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SPECIAL ISSUE: RESEARCH ON THE SOUTH WEST MARGIN OF GONDWANA

# Zealandia in Antarctica: early Paleozoic basement in Marie Byrd Land, West Antarctica and possible connections to its Gondwana neighbours

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**ABSTRACT.** The early Paleozoic geology of New Zealand and evidence for the wider continental mass of Zealandia are reviewed in this contribution, especially with regard to the record of detrital zircon chronology. U-Pb age populations are reported from three new samples of siliciclastic and volcaniclastic sandstones in late Cambrian to Ordovician Swanson Formation, which constitutes the basement in the Ford Mountains and Edward VII Peninsula of western Marie Byrd Land, West Antarctica. Comparison with previously published data shows the same prominent age groups: 480-700 Ma (Early Ordovician to late Neoproterozoic) and 900-1,100 Ma (early Neoproterozoic to late Mesoproterozoic). These are related respectively to ultimate sources formed during earliest Gondwana and late Rodinia supercontinental assembly. They conform to a common and widespread pattern seen in early Paleozoic basement throughout the Western Province of Zealandia and which continues over much of the Campbell Plateau of New Zealand, as well as other parts of West Antarctica and South America. South Zealandia is conjectured to have extensive Mesoproterozoic and late Neoproterozoic-Cambrian igneous/metamorphic basement which supplied sediment to earliest Paleozoic basins over a wide region, including western Marie Byrd Land, which is considered as an integral part of Zealandia. It may also have provided late Neoproterozoic and Cambrian sediment to contemporary sedimentary basins in adjacent North Victoria Land (East Antarctica) and the central Transantarctic Mountains. Eastward continuation of any Zealandia continental margin into the Weddell Sea area is very uncertain but essentially comparable early Paleozoic sediment provenance in southern South America at least confirms the continuity of Rodinia and Gondwana assembly processes.

*Keywords: U-Pb dating, Detrital zircon, Marie Byrd Land, West Antarctica, Zealandia, Cambrian, Ordovician, Gondwana, Rodinia.*

**RESUMEN. Zelandia en la Antártida: basamento del Paleozoico temprano en Marie Byrd Land, Antártida Occidental y posibles conexiones con sus vecinos de Gondwana.** La geología del Paleozoico temprano de Nueva Zelanda y la evidencia de la masa continental más amplia de Zelandia se revisan en esta contribución, especialmente en relación con el registro de la cronología detrítica mediante circones. Se reportan poblaciones de edades U-Pb de tres nuevas muestras de areniscas siliciclásticas y volcanoclásticas de la Formación Swanson (Cámbrico tardío a Ordovícico), la que constituye el basamento en las montañas Ford y de la península Eduardo VII en el oeste de Marie Byrd Land, Antártida Occidental. La comparación de estas nuevas edades con datos publicados previamente destaca los mismos grupos: 480-700 Ma (Ordovícico temprano a Neoproterozoico tardío) y 900-1.100 Ma (Neoproterozoico temprano a Mesoproterozoico tardío). Estos grupos están relacionados respectivamente con fuentes últimas formadas durante el ensamblaje supercontinental más temprano de Gondwana y tardío de Rodinia. Siguen un patrón común y extendido que se observa en el basamento del Paleozoico temprano en toda la provincia occidental de Zelandia y que continúa en gran parte de la meseta Campbell en Nueva Zelanda, así como en otras partes de Antártida Occidental y Sudamérica. Se conjetura que el sur de Zelandia poseía un extenso basamento ígneo/metamórfico de edad mesoproterozoica a neoproterozoica tardía-cámbrica, que suministraba sedimento a las cuencas del Paleozoico más temprano en una amplia región, incluyendo el oeste de Marie Byrd Land, que se considera parte integral de Zelandia. También pudo haber proporcionado sedimentos del Neoproterozoico tardío y Cámbrico a cuencas sedimentarias contemporáneas en la adyacente North Victoria Land (Antártida Oriental) y las montañas transantárticas centrales. Si bien la continuación hacia el este de cualquier margen continental de Zelandia en la zona del mar de Weddell es bastante incierta, la procedencia de sedimentos del Paleozoico temprano en el sur de Sudamérica confirma, al menos, la continuidad de los procesos de ensamblaje de Rodinia y Gondwana.

*Palabras clave: Datación U-Pb, Circón detrítico, Marie Byrd Land, Antártida occidental, Zelandia, Cámbrico, Ordovícico, Gondwana, Rodinia.*

## 1. Introduction

Until relatively recently, New Zealand and its surrounding shallow ocean plateaux (<2,000 m depth) were merely regarded as the site of early Paleozoic and Mesozoic depositional basins adjacent to the eastern Australian Gondwana margin. This view changed with the recognition, from bathymetric and geophysical data, that the region represents a true continent, albeit 95% submerged, named Zealandia (Mortimer *et al*., 2017) (Fig.1). The geology of New Zealand was also dramatically reassessed with the realisation that several Permian to Cretaceous allochthonous tectonostratigraphic terranes (collectively an Eastern Province) had original depositional sites much farther north and adjacent to eastern Australia (Bishop *et al*., 1985; Pickard *et al*., 2000; Adams *et al*., 2007; Mortimer *et al*., 2014; Adams and Campbell, 2020). Recently, it has been proposed that the early Paleozoic Takaka Terrane also joins this allochthonous collage (Adams and Campbell, 2025).

Over 30 years, the recompilation of geological data and new detrital zircon studies have established that the early Paleozoic sedimentary rocks of Zealandia, collectively incorporated within a Western Province (WP) (Figs. 1 and 2), are not derived from Australia (or formerly adjacent Antarctica) but from a now hidden Precambrian basement somewhere within southern Zealandia (Adams *et al*., 2015; Adams and Ramsay, 2022; Adams and Campbell, 2023). A similar conclusion was reached from detrital zircon studies in Cretaceous cover successions across much of southern Zealandia (Adams and Griffin,

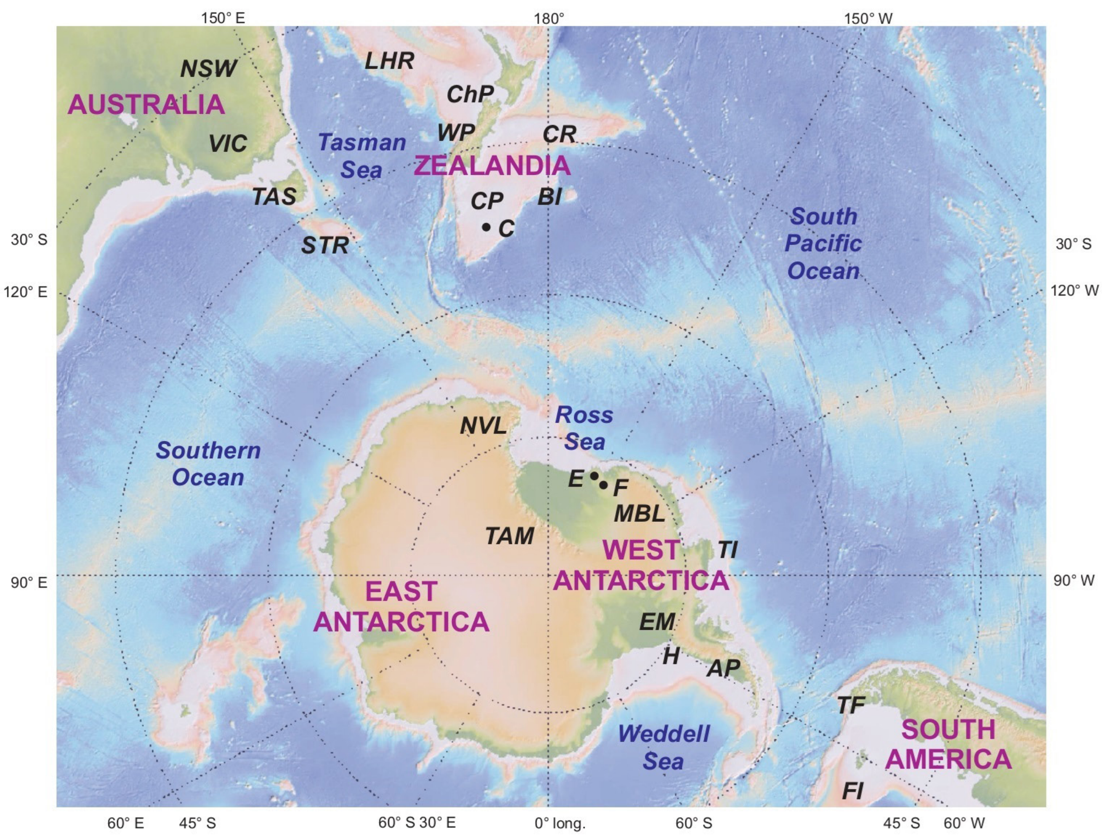


FIG. 1. The southern margins of the Pacific Ocean. **Australia**: **NSW**, New South Wales; **STR**, South Tasman Rise; **TAS**, Tasmania; **VIC**, Victoria. **Zealandia**: **BI**, Bounty Islands; **C**, Campbell Island; **ChP**, Challenger Plateau; **CP**, Campbell Plateau; **CR**, Chatham Rise; **LHR**, Lord Howe Rise; **WP**, Western Province. **Antarctica**: **AP**, Antarctic Peninsula; **E**, Edward VII Peninsula; **EM**, Ellsworth Mountains; **F**, Ford Mountains; **H**, Haag Nunataks; **MBL**, Marie Byrd Land; **NVL**, North Victoria Land; **TAM**, Transantarctic Mountains; **TI**, Thurston Island. South America: **FI**, Falkland Islands; **TF**, Tierra del Fuego.

2012; Adams *et al*., 2016). A Paleozoic connection to western Marie Byrd Land was also early recognized (Adams, 1986; Adams *et al*., 2013).

The concept of Zealandia as a continent impacts many previous regional models of the Eastern Gondwana margin, for example SWEAT (Dalziel, 1991; Moores, 1991; Fioretti *et al*., 2005; Goodge *et al*., 2008), AUSWUS (Blewett *et al*., 1998; Karlstrom *et al*., 1999; Burrett and Berry, 2000) and AUSMEX (Wingate, 2002). In particular, it affects the relationships of formerly adjacent parts of Australia, the Ross Sea regions of Antarctica and, more distantly, parts of South China and Laurentia.

Within the context of this review, new detrital zircon age patterns from Marie Byrd Land are reported. They are compiled with published data to better understand the basement of South Zealandia (here defined as South Island New Zealand, the Campbell Plateau and Chatham Rise) in terms of its endemic sediment sources and possible relationship to contemporary continental neighbours.

## 2. Geological background

The South Zealandia basement is largely unknown as a result of extensive cover by post-Cretaceous successions. The oldest, Cambrian-Ordovician, rocks (Greenland Group) crop out discontinuously along the Westland coast of South Island (Fig. 2) but otherwise there are only small, km-scale outcrops on Campbell Island and an indeterminate basement schist recovered in the Kawau-1 Great South Basin oil-exploration borehole (K) (Fig. 3). Together these comprise the New Zealand Western Province, which has constituent Buller and Takaka terranes (Fig. 2). The Median Batholith (Cambrian to Cretaceous), in southern South Island mostly Jurassic to Cretaceous

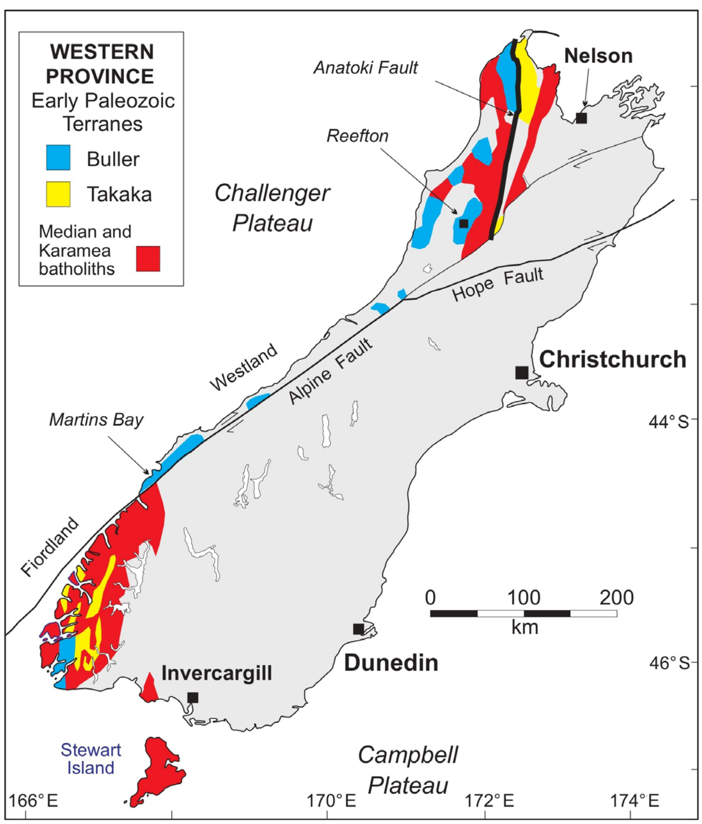


FIG. 2. Schematic terrane map of the Western Province, South Island, New Zealand, showing the distribution of the Buller and Takaka early Paleozoic terranes and the Devonian to Cretaceous granitic rocks of the Median and Karamea batholiths. Map based on Mortimer (2025) through collaboration with R. Pankhurst.

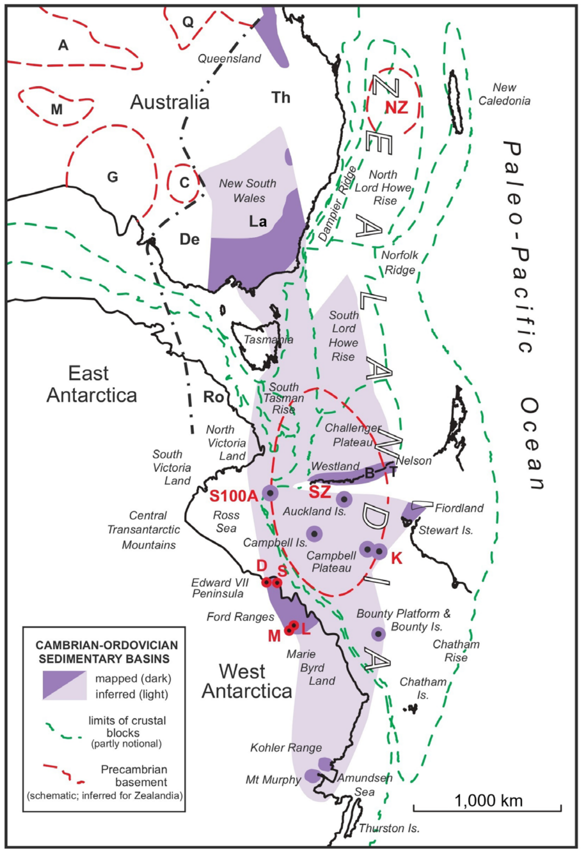


FIG. 3. The Zealandia continent at the eastern Gondwanaland margin showing Cambrian-Ordovician sedimentary basins from outcrop (dark shading) and inferred (light shading) extensions, using a mid-Cretaceous reconstruction, principally after Gaina *et al.* (1998) but disregarding post-Permian components in eastern Zealandia. Major Cambro-Ordovician orogenic belts in Australia and the Ross Sea regions of **East Antarctica**: **De**, Delamerian; **La**, Lachlan; **Ro**, Ross; **Th**, Thomson. The dashed-dotted black line separates these from major older Precambrian cratons to the west in central **Australia**: **A**, Arunta; **C**, Curnamona; **G**, Gawler; **Q**, Queensland (all mostly Paleoproterozoic); **M**, Musgrave (mostly Mesoproterozoic). Precambrian basement blocks inferred in **Zealandia**: **NZ**, North Zealandia; **SZ**, South Zealandia. Western Province terranes of **New Zealand**: **B**, Buller; **T**, Takaka. Sample locations in **Western Marie Byrd Land**: **D**, Drummond Peak; **L**, Lewisohn Nunatak; **M**, Mt Palombo, Mackay Mts.; **S**, Mt Swadener. **Other locations**: **K**, Kawau-1 and Hoiho-1 oil exploration drillholes; **S100A**, dredge sample.

plutons, separates the Western Province from the Eastern Province. In the north, west of Nelson, the early Paleozoic rocks are also intruded by Late Devonian to early Carboniferous granitoids of the Karamea Batholith (Rattenbury *et al.*, 1998; Nathan *et al.*, 2002) (Fig. 2).

### 2.1. Buller Terrane

The Greenland Group, the principal component of the major Buller Terrane, is a rather monotonous tightly folded sandstone-siltstone succession, deposited as proximal to mid-fan turbidites. There is a single, Early Ordovician, fossil locality in Westland (Cooper, 1974). Sediment transport directions are from south/southeast to north/northwest (Laird, 1972). Metamorphism is usually greenschist facies, dated by K-Ar and Rb-Sr as latest Ordovician, *ca.* 445 Ma (Adams *et al.*, 1975; Adams, 2004). In south Westland, metamorphism increases to amphibolite facies (Mortimer, 2009). In northwest Nelson (Fig. 2), there is a local transition to Middle Ordovician quartzite and graptolitic black slate (Cooper, 1979, 1989). Volcanic rocks are extremely rare, but Ordovician and Cambrian youngest detrital zircons in sandstones are invariably euhedral and, where it can be established, close to the depositional age (*e.g.*, Adams *et al*., 2015). The dominant sandstones are quartz-arenites with volcanic and metamorphic lithic clasts and only modest K-feldspar contents, which together suggest a recycled-orogen source at a passive margin (Nathan, 1976; Roser *et al*., 1996; Mortimer, 2009). Limestones are rare, but dm- to m-scale calcareous horizons (now marble, Martins Bay Formation) occur locally in south Westland (Mutch, 1964): late Cambrian youngest ages from euhedral detrital zircon in the associated sandstones suggest possible correlation with late Cambrian limestones in the Takaka Terrane. Calcareous nodules of dm size are quite common in the greywackes. Local Early Devonian (Emsian) outliers near Reefton, in the northern part of South Island (Fig. 2), consist of shallow water sandstones, siltstones and limestones (Bradshaw, 1995) regarded as belonging to the Malvinokaffric Realm (mainly Antarctica and southern South America and Africa).

### 2.2. Takaka Terrane

Although smaller than the Buller Terrane, the Takaka Terrane shows considerable lithological variety. There are mid-to-late Cambrian active-margin volcanic rocks, volcaniclastic sandstones, an ultramafic complex, and local cherts, limestones and conglomerates (Cooper, 1979, 1989; Müncker and Cooper, 1995, 1999; Rattenbury *et al*., 1998). Ordovician lithologies are more indicative of a passive-margin setting, dominated by major shelf-facies limestones and then quartz-sandstones in Late Ordovician and Silurian time (Rattenbury *et al*., 1998, and references therein). Local outliers of shallow-water Devonian sandstones and siltstone (Baton Group) complete the succession (Bradshaw, 2000). A Carboniferous plutonic complex (Riwaka Complex) is only very local (Turnbull *et al*., 2017). Adams and Campbell (2025) inferred that the pre-Triassic Takaka succession is allochthonous, with original depositional basins far to the north on the Australian Gondwana margin. The western Takaka Terrane boundary with the Buller Terrane is the major Anatoki Fault (Jongens, 2006), but any eastern margin is obscured by Jurassic-Cretaceous granites of the Median Batholith (Fig. 2).

### 2.3. Campbell Island and Campbell Plateau

On Campbell Island (C) (Fig. 1), in a rather inaccessible km-scale cliff outcrop, the Complex Point Formation comprises mainly metasandstones and pelites resembling those of the Greenland Group, with low-grade greenschist metamorphism dated at *ca.* 440 Ma (Adams *et al*., 1979). The Garden Cove Schist in nearby Perseverance Harbour forms a tiny 100 m outcrop of quartz-mica-schist which is significantly older (early Cambrian) (Adams, 2008; Adams and Campbell, 2023).

Several oil-exploration drillholes through Cretaceou-Cenozoic successions in and around the Great South Basin of Campbell Plateau have reached older basement in Carboniferous and Cretaceous granites. However, at Kawau-1, drill cuttings of indeterminate quartz-mica schists (Cook *et al*., 1999) have a zircon age pattern that strongly resembles Greenland Group examples, with a major Cambrian-Ordovician peak, minor Mesoproterozoic groups, and a Mid-Ordovician (*ca.* 460 Ma) youngest component (Adams *et al*., 2015) (Fig. 4).

### 2.4. Bounty Islands and Bounty Platform

On the Bounty Islands (Figs. 1 and 3), an Early Jurassic granodiorite yielded a Rb-Sr age of 183±9 Ma (Adams, 2008) and a U-Pb zircon age of 191±2 Ma (Adams *et al*., 2016). Metasandstone pebbles dredged at seafloor localities on the surrounding Bounty Platform have an Ordovician youngest U-Pb detrital zircon age (482±5 Ma) but Jurassic $^{40}Ar/^{39}Ar$ (182±3 Ma, mica age) and Rb-Sr (174±32 Ma, metamorphic age with a high intercept $^{87}Sr/^{86}Sr$ ratio of 0.746) ages (Adams, 2008).

### 2.5. Marie Byrd Land, West Antarctica

In a large sector (350×450 km) of coastal western Marie Byrd Land, from Edward VII Peninsula into the Ford Ranges (Figs. 1 and 3), the Swanson Formation is a major sedimentary unit with many similarities to the Greenland Group. It also represents a mid-to-proximal fan environment of quartz-rich flysch comprising sandstones and siltstone (but rare mudstones). The sandstones are lithic and volcanic-lithic felsarenites, with quartzite and acid-volcanic lithics: quartz, muscovite and zircon (commonly euhedral) occur as detrital minerals (Bradshaw *et al*., 1983). The sandstones frequently contain dm-size calc-silicate concretions. The formation is unfossiliferous except for *Paleodictyon* trace fossils, possibly Ordovician. Tight folding and greenschist

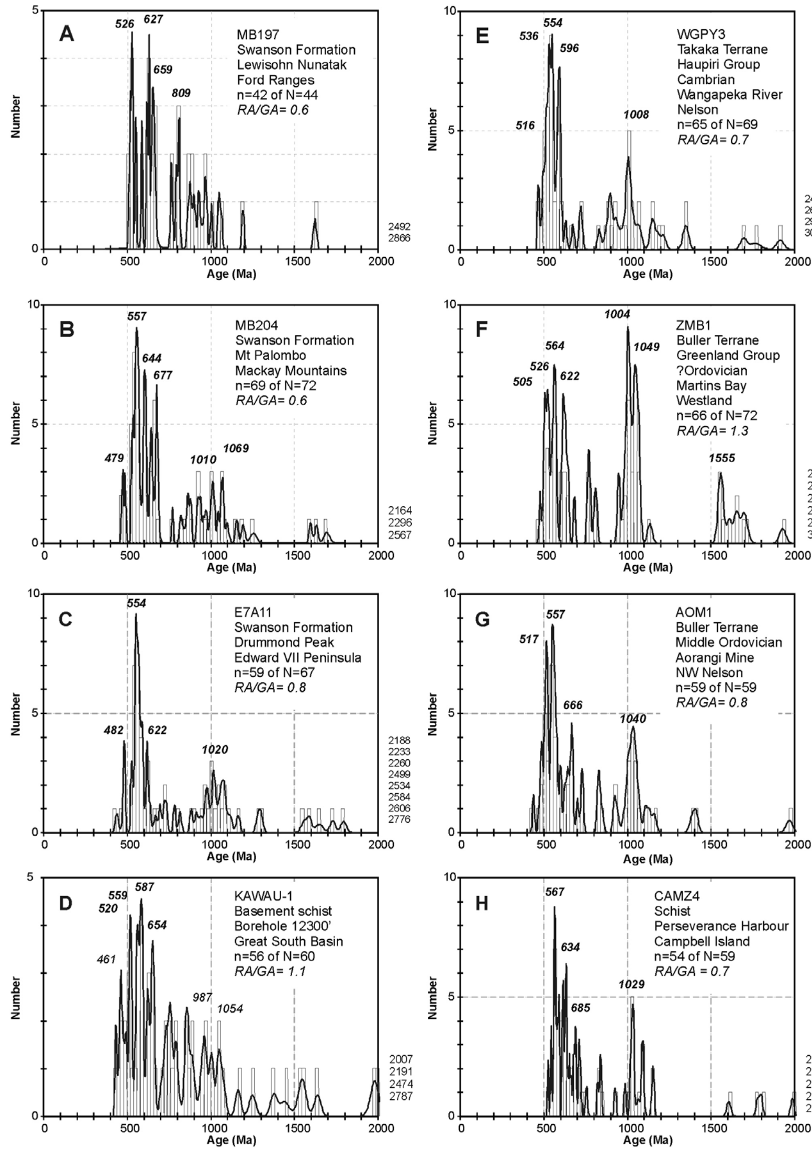


FIG. 4. Combined probability density/histogram diagrams of U-Pb detrital zircon ages: **A-C.** Swanson Formation sandstones from Western Marie Byrd Land (this study). **D.** Campell Island borehole. **E-G.** Representative Cambrian-Ordovician sandstones from Western Province basement in New Zealand. **H.** Campbell Island. Published data are from Adams *et al*. (2015) (E7A11 very slightly revised), except H from Adams and Campbell (2023). Ages >2,000 Ma are stacked at right margin. Significant component ages are shown in bold italics for Rodinia (RA) and Gondwana (GA) assemblies.

metamorphism (higher grade within the contact aureoles of later granitoids) is Late Ordovician (*ca.* 445 Ma, K-Ar and Rb-Sr ages; Adams, 1986). Adams (1980) first noted the similar Late Ordovician metamorphic histories of Marie Byrd Land, New Zealand, North Victoria Land, and Tasmania (Fig. 1). In the southernmost outcrops at Lewisohn Nunatak (an isolated nunatak, ~20 km southeast of the Mackay Mountains), there is a distinct volcaniclastic facies (Lewisohn Member) with thin augite-bearing crystal tuffs and tuffaceous sandstones. Similar volcaniclastic sandstones also occur at Mt Palombo in the Mackay Mountains (M; Bradshaw *et al*., 1983) (Fig. 3). To the east, at Milan Rock on the Ruppert Coast, there are local erratic blocks of a possible cover succession of Devonian, plant-bearing, fluviatile siltstones (Grindley and Mildenhall, 1981). SHRIMP (Sensitive High Resolution Ion Microprobe) U-Pb zircon age patterns for the Swanson Formation have been previously reported by Pankhurst *et al*. (1998), Adams *et al*. (2013), and Yakymchuk *et al*. (2013): they show dominant age groups of 550-650 Ma and *ca*. 1,000 Ma. Subsequent datasets obtained using LA-ICP-MS (Laser Ablation Inductively Coupled Plasma Mass Spectrometry) reinforced these results (Adams *et al*., 2015; Yakymchuk *et al*., 2015).

From the Ford Ranges to Thurston Island, the early Paleozoic basement is intruded by Late Devonian-Carboniferous, Ford Granodiorite and mid-Cretaceous Byrd Coast Granite (Adams, 1987; Weaver *et al*., 1992; Mukasa and Dalziel, 2000; Yakymchuk *et al*., 2013, 2015; Riley *et al*., 2017).

### 2.6. A Precambrian basement in Western Province of South Zealandia

Late Cretaceous fluviatile sandstones in Westland (Fig. 2), *i.e*., when Zealandia had already separated from Australia, contain a high proportion (~40%) of Proterozoic detrital zircon (*ca*. 1,100 and 800 Ma), interpreted as evidence of underlying Precambrian basement (Adams and Griffin, 2012). Rocks of this age are not found in outcrop in Zealandia, but a sample of granodiorite-gneiss with a biotite K-Ar age of 1,170±10 Ma was dredged from the southwesternmost extremity of Zealandia (S100A; Challis *et al*., 1982) (Fig. 3). Mortimer *et al*. (2016) suggested that this could be a distant (~5000 km) ice-rafted erratic from East Antarctica. In contrast, Adams and Griffin (2012) and Adams *et al*. (2015) preferred a local Zealandia origin at the steep continental scarp edge, supported by rough sea-floor topography above the dredge site. These authors argued for a Precambrian basement source, uplifted and exhumed at the southwestern flank of Zealandia during incipient opening of the Tasman Sea.

### 2.7. Early Paleozoic extent across South Zealandia

Early Paleozoic outcrops across South Zealandia are limited to its western flank (Fig. 3). The ages of detrital zircon in the Cretaceous-Cenozoic cover rocks, the Kawau-1 drillhole basement and rare dredge samples, consistently point to early Paleozoic sources (Adams *et al*., 2016), with no evidence of younger Permian to Cretaceous terrane sedimentary rocks. In Great South Basin boreholes, Late Cretaceous sandstones include Cambrian and Precambrian zircons from sediment sources similar to those of the Greenland Group (Adams *et al*., 2016; Adams and Campbell, 2023). To the west, on Auckland Island (Fig. 3), a mica-schist boulder in the Late Cretaceous Camp Cove Conglomerate has detrital zircon age patterns characteristic of the Greenland Group (Adams *et al*., 2015). In the easternmost sector, metasandstone pebbles dredged from the Bounty Platform have petrographic and geochemical features resembling Greenland Group and Early Ordovician detrital zircons (see above).

The eastern flank of South Zealandia is unclear. Through South Island and Stewart Island (Fig. 2), the boundary with the Eastern Province is everywhere obscured by Jurassic and Cretaceous plutons of the intervening Median Batholith, which have a strong topographic expression, up to 900 m a.s.l., approximately 20 km broad and 200 km long. However, eastwards offshore to ~2,000 m depth on the Campbell Plateau, there is no comparable bathymetric expression of the batholith and no known seafloor granitoid outcrops or dredge samples. Great South Basin oil-exploration boreholes also suggest only Paleozoic basement rocks exposed nearby. Regional magnetic patterns show no significant features attributable to the Median Batholith (Sutherland, 1996, 1999; Maus *et al*., 2009). Indeed, the medium-amplitude magnetic pattern is quite consistent from west to east over much of the Campbell Plateau. Thus, extension of the Median Batholith across the Campbell Plateau should be regarded as unproven and uncertain: early Paleozoic metasedimentary rocks of the Buller Terrane probably extend across the entire Campbell Plateau to its eastern edge.

Comparing detrital zircon age patterns in early Paleozoic sedimentary rocks of Zealandia and Australia/Antarctica, Adams *et al*. (2015) and Adams and Campbell (2023) concluded that Zealandia had only endemic sources and suggested that Mesoproterozoic and late Neoproterozoic basement igneous/metamorphic complexes must have been exposed as enduring sediment sources somewhere within South Zealandia (Fig. 3).

### 2.8. Eastern Province tectonostratigraphic terranes

The Eastern Province of New Zealand may be entirely allochthonous, with all its marine sedimentary basins originally offshore of eastern Australia. Several terranes are now recognized: late Carboniferous, middle to late Permian, Middle to Late Triassic, Jurassic, and late Early Cretaceous (Barremian to Albian) (Mortimer *et al*., 2014). Offshore, the Permian-Triassic Rakaia Terrane makes up the Chatham Rise and Chatham Islands (Adams *et al*., 2008a) (see Fig. 3).

## 3. Detrital zircon provenance studies

U-Pb zircon dating by surface ionisation mass-spectrometry is well established as a tool for investigating sediment and metasediment provenance. It has been intensely applied to early Paleozoic and Mesozoic fold-belts in Australasia. The provenance data share variably defined but clearly separate detrital zircon age groups within the Precambrian-Paleozoic interval. The dominant groups may be related to initial igneous crystallization of zircon during three episodes of supercontinent assembly, as follows:

1. Gondwana assembly (GA), comprising a younger Cambrian-Ordovician interval (GAa, 440-550 Ma) and an older, late Neoproterozoic, interval (GAb, 550-700 Ma).
2. Rodinia assembly (RA), 700-1,600 Ma but especially 900-1,200 Ma.
3. Nuna assembly (NU), 1,800-2,500 Ma but taken here as ages older than 1,600 Ma.

Although broadly similar throughout, the age populations vary somewhat in the relative importance of these primary sources, assessed in previous works as the ratio of the number of analyses in each group, *e.g.*, RA/GA.

Throughout Zealandia, mid-Cambrian to Devonian sandstones have RA/GA ratios of mostly 0.6-0.8 in the Takaka Terrane and mostly 0.8-1.7 in the Buller Terrane, whereas those in southeast Australia have RA/GA ratios <0.7 (Adams and Campbell, 2023).

In the GA group in Australia, the younger GAa subgroup dominates, whilst in the Buller and Takaka terranes it is the GAb subgroup. In Zealandia there are also commonly significant age components at 600-650 Ma, but these are very rare in southeast Australia and North Victoria Land (Adams *et al*., 2015; Adams and Campbell, 2023).

RA components are similar in both southeast Australia and Zealandia, suggesting that the two regions shared a common heritage until Rodinia supercontinental breakup at *ca*. 700 Ma. After this, sediment provenance diverges such that Australia became dominated by GAa magmatic arc sources, principally reflecting the Ross (Ro) and Delamerian (De) orogens (Fig. 3), while Zealandia has endemic provenances related to dominant and somewhat cryptic GAb, late Neoproterozoic, magmatic arcs (SZ, NZ) (Fig. 3). Adams *et al*. (2015) and Adams and Campbell (2023) concluded that this difference reflected Zealandia origins exclusively from two major sources: (1) late Mesoproterozoic, and (2) late Neoproterozoic to Ordovician igneous and metamorphic complexes, with only small RA/GA differences between Buller and Takaka terranes. In addition, Adams and Ramsay (2022, 2025) noted that Late Ordovician sandstones also had dramatically higher proportions (>20%) of pre-2,000 Ma zircons (up to *ca.* 3,650 Ma), reflecting very local and short-lived early Paleoproterozoic-Archean sources. High proportions of unabraded and euhedral grains from all the Zealandia sources suggest relatively short sediment transport distances within and/or across the South Zealandia continent (Adams and Ramsay, 2022, 2025; Adams and Campbell, 2023).

## 4. Samples

Further work was undertaken to confirm a Paleozoic basement connection between Zealandia and western Marie Byrd Land. Three samples from material collected during 1978 and 1988 New Zealand Antarctic Research Programme expeditions were selected for detrital zircon geochronology. Two are lowest metamorphic grade Swanson Formation metasandstones: (1) MB204, a grey-green, moderately volcaniclastic metasandstone from Mt. Palombo, Mackay Mountains, at the southern margin of the Ford Ranges (Fig. 3), with associated chipwackes (unsorted brecciated greywackes), ripple-marking and carbonate concretions; (2) MB197, a coarse-grained volcaniclastic sandstone within a succession including several augite-crystal tuffs from Lewisohn Nunatak, Ford Ranges, the southeasternmost Swanson Formation outcrop. A third sample, E7A48, of quartz-biotite-paragneiss at Mt Swadener, Alexandra Mountains, Edward VII Peninsula, was analysed mainly to assess whether it could be Swanson Formation.

## 5. Methodology

Sample preparation, zircon separation and analysis closely followed the procedures of previous works, detailed by Adams and Ramsay (2025). U-Pb analyses were performed at the Department of Earth and Environmental Sciences, Macquarie University, Sydney, on an Agilent 7700 Series LA-ICP-MS instrument and Photon Instruments 212 nm laser. Instrumental details, calibration, standardisation, and common Pb corrections are described in Jackson *et al*. (2004), Adams *et al*. (2015), and Adams and Ramsay (2025). The outer parts of grains were targeted, close to dihedral terminations where possible; grain cores were not analysed. Common-Pb corrections had a trivial effect on $^{206}Pb/^{238}U$ age calculations. Only ages <10% discordant were accepted.

Full U, Pb, Th isotopic ratios and abundances, individual zircon age data, individual zircon grain morphologies, and significant age components are given in the Supplementary Material. The new data (zircon age and generalised morphology) are summarised and sorted by calculated $^{206}Pb/^{238}U$ age in table 1. In the results for each sample, 'components' representing possibly significant events are identified by weighted means of any three or more ages that overlap within 2-sigma uncertainty.

## 6. Results

All samples show a broad range of ages, with prominent Ordovician, Cambrian, late Neoproterozoic and late Mesoproterozoic clusters, comparable to the previous results mentioned above. The youngest concentrations (Table 1), discounting very few single ages, give weighted mean ages of 520-530 Ma for MB197, 470-480 for MB204, and 530-540 Ma for E7A48 (but, given the low number of measurements, possibly as young as *ca*. 440 Ma). Although strictly these record only maximum possible ages of sedimentation, all are for large euhedral zircon grains and are consistent with Cambrian, Ordovician, and perhaps Silurian deposition, respectively.

Probability density/histogram plots using Isoplot 3.00 (Ludwig, 2003) are shown in figure 4, not including E7A48, for which the data are sparse. To better represent Edward VII Peninsula outcrops, a slightly modified previous U-Pb age plot is shown for Drummond Peak, Swanson Formation sample E7A11 (Adams *et al*. 2015). Data for this sample are included in the Supplementary Material. Selected published plots for samples from Zealandia are also shown in figure 4 for critical comparison. A detailed analysis of the constituent zircon age groups for Marie Byrd Land and Zealandia is shown in figure 5.

Despite variations in the methodologies employed, the broad similarity of the patterns for all these samples is clear. The Marie Byrd Land samples show the main RA and GA age groups familiar in Western Province Buller Terrane datasets and, with the exception of those analysed by SHRIMP (indicated in Fig. 5), comparable RA/GA ratios of 0.6-0.9. In the GA groups, the GAb subgroup is prominent and includes 600-650 Ma components (both characteristic of Zealandia). Euhedral zircons dominate (up to 80%) throughout the datasets (Table 1), particularly in the youngest grains, indicating that they did not suffer long distance transport or multiple sedimentation cycles. An early Cambrian age of *ca*. 520 Ma or younger would not be unreasonable for MB197 at Lewisohn Nunatak, as for schist CAMZ4 from Campbell Island and perhaps Greenland Group sandstone ZMB1 from South Westland (Fig. 5). Similarly, an Early Ordovician age of *ca*. 475 Ma or younger is possible for MB204 at Mt Palombo and sandstone E7A11 at Drummond Peak, Edward VII Peninsula. E7A11 has a high proportion of subhedral grains, especially in the GAb subset (40%; Supplementary Material) and is similar to many Ordovician examples in the Western Province (Adams and Campbell, 2023). However, paragneiss E7A48 (Mt Swadener) contains almost entirely euhedral grains with 50% as GA zircons and the youngest are Late Ordovician (Fig. 5; Table 1); this paragneiss most probably has a Swanson Formation protolith. Older and rather scattered NU grains, *i.e.*, >1,600 Ma, extending into the Archean, constitute about 5% of the total in the Ford Ranges and up to 20% on Edward VII Peninsula (Fig. 5; Table 1); even so they may be under-represented due to the avoidance of zircon cores during analysis.

## 7. Discussion

### 7.1. Zealandia into Antarctica

The South Zealandia area is comparable to that of France (~$10^6$ km$^2$), yet its early Paleozoic outcrops

**TABLE 1. U-PB ZIRCON AGES AND MORPHOLOGY, EARLY PALEOZOIC ROCKS, MARIE BYRD LAND.**

**(1) MB197 (R7396) volcaniclastic sandstone, Lewisohn Nunatak, Ford Ranges, Lat. 77°38' S, Long. 142°49' W.**

| Analysis | $^{206}Pb/^{238}U$ Age | 1σ | Comp. age | Size | L/D | Shape | Analysis | $^{206}Pb/^{238}U$ Age | 1σ | Comp. age | Size | L/D | Shape | Analysis | $^{206}Pb/^{238}U$ Age | 1σ | Comp. age | Size | L/D | Shape |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MB197-45 | 512 | 4 | - | m | 1 | eu | MB197-30 | 646 | 9 | - | m | 1 | sh | MB197-51 | 927 | 6 | - | m | 1 | eu |
| MB197-43 | 519 | 4 | - | s | 1 | eu | MB197-02 | 648 | 4 | - | l | 2 | eu | MB197-16 | 943 | 12 | - | l | 1 | sh |
| MB197-48 | 520 | 4 | 526±3 | m | 1 | eu | MB197-49 | 654 | 4 | - | l | 1 | eu | MB197-01 | 965 | 7 | - | m | 1 | eu |
| MB197-35 | 529 | 3 | n=5 | s | 1 | eu | MB197-26 | 662 | 9 | 659±5 | m | 1 | eu | MB197-04X | 972 | 7 | - | l | 1 | eu |
| MB197-46 | 530 | 4 | - | m | 1 | eu | MB197-33 | 662 | 4 | n=4 | m | 1 | sh | MB197-05 | 1004 | 6 | - | l | 1 | eu |
| MB197-25 | 532 | 5 | - | s | 1 | eu | MB197-09 | 665 | 11 | - | m | 1 | eu | MB197-07 | 1047 | 6 | - | m | 1 | eu |
| MB197-19 | 549 | 3 | - | l | 2 | sh | MB197-28 | 763 | 5 | - | l | 1 | eu | MB197-34 | 1060 | 8 | - | m | 2 | eu |
| MB197-41 | 554 | 3 | - | l | 1 | eu | MB197-32 | 768 | 7 | - | m | 1 | sh | MB197-21 | 1192 | 7 | - | l | 2 | eu |
| MB197-22 | 586 | 4 | - | m | 1 | eu | MB197-23 | 793 | 4 | - | l | 1 | eu | MB197-08 | 1455 | 28 | - | l | 1 | eu |
| MB197-29 | 589 | 4 | - | m | 1 | sh | MB197-31 | 802 | 6 | - | l | 1 | eu | MB197-40 | 1623 | 9 | - | m | 1 | eu |
| MB197-27 | 617 | 4 | - | m | 1 | eu | MB197-10 | 810 | 6 | - | l | 1 | ro | MB197-44 | 2492 | 21 | - | l | 2 | eu |
| MB197-06 | 618 | 4 | 627±3 | l | 1 | eu | MB197-42 | 865 | 8 | - | l | 2 | eu | MB197-39 | 2866 | 12 | - | s | 1 | eu |
| MB197-24 | 626 | 6 | n=5 | s | 1 | sh | MB197-11 | 877 | 6 | 886±9 | l | 1 | sh | - | - | - | - | - | - | - |
| MB197-37 | 631 | 3 | - | m | 1 | eu | MB197-14 | 896 | 14 | n=3 | m | 1 | eu | - | - | - | - | - | - | - |
| MB197-50 | 633 | 3 | - | m | 1 | eu | MB197-36 | 899 | 8 | - | m | 2 | eu | - | - | - | - | - | - | - |

**(2) MB204 (R7403), metasandstone, Mt. Palombo, Mackay Mts, Ford Ranges, Lat. 77°30'S, Long. 143°08'W.**

| Analysis | $^{206}Pb/^{238}U$ Age | 1σ | Comp. age | Size | L/D | Shape | Analysis | $^{206}Pb/^{238}U$ Age | 1σ | Comp. age | Size | L/D | Shape | Analysis | $^{206}Pb/^{238}U$ Age | 1σ | Comp. age | Size | L/D | Shape |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| mb204-32 | 470 | 5 | 479±3 | m | 1 | eu | mb204-88 | 596 | 7 | - | s | 1 | eu | mb204-34 | 865 | 11 | - | l | 2 | sh |
| mb204-27 | 474 | 4 | n=3 | m | 2 | eu | mb204-78 | 601 | 5 | - | l | 2 | eu | mb204-28 | 880 | 5 | - | l | 1 | eu |
| mb204-46 | 485 | 3 | - | l | 2 | eu | mb204-63 | 603 | 5 | 604±5 | m | 1 | eu | mb204-64 | 923 | 9 | - | m | 1 | sh |
| mb204-33 | 492 | 5 | - | m | 1 | sh | mb204-87 | 606 | 5 | n=6 | m | 1 | eu | mb204-94 | 926 | 7 | - | m | 1 | eu |
| mb204-74 | 523 | 3 | - | l | 2 | eu | mb204-30 | 608 | 7 | - | m | 1 | eu | mb204-01 | 939 | 5 | - | l | 2 | eu |
| mb204-04 | 528 | 4 | 528±4 | m | 1 | eu | mb204-83 | 608 | 5 | - | l | 1 | eu | mb204-43 | 956 | 7 | - | l | 2 | eu |
| mb204-79 | 532 | 5 | n=4 | s | 1 | an | mb204-76 | 613 | 4 | - | m | 1 | sh | mb204-11 | 972 | 6 | - | l | 2 | eu |
| mb204-100 | 534 | 4 | - | l | 1 | eu | mb204-03 | 618 | 8 | - | l | 2 | eu | mb204-86 | 996 | 9 | - | l | 2 | eu |
| mb204-75 | 538 | 3 | - | m | 1 | eu | mb204-42 | 636 | 7 | - | l | 2 | sh | mb204-65 | 1010 | 11 | 1010±9 | l | 1 | eu |
| mb204-08 | 546 | 5 | 548±5 | m | 1 | eu | mb204-61 | 639 | 4 | - | m | 1 | eu | mb204-99 | 1014 | 8 | n=4 | m | 1 | eu |
| mb204-13 | 548 | 4 | n=3 | l | 1 | eu | mb204-97 | 646 | 4 | 644±5 | m | 1 | eu | mb204-35 | 1017 | 8 | - | l | 1 | eu |
| mb204-90 | 549 | 4 | - | l | 1 | eu | mb204-39 | 649 | 5 | n=4 | l | 1 | eu | mb204-40 | 1044 | 6 | - | m | 1 | eu |
| mb204-80 | 556 | 7 | - | s | 2 | eu | mb204-18 | 650 | 11 | - | m | 1 | eu | mb204-21 | 1065 | 9 | 1069±9 | l | 2 | sh |
| mb204-20 | 557 | 4 | 557±5 | l | 2 | eu | mb204-53 | 664 | 12 | - | l | 1 | sh | mb204-67 | 1070 | 7 | n=3 | l | 2 | eu |
| mb204-60 | 557 | 4 | n=5 | l | 1 | eu | mb204-92 | 672 | 9 | - | m | 2 | eu | mb204-96 | 1071 | 8 | - | l | 1 | eu |
| mb204-72 | 557 | 7 | - | l | 2 | sh | mb204-77 | 676 | 4 | 677±5 | s | 1 | eu | mb204-69 | 1099 | 9 | - | m | 1 | eu |
| mb204-29 | 558 | 9 | - | m | 1 | eu | mb204-52 | 677 | 4 | n=5 | l | 2 | sh | mb204-62 | 1156 | 8 | - | m | 1 | eu |
| mb204-41 | 562 | 7 | - | l | 2 | eu | mb204-16 | 678 | 7 | - | l | 1 | sh | mb204-05 | 1194 | 10 | - | m | 1 | eu |
| mb204-25 | 564 | 6 | 566±5 | l | 2 | eu | mb204-70 | 679 | 12 | - | s | 1 | ro | mb204-17 | 1255 | 19 | - | m | 1 | eu |
| mb204-98 | 567 | 4 | n=4 | m | 1 | sh | mb204-85 | 687 | 4 | - | m | 1 | eu | mb204-68 | 1597 | 9 | - | l | 1 | eu |
| mb204-45 | 568 | 5 | - | | | | mb204-93 | 772 | 5 | - | m | 2 | eu | mb204-66 | 1632 | 10 | - | s | 1 | sh |
| mb204-15 | 575 | 7 | - | l | 1 | eu | mb204-26 | 821 | 8 | - | l | 1 | eu | mb204-91 | 1693 | 17 | - | l | 2 | eu |
| mb204-82 | 585 | 9 | - | m | 1 | eu | mb204-54 | 841 | 15 | - | l | 2 | eu | mb204-73 | 2164 | 18 | - | m | 1 | sh |
| - | - | - | - | - | - | - | mb204-89 | 864 | 6 | - | s | 1 | eu | mb204-09 | 2296 | 52 | - | l | 1 | eu |

**table 1 continued.**

**(3) E7A48 (R13200), mica-schist, Mt Swadener, Alexandra Mts, Edward VII Penin., Lat. 76°16'S, Long. 153°47'W.**

| Analysis | $^{206}Pb/^{238}U$ Age | 1σ | Comp. age | Size | L/D | Shape | Analysis | $^{206}Pb/^{238}U$ Age | 1σ | Comp. age | Size | L/D | Shape | Analysis | $^{206}Pb/^{238}U$ Age | 1σ | Comp. age | Size | L/D | Shape |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E7A48-6 | 433 | 7 | - | l | 1 | eu | E7A48-2 | 585 | 9 | - | l | 2 | eu | E7A48-8 | 1979 | 28 | - | l | 2 | eu |
| E7A48-7 | 443 | 5 | - | l | 2 | eu | E7A48-14 | 585 | 7 | - | m | 1 | eu | E7A48-13 | 2119 | 21 | - | l | 1 | sh |
| E7A48-17 | 455 | 7 | - | l | 2 | eu | E7A48-11 | 708 | 9 | - | l | 2 | eu | E7A48-4 | 2623 | 41 | - | l | 1 | eu |
| E7A48-20 | 475 | 6 | - | m | 1 | eu | E7A48-18 | 909 | 13 | - | l | 1 | sh | - | - | - | - | - | - | - |
| E7A48-19 | 493 | 7 | - | m | 1 | eu | E7A48-21 | 934 | 12 | 1015±12 | m | 1 | eu | - | - | - | - | - | - | - |
| E7A48-5 | 499 | 6 | - | l | 2 | eu | E7A48-16 | 1000 | 15 | n=4 | m | 1 | eu | - | - | - | - | - | - | - |
| E7A48-3 | 530 | 6 | 535±7 | l | 2 | eu | E7A48-12 | 1010 | 11 | - | l | 1 | eu | - | - | - | - | - | - | - |
| E7A48-10 | 537 | 6 | n=3 | l | 2 | eu | E7A48-15 | 1017 | 11 | - | l | 2 | eu | - | - | - | - | - | - | - |
| E7A48-1 | 539 | 6 | - | l | 2 | eu | E7A48-22 | 1030 | 13 | - | m | 2 | eu | - | - | - | - | - | - | - |

**Notes**:
*accepted set: 206/238 and 207/235 zircon age concordance outside 99% confidence limits not included in probablity density estimates.
Gondwana association (GA), unshaded; RA, light shading; NU, dark shading.
n = component (overlapping errors at 2σ).
Size: max. length in microns (s=50, m=100, l=>100); L/D: nominal length to diameter ratio.
Shape: eu: euhedral grains, >4 crystal faces recognised; sh: shbhedral: moderately abraded grains, but recognisable faces remain; ro: rounded grains, no crystal faces remain; an: anhedral grains, no crystal faces

are mainly in western South Island, with only tiny outposts on Campbell Island and Bounty Platform (Fig. 3). Understanding regional Gondwana-wide differences such as age, depositional environment and sediment provenance across such a largely unknown area has to rely on this very sparsely spaced dataset.

In Paleozoic times, the southernmost Buller Terrane (ZMB1; Fig. 4) would have been situated much farther south (in a present-day sense), adjacent to the Campbell Plateau escarpment and south of Auckland Islands. The localities of ZMB1 and CAMZ4 would have been closer together, in a region underlain by Precambrian basement according to Adams and Griffin (2012) and Adams *et al*. (2015). The 1,170±10 Ma, granodiorite-gneiss seafloor dredge-sample (S100A) might represent such local basement.

The detrital zircon age patterns of these samples extending eastwards across South Zealandia retain general Buller Terrane characteristics with little significant variation as far as the Bounty Islands. These are: RA/GA ratios >0.7, GAb proportions dominating GAa (Fig. 5), common components at *ca.* 600-650 Ma, and high proportions of euhedral grains (Adams and Campbell, 2023). The RA zircon group is consistently dominated by Mesoproterozoic 1,000-1,100 Ma ages (Figs. 4 and 5). Takaka Terrane detrital zircon patterns are also comparable, perhaps with slightly higher NU proportions in the Ordovician deposits (Fig. 5). However, the Takaka Terrane shows greater lithostratigraphic variation (volcanic, carbonate, black shale, quartzite) compared with the rather monotonous, passive-margin Buller Terrane environment (sandstone, siltstone).

The above 'Buller-type' features are seen in the data from the Swanson Formation. It is proposed that this early Paleozoic metasedimentary basement of South Zealandia extends southwards to encompass western Marie Byrd Land. This would require source areas of comparable extent supplying siliciclastic sediments from relatively local igneous and/or metamorphic complexes of Mesoproterozoic and late Neoproterozoic age. As noted above, the high proportions of euhedral zircons argue against distant sediment transport. It is therefore suggested that several medium-scale rivers radiated from a central (1,000 km scale) source region and flowed towards the north, west and south margins of South Zealandia.

The South Zealandia early Paleozoic zircon age patterns commonly show age gaps at 700-900 Ma (Fig. 4), *i.e.*, during continental re-organization presaging the birth of Gondwana. There are exceptions to this age gap at the eastern and southern margins, *e.g.*, MB197 at Lewisohn Nunatak and Kawau-1, Great South Basin (Fig. 4). A possible

Early Paleozoic-Precambrian detrital zircon age percentages in Zealandia and Marie Byrd Land

| Sample name | Age range | GA 444-700 | RA 700-1600 | RA/GA | | GAa 440-550 | GAb 550-700 | RAa 700-900 | RAb 900-1600 | NUa 1600-2500 | NUb >2500 | Ma |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1. WESTERN ZEALANDIA*** | | | | | | | | | | | | Data source |
| *Buller Terrane* | | | | | | | | | | | | |
| AOM1 (Fig. 4) | Ord | 54 | 42 | 0,8 | | 20 | 34 | 10 | 32 | 2 | | 1 |
| SALS2 | Ord | 55 | 41 | 0,7 | | 17 | 38 | 12 | 28 | 3 | 1 | 1 |
| WB2 | Ord | 34 | 54 | 1,6 | | 18 | 16 | 8 | 46 | 5 | 5 | 1 |
| 14MBX | Ord | 41 | 50 | 1,2 | | 13 | 29 | 10 | 40 | 7 | 1 | 1 |
| LYX1 | Ord | 48 | 46 | 1,0 | | 13 | 35 | 17 | 29 | 5 | | 1 |
| ZR1 | Ord | 33 | 49 | 1,5 | | 14 | 19 | 9 | 40 | 13 | 4 | 1 |
| RFTH2 | Ord | 50 | 41 | 0,8 | | 22 | 28 | 7 | 34 | 4 | 4 | 1 |
| ZYXX1 | Ord | 44 | 48 | 1,1 | | 15 | 29 | 11 | 33 | 6 | 6 | 1 |
| WPI1 | Ord | 33 | 49 | 1,5 | | 19 | 14 | 10 | 39 | 17 | 1 | 1 |
| JBX1 | Ord | 48 | 38 | 0,8 | | 20 | 28 | 9 | 31 | 12 | 2 | 1 |
| ZMB1 (Fig. 4) | Ord | 36 | 47 | 1,3 | | 14 | 22 | 9 | 40 | 14 | 3 | 1 |
| PROV1 | Ord | 45 | 47 | 1,0 | | 9 | 36 | 11 | 36 | 6 | 2 | 1 |
| *Campbell Island and Campbell Plateau* | | | | | | | | | | | | |
| AUX24 | ?Ord | 62 | 36 | 0,6 | | 36 | 26 | 8 | 28 | 2 | | 1 |
| CAM11 | Cam | 30 | 51 | 1,7 | << | 10 | 20 | 9 | 42 | 15 | 4 | 2 |
| CAMZ4 (Fig. 4) | Cam | 49 | 36 | 0,7 | | 2 | 47 | 15 | 31 | 14 | 2 | 5 |
| Kawau-1 (Fig. 4) | ?Ord | 42 | 45 | 1,1 | | 15 | 27 | 22 | 23 | 10 | 2 | 1 |
| ***2. WEST ANTARCTICA*** | | | | | | | | | | | | |
| *Marie Byrd Land - Edward VII Peninsula* | | | | | | | | | | | | |
| E7A11 (Fig. 4) | | 45 | 37 | 0,8 | | 9 | 36 | 7 | 30 | 10 | 6 | 1,7 |
| Z1851 | | 30 | 53 | 1,7 | << | 7 | 22 | 13 | 40 | 17 | | 3 |
| E7A48 | | 50 | 36 | 0,7 | | 38 | 10 | 5 | 30 | 10 | 5 | 7 |
| *Marie Byrd Land - Ford Ranges and Kohler Range* | | | | | | | | | | | | |
| MB204 (Fig. 4) | | 61 | 34 | 0,6 | | 13 | 48 | 8 | 25 | 6 | | 7 |
| MB197 (Fig. 4) | | 51 | 42 | 0,8 | | 14 | 37 | 21 | 21 | 5 | 2 | 7 |
| 26,2 | | 46 | 43 | 0,9 | << | 18 | 29 | ç | 29 | 8 | 3 | 2 |
| MURZ1 (MB.422.6S) | | 47 | 48 | 1,0 | << | 23 | 24 | 24 | 24 | 1 | | 3 |
| ***3. EASTERN ZEALANDIA*** | | | | | | | | | | | | |
| *Takaka Terrane* | | | | | | | | | | | | |
| ELL1 | Sil | 44 | 45 | 1,0 | | 24 | 20 | 9 | 36 | 14 | 4 | 1 |
| WGPY2 | Sil | 49 | 41 | 0,8 | | 17 | 32 | 8 | 33 | 5 | 4 | 1 |
| WGPKX3 | Sil | 48 | 38 | 0,6 | | 28 | 21 | 6 | 32 | 7 | 7 | 1 |
| TAKX10 | Sil | 46 | 46 | 1,0 | | 9 | 37 | 15 | 31 | 14 | 4 | 1 |
| TAKX9 | Sil | 76 | 16 | 0,2 | | 60 | 16 | 3 | 13 | 5 | 2 | 1 |
| TAK1 | Ord | 40 | 31 | 0,8 | | 10 | 30 | 13 | 19 | 16 | 13 | 1 |
| TAK1c | Ord | 43 | 23 | 0,5 | | 4 | 39 | 6 | 17 | 13 | 20 | 4 |
| TAK1X | Ord | 48 | 30 | 0,6 | | **23** | **25** | **11** | **19** | **7** | **15** | 4 |
| TAK2 | Ord | 39 | 33 | 0,8 | | 13 | 26 | 11 | 22 | 16 | 13 | 1 |
| TAK2c | Ord | 38 | 31 | 0,8 | | 2 | 35 | 8 | 23 | 12 | 21 | 4 |
| TAK2X | Ord | 49 | 29 | 0,6 | | **13** | **36** | **8** | **21** | **13** | **9** | 4 |
| ANAX1 | Ord | 37 | 32 | 0,9 | | **10** | **27** | **7** | **25** | **14** | **17** | 6 |
| WGPY3 (Fig. 4) | Cam | 52 | 38 | 0,7 | | 23 | 29 | 9 | 29 | 6 | 4 | 1 |
| COBX1 | Cam | 40 | 51 | 1,3 | | 9 | 31 | 10 | 41 | 6 | 4 | 1 |
| JCT21 | Cam | 40 | 37 | 0,9 | | 9 | 32 | 11 | 26 | 18 | 5 | 1 |
| JCT1 | Cam | 53 | 31 | 0,6 | | 4 | 49 | 9 | 22 | 14 | 2 | 1 |

<< SHRIMP data

| KEY: | | |
|---|---|---|
| <0.8 | | 0-10% |
| 0.8-1.0 | | 10-20% |
| 1.0-1.2 | | 20-30% |
| >1.2 | | 30-40% |
| | | >40% |

FIG. 5. Detrital zircon ages in Ordovician and Cambrian sandstones across southern Zealandia and West Antarctica as percentages of totals for each sample. GA, RA, and NU are notionally derived from Gondwana, Rodinia, and Nuna assemblies, respectively. Datasets within each area are arranged in rough stratigraphic order. Data sources: **1.** Adams *et al*. (2015). **2.** Adams *et al*. (2012). **3.** Pankhurst *et al*. (1998). **4.** Adams and Ramsay (2022). **5.** Adams and Campbell (2023). **6.** Adams and Ramsay (2025). **7.** This work.

Swanson Group paragneiss, MB.422.6S, at Mt Murphy in eastern Marie Byrd Land (Pankhurst *et al*., 1998) could also be included here (sample MURZ1 in Fig. 5). All have >20% RA zircons in this 700-900 Ma interval, interpreted as indicating local but cryptic sources.

### 7.2. Zealandia neighbours in the early Paleozoic: Australia and East Antarctica

There is some evidence that the early Paleozoic 'Buller-type' rocks of South Zealandia extend northwards on to Challenger Plateau (Figs. 2

and 3). This has a uniform submarine topography (at 1,000 m depth) with no evidence of basement outcrop apart from a single Carboniferous-Devonian granite sample dredged from its northwest margin (Tulloch *et al*., 1991). The regional magnetic anomaly pattern along western South Island, the Challenger Plateau and South Lord Howe Rise (Figs. 1 and 3) is similar to that west to east across the Campbell Plateau (EMAG2 compilation; Maus *et al*., 2009), which is taken to reflect the presence of early Paleozoic rocks and younger granitoids. In the mid-Cretaceous Gondwana reconstruction of figure 3, the Challenger Plateau is adjacent to the South Tasman Rise, from where Fioretti *et al*. (2005) reported a dredged syenite dated at *ca.* 1,150 Ma. This would allow correlation with gneiss sample S100A (see above), representing the proposed South Zealandia Mesoproterozoic basement. It should be noted that a Precambrian basement block (NZ in Fig. 3), exhumed in Triassic time, also occurs on the North Lord Howe Rise (Adams *et al*., 2022).

As discussed above, detrital zircon studies place Zealandia as a discrete continental block within Gondwana that was separated from eastern Australia by a broad marine depositional basin throughout the early Paleozoic. Along its Australian margin, the distinctive RA and GAa zircon patterns have possible provenance in the *ca.* 500 Ma granitoids and metamorphic basement of the Ross-Delamerian orogen and inboard Mesoproterozoic (1,000-1,200 Ma) and Paleoproterozoic (1,700-1,900 Ma) basement complexes of central Australia (Fig. 3). The Ross-Delamerian orogen influence continues at least into the coastal area of adjacent North Victoria Land, East Antarctica and beyond (Bradshaw, 2023). The proportions of these major age groups and their significant components resemble those of the early Paleozoic rocks of Zealandia, implying a common provenance. Farther inland and southwards into South Victoria Land there are higher grade rocks of Neoproterozoic to earliest Cambrian depositional age, metamorphosed or injected by late Cambrian granites, which have high proportions of GAb and Mesoproterozoic RA (1,000-1,100 Ma, ~30%) and early Paleoproterozoic or Archean zircons (>2,000 Ma, ~25%) (Wysoczanski and Allibone, 2004; Adams *et al*., 2013). In the Cambrian-Ordovician metasedimentary rocks of Zealandia, such high proportions of >2,000 Ma zircons (>30%, Fig. 5) are restricted to the Takaka Terrane and within a narrow Late Ordovician stratigraphic interval (*ca*. 445 Ma; Adams and Ramsay, 2025). In the Buller Terrane and Marie Byrd Land, pre-2,000 Ma zircons constitute less (<20%, Fig. 5).

This same pattern of 'outboard' syn-Ross detritus and 'inboard' pre-Ross metamorphic rocks continues into the Central Transantarctic Mountains (Goodge *et al*., 2002, 2004). The inboard belt includes the Mesoarchean to Paleoproterozoic Nimrod Complex, which underwent *ca*. 1,700 Ma high-grade metamorphism but shows discordant zircon age evidence of an Archean protolith >2,700 Ma (Goodge and Fanning, 1999, 2016; Goodge *et al*., 2001). It also includes Neoproterozoic metasedimentary rocks of the Beardmore Group containing dominantly RA zircons and no GA age components (Goodge *et al.*, 2002, 2004).

A granitic glacial boulder from the Central Transantarctic Mountains (Goodge *et al*., 2008), presumably originating beneath the East Antarctic icecap, was dated at *ca.* 1,440 Ma; this is a distinctive age of particular relevance to the SWEAT model for a Precambrian connection between East Antarctica and southwest Laurentia (Dalziel, 1991; Moores, 1991; Borg and DePaolo, 1994; Goodge *et al*., 2008). Subsequently, a larger range of Paleoproterozoic and Mesoproterozoic ages has been obtained from glacial erratics with Laurentian affinities, including 1,400-1,500 Ma (Goodge *et al.*, 2017). Both *ca.* 1,700 Ma and *ca.* 1,400 Ma ages are very rare (<2% total) in detrital zircon age compilations from Zealandia (Adams *et al*., 2015) and a similar early Mesoproterozoic (or older) connection with this sector of East Antarctica is considered unlikely.

A Van Dieland microcontinent has been recognised in Tasmania, with unproven extensions into Victoria (Cayley *et al*., 2002; Cayley, 2011; Clemens and Buick, 2019). Late Neoproterozoic siliciclastic high-grade metasedimentary formations of the Tyennan Nucleus and lower-grade Rocky Cape Group include much diminished late Mesoproterozoic (1,000-1,100 Ma) detrital zircons and, in their place, very unusual early Mesoproterozoic to late Paleoproterozoic components (*ca.* 1,400-1,800 Ma) that are also reworked into adjacent Ordovician successions (Black *et al*., 2004; Adams and Campbell, 2023). These features seem to rule out any connection with South Zealandia and more probably reflect provenance within East Antarctica. Van Dieland has to be regarded as an allochthonous microcontinent until its incorporation into the Australia Gondwana margin in Late Ordovician time.

With its particular emphasis on the connection between Laurentia (principally the Grenville Fold Belt and the Mojave, Yavapai, and Mazatzal provinces) and the Central Transantarctic Mountains of East Antarctica, the SWEAT hypothesis could still accommodate Zealandia (Fig. 6) close to its crucial 'piercing points', namely late Mesoproterozoic (*ca.* 1,000-1,100 Ma), early Mesoproterozoic (*ca.* 1,400 Ma) and late Paleoproterozoic (*ca.* 1,700-1,900 Ma) tectonic provinces between East Antarctica and Laurentia. However, there is no convincing 'piercing point' to connect Zealandia and Laurentia. This is a drawback for models that emphasise the Australia-Laurentia connection, like AUSWUS and AUSMEX.

### 7.3. Zealandia neighbours in the early Paleozoic: West Antarctica and Ellsworth Mountains

There are scattered rock exposures along the Ruppert, Hobbs and Wallgreen coasts of central Marie Byrd Land as far as the Amundsen Sea coast (Fig. 3). The basement here comprises mostly late Carboniferous, Permian, Triassic and Jurassic plutonic rocks and occasional indeterminate sedimentary successions upon them, all grouped as an Amundsen Province (Pankhurst *et al*., 1998), here including Thurston Island (Riley *et al*., 2017). It was suggested that this province had connections with southern South America and the southern Antarctic Peninsula, but also possibly one into the Median Tectonic Zone of Zealandia (now redefined as the Median Batholith).

Further inland basement outcrops are extremely scarce, but Pankhurst *et al*. (1998) extend the early Paleozoic basement of western Marie Byrd Land, *i.e.*, Swanson Formation and the younger, Devonian-early Carboniferous, Ford Granites, as far as the Kohler Range and Mt. Murphy (Fig. 3). Extension into the Western Province of New Zealand and the Ross orogen of North Victoria Land have been suggested (Bradshaw, 2023), but correlation over 2,000 km of a late Cambrian orthogneiss (505±5 Ma) at Mt Murphy with a small Zealandia granite unit in Fiordland seems tenuous. On the other hand, a paragneiss at Mt Murphy with both GA and RA has

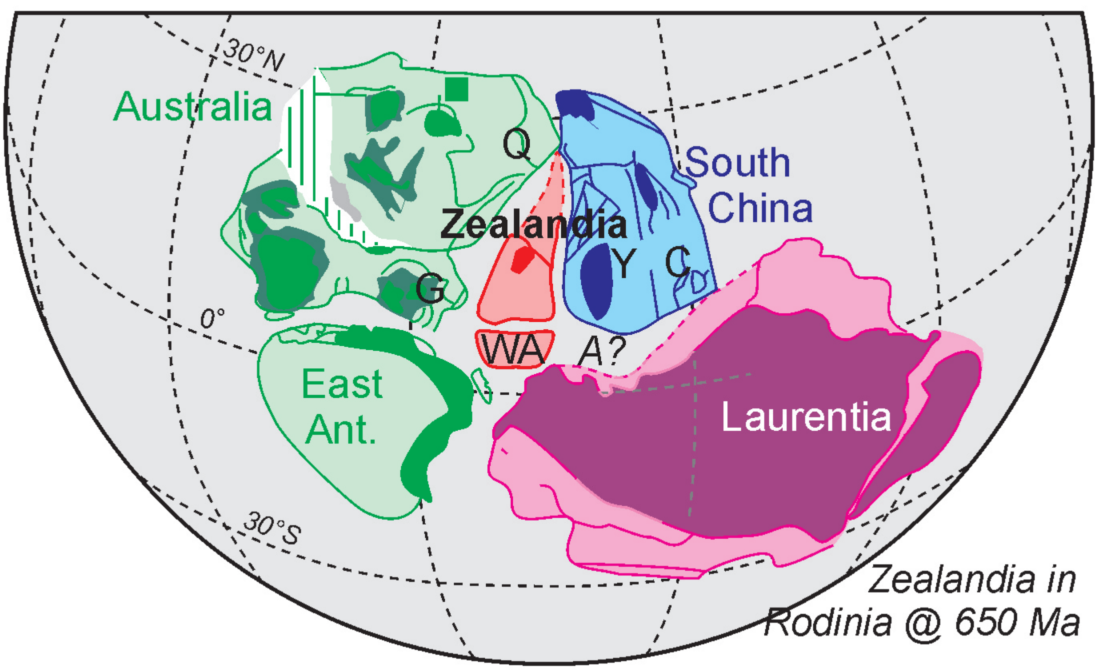


FIG. 6. Reconstruction of the Rodinia supercontinent at *ca.* 650 Ma prior to onset of Gondwana supercontinent assembly (after Adams and Ramsay 2022, based on Li and Evans, 2011). Zealandia is placed within this and includes Marie Byrd Land, West Antarctica (WA). A possible location (**A?**) of southern Argentine cratons (*e.g.*, Río de la Plata, Maz, Arequipa, Río Apa) is also noted. **C**: Cathaysia Block, South China craton; **G**: Gawler Block, South Australia; **Q**: North Queensland cratons (Mt Isa, Coen, Croydon); **Y**: Yangtze Block, South China craton. Shading represents Rodinia (light) and older (dark) continental blocks.

a detrital zircon age pattern typical of the Swanson Formation basement (Pankhurst *et al*., 1998).

Beyond the Amundsen Sea region shown in figure 3, early Paleozoic basement is not recognised for nearly 1,000 km until the Ellsworth Mountains at the southern margin of the Weddell Sea (EM) (Fig. 1), where Cambrian, Devonian and Permian formations have been well-established (Webers *et al*., 1992; Curtis and Lomas, 1999; Flowerdew *et al*., 2007; Craddock *et al*., 2017). Flowerdew *et al*. (2007) reported major age groups at 900-1,150 Ma and 510-750 Ma for Cambrian Heritage Group zircons, and the remainder (~20%) at 1,400-1,750 Ma. The late Mesoproterozoic zircon group might have sources in the 'Grenville' basement seen at Haag Nunataks (Riley *et al*., 2020) or perhaps more distantly in the Falkland Islands (Jacobs *et al*., 1999) (Fig. 1). More recently, Castillo *et al*. (2017) found mainly *ca*. 900-1,300 Ma zircon in the Heritage Group, but with some *ca*. 675 Ma zircon indicating proximal Cryogenian volcanism: igneous and metamorphic zircons of 530-650 Ma were a secondary component. This was taken to show derivation from the paleo-Pacific margin of the Australian-Antarctic plate. The Ellsworth Mountain block has been interpreted as contiguous with the Transantarctic Mountains and East Antarctica during the formation of Gondwana (Castillo *et al*., 2024). Any connection with Zealandia is unclear.

### 7.4. Zealandia neighbours in the early Paleozoic: southern South America

Zealandia could have been much closer to South America in the Paleozoic, prior to complex Mesozoic and Cenozoic seafloor spreading, continental plate movements and Andean subduction. There is little evidence of pre-Devonian basement in the Antarctic Peninsula, but Cambrian and Ordovician detrital zircons are prominent in later rocks (see Riley *et al*., 2023 for summary). Early Cambrian igneous and metamorphic rocks underlie the Magallanes Basin of southern Patagonia and Tierra del Fuego (TF) (Hervé *et al*., 2010) (Fig. 1), including a migmatitic gneiss with inherited zircon ages of *ca*. 560, 620 and (abundant) 900-1,100 Ma. Outcrops of Mesoproterozoic basement (mainly 1,000-1,150 Ma) occur at Haag Nunataks (Riley *et al*., 2020) and in the Falkland Islands (Jacobs *et al*., 1999). These observations are generally taken as indicating a close connection to the proto-Kalahari craton of southern Africa.

Throughout the western margin of South America, Paleozoic and Mesozoic metasedimentary rocks have detrital zircon with dominant ages reflecting two main orogenic events either side of Gondwana assembly: the Pampean (520-545 Ma) and Famatinian (430-490 Ma) orogenies, as well as *ca*. 900-1,100 Ma (*e.g.*, Hervé *et al*., 2003).

Much farther north, the Sierras Pampeanas of northwestern Argentina expose Mesoproterozoic metamorphic basement (1,030-1,330 Ma; Casquet *et al*., 2006; Rapela *et al*., 2010) and both pre-Pampean and post-Pampean metasedimentary and sedimentary rocks. Detrital zircon studies of late Neoproterozoic to early Cambrian low-grade metasediments (Adams *et al*., 2008b, 2011; Ramacciotti, 2018) match sources from the surrounding cratons, *e.g.*, the Paleoproterozoic-Archean Río de la Plata (Rapela *et al*., 2007) and the late Mesoproterozoic Sunsas and MARA cratons (Casquet *et al*., 2012), together with the earliest orogenic magmatism of the Pampean orogen. Late Neoproterozoic-early Cambrian zircon ages (*ca*. 550-750 Ma) derived from the Brasiliano orogen of southeastern Brazil (Brito Neves *et al*., 2014) feature in all the datasets, equivalent to the GAb subgroup in Zealandia. The Western Sierras Pampeanas thus developed in a Cambrian cycle where sources were locally uplifted Neoproterozoic sedimentary rocks and a Pampean orogen core (520-545 Ma), and then, in the Ordovician, Famatinian cycle which now included eastern sources in Paleoproterozoic rocks of the Río de la Plata craton and late Neoproterozoic of the Brasiliano orogen. On a Rodinia supercontinent scale, the latter orogen is commonly associated with its 'Pan-African' counterparts to the east in southern Africa.

In the large dataset of Adams *et al*. (2008b, 2011) it is observed that the RA group dominates (up to 88%) in the late Neoproterozoic deposits but gradually declines to 10% in the late Cambrian, whilst the GA group increases from 0 to 88% over the same interval. RA zircons have significant age components at 1,000-1,100 Ma, with rare early Mesoproterozoic components (*ca*. 1,320 and 1,560 Ma). GA zircons, which are mainly in the GAb subgroup (Fig. 7), have significant age components at 510-530, 550 and 600-630 Ma, all of which are important features of Zealandia datasets

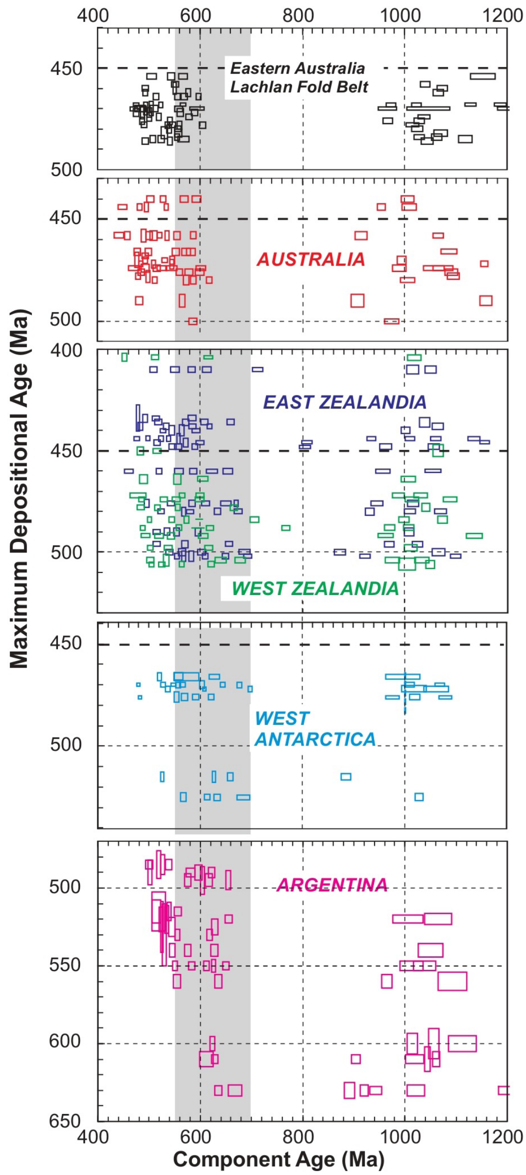


FIG. 7. Detrital zircon significant age components up to 1,200 Ma (not individual zircon ages) in early Paleozoic and Neoproterozoic (meta)sedimentary rocks along the present-day southern Pacific margin of Gondwana. The shaded band corresponds to 550-700 Ma (GAb). The East Zealandia data (mainly from the Takaka Terrane) almost always have good biostratigraphic control, while the West Zealandia data from the Buller Terrane (mostly Greenland Group) only rarely have biostratigraphic control. Significant detrital zircon $^{238}U/^{206}Pb$ age components are plotted on the x-axis, derived from the data of Fergusson and Fanning (2002), Adams *et al*. (2008a, b, 2011, 2015), Glen *et al*. (2017), Adams and Campbell (2023), and this work. The individual sample datasets are stacked vertically from top to bottom in order of ascending maximum biostratigraphic age or, where uncertain, the youngest significant zircon age component, whose position and width on the x-axis represent the component age and error; height on the y-axis represents the proportion of that component in the sample. The horizontal dashed lines at 450 Ma (Late Ordovician) are to facilitate comparison of the depositional age ranges between the different areas.

(see above). Ages >2,000 Ma are commonly present (up to 12%). Sediment provenances for the late Neoproterozoic and early Cambrian rocks were thus proposed within Western Gondwana, in the Sunsas orogen (1,000-1,200 Ma) of southwest Brazil and the Brasiliano orogen (550-750 Ma) of southeast Brazil.

### 7.5. Summary

Figure 7 is a comparison of the U-Pb detrital zircon age groups and their constituent age components using all the data determined by the author and collaborators using a consistent LA-ICP-MS methodology and data analysis over 20 years. The most distinguishable patterns are as follows:

1. Across the SW Pacific margin from Australia to South America there is always a concentration of similar late Mesoproterozoic to early Neoproterozoic (RA, 900-1,000 Ma) source components that reflect a shared Rodinia heritage.
2. Similarly, there are invariably abundant Cambrian-Ordovician (GAa) source components across this region.
3. There is a significant increase in late Neoproterozoic (GAb, 550-700 Ma) source components from almost none in Australia, to common in Zealandia, West Antarctica and Argentina.

The idea of Zealandia and South America sharing a common Rodinia and early Gondwana heritage is intriguing and clearly invites further comparative study of their sedimentary rock chemistry, detrital zircon chronology and Hf-isotope ancestries.

## 8. Conclusions

Detrital zircon U-Pb age populations in late Cambrian to Ordovician, Swanson Formation sandstones on Edward VII Peninsula and in the Ford Mountains of western Marie Byrd Land have principal age groups of early Neoproterozoic to late Mesoproterozoic (900-1,100 Ma) and Early Ordovician to late Neoproterozoic (480-700 Ma). These reflect, respectively, the late stage of assembly of the Rodinia supercontinent and the early tectonic activity associated with Gondwana assembly.

Within these groups, significant age components are commonly *ca.* 520-530, 550-560, 600-620 and 1,000-1,100 Ma. These age populations resemble the widespread age pattern seen throughout the early Paleozoic basement of the Western Province of Zealandia, which continues over much of the Campbell Plateau of New Zealand.

South Zealandia probably has a widespread Mesoproterozoic and late Neoproterozoic-Cambrian basement that was uplifted and endured through early Paleozoic time, providing sediment sources across this region and including western Marie Byrd Land. The latter is thus considered as an integral part of Zealandia.

Zealandia may have provided late Neoproterozoic and Cambrian sediment sources to contemporary metasedimentary basement in adjacent North Victoria Land. Possible continuation of the Zealandia continental margin into the Weddell Sea area remains very uncertain. The comparable detrital zircon age patterns of Zealandia and southern South America show a remarkable shared Cambrian provenance throughout the Western Gondwana margin, but the significance of this relationship has yet to be explored.

**Acknowledgments**

This article is dedicated to the memory of my long-time friend and colleague, J. Bradshaw (1939-2025), from student days at London University and then across fifty years of geological science collaboration, particularly exploring the relationship of the New Zealand region to North Victoria Land in East Antarctica and Marie Byrd Land in West Antarctica. The latter involved both of us in further research very much stimulated and facilitated by Pancho Hervé, in Chile, Argentina, and the Antarctica Peninsula. We always enjoyed his friendly and enthusiastic support for international collaboration in Gondwana research. L. Easterbrook-Clarke, GNS Science Dunedin, is thanked for preparation of map figures.

**Added Note**

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## Supplementary Material

Detrital zircon U-Pb age populations reported from four siliciclastic and volcaniclastic sandstones in late Cambrian to Ordovician, Swanson Formation in the Ford Mountains and on Edward VII Peninsula, western Marie Byrd Land, West Antarctica. E7A11 data are republished from Adams *et al*. (2015), with slight modification and additional information on zircon morphology. The datasets show prominent age groups: early Cambrian to late Neoproterozoic (530-700 Ma) and early Neoproterozoic to late Mesoproterozoic (900-1,100 Ma) that are related respectively to derivation from Gondwana and late Rodinia supercontinental assemblies.