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Key Points:

- A coherent 18 km^2 ophiolite block within the Great Serpentinite Belt, eastern Australia is Early Permian in age
- Cambrian to Ordovician ophiolite inclusions (often <50 m^2) do not date the main ophiolite but are inherited from previous subduction events
- A new reconstruction of the Early Permian east Gondwana paleogeography that incorporates coeval ophiolites in New Zealand and New Caledonia

Supporting Information:

- Supporting Information 1
- Supporting Information 2

Correspondence to:
L. A. Milan,
luke.milan@une.edu.au

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A New Reconstruction for Permian East Gondwana Based on Zircon Data From Ophiolite of the East Australian Great Serpentinite Belt

L. A. Milan[1], E. A. Belousova[2], R. A. Glen[2], T. Chapman[1], J. Kalmbach[1], B. Fu[3], and P. M. Ashley[1]

[1]Division of Earth Sciences, School of Environmental and Rural Science, University of New England, Armidale, NSW, Australia, [2]Australian Research Council Centre of Excellence for Core to Crust Fluid Systems (CCFS)/GEMOC, Department of Earth and Environmental Sciences, Macquarie University, Macquarie, NSW, Australia, [3]Research School of Earth Sciences, Australian National University, Canberra, ACT, Australia

Abstract The Great Serpentinite Belt of eastern Australia is a ∼1500 km long dismembered ophiolite assumed to be Cambrian based on studies of small (typically <50 m^2) exotic meta-igneous inclusions despite contrasting ages (Cambrian—Devonian) and complex P-T histories. To overcome these issues, we studied a ∼18 km^2 coherent block of dismembered ophiolite that provides robust geological context to sampling the ophiolite. Zircon U-Pb-Hf-O isotope and trace analyses from three plagiogranite dykes cutting massive gabbro confirm ∼283–277 Ma ages and a mantle source. As a result, we argue older Cambrian to Devonian plagiogranite and subducted blocks were inherited from previous subduction events in eastern Australia. These findings allow us to match the Great Serpentinite Belt with the contemporary Dun Mountain ophiolite (New Zealand) and the Koh ophiolite (New Caledonia), thus supporting a new, integrated Pacific Gondwana margin paleogeography involving multiple arcs and subduction zones.

Plain Language Summary Ophiolites are fragments of oceanic crust and mantle that have been thrusted onto continents by tectonics. Ophiolites provide important records of oceanic lithosphere and for assessing the timing of significant tectonic events. Previous studies of the Great Serpentinite Belt of eastern Australia, established a ∼530 Myr age. However, studies focused on small (typically < 50 m^2) exotic fault bounded blocks of ophiolitic material of varying geological ages and complex metamorphic histories. By focusing on an intact 18 km^2 fragment of oceanic crust with reliable geological relationships and low degrees of metamorphism, our results show this ophiolite is far younger (∼280 Myr old). This age overlaps with ophiolites in New Caledonia and New Zealand on what was the paleo-Pacific Gondwana margin. This new discovery leads to a new paleogeography for this period and improves geological links between eastern Australia, New Zealand, and New Caledonia.

1. Introduction

Eastern Australia preserves a very detailed record of complex convergent plate margin activity along paleo-Pacific Gondwana. Broadly, the margin is typified by cycles of extension and contraction (e.g., Collins, 2002). Extension cycles occur during brief phases of slab retreat, with resultant metamorphic complexes, S-type granitic magmatism, extensional back-arc basins on the continent with arcs forming offshore. These phases are followed by contraction and a renewal of continental arc magmatism (e.g., Collins & Richards, 2008; Glen, 2013; Jenkins et al., 2002; Jessop et al., 2019).

Despite significant proportions of eastern Gondwana being excised due to rifting and submersion forming the continent Zealandia (Mortimer et al., 2017), geological links have been established between Australia, New Zealand, and New Caledonia (e.g., Mortimer, 2004; Spandler et al., 2005; Tulloch et al., 2009). Along the paleo-Pacific Gondwana margin widespread Early Permian slab roll back and extension produced back-arc basins in Australia, New Zealand, and New Caledonia (Jessop et al., 2019; Maurizot et al., 2020; Robertson et al., 2019). Early Permian ophiolites are now dispersed within Zealandia, e.g., the Dun Mountain (New Zealand) and Koh ophiolites (New Caledonia). Ophiolites are defined as remnants of mafic, ultramafic and minor felsic rocks that represent coherent slivers of oceanic crust and upper mantle that have been

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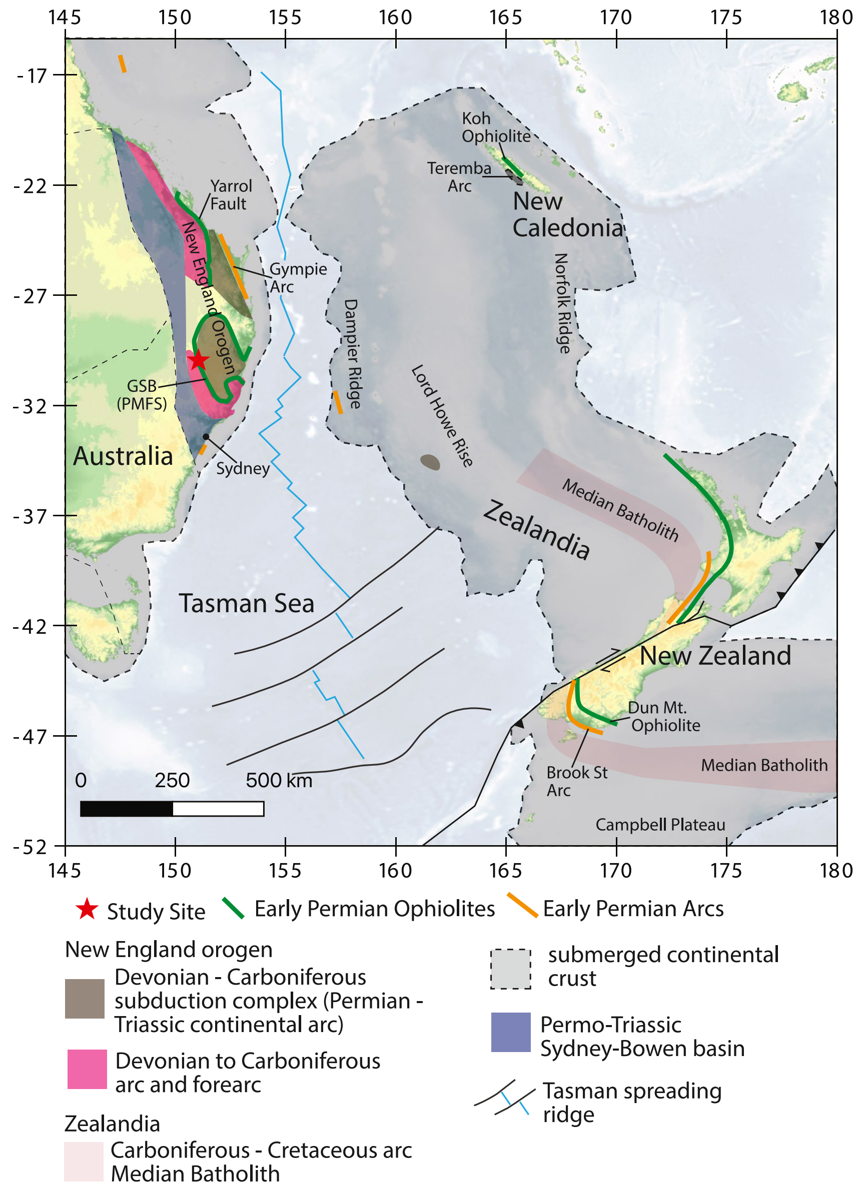

Figure 1. Geological map of eastern Australia (New England Orogen) and Zealandia, incorporating New Zealand and New Caledonia. Adapted from Jugum et al. (2019), Mortimer et al. (2017), Mortimer et al. (2008), and Spandler et al. (2005). Abbreviations: NC, New Caledonia; NZ, New Zealand; NCT, New Caledonia Trough; LHR, Lord Howe Rise, DR, Dampier Ridge; DMO, Dun Mountain Ophiolite; GSB, Great Serpentinite Belt; CP, Campbell Plateau. ETOPO1 global relief model used as base map (Amante, 2009).

tectonically thrusted and obducted onto continental crust. Until now, a contemporary Early Permian ophiolite was unknown in eastern Australia.

1.1. Background Geology

The Australian sector of the eastern Gondwana margin was the site of Cambrian to Cretaceous convergent margin orogens that now comprise the Tasmanides (Glen, 2013). The New England Orogen (NEO) of eastern Australia is the easternmost of these orogens (Figure 1), however terranes of similar age occur further to the east in the rifted Zealandia continent (e.g., Mortimer, 2004). The southern portion of the NEO contains five main components: (1) a Devonian—Carboniferous western arc; (2) a Devonian—Carboniferous central fore-arc basin; (3) an eastern Devonian—Carboniferous accretionary wedge; (4) Early Permian rift basins and related granites hosted within the accretionary wedge; (5) Mid-Permian—Triassic granitoids and coeval felsic volcanic rocks (also hosted within the accretionary wedge) that developed in a continental arc setting (Glen, 2013; Jessop et al., 2019). The boundary between components 2 and 3 is faulted and is known as the Peel Manning Fault System (PMFS). This fault system hosts the Great Serpentinite Belt (GSB) the topic of this study (Figure 1).

The GSB is a ~1500 km belt of dismembered ophiolite hosted within the PMFS. For much of its length, the GSB consists of schistose serpentinite that hosts uncommon meter scale tectonic inclusions of ophiolitic affinity, e.g., plagiogranite (Aitchison & Ireland, 1995; Aitchison et al., 1992) to exotic tectonic inclusions with high-P to low-P metamorphic histories including blueschists and eclogites (Manton et al., 2017; Phillips et al., 2015; Tamblyn et al., 2019). These meter scale inclusions are typically enveloped in schistose serpentinite and exhibit a spread in ages from the Cambrian to the Devonian (~530-377 Ma) (see Table S1 for a compilation of inclusion ages and Aitchison & Ireland, 1995; Aitchison et al., 1992; Manton et al., 2017; Phillips et al., 2015). Despite this age range, the GSB is generally regarded as a dismembered remnant of a Cambrian ophiolite (Manton et al., 2017; Phillips et al., 2015). The first known evidence of movement in the PMFS is Early Permian (Allan & Leitch, 1990; Cross et al., 1987; White et al., 2016).

2. Sample Background

The age of the GSB is critical not just for establishing the history of ophiolite formation, but also for any paleogeographic models of eastern Gondwana. To circumvent the contrasting reported ages from small (typically <50 m^2) metaigneous blocks embedded in schistose serpentinite of the GSB, we have instead focused on a 18 km^2 block of ophiolite near Barraba, 400 km north of Sydney. Here we mapped and sampled a ~1 × 1.5 km area that revealed coherent exposures of lower oceanic crust (see Figure S1). Unlike small exotic tectonic inclusions, the large 18 km^2 block of ophiolite is more suitable to date the age of the majority of the ophiolite. The field area is dominated by gabbro with minor (meter scale) dolerite and plagiogranite dykes, serpentinized ultramafic cumulates (subvertical massive wehrlite and uncommon dunite) and fault bounded mantle harzburgite and schistose serpentinite. This block as a whole preserves an east-younging igneous stratigraphy, in contrast to Blake and Murchey (1988) who reported a west facing sequence in a structurally complex area. The massive gabbro commonly preserves primary textures and originally contained coarse plagioclase and clinopyroxene, with replacement by prehnite, minor chlorite, and tremolite/actinolite due to low-grade metamorphism. Whole rock geochemistry of dolerite dykes within this coherent block of ophiolite have been ascribed to a back-arc setting with affinities transitional between MORB and IAB (Yang & Seccombe, 1997). Three plagiogranite dykes hosted within the gabbro were sampled for in situ zircon U-Pb-Hf-O-isotope and trace analyses. These plagiogranites preserve magmatic textures and contain plagioclase (± quartz) phenocrysts in a groundmass of interlocking plagioclase and minor quartz overprinted by prehnite, sericite, and carbonate. They are classified as quartz diorites or tonalites and range from 71.2 to 73.4 wt% SiO_2,, 0.2–1.5 wt% K_2O and 5.4–7.1 wt% Na_2O. Their metamorphic mineral assemblage is consistent with the metamorphic field gradient in much of the surrounding accretionary complex, at T of 200–300 °C and P of 0.3–0.4 GPa (Phillips et al., 2010).

For comparison, we also resampled the ~3 × 3 m tectonic inclusion of plagiogranite enclosed by schistose serpentinite described by Aitchison et al. (1992) from 30 km north. It is completely recrystallized and contains plagioclase, quartz, Na-Ca amphibole suggestive of low-T (300–400 °C) metamorphism at P of 0.4–1.0 GPa (e.g., Chapman et al., 2019; Pawley, 1992; Shi et al., 2003).

The geological map, field photos, petrography, mineral chemistry, whole rock geochemistry and all details of sample preparation, instrumentation, and zircon analysis can be found in Figures S1–S6, Table S2, and Text S1–S3.

3. Results

3.1. New U-Pb Zircon Geochronology

Zircons from the dykes (GSB03, GSB101 and GSB201) are prismatic (~250 × 50 μm) with magmatic oscillatory zoning. LA-ICPMS analyses of GSB03 zircon yield a concordant single U-Pb age, $^{206}Pb/^{238}U$ weighted

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(a)

in-situ zircon U-Pb-Hf-O isotope data summary

Sample	Type	Lat. Long.	Age (Ma)	ε_{Hf} (avg.)	$\delta^{18}O$(avg.) (‰,VSMOW)
GSB03	plagiogranite dyke	30°17'14.10" S, 150°41'29.5" E	283.0 ± 1.7	13.1	5.68
GSB101	plagiogranite dyke	30°17'22.07"S, 150°41'28.73"E	277.6 ± 1.8	11.7	5.80
GSB201	plagiogranite dyke	30°17'11.00"S, 150°41'12.15"E	278.3 ± 2.2	12.1	5.53
GSB112	plagiogranite inclusion	30° 0'35.09"S, 150°37'38.62"E	c. 535	12.4	3.56

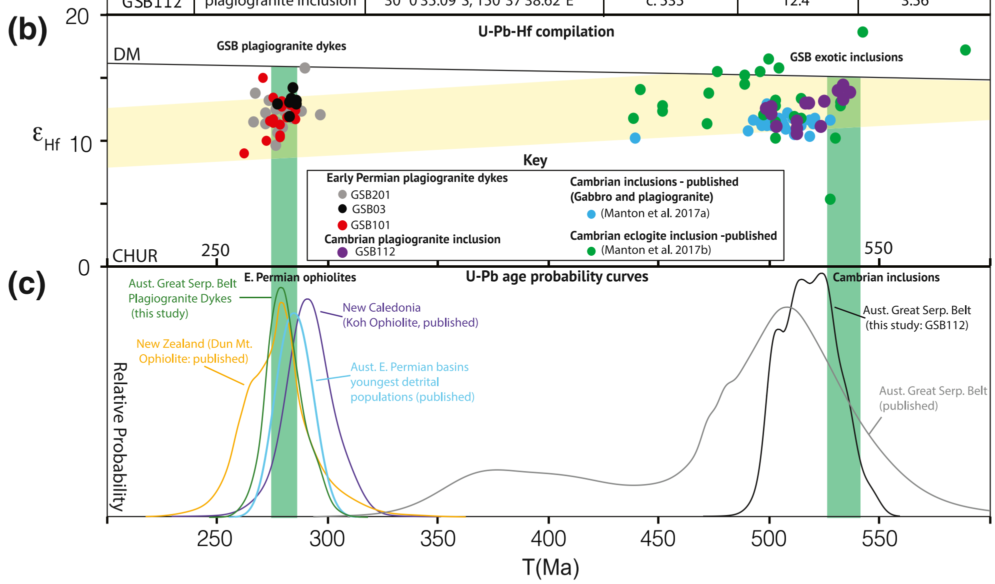

Figure 2. (a) Compilation of zircon U-Pb-Hf-O isotopic data for this study; (b) zircon ε_{Hf} (left axis) versus U-Pb age plot of Permian plagiogranites and Cambrian inclusions from this study, Phillips et al. (2015) and Manton et al. (2017). The sloping yellow bar shows evolution of average mafic crust, $^{176}Lu/^{177}Hf = 0.02$, the vertical green bars mark periods of repeated melting of a common NEO mantle source with model ages ~650–400 Ma; (c) U-Pb age relative probability (vertical axis) versus age plot. The ~280 Ma probability curve peaks emphasize contemporaneous eastern Gondwana margin extension. Probability data compilation: youngest mean population from eastern Australian Permian basins: Campbell et al. (2015), Shaanan et al. (2015) and White et al. (2016); Dun Mountain ophiolite: Jugum et al. (2019), Kimbrough et al. (1992); Koh ophiolite: Aitchison et al. (1998). NEO, New England Orogen.

mean age of 283.0 ± 1.7 Ma (n = 12, 95% confidence level or c.l. with a MSWD of 1.06). GSB101 zircon analyses reveal a more scattered U-Pb data producing a $^{206}Pb/^{238}U$ weighted mean age of 276 ± 1.5 Ma (n = 18, 95% c.l. with a MSWD of 1.3). GSB201 zircon analyses returned a $^{206}Pb/^{238}U$ weighted mean age of 278 ± 1.8 Ma (n = 11, 95% c.l. with a MSWD of 1.4).

Zircons from the exotic block of plagiogranite (GSB112) range from prismatic (~150 × 50 μm) to fragmentary and broken (40–200 μm across). The zircon grains commonly exhibit cracks and are oscillatory zoned. The age analyses range from ~545 to 500 Ma (see Figure S10 and Text S3), most likely indicating a protracted history of Pb loss. The $^{206}Pb/^{238}U$ weighted mean age for the main population is 518 ± 3.2 Ma (n = 13, 95% c.l. with a MSWD of 17). However, we suggest that the older population of six grains that experienced the least Pb loss provides with the best estimate for the age for this exotic block of plagiogranite (weighted mean age of 535 ± 5 Ma (MSWD of 1.3). See supporting information file DS1 for raw data and Figures 7–9 for zircon cathodoluminescence (CL) images and plots.

3.2. Zircon Hf-O Isotopes

Lu-Hf isotope analyses of Early Permian zircons indicate a juvenile source, with ε_{Hf} averages of plagiogranite dykes ranging from +11.7 to +13.1 (Figure 2). An average of 15 ε_{Hf} analyses for the Cambrian plagiogranite (GSB112) is +12.4. T_{DM} crustal Hf Model ages for all samples suggest a ~650–400 Ma source based on $^{176}Lu/^{177}Hf = 0.02$ (Figure 2).

A total of 20 $^{18}O/^{16}O$ SIMS analyses on 17 zircon grains for GSB03 yielded zircon $\delta^{18}O$ of 5.2 – 6.5‰, with an average of 5.7‰. Analyses of GSB101 range from $\delta^{18}O$ 5.16–6.42‰ (n = 8). GSB201 analyses range from

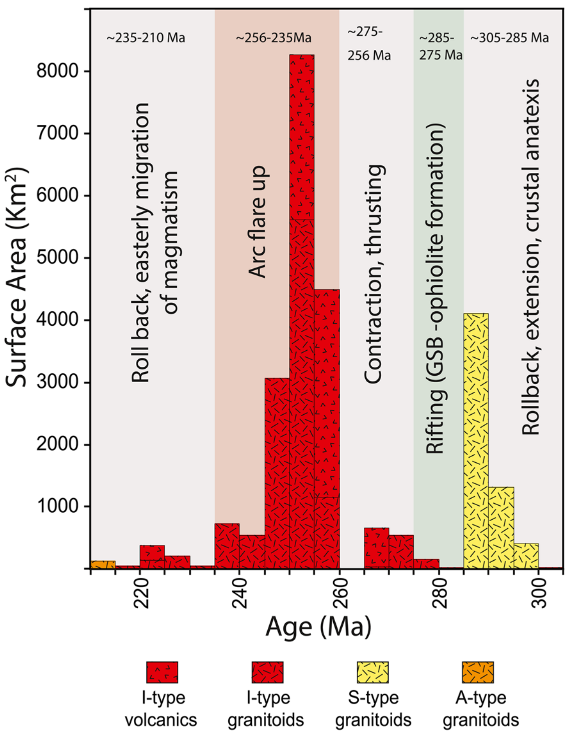

Figure 3. Age versus area (km^2) plot of the igneous and volcanic rocks for the Southern New England Orogen with Cenozoic cover removed. Over time, the shifts in magmatism track the tectonic setting of the NEO. GIS and age data publicly available from: https://minview.geoscience.nsw.gov.au and references therein. NEO, New England Orogen.

$\delta^{18}O$ 5.17–6.16‰ (n = 7). The Early Permian plagiogranite zircon $\delta^{18}O$ analyses lie within or straddle the typical mantle range of 5.3 ± 0.6‰ (2SD) (Valley, 2003), and the range of 3.9–5.6‰ for ophiolite plagiogranites (Grimes et al., 2013), see Figures 2 and S11. These dykes contrast with the Cambrian (GSB112) inclusion that has low $\delta^{18}O$ ranges of 2.93–3.97‰. This low $\delta^{18}O$ range for the Cambrian plagiogranite suggests contamination by hydrothermally altered oceanic crust in the source region, e.g., Grimes et al. (2013).

3.3. Zircon Trace-Elements

Both Early Permian and Cambrian plagiogranite zircon trace-element compositions show typical chondrite-normalized REE patterns (Figure S12) and plot in intermediate to felsic compositions on a Hf (wt.%) v Y (ppm) discriminant plot of Belousova et al. (2002) (Figure S13). All plagiogranites (Cambrian and Early Permian) overlap fields of continental arc and Mid Ocean Ridge zircons on a $\log_{10}$(U/Yb) – $\log_{10}$(Nb/Yb) diagram of Grimes et al. (2015), and plot in the continental field on a U/Yb—Y diagram of Grimes et al. (2007) (Figure S14).

4. Discussion

4.1. Significance of New U-Pb-Hf-O Data

The consistent ~280 Ma ages for the plagiogranite dykes provide compelling evidence that the coherent 18 km^2 block of ophiolite is Early Permian in age. The zircon Hf-O isotope and trace-element results confirm a mantle source for all our samples of plagiogranite, and correlate with established ranges for plagiogranite in ophiolites (Grimes et al., 2013, 2015). We interpret the 18 km^2 block of ophiolite to represent dismembered remnants of back-arc basin crust that underlay Early Permian basin infill known as the Manning or Barnard Basin (see White et al., 2016 and references therein).

These results imply that previous Cambrian-Devonian ages on meter scale exotic blocks in schistose serpentinite matrix are relics from pre-existing subduction events resampled from deeper crustal levels. These relict blocks were subsequently preserved in the mid to upper crust and incorporated and exhumed within serpentinite diapirs in the Early Permian (Glen, 2013; Phillips & Offler, 2011). The observed range in zircon U-Pb ages, and recrystallized nature of the Cambrian plagiogranite inclusion (Figure s4), including the growth of Na–Ca amphiboles (see Text S1 and Figures 5–6), indicate a higher-P (0.4 – 1.0 GPa) history not observed in the 18 km^2 block of Early Permian ophiolite of this study. The latter (including the plagiogranite dykes and host gabbro) are of low-P prehnite-pumpellyite grade (P ~ 0.3 – 0.4, Figure S4). The revelation of contrasting ages and tectonic histories present new constraints on the tectonic evolution of the paleo-Pacific Gondwana margin.

4.2. A New Permian Model for New England Orogen

The southern NEO was formed by west-dipping subduction of the paleo-Pacific plate beneath a continental margin arc that was interrupted at ~305 Ma by slab roll back and a rapid change to an extensional, transtensional rift setting (Jessop et al., 2019; Korsch et al., 2009b; McKibbin et al., 2017; Roberts et al., 2006; White et al., 2016). This shift led to the development of rift basins, voluminous S-type granites and coeval mafic back-arc volcanism in the now attenuated and thinned accretionary wedge (see ~305 – 285 Ma in Figure 3, a compilation of area (km^2) versus age of magmatic rocks of the southern NEO, and Craven et al., 2012; Dirks et al., 1992; Jenkins et al., 2002; McKibbin et al., 2017; Rosenbaum et al., 2012).

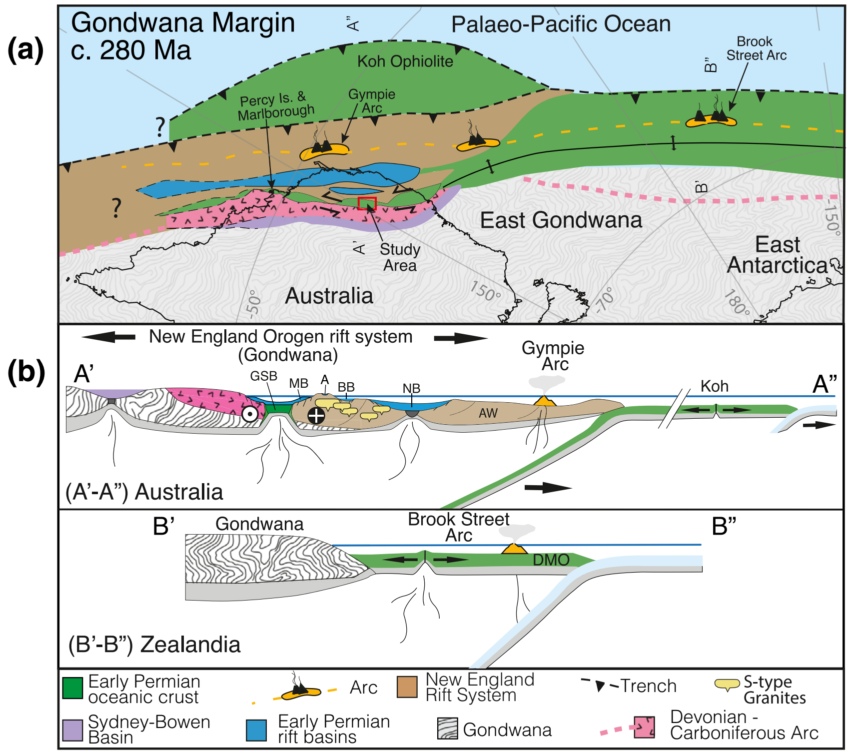

Figure 4. (a) Schematic tectonic reconstruction for the eastern Gondwana margin at ~280 Ma, adapted from Matthews et al. (2016); (b) tectonic cross sections (Schematic, not to scale) A'-A" and B'-B" of Early Permian Gondwana margin at Australia and New Zealand. AW, accretionary wedge, Early Permian basins: GSB, Great Serpentinite Belt; MB, Manning Basin; A, Ashford Coal Measures; BB, Bondonga beds; NB, Nambucca Basin. Yellow plutons: ~290 Ma S-type granites.

Early Permian NEO-wide rapid unroofing and extension created three main rift basins (Figure 4): (1) the early stages of the Bowen, Gunnedah, and Sydney basins inboard of the former arc; (2) the transtensional and now dismembered Early Permian (283 – 277 Ma) GSB and Manning Basin high energy infill (maximum depositional age of ~288 Ma, White et al., 2016); and (3) the Nambucca Basin above the outboard margin of the accretionary wedge (Glen, 2013). The location of the GSB at the boundary of the former fore-arc basin and accretionary wedge suggests the Early Permian Manning Basin was floored by newly generated oceanic crust. Transtensional rifting (White et al., 2016) was localized at the boundary between these two former terranes, facilitated and localized by the weak rheological properties and buoyancy of serpentinite (Guillot et al., 2015).

Our zircon U-Pb age data shows that formation of the GSB ophiolite (and the overlying Manning Basin) in the Early Permian coincides with a hiatus of arc magmatism in the NEO at ~280 Ma (Figure 3 and the "magmatic gap" of zircon ages, Rosenbaum et al., 2012). These observations are consistent with variable plate boundary rollback, oroclinal bending of the margin (Figure 1) (Glen & Roberts, 2012; Rosenbaum et al., 2012), and widespread formation of transtensional back-arc ocean basins. This transtensional framework aided exhumation of serpentinite diapirs that shed serpentinite detritus into the Early Permian Manning Basin (Aitchison & Flood, 1992; Cawood, 1982; White et al., 2016) and the Sydney Basin to the west (Allan & Leitch, 1990; Cross et al., 1987). Exhumation of serpentinite diapirs is measured by 286 ± 6 and 279 ± 6 Ma (re-calculated) K-Ar ages of nephrite altered serpentinite in splay faults (Glen, 2013; Lanphere & Hockley, 1976). A cluster of 290–270 Ma Ar–Ar ages reported from an exotic block of meta-andesite (Offler et al., 2004) hosted within the GSB may also record exhumation.

Extension was short-lived, with rollback likely terminated by ~275 Ma, based on studies of deformation in the Early Permian Nambucca Basin east of the GSB (Shaanan et al., 2014). Resumption of subduction-related magmatism commenced by ~256 Ma culminating in a magmatic flare up (Figure 3) that lasted ~15 Myr.

We propose that the ~283 – 277 Ma transtensional oceanic basin represented by the GSB extended north into the Queensland part of the NEO, along the Yarrol Fault (Figure 1), which like the PMFS separates a Carboniferous fore-arc basin to the west from a Carboniferous accretionary wedge to the east (Korsch et al., 2009a). Extension yet further north to the Queensland coast is made plausible by the contemporary 295 ± 35 Ma, Sm-Nd ages reported on an event in the Marlborough Ophiolite, and by the 271.6 ± 3.5 Ma (U-Pb) and 277 ± 7 Ma (K-Ar) ages reported on a dismembered ophiolite sequence in the offshore Percy islands (Bruce & Niu, 2000a, 2000b; Hoy et al., 2018) (Figure 3). East of this most northern extent of the GSB, a new outboard ~290 – 275 Ma arc (Gympie arc terrane) developed ocean-ward on a portion of rifted and attenuated accretionary complex (Glen, 2013; Hoy & Rosenbaum, 2017; Jessop et al., 2019; Korsch et al., 2009b; Li et al., 2015; Sivell & McCulloch, 2001).

4.3. Significance of Older Blocks in Great Serpentinite Belt

The ~535 Ma exotic plagiogranite inclusions have mantle like Hf-O signatures and T_{DM} crustal Hf model ages that match established ~500 – 600 Ma Re/Os ages of the underlying NEO mantle (Powell & O'Reilly, 2007). Cambrian—Ordovician aged (~530 – 377 Ma) tectonic inclusions of plagiogranite, blueschist, and eclogite are well documented in the NEO (see Table S1 and Aitchison & Ireland, 1995; Aitchison et al., 1992; Manton et al., 2017; Tamblyn et al., 2019). These blocks are encapsulated within schistose serpentinite and are interpreted as relics of Early Paleozoic subduction (Glen, 2013; Manton et al., 2017). Their location in the most outboard orogen in the Tasmanides is attributed to rift displacement during Cambrian rollback or accretion of intraoceanic arc crust (Glen, 2013; Manton et al., 2017; Phillips et al., 2015; Phillips & Offler, 2011; Tamblyn et al., 2019). The Cambrian ophiolitic crust formed the basement to the fore-arc basin (Tamworth Belt) to the west of the GSB (Cawood et al., 2011; Phillips et al., 2015). Early Permian transtension resulted in serpentinite diapirs exhuming the trapped relics of Early Paleozoic subduction and ophiolites as exotic tectonic inclusions along the deep-rooted GSB. Serpentinites in strike-slip settings are commonly characterized by extensive and deep diapirism, that aid in the exhumation of high grade blocks from deep crustal levels, such as modern day examples in New Idria massif of the California Coastal Ranges (Guillot et al., 2015).

4.4. Linking the NEO to New Zealand

Establishing Permian linkages between the GSB and the Dun Mountain Ophiolite (DMO) strengthens Australia-New Zealand correlations. Most previously established links focus on the Cretaceous Whitsunday Volcanic Province on the Queensland coast as a correlative to the Median Batholith of New Zealand, via the offshore Lord Howe Rise (Milan et al., 2017; Mortimer et al., 2017).

Our ~280 Ma GSB ophiolite ages match with ~285 – 275 Ma ages of the DMO (Jugum et al., 2019; Kimbrough et al., 1992; Sivell & McCulloch, 2000). This correlation is strengthened by comparable magmatic gaps (~280 Ma) in both New Zealand (Campbell, Rosenbaum, Allen, Mortimer, et al., 2020; Mortimer et al., 1999) and the NEO during rifting (see Figure 3). This correlation also supports the speculations of Harrington (1983) and Waterhouse and Sivell (1987) that the Permian Maitai Terrane and Brook Street Terrane (BST) in New Zealand and the Gympie arc terrane in Queensland were elements of one long continuous arc.

5. Toward a New Early Permian Paleogeography of the East Gondwana Margin

Pre Cretaceous reconstructions in the south west Pacific rely heavily on geological data due to the lack of seafloor magnetic data (see Shaananet al., 2019). Various competing reconstructions of Early Permian paleogeographies along the Gondwana margin are based on the correlation between Permian-Triassic intraoceanic fore-arc and arc terranes in New Zealand (Murihiku Terrane and BST) with those in New Caledonia (Teremba Terrane) (e.g., Adams et al., 2009; Campbell et al., 2020a, 2020b; Maurizot et al., 2020; Spandler et al., 2005; Waterhouse & Sivell, 1987). Both islands are part of Zealandia (Mortimer et al., 2017) and constitute the end elements of the present day Norfolk Ridge. Similarities of these two terranes to the Gympie Terrane have led to models of a single intraoceanic arc extending along the Gondwana margin, e.g., Spandler et al. (2005). Several problems exist, however, with that interpretation: (1) the Teremba Arc did not exist in the Early Permian. Its basal unit is dated as Late Permian, ~260 Ma, (Maurizot et al., 2020); (2) the Gympie Terrane formed close to the continental margin based on detrital zircons sourced from the underlying Devonian-Carboniferous accretionary wedge (Li et al., 2015). The Gympie Terrane is across strike, far to the west of the Norfolk Ridge and New Caledonia; (3) the setting of the two arcs are different, with the Teremba arc developing offshore Gondwana (Campbell et al., 2018); (4) a speculative large scale fault is required to offset the Gympie arc from the Teremba arc in the model of Spandler et al. (2005); (5) similarities between the Dun Mountain and Koh Ophiolites of New Zealand and New Caledonia (Aitchison et al., 1998; Maurizot et al., 2020), have been based on a singular arc model.

Our data alleviate the need to force the Teremba Terrane into a single arc that included both the Gympie, and Brook Street intraoceanic arcs. In our model, the Early Permian paleogeography of the east Gondwana margin involves one west-dipping subduction system in the south, producing the BST (largely in front of the DMO), but two west-dipping systems in the north. The outboard system is reflected by the Koh ophiolite which formed behind (west) of a trench in a supra subduction zone, back-arc setting (Maurizot et al., 2020; Meffre et al., 1996). While we acknowledge that the oldest known arc magmatism in the Teremba Arc is Late Permian (~260 Ma, Maurizot et al., 2020), studies show arc magmatism can shut off during phases of back-arc spreading, see Magni (2019) and this study (Figure 3).

The inboard subduction system is represented by the Gympie Arc, with the GSB and related Manning Basin (and other adjacent rift basins in its backarc) (Figure 4). The NEO thus became the site of a "western" rift system (Korsch et al., 2009b), with a series of Early Permian basins forming along attenuated margin, but with at least one basin (Manning) underlain by oceanic crust as represented by the GSB ophiolite. A series of continental basins developed inboard of the GSB, but also outboard, on the accretionary wedge of Gondwana. This outboard crust now lies in undersea portions of Zealandia (Tasman Sea), on the Lord Howe Rise and the Dampier Ridge (Figure 1).

Data Availability Statement

The data supporting this study can be found in the supporting information and at the website https://osf.io/D54NA/. Analytical data were obtained using instrumentation at UNE, ANU RSES, Curtin, and also instrumentation funded by DEST Systemic Infrastructure Grants, ARC LIEF, NCRIS/AuScope, industry partners, and Macquarie University. This is contribution 1539 from the ARC Centre of Excellence for Core to Crust Fluid Systems (http://www.ccfs.mq.edu.au) and 1407 in the GEMOC Key Centre (http://www.gemoc.mq.edu.au).

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