Coast Basin in the absence of a Median Batholith source (Figs. 9 and 11C) was problematic considering that the paleodrainage divide was previously established along the Cretaceous magmatic arc (Fig. 11B). Adams et al. (2013b) postulated several explanations for these enigmatic sources, including an antecedent river that dissected the continent (see Mid–Late Cretaceous Paleogeography section above), and sinistral displacement of central Zealandia would have sufficiently breached the Median Batholith to allow detritus exclusively of western origin to be delivered to the East Coast Basin. This sediment conduit would have subsequently delivered Western Province sources to the central portion of the basin throughout the Paleogene (Fig. 11D) and into the Miocene (Fig. 12).

Considering the provenance history of the East Coast Basin within the context of Neogene initiation of the transform margin is more straightforward. During early Miocene time, western sources were shut off entirely as the continent emerged above sea level and established a drainage divide that was likely associated with early uplift along the newly developing plate boundary (Fig. 11E). Uplift was accompanied by westward expansion of the drainage in southern Zealandia as a result of exhumation and tectonic excision of the Murihiku Terrane. By middle Miocene time, the major faults within the Marlborough Fault System had become active due to regional shear between the Alpine Fault and Hikurangi subduction zone. Uplift and exhumation of local basement blocks composed of the Lower Cretaceous Papau Terrane resulted in an influx of recycled, locally derived sediment into rapidly subsiding Neogene basins (Fig. 11F). However, middle–late Miocene dextral translation along the Alpine Fault displaced the Western Province northwards to a more proximal position to the southern East Coast Basin. Exhumation and erosion of Western Province basement in the Nelson Region resulted in the delivery of sediment from the Median Batholith and ultimately from the Buller and Takaka Terranes to the northern Wairarapa, Cape Campbell, and Marlborough segments of the East Coast Basin (Figs. 11G–11H). Subsequent development of topography (e.g., Southern Alps) along the Alpine Fault partitioned the southern Zealandia drainages during middle Miocene–Pliocene time. This drainage reorganization resulted in a southern sediment route that transported sediment from the Murihiku, Caples, and Rakaia Terranes in the Otago region northeastward to the southern extent of the East Coast Basin (Figs. 11F–11H). Continued Pliocene dextral displacement along the Alpine Fault and subsidiary faults in the Marlborough region produced topography that ultimately segregated the Western and Eastern Provinces on the South Island and caused locally sourced non-marine gravels to be shed directly across the Alpine Fault and into the Wairau sub-basin (Fig. 11H).

CONCLUSIONS

While previous studies have extensively investigated the detrital zircon provenance characteristics of the metasedimentary basement of Zealandia, comparatively little effort had been directed toward Cenozoic basins that record rapidly changing tectonic conditions throughout the Neogene. Moreover, the overlapping provenance characteristics of pre-Cretaceous basement terranes of Zealandia have limited ability to interpret detrital zircon U-Pb age populations in terms of source region(s). This study assembles a comprehensive data set of new (61 samples; 8315 analyses) and published (14 samples; 788 analyses) detrital zircon U-Pb ages for Cretaceous and Cenozoic sediments from a 700 km latitudinal extent of the East Coast Basin of New Zealand. Mixture modeling of principal igneous and metasedimentary basin terranes of Zealandia using an inverse Monte Carlo approach (DZMix) allows the relative sediment source contributions to strata of the East Coast Basin to be quantitatively characterized. Results are integrated with existing palinspastic reconstructions and regional paleoenvironmental data to interpret paleogeographic maps and hypothesized sediment routes to the East Coast Basin during Early Cretaceous to Pliocene time. Modeling results reveal distinct changes in extraregional and local sediment sources, from which inferred sediment transport distances tie closely with evolving tectonic conditions over the past 120 m.y.

Provenance data demonstrate that a widespread transition from a Gondwana interior-derived source to a Median Batholith-derived source occurred as a result of middle Cretaceous exhumation of the magmatic arc. Concurrent collision of the Hikurangi Plateau with southern Zealandia ultimately resulted in the termination of the Cretaceous subduction zone. Subsequent Late Cretaceous rifting of Zealandia initiated a prolonged passive margin drift phase that was sedimentologically expressed by major drainage reorganization and the influx of Eastern Province sediment sources to the East Coast Basin during Late Cretaceous through Paleogene time. However, a sediment corridor that continued to supply extraregional sediment from the Buller-Takaka Terranes and Median Batholith to the south-central East Coast Basin appears to have paralleled the future trace of the transform plate boundary and may imply a pre-existent structural control for the development of the Alpine transform fault.
The late Oligocene–early Miocene initiation of the Hikurangi subduction margin and concurrent development of the Alpine Fault resulted in an increased supply of sediment from the Torlesse Composite Terrane as plate convergence caused the uplift and exhumation of the Axial Ranges, Southern Alps, and Kaikoura Ranges. These relationships were accompanied by progressively decreasing sediment transport distances as the paleodrainage divide migrated eastward. Contemporaneous Neogene zircon in the northern East Coast Basin preserves a record of the onset of arc-related volcanism in the Neogene Coromandel Volcanic Zone. Volcanic detritus was accompanied by sediment sources derived from the interior of the North Island that provide evidence for drainages that breached or circumvented the uplifting Axial Ranges. Finally, the development of topography along the Alpine Fault and subsequent dextral translation resulted in partitioned sediment dispersal systems to the East Coast Basin during middle Miocene through Pliocene time. This study illustrates the power of large databases of detrital zircon U-Pb provenance data and interpretative tools such as mixture modeling for deciphering sediment dispersal and drainage-age divergence in response to changing tectonic conditions.

ACKNOWLEDGMENTS

This research greatly benefited from collaborators at Geological and Nuclear Sciences (GNS) in Lower Hutt, New Zealand. Specifically, G. Browne, R. King, and K. Bland are gratefully acknowledged for valuable discussions related to this work. G. Browne provided a comprehensive field introduction to the stratigraphic framework of the South Island. B. Burgreen-Chan, L. Shumaker, S. Sieckmann, and Z. Burton helped in the field. We extend thanks to T. Dumitru and K. Dunn for assistance with mineral separation and J. Hourigan for instruction with data reduction. S. Graham provided guidance and support in this study and M. Grove provided technical reviews and edits that greatly improved the clarity of an early draft of the manuscript. We thank B. Romans and N. Mortimer for constructive and thoughtful comments on the journal submission. Primary funding for this research was provided by the Stanford Project on Deep-water Depositional Systems (SPDDS). Additionally, the completion of this manuscript was partially funded by the U.S. Geological Survey Energy Resource Program and Coastal and Marine Geology Program. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

REFERENCES CITED

Adams, C.J., Graham, I.J., Seward, D., Skinner, D.N.B., and Moore, P.R., 1994, Geochronological and geochemical evolution of late Cenozoic volcanism in the Coromandel Peninsula, New Zealand: New Zealand Journal of Geology and Geophysics, v. 37, p. 359–379, https://doi.org/10.1080/00288300909509988.
Adams, C.J., Mortimer, N., Campbell, H.J., and Griffin, W.L., 2009b, Age and isotopic characterization of metasedimentary rocks from the Torlesse Supergroup and Waipapa Group in the central North Island, New Zealand: New Zealand Journal of Geology and Geophysics, v. 52, p. 149–170, https://doi.org/10.1080/00288300909509988.
Adams, C.J., Mortimer, N., Campbell, H.J., and Griffin, W.L., 2011, Recognition of the Kaweka Terrane in northern South Island, New Zealand: Preliminary evidence from Rb-Sr metamorphic and U-Pb detrital zircon ages: New Zealand Journal of Geology and Geophysics, v. 54, p. 291–309, https://doi.org/10.1080/00288306.2011.656928.
Adams, C.J., Mortimer, N., Campbell, H.J., and Griffin, W.L., 2013a, Detrital zircon geochronology and sandstone provenance of basement Waipara Terrane (Triassic-Cretaceous) and Cretaceous cover rocks (Northland Allochthon and Houhora Complex) in northern North Island, New Zealand: Geological Magazine, v. 150, p. 89–109, https://doi.org/10.1017/S0016756812000258.
Adams, C.J., Mortimer, N., Campbell, H.J., and Griffin, W.L., 2013b, The mid-Cretaceous transition from basement to cover within sedimentary rocks in eastern New Zealand: Evidence from detrital zircon age patterns: Geological Magazine, v. 150, p. 456–478, https://doi.org/10.1017 /S0016756812006611.
Adams, C.J., Mortimer, N., Campbell, H., and Griffin, W., 2015, Detrital zircon ages in Buller and Takaka terranes, New Zealand: Constraints on early Zealandia history: New Journal of Geology and Geophysics, v. 58, p. 176–201, https://doi.org/10.1080/00288306.2015.1025798.
Adams, C.J., Campbell, H.J., Mortimer, N., and Griffin, W.L., 2016, Perspectives on Cretaceous Gondwana break-up from detrital zircon provenance of southern Zealandia sandstones: Geological Magazine, v. 154, p. 661–682, https://doi.org/10.1017 /S0016756816002985.
Bailleul, J., Robin, C., Chanier, F., Guillocheau, F., Field, B., and Ferriere, J., 2007, Turbidite systems in the inner fore-arc domain of the Hikurangi transform margin (New Zealand): new constraints on the development of trench-slope basins: Journal of Sedimentary Research, v. 77, no. 4, p. 283–293, https://doi.org/10.2110/jsr.2007.028.
Bailleul, J., Chanier, F., Ferriere, J., Robin, C., Nicoll, A., Mahieux, G., Gorini, C., and Caron, V., 2013, Neogene evolution of lower trench-slope basins and wedge development in the central Hikurangi subduction margin, New Zealand: Tectonophysics, v. 591, p. 152–174, https://doi.org/10.1016/j.tecto.2013.01.003.
Baker, J., and Seward, D., 1996, Timing of Cretaceous extension and Miocene compression in northeast South Island, New Zealand: Constraints from Rb-Sr and fission-track dating of an igneous pluton: Tectonics, v. 15, no. 5, p. 976–983, https://doi.org/10.1029/96TC00626.
Ballance, P.F., 1976, Evolution of the upper Cenozoic magmatic arc and plate boundary in northern New Zealand: Earth and Planetary Science Letters, v. 28, no. 3, p. 356–370, https://doi.org/10.1016 /0012-821X(76)90197-2.
Ballance, P.F., 1993, The New Zealand Neogene forearc basins: Sedimentary Basins of the World, v. 2, p. 177–193.
Barnes, P.M., Sutherland, R., and Deltei, J., 2005, Strike-slip structure and sedimentary basins of the southern Alpine Fault, Fiordland, New Zealand: Geological Society of America Bulletin, v. 117, p. 411–435, https://doi.org/10.1130/B26458.1.
Black, L.P., Kamo, S.L., Allen, C.M., Davis, D.W., Aleinikoff, J.N., Valley, J.W., and Foudoulis, C., 2004, Improved Pb/Ar microprobe geochronology by the monitoring of a trace-element related matrix effect; SHRIMP–ID–TIMS, ELA–ICP–MS and oxygen isotope documentation for a series of zircon standards: Chemical Geology, v. 206, no. 1, p. 115–140, https://doi.org/10.1016/j.chemgeo.2004.01.002.
Black, P.M., Clark, A.S.B., and Hawke, A.A., 1993, Diagenesis and very low-grade metamorphism of volcaniclastic sandstones from contrasting geodynamic environments, North Island, New Zealand: The Murihiku and Waipapa terranes: Journal of Metamorphic Geology, v. 11, no. 3, p. 429–435, https://doi.org/10.1111 /j.1525-1341.1993.tb01919.x.
Bloland, K.J., and Urrycki, C.L., 2015, Pegasus Basin, eastern New Zealand: A stratigraphic record of subsidence and subdivision, ancient and modern: New Zealand Journal of Geology and Geophysics, v. 58, no. 4, p. 319–343, https://doi.org/10.1080/00288306.2015.1076682.
Borg, S.G., and DePaolo, D.J., 1991, A tectonic model of the Antarctic Gondwana margin with implications for southeastern Australia: Isotopic and geochemical evidence: Tectonophysics, v. 196, p. 339–358, https://doi.org/10.1016/0040-1951(91)90329-Q.
Browne, G.H., 1995, Sedimentation patterns during the Neogene in Marlborough, New Zealand: Journal of the Royal Society of New Zealand, v. 25, p. 459–483, https://doi.org/10.1080 /03014223.1995.9517497.
Gooley and Nieminski | Cretaceous–Neogene tectonics and drainage reorganization of the Pacific margin of Zealandia

Foster, D.A., and Goscombe, B.D., 2013, Continental growth and recycling in convergent orogens with large turbidite fans on oceanic crust: Geosciences, v. 3, no. 3, p. 354-388, https://doi.org/10.3390/geosciences3030354.

Gardiner, N.P., and Hall, M., 2021, Discordant forearc deposition and volcanism preceding late-Cretaceous subduction shutdown in Marlborough, north-eastern South Island, New Zealand: Earth-Science Reviews, v. 214, 103530, https://doi.org/10.1016/j.earscirev.2021.103530.

Gardiner, N.P., Hall, M.W.D., and Cowd, P.A., 2021, A forearc stratigraphic response to Cretaceous plateau collision and slab detachment, South Island, New Zealand: Tectonics, v. 40, https://doi.org/10.1029/2021TC006806.

Gehrels, G.E., Valencia, V., and Ruiz, J., 2008, Enhanced precision, accuracy, efficiency, and spatial resolution of U-Pb ages by laser ablation-multicollector-inductively coupled plasma-mass spectrometry: Geochemistry, Geophysics, Geosystems, v. 9, no. Q03017, https://doi.org/10.1029/2007GC001805.

Gooley, J.T., 2020, From forearc to transform: Sedimentary record of changing tectonic setting in the central California and Eastern Australia continental margins (Ph.D. thesis): Stanford, California, USA, Stanford University, 238 p.

Govers, R., and Wortel, M.J.R., 2005, Lithosphere tearing at STEP faults: Response to edges of subduction zones: Earth and Planetary Science Letters, v. 236, p. 505–513, https://doi.org/10.1016/j.epsl.2005.03.022.

Hall, L.S., Lamb, S.H., and Nocia, C.M., 2004, Cenozoic distributed rotational deformation, South Island, New Zealand: Tectonics, v. 23, TC0202, https://doi.org/10.1029/2002TC001421.

Holt, W.E., and Haines, A.J., 1996, The kinematics of northern South Island, New Zealand, determined from geologic strain rates: Journal of Geophysical Research: Solid Earth, v. 100, p. 12981–12990, https://doi.org/10.1029/95JB01059.

Hopcroft, B.S., 2009, Lithology and provenance of late Eocene-Oligocene sediments in eastern Tarakan Basin margin and implications for paleogeography (M.S. thesis): Hamilton, New Zealand, University of Waikato, 618 p.

Howell, D.G., 1980, Mesozoic accretion of exotic terranes along the New Zealand segment of Gondwana: Geology, v. 8, no. 10, p. 487–491, https://doi.org/10.1130/0091-7613(1980)8<487:MAOTAE>2.0.CO;2.

Jiao, R., Seward, D., Little, T.A., and Kohn, B.P., 2014, Thermal history and exhumation of base- ment rocks from Mesozoic to Cenozoic subduction cycles, central North Island, New Zealand: Tectonics, v. 33, no. 2014TC003653.

Jiao, R., Seward, D., Little, T.A., and Kohn, B.P., 2015, Unroofing of fore-arc ranges along the Hikurangi Margin, New Zealand: Constraints from low-temperature thermochronology: Tectonophysics, v. 656, p. 29-61, https://doi.org/10.1016/j.tecto.2015.06.004.

Jiao, R., Seward, D., Little, T.A., Herman, F., and Kohn, B.P., 2017 Constraining provenance, thickness and erosion of nappes using low-temperature thermochronology: The Northland Allochthon, New Zealand: Basin Research, v. 29, no. 1, p. 81–95, https://doi.org/10.1111/bre.12166.

Kamp, P.J., 2019, Tracking crustal processes by 87thermochronology in a forearc high (Hikurangi margin, New Zealand) involving Cretaceous subduction termination and mid-Cenozoic subduction initiation: Tectonophysics, v. 307, no. 3, p. 313-343, https://doi.org/10.1016/S0040-1951(99)00102-X.

Kamp, P.J., 2003, Possible Jurassic age for part of Rakaia Terrane: Implications for tectonic development of the Torlesse accretionary prism: New Zealand Journal of Geology and Geophysics, v. 44, no. 2, p. 189-203, https://doi.org/10.1080/00288306.2003.9514934.

Kamp, P.J., Vincent, K.A. and Tayler, M.J., 2015, Cenozoic sedimentary and volcanic rocks of New Zealand in the Central California and Eastern Zealandia continental margins [Ph.D. thesis]: Stanford, California, USA, Stanford University, 335 p.

Kamp, P.J., 2016, The mid-Cenozoic challenge rift system of western New Zealand and its implications for the age of Alpine Fault inception: Geological Society of America Bulletin, v. 128, no. 3-4, p. 415-433, https://doi.org/10.1130/B31174.1.

Kamp, P.J., Webster, K.S., and Nathan, S., 1996, Thermal history analysis by integrated modeling of apatite fission track and vitrinite reflectance data: Application to an inverted basin [Buller Coalfield, New Zealand]: Basin Research, v. 8, no. 4, p. 383–402, https://doi.org/10.1046/j.1365-2171.1996.00152.x.

Kimbrough, D.L., Tulloch, A.J., Combes, D.S., Landis, C.A., Johnston, M.R., and Mattinson, J.M., 1994, Uranium-lead ages from the Median Tectonic Zone, New Zealand: New Zealand Journal of Geology and Geophysics, v. 37, p. 303–319.

King, P.R., 2000, Tectonic reconstructions of New Zealand: 40 Ma to the Present: New Zealand Journal of Geology and Geophysics, v. 43, p. 611–636, https://doi.org/10.1080/00288306.2000.9614913.
Knuepfer, FLK., 1992, Temporal variations in latest Quaternary slip across the Australian-Pacific plate boundary, northeastern South Island, New Zealand: Tectonics, v. 11, p. 449-464, https://doi.org/10.1029/91TC02900.

Kula, J., Tulloch, A., Spell. T.L., and Wells, M.L., 2007, Two-stage rifting of Zealandia-Australia-Antarctica: Evidence from 40Ar/Ar thermochronometry of the Sisters shear zone, Stewart Island, New Zealand: Geology, v. 35, p. 411-414, https://doi.org/10.1130/G23432A.1

Laird, M.G., and Bradshaw, J.D., 2004, The break-up of a long-term relationship: The Cretaceous separation of New Zealand from Gondwana: Gondwana Research, v. 7, no. 1, p. 273-286, https://doi.org/10.1016/S1342-937X(05)70325-7.

Lamb, S., Mortimer, N., Smith, E., and Turner, G., 2016, Focusing of relative plate motion at a continental transform fault: Chronology of granitic magmatism in the Western Province of the South Island, New Zealand: Chemical Geology (Isotope Geoscience Section), v. 113, p. 171-189.

Muir, R.J., Ireland, T.R., Weaver, S.D., and Bradshaw, J.D., 1994, Lomicroprobe U-Pb zircon geochronology of the Farewell Sandstone by integrating sedimentological and well log analysis in the Kupe Basin, New Zealand: Journal of the Geological Society, v. 173, p. 370-383, https://doi.org/10.1144/1440-0952.2000.00826.x.

Nicol, A., Mazengarb, C., Chanier, F., Rait, G., Urban, C.I., and Wallace, L., 2007, tectonic evolution of the active Hikurangi subduction margin, New Zealand, since the Oligocene: Tectonics, v. 26, p. 1-24, https://doi.org/10.1029/2006TC002219.

Paces, J.B., and Miller, J.D., 1993, Precise U-Pb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota: Geochronological insights to physical, petrogenetic, paleomagnetic, and tectonomagmatic processes associated with the 1.1 Ga Midcontinent Rift system: Journal of Geophysical Research: Solid Earth, v. 98, no. B8, p. 13,997-14,013, https://doi.org/10.1029/93JB01159.

Pickard, A.L., Adams, C.J., and Barley, M.E., 2000, Australian provenance for Upper Permian to Cretaceous rocks forming accretionary complexes on the New Zealand sector of the Gondwanaland margin: Australian Journal of Earth Sciences, v. 47, p. 987-1007, https://doi.org/10.1046/j.1440-0952.2000.00882.x.

Prebble, W.M., 1980, Late Cenozoic sedimentation and tectonics of the East Coast deformed belt in southern New Zealand: New Zealand Journal of Geology and Geophysics, v. 5, no. 2, p. 209-218, https://doi.org/10.1080/00288306.2014.901230.

Rait, G., Chanier, F., and Waters, D.W., 1991, Landward- and seaward-directed thrusting accompanying the onset of subduction beneath New Zealand: Journal of Petroleum Exploration and Production Technology, v. 11, p. 11-31, https://doi.org/10.1016/S1320-2010-0135-8.

Rait, G., Chanier, F., and Waters, D.W., 1991, Landward-and seaward-directed thrusting accompanying the onset of subduction beneath New Zealand: Journal of Petroleum Exploration and Production Technology, v. 11, p. 11-31, https://doi.org/10.1016/0899-5369(93)90204-2.

R artisans, S., and Muir, R.J., 2019, Late Cretaceous oceanic plate reorganization and the breakup of Zealandia and Gondwana: Gondwana Research, v. 65, p. 1-42, https://doi.org/10.1016/j.gr.2018.07.010.

Mortimer, N., van den Bogaard, P., Hoemle, K., Timm, C., Gans, P.B., Werner, R., and Riefstahl, F., 2019, Late Cretaceous oceanic plate reorganization and the breakup of Zealandia and Gondwana: Gondwana Research, v. 65, p. 1-42, https://doi.org/10.1016/j.gr.2018.07.010.

Muir, R.J., Ireland, T.R., Weaver, S.D., and Bradshaw, J.D., 1994, Ion microprobe U-Pb zircon geochronology of the Farewell Sandstone by integrating sedimentological and well log analysis in the Kupe Basin, New Zealand: Journal of the Geological Society, v. 173, p. 370-383, https://doi.org/10.1144/1440-0952.2000.00826.x.
Rattenbury, M.S., Townsend, D., and Johnston, M.R., compilers, 2006, Geology of the Kaikoura area: Institute of Geological & Nuclear Sciences, Geological Map 1, scale 1:250,000, 1 sheet, 70 p. text.

Reyners, M., 2013, The central role of the Hikurangi Plateau in the Conozoic tectonics of New Zealand and the Southwest Pacific: Earth and Planetary Science Letters, v. 361, p. 460–468, https://doi.org/10.1016/j.epsl.2012.11.010.

Reyners, M., Eberhart-Phillips, D., Upton, P., and Gubbins, D., 2013, Three-dimensional imaging of impact of a large igneous province with a subduction zone: Earth and Planetary Science Letters, v. 460, p. 143–151, https://doi.org/10.1016/j.epsl.2016.12.025.

Richard, S.M., Smith, C.H., Kimbrough, D.L., Fitzgerald, P.G., Luyendyk, B.P., and McWilliams, M.O., 1994, Cooling history of the northern Ford Ranges, Marie Byrd Land, West Antarctica: Tectonics, v. 13, p. 837–857, https://doi.org/10.1029/93TC03222.

Rivera, K., 2010, Characteristics of Miocene to Pliocene sandy units in the Hikurangi forearc, North Island, New Zealand (M.S. thesis): Northridge, California, USA, California State University, 68 p.

Roberts, A.P., 1992, Paleomagnetic constraints on the tectonic rotation of the southern Hikurangi margin, New Zealand: New Zealand Journal of Geology and Geophysics, v. 35, no. 3, p. 311–322, https://doi.org/10.1080/00288306.1992.9514524.

Rotzien, J.R., Browne, G.H., and King, P.R., 2018, Geochemical, petrogenetic, and uranium-lead geochronological evidence for multisourced polyyclic provenance of deep-water strata in a hybrid tectonic setting: The upper Miocene Mount Messenger Formation, Taranaki Basin, New Zealand: American Association of Petroleum Geologists Bulletin, v. 102, no. 9, p. 1763–1802, https://doi.org/10.1306/0206181616817222.

Sagar, M.W., Pain, J.M., Tulloch, A.J., and Heath, L.A., 2016, The geology, geochronology and affiliation of the Glenroy Complex and adjacent plutonic rocks, southeast Nelson: New Zealand Journal of Geology and Geophysics, v. 59, p. 213–235, https://doi.org/10.1080/00288306.2015.1010004.

Saylor, J., and Sundell, K., 2016, Quantifying comparison of large detrital geochronology data sets: Geochemistry, Geophysics, Geosystems, v. 17, no. 1, p. 203–220, https://doi.org/10.1002/2015GC006271.

Seward, D., and Tulloch, A.J., 1991, Fission-track analysis of Tertiary uplift history of granitic basement in the Victoria Range, West Coast, New Zealand: New Zealand Journal of Geology and Geophysics, v. 34, no. 2, p. 115–120, https://doi.org/10.1080/00288306.1991.9514448.

Seward, D., and Weis, P.J., 1992, Evolution and erosion of a tertiary sedimentary basin, Paparoa Range, West Coast, South Island, New Zealand: Evidence from fission-track dating: New Zealand Journal of Geology and Geophysics, v. 35, no. 3, p. 265–271, https://doi.org/10.1080/00288306.1992.9514520.

Shane, P., Black, T., Eigins, S., and Westgate, J., 1998, Late Miocene marine tephra beds: Recorders of riftogenic volcanism in North Island, New Zealand: New Zealand Journal of Geology and Geophysics, v. 41, p. 165–178, https://doi.org/10.1080/00288306.1998.9514801.

Shumaker, L.E., 2016, Sedimentology, seismic geomorphology, and provenance investigations of deep-water deposits: Taranaki Basin, New Zealand (Ph.D. thesis): Stanford University, California, USA, Stanford University, 197 p.

Slama, J., Kössler, J., Condon, D.J., Crowley, J.L., Gerdes, A., and Hanchar, J.M., 2006, Petroleum system, Paleocene–Eocene tectonics, and rejuvenation of the Hohonu Batholith, New Zealand: New Zealand Journal of Geology and Geophysics, v. 49, no. 4, article no. RG4002, https://doi.org/10.1080/00288306.2005.9514736.

Spörli, K.B., 1978, Mesozoic tectonics, North Island, New Zealand: Geological Society of America Bulletin, v. 89, p. 415–425, https://doi.org/10.1130/0016-7606.1978.89(415)<415:MNZNZ-2.0.CO;2.

Stern, T.A., Stratford, W.R., and Salmon, M.L., 2006, Subduction evolution and mantle dynamics at a continental margin: Central North Island, New Zealand: Reviews of Geophysics, v. 44, no. 4, article no. RG4002, https://doi.org/10.1029/2005RG000171.

Strogen, D.F., 2011, Petrographic study of core samples from wells Ouri-1A and Te Mai-2, onshore East Coast Basin: Geological and Nuclear Sciences Science Report 2011/315, 31 p.

Sundell, K.E., and Saylor, J.E., 2017, Unmixing detrital geochronology age distributions: Geophysics, Geochimistry, Geosystems, v. 18, p. 2872–2886, https://doi.org/10.102012/GC006774.

Sutherland, R., 1996, Transpressional development of the Australia-Pacific boundary through southern South Island, New Zealand: Constraints from Miocene–Pliocene sediments, Waiho-1 borehole, South Wellington: New Zealand Journal of Geology and Geophysics, v. 39, no. 2, p. 251–264, https://doi.org/10.1080/00288306.1996.9514709.

Sutherland, R., Davey, F.J., and Beavan, J., 2000, Plate boundary deformation in South Island, New Zealand, is related to inherited lithospheric structure: Earth and Planetary Science Letters, v. 172, p. 141–151, https://doi.org/10.1016/S0012-821X(00)00431-3.

Tulloch, A.J., and Kimbrough, D.L., 2003, Paired plutonic belts in convergent margins and the development of high Sr/Y magmatism: Peri-Bathynian Ranges basaltic rocks of the Median batholith in New Zealand, in Johnson, S.E., Paterson, S.R., Fletcher, J.M., Girtie, G.H., Kimbrough, D.L., and Martin-Barajas, A., eds., Tectonic Evolution of Northwestern Mexico and the southwestern USA: Geological Society of America Special Paper 374, p. 275–295, https://doi.org/10.1130/8137-2374-4.275.

van der Lingen, G.J., 1982, Development of the North Island subduction system, New Zealand, in Leggett, J.K., ed., Trench-forearc Geology: Sedimentation and Tectonics on Modern and Ancient Active Plate Margins: Geological Society, London, Special Publication 10, no. 1, p. 259–272, https://doi.org/10.1144/GSL.SP.1982.010.01.17.

van der Lingen, G.J., and Pettinga, J.R., 1980, The Makara Basin: A Miocene slope-basin along the convergent plate boundary in the New Zealand sector of the Australian-Pacific obliquely convergent plate boundary, in Ballance, P.F., and Reading, H.G., eds., Sedimentation in Oblique-Slip Mobile Zones: International Association of Sedimentologists Special Publication 4, v. 34, p. 191–215, https://doi.org/10.1080/00288306.1991.9514430.

Van den Dissen, R., and Yeats, R.S., 1991, Hope fault, Jordan thrust, and uplift of the seaward Kaikoura range, New Zealand: Geology, v. 19, p. 393–396, https://doi.org/10.1130/0091-7613(1991)019<0393:HFJTAU>2.3.CO;2.

Waight, T.E., Weiser, S.D., Ireland, T.R., Maas, R., Muir, R.J., and Shelley, D., 1997, Field characteristics, petrography and geochronology of the Hohonu Batholith and adjacent Granite Hill Complex, North Westland, New Zealand: New Zealand Journal of Geology and Geophysics, v. 40, p. 1–17, https://doi.org/10.1080/00288306.1997514736.

Walcott, R.I., 1987, Geotectonic strain and the deformational history of the North Island of New Zealand during the late Cainozoic: Tectonic settings of regional metamorphism: Philosophical Transactions of the Royal Society A: Mathematical, Physical, and Engineering Sciences, v. 321, p. 163–181.

Wandres, A.M., Bradshaw, J.D., Weiser, S., Maas, R., Ireland, T.R., and Eby, N., 2004, Provenance of the sedimentary Rakaia subterrane, South Island, New Zealand: The use of igneous clast compositions to define the source: Sedimentology, v. 168, p. 193–226.

Watters, W.A., 1990, Petrography and diagenesis of rocks from coastal Wairarapa, adjacent to PPL38318 and 38323 East Coast Belt, New Zealand: Amoco Exploration New Zealand Ltd., New Zealand Petroleum Report PR1586.