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Zircon Inheritance Refines the Cambrian Orogenic Architecture of Southeast Australia

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Abstract The Selwyn Block is one of the few accreted terranes identified in the vast Paleozoic Tasmanides of eastern Australia and its incorporation into this orogen marks a first-order event in the tectonic evolution of the Pacific margin of Gondwana. However, the age, composition, and paleogeography of the Selwyn Block are poorly understood because it is almost completely concealed in the middle and lower crust. The prevailing hypothesis suggests the Selwyn Block is a northern continuation of the Proterozoic Western Tasmania Terrane. We test this hypothesis by comparing inherited zircon U-Pb ages (n = 881) from early Paleozoic granitoids intruding the Selwyn Block and the Western Tasmania Terrane. Phase equilibria modelling confirms that typical Western Tasmania Terrane lithologies are melt-fertile and would have contributed inherited zircon grains to local granitoids. The inherited zircon age signature of granitoids in the Western Tasmania Terrane mirrors detrital zircon ages from local Proterozoic strata with age populations at ca. 1430 Ma and 1800–1600 Ma. In comparison, granitoids intruding the Selwyn Block have ca. 600–500 Ma and ca. 1200–900 Ma inherited zircon age populations, likely derived from local Paleozoic strata. Previously published wholerock radiogenic Sr isotopic data and new zircon radiogenic hafnium isotope data also imply distinct melt sources with granitoids intruding the Selwyn Block granitoids having lower initial $^{87}Sr/^{86}Sr$ and higher initial εHf compositions compared to granitoids intruding the Western Tasmania Terrane. Outcrop and inherited zircon evidence are consistent with the interpretation that the Selwyn Block comprises a Cambrian intra-oceanic island arc, rather than a continuation of the Western Tasmania Terrane.

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1 Introduction

Accretionary orogens are important sites of continental growth and evolve through the transfer of oceanic crust, oceanic plateaus, seamounts, island arcs, and microcontinents from the subducting plate to the overriding plate (*Cawood et al.*, 2009). This accreted material, which can often be mapped into distinct fault-bound terranes, defines the fundamental lithospheric architecture of accretionary orogens by controlling the location of major faults and shear zones and influencing basin development, regional geothermal gradients and the location and composition of magmatism and mineral deposits (*Snyder et al.*, 1996; *Fuis*, 1998; *Korja and Heikkinen*, 2005; *Cawood et al.*, 2009; *Hronsky et al.*, 2012). Resolving the spatial extent and composition of accreted terranes also provides insight into the location, type, and geometry of paleo-plate boundaries, which underpin tectonic models of ancient accretionary orogens. However, characterising the geology of accreted terranes can be challenging because they are often strongly deformed and metamorphosed during accretion and concealed by syn- and post-orogenic cover.

Characterising accreted terranes has proved particularly difficult in the Paleozoic Tasmanides orogenic system of eastern Australia (inset, Figure 1A). The Tasmanides comprise a series of orogenic belts that built the eastern third of the Australian continent from the Cambrian to Triassic (*Cawood*, 2005; *Cawood et al.*, 2009; *Glen*, 2013; *Fergusson and Henderson*, 2015; *Rosenbaum*, 2018). Although the tectonic history of the Tasmanides is dominated by roll-back of a continent-dipping subduction zone, orogenesis and the outward growth of continental crust are intimately linked to periods of subduction zone advance that were possibly triggered by terrane accretion (*Collins*, 2002). However, few accreted terranes have been identified in the Tasmanides, with most of the exposed geology comprising sedimentary and magmatic rocks that are

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inferred to have been emplaced in a back arc setting (*Glen*, 2013; *Glen et al.*, 2016).

The rare examples of exposed accreted terranes in the Tasmanides include a Proterozoic microcontinent in the Western Tasmania Terrane, dismembered seamounts in the most outboard accretionary complexes, and a series of possibly exotic (i.e., lower plate) Paleozoic arc complexes (*Glen*, 2013; *Kemp et al.*, 2020; *Glen and Cooper*, 2021; *Milan et al.*, 2021). Other possible accreted terranes are inferred from regional geophysics or the isotopic composition of younger magmatic rocks and are either completely, or mostly, concealed in the middle and lower crust (*Glen*, 2013). Of these more enigmatic concealed accreted terranes, the Selwyn Block in central Victoria is the most extensively investigated (*Cayley*, 2011; *Cayley et al.*, 2002, 2011; *Moore et al.*, 2016; *Clemens*, 2023; *Clemens and Buick*,

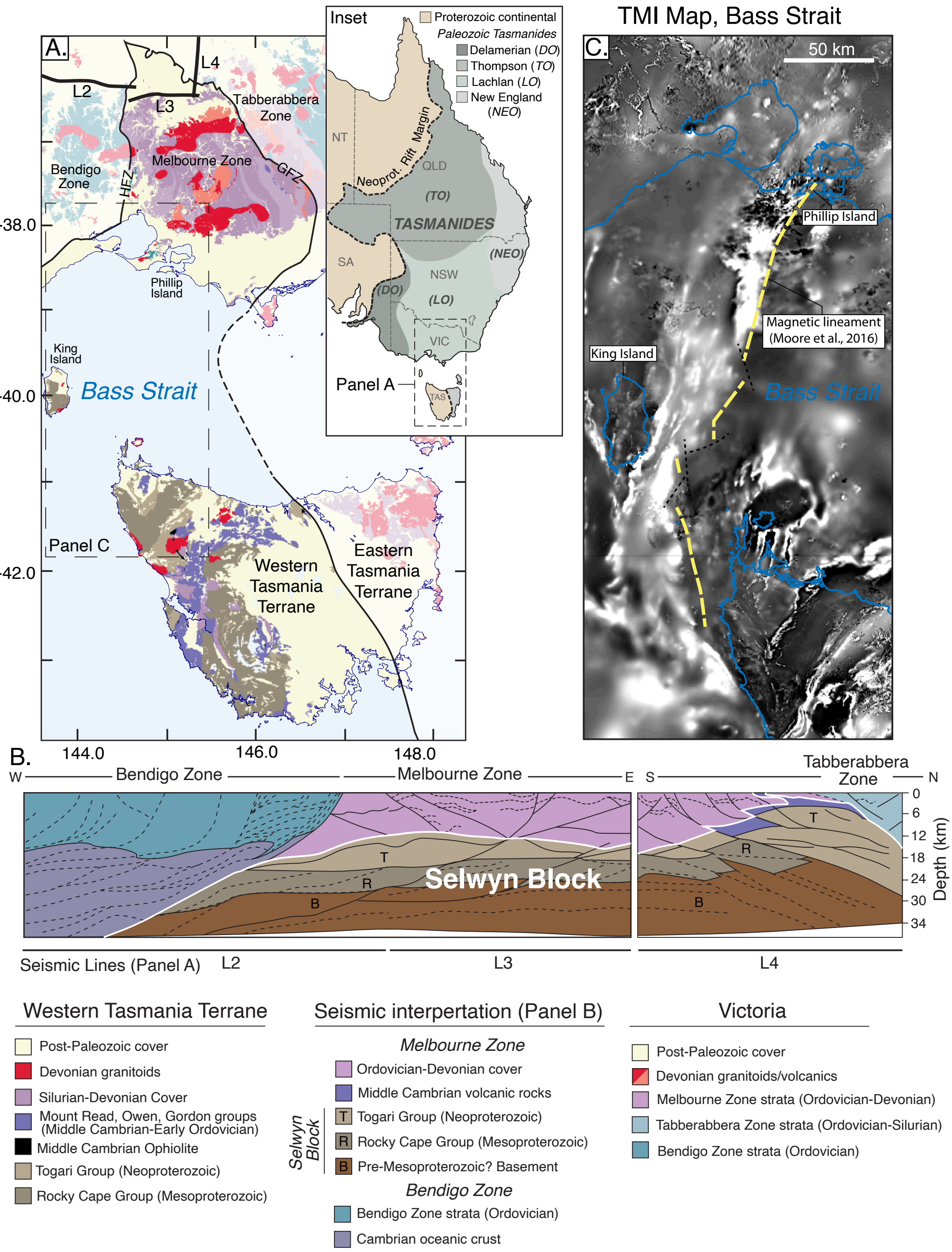

Figure 1 – Geological context of the Selwyn Block and Western Tasmania Terrane. **A)** Surface geology of central Victoria and Tasmania highlighting the exposed geology of the Melbourne Zone and Western Tasmania Terrane. Seismic reflection survey lines across the Melbourne Zone are shown as L2, L3, and L4. Inset: distribution of orogens within the Tasmanides. HFZ - Heathcote Fault Zone; GFZ - Governor Fault Zone. **B)** Interpreted geology of Selwyn Block based on seismic reflection profiles across the Melbourne Zone (see panel A) after *Moore et al.* (2016). Thick white line marks the upper limit of the Selwyn Block. **C)** Total magnetic intensity map of Bass Strait highlighting prominent magnetic anomaly originating from the eastern margin of King Island and possibly extending to Phillip Island on the south coast of Victoria. Dashed yellow line shows the continuity of this lineament as inferred by *Moore et al.* (2016). Data in panels A and B are derived from the Geoscience Australia data portal (https://portal.ga.gov.au/).

2019, Figure 1A–C;). The Selwyn Block is a distinct 20-30 km-thick seismic province in the lower and middle crust of the Melbourne Zone of central Victoria (*Cayley et al.*, 2011, Figure 1B;). The Selwyn Block behaved as a rigid and topographically elevated province throughout the Paleozoic and influenced regional deformation, metamorphism, sedimentation, and magmatism (*Cayley et al.*, 2002). The early Paleozoic accretion of the Selwyn Block may have triggered a fundamental plate boundary reorganisation along the margin of eastern Australia, making it an important component of tectonic models for the Tasmanides (*Cayley et al.*, 2011; *Moresi et al.*, 2014; *Musgrave*, 2015; *Moore et al.*, 2016; *Rosenbaum*, 2018; *Glen and Cooper*, 2021).

Despite being a prominent feature of the early Paleozoic orogenic architecture of southeast Australia, the geology of the Selwyn Block remains poorly understood because it is almost entirely covered by younger rocks. The prevailing view is that Selwyn Block is a northern extension of Proterozoic continental crust exposed in the Western Tasmania Terrane, which together comprise an exotic microcontinent accreted to the Paleozoic margin of eastern Australia (*Berry et al.*, 2008; *Cayley*, 2011; *Moore et al.*, 2016). However, no Proterozoic continental crust has been definitively identified within the Selwyn Block and its only known exposures are dominated by mafic and ultramafic (meta)igneous rocks, which yield Cambrian ages, where directly dated (*Crawford et al.*, 2003; *Spaggiari et al.*, 2003; *Habib et al.*, 2022). Confirming a geological link between the Selwyn Block and the Western Tasmania Terrane remains an important challenge for defining the early Paleozoic orogenic architecture of southeast Australia upon which tectonic models for this region are based.

Here, we investigate the geology of the Selwyn Block and test its connection with the Western Tasmania Terrane by examining the inherited zircon ages of voluminous Devonian granitoids that intrude both terranes (Figure 2). Inherited (or xenocrystic) zircons are entrained in magmas from the melt source and country rock and therefore offer valuable opportunities to sample deep or poorly exposed crust (e.g., *Bea et al.*, 2021). However, because inherited zircons are unintentionally analysed or purposefully avoided during the routine dating of magmatic rocks, only a small number of grains are often available to define the extent and geological character of their source rocks. To overcome this issue, we employ a screening method adapted from detrital zircon U-Pb geochronology in which shorter analysis times are used to collect large datasets to identify uncommon age populations (e.g., *Holden et al.*, 2009; *Matthews and Guest*, 2017; *Clark et al.*, 2023). Using this method, we identify inherited zircon grains in 24 Devonian granitoids intruding the Selwyn Block and Western Tasmania Terrane. Together with previously published data, these concordant inherited zircon ages (n = 881) provide a robust dataset with which to study the age and composition of the Selwyn Block, providing new insights into the Paleozoic orogenic architecture and tectonic evolution of southeast Australia.

2 Geological Background

The Tasmanides comprises a series of Paleozoic orogens in eastern Australia that record convergent tectonics along the Pacific margin of Gondwana (*Cawood*, 2005). The Tasmanides young eastward from the Cambrian-Ordovician Delamerian orogen (*Foden et al.*, 2020) to the Permo-Triassic New England orogen (*Milan et al.*, 2021). This study focuses on the Silurian to Carboniferous Lachlan orogen, which forms the central part of the Tasmanides (inset, Figure 1A). Most of the Lachlan orogen is underlain by Cambrian–Ordovician turbidites deposited on Cambrian oceanic crust (*Cayley et al.*, 2002). The Western Tasmania Terrane and the Selwyn Block are embedded in this early Paleozoic oceanic substrate in the southern Lachlan orogen (inset, Figure 1A).

The Western Tasmania Terrane is the only known Proterozoic crust exposed in the Lachlan orogen (Figure 1A). Most of the terrane comprises Proterozoic sedimentary rocks including the >10-km-thick siliciclastic Mesoproterozoic Rocky Cape Group (Figure 2A; *Calver et al.*, 2014; *Halpin et al.*, 2014) and siliciclastic, carbonate, and rift-related mafic rocks of the Neoproterozoic Togari Group (Figure 2A; *Crawford and Berry*, 1992; *Mulder et al.*, 2020). The provenance and stratigraphy of Proterozoic strata in the Western Tasmania Terrane differ from time-equivalent strata in Australia and instead have closer affinities to western North America (*Berry et al.*, 2001, 2008; *Black et al.*, 2004; *Halpin et al.*, 2014; *Mulder et al.*, 2015a, 2018a,b, 2020; *Lloyd et al.*, 2024). The distinct Proterozoic geology of the Western Tasmania Terrane suggests it represents an exotic microcontinent derived from North America during the Neoproterozoic opening of the Pacific Ocean that was subsequently accreted onto the Pacific margin of Gondwana in the Paleozoic (*Berry et al.*, 2008; *Moore et al.*, 2016; *Mulder et al.*, 2020).

The Western Tasmania Terrane records two regional Paleozoic orogenic events. The middle Cambrian Tyennan Orogeny records the collision of the Tasmanian microcontinent with an intra-oceanic island arc at ca. 515–510 Ma and was accompanied by ophiolite obduction and high-pressure metamorphism (*Berry and Crawford*, 1988; *Turner et al.*, 1998; *Meffre et al.*, 2000; *Chmielowski and Berry*, 2012; *Mulder et al.*, 2015b, 2016; *Brown et al.*, 2021, 2025; *Gray et al.*, 2023) and followed by post-collisional volcanism (Mount Read Volcanics) and deposition of the Late Cambrian–Early Ordovician Owen Group (Figure 2A; *Noll and Hall*, 2003, 2005; *Calver et al.*, 2014; *Mortensen et al.*, 2015; *O'mara et al.*, 2018). The middle Devonian (ca. 390 Ma) Tabberabberan Orogeny involved regional deformation and emplacement of granitoids throughout the Western Tasmanian Terrane (Figure 2A and 2C). The Devonian granitoids are a focus of this study and occur as plutons of strongly fractionated biotite- or biotite-hornblende monzogranite to alkali-feldspar granite and include

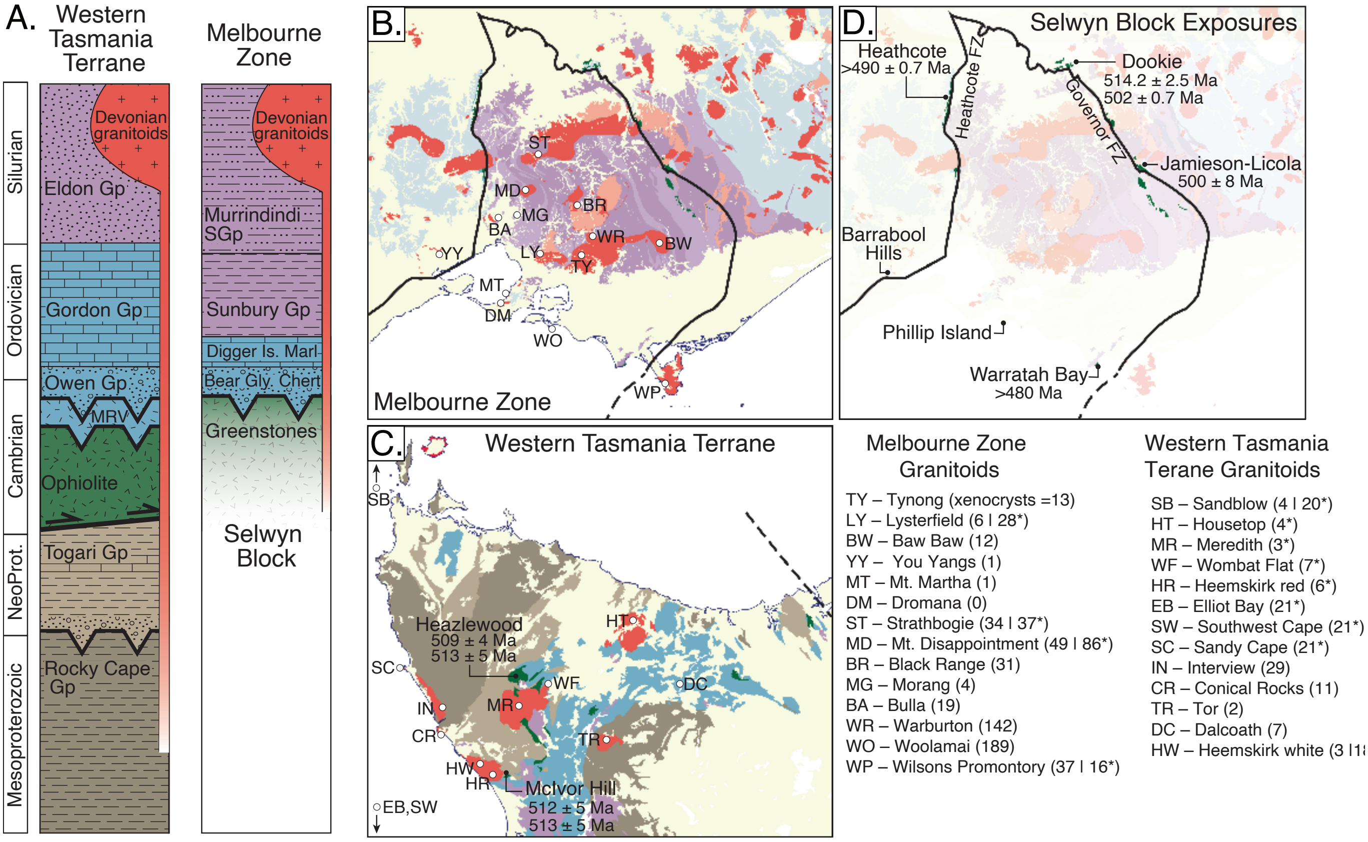

Figure 2 – Simplified stratigraphy and geological context of Devonian granitoids in the Western Tasmania Terrane and Melbourne Zone. **A)** Stratigraphic columns summarising Proterozoic and Paleozoic geology of the Western Tasmania Terrane and Melbourne Zone. **B)** Location of Devonian granitoid samples from the Melbourne Zone. **C)** Location of Devonian granitoid samples from the Western Tasmania Terrane and location of dated Cambrian ophiolite exposures. **D)** Location and age of exposures of the Selwyn Block. The Heathcote and Governor fault zones mark the surface boundary of the Selwyn Block. Abbreviations and number of xenocrysts for sampled granitoids are summarised below panel D. Number of xenocrysts marked with asterisks are compiled from *Clemens* (2023) for Melbourne Zone granitoids and *Black et al.* (2005) for Western Tasmania Terrane granitoids.

metaluminous or mildly peraluminous ('I-type') and more peraluminous ('S-type') varieties (*McClenaghan*, 2006).

The Selwyn Block mostly occupies the lower and middle crust of the Melbourne Zone of the southern Lachlan orogen in central Victoria. The Melbourne Zone is separated from the adjacent Bendigo and Tabberabbera zones by the Heathcote and Governor fault zones, respectively (Figure 1A). On a crustal seismic reflection transect across the Melbourne Zone, the Selwyn Block defines a distinct, sub-horizontally layered province in the middle and lower crust (Figure 1B; *Cayley et al.*, 2011). This province is defined by a thin, highly reflective upper layer, a poorly reflective middle layer, and moderately reflective lower layer (*Cayley et al.*, 2011). The upper seismic layer may correlate with Cambrian sedimentary and igneous rocks outcropping in the Governor Fault Zone approximately 40 km south of the seismic line (Figure 1B; *Cayley et al.*, 2011). The lower two seismically defined layers are not exposed but most recent interpretations suggest they comprise Proterozoic continental crust based on the inferred connection between the Selwyn Block and the Western Tasmania Terrane (Figure 1B; *Cayley et al.*, 2002, 2011; *Pilia et al.*, 2015; *Moore et al.*, 2016). This connection was initially based on tracing a magnetic lineament outcropping as Neoproterozoic basalts on the east coast of King Island off the northwest coast of Tasmania to a small (∼100 m wide) exposure of mafic and ultramafic metaigneous rocks at Phillip Island on the south coast of Victoria (Figure 1C; *VandenBerg et al.*, 2000; *Cayley et al.*, 2002). *Moore et al.* (2016) furthered this interpretation by using inverse modelling of regional gravity and magnetic data to correlate seismically defined layers in the Selwyn Block with the Proterozoic geology of the Western Tasmania Terrane at the scale of individual groups and formations (Figure 1B).

The only conclusive exposures of the Selwyn Block are undated, greenschist to amphibolite facies, mafic and ultramafic metaigneous rocks exposed along the south coast of Victoria (Figure 2D). These exposures include tholeiitic gabbro in the Barrabool Hills (*Cayley et al.*, 2002), bonititic lava, dolerite, and depleted ultramafic cumulate rocks on Phillip Island (*Henry and Birch*, 1992; *Crawford et al.*, 2003), and basalt, dolerite, gabbro, and ultramafic cumulates at Waratah Bay (*Cayley et al.*, 2002; *Crawford et al.*, 2003). The metaigneous rocks at Waratah Bay are at least Cambrian in age as they are unconformably overlain by a thin siliciclastic unit (Bear

Gully Chert) and earliest Ordovician (Lancefieldian; ca. 480 Ma) limestone (Figure 1B; *Cayley et al.*, 2002).

The coastal outcrops of the Selwyn Block may correlate with lithologically and geochemically similar Cambrian igneous and sedimentary rocks exposed in the Heathcote and Governor fault zones to the north (Figure 2D; *Crawford et al.*, 2003). The Heathcote Fault Zone includes boninitic and tholeiitic volcanic rocks overlain by $< 490 \pm 4.3$ Ma chert and shale (*Edwards et al.*, 1998; *Crawford et al.*, 2003; *Habib et al.*, 2022). Cambrian rocks in the Governor Fault Zone include the 500 ± 8 Ma calc-alkaline andesitic and rhyolitic Jamieson and Licola volcanics (*Crawford et al.*, 2003; *Spaggiari et al.*, 2003). Bonititic and tholeiitic rocks are exposed in a series of discontinuous inliers in the northern Governor Fault Zone (*Crawford et al.*, 2003) and have been directly dated at Dookie (Figure 2D), where a polyphase gabbro complex yields U-Pb zircon ages of 502 ± 0.7 Ma (*Spaggiari et al.*, 2003) and 514.2 ± 2.5 Ma (*Habib et al.*, 2022).

The middle Devonian Tabberabberan Orogeny also affected the Melbourne Zone and involved thin-skinned deformation of sedimentary cover above the rigid basement of the Selwyn Block (*Cayley*, 2011). As in Tasmania, the Tabberabberan Orogeny was accompanied by widespread granitoid emplacement. Middle Devonian granitoids in the Melbourne zone are generally post-kinematic and include small, isolated plutons and large, composite batholiths (Figure 2B; *VandenBerg et al.*, 2000). Most are high-K, calc-alkaline, biotite monzogranites and biotite granodiorites, including hornblende-bearing I-type and cordierite- and garnet-bearing S-type varieties (*VandenBerg et al.*, 2000).

3 Sampling Strategy and Analytical Methods

The primary aim of this study is to compare the inherited zircon signature of Devonian granitoids in the Melbourne Zone and western Tasmania to test the hypothesis that the Selwyn Block comprises a continuation of the Proterozoic Western Tasmania Terrane. A strength of this approach is that the detrital zircon age signature of the Proterozoic sedimentary rocks that make up most of the Western Tasmania Terrane is distinct from sedimentary sequences elsewhere in southeast Australia (cf. Section 4.2). Therefore, recognising this distinct detrital zircon signature as inherited zircons in Devonian granitoids of the Melbourne Zone would strongly support the continuation of Proterozoic continental crust of the Western Tasmania Terrane into the Selwyn Block. We also measured the radiogenic hafnium isotopic composition (^{176}Hf/^{177}Hf) of magmatic zircon grains as an additional test of the presence of Proterozoic continental crust in the Selwyn Block. The ^{176}Hf/^{177}Hf of zircon is sensitive to the age and composition of the magmatic reservoirs from which their host melts are derived and is a useful proxy for tracing contributions from ancient continental crust (e.g., *Kemp et al.*, 2007).

New zircon U-Pb ages and Hf isotope data were collected from surface exposures of 14 granitoids in the Melbourne Zone and 9 granitoids in the Western Tasmania Terrane (Figure 2B and Figure 2C; Supplementary File 1). Two of the Melbourne Zone granitoids (You Yangs Granite and Wilsons Promontory Batholith) are located outside the surface limits of the Melbourne Zone but are included in our analysis as they may still sample the Selwyn Block at depth (Figure 2B). In addition to the new zircon data, our analysis also includes previously published inherited zircon ages from Devonian granitoids in the Melbourne Zone (*Clemens et al.*, 2023) and Cambrian and Devonian granitoids in the Western Tasmania Terrane (*Black et al.*, 2010). Zircons were separated from ~2 kg samples using standard magnetic and heavy liquid techniques at Monash University. The zircon-rich heavy mineral separate was poured onto double sided sticky tape and prepared into 2.5 cm epoxy mounts, which were polished to a 1 μm finish. Each epoxy mount contained at least 200 zircon grains from a given sample. Zircon U-Pb ages were collected via laser ablation inductively coupled plasma mass spectrometry at Monash University using either a rapid 'screening method' or a split-stream method in which Lu-Hf isotopes were collected concurrently with U-Pb data. Instrumental set-ups and analytical conditions are detailed in *Mulder et al.* (2021) and *Zoleikhaei et al.* (2024).

The 'screening method' follows the analytical procedure outlined by *Matthews and Guest* (2017) and involves ablation with a 25 μm spot at 10 Hz repetition rate and fluence of 1.9 Jcm^{-2}. An attempt was made to analyse every zircon grain on each mount with ablation spots placed as close as practical to the centre of grains while avoiding inclusions or cracks. Each analysis consisted of ~5 seconds of background, ~10 seconds of ablation, and 5 seconds of washout. The reference zircon Plešovice (Sláma et al., 2008) was used as primary standard to calibrate downhole fractionation and monitor instrument drift and reference zircon GJ-1 (*Jackson et al.*, 2004) was used as a secondary standard to monitor data quality (Supplementary File 2). Each analytical session consisted of analysis of approximately 20 unknowns bracketed by primary and secondary standards.

The split-stream U-Pb + Lu-Hf method aimed to characterise the Hf isotopic signature of magmatic zircon grains and targeted euhedral grains that were free from cracks and inclusions. The analytical procedure follows that outlined by *Mulder et al.* (2021). The U-Pb data was calibrated against Plešovice as the primary standard with 91500 (*Wiedenbeck et al.*, 1995), GJ1 (*Jackson et al.*, 2004), and QGNG (*Black et al.*, 2003) reference zircons analysed as secondary standards. The Mud Tank zircon reference material (*Woodhead and Hergt*, 2005) was used as a primary standard to normalise Hf isotope ratios with Plešovice, 91500, GJ1, and QGNQ used as secondary standards to monitor data quality (Supplementary File 3). Initial εHf values ($\varepsilon Hf_{(i)}$) are calculated using the measured ^{176}Hf/^{177}Hf, the

^{176}Lu decay constant of *Scherer et al.* (2001), and the Chondritic Uniform Reservoir values of *Bouvier et al.* (2008).

Data reduction for both methods was performed using iolite 4 (*Paton et al.*, 2011). Concordia diagrams, histograms, and kernel density estimates were plotted using isoplotR (*Vermeesch*, 2018). We classify zircon grains older than 450 Ma as inherited. This is a conservative age cut-off that excludes antecrysts or magmatic zircons compromised by common-Pb. We use $^{206}Pb/^{238}U$ ages for grains younger than 1000 Ma and $^{207}Pb/^{206}Pb$ ages for grains older than 1000 Ma. Only zircon grains with less than ± 10% discordance between $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages for grains <1000 Ma and $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ages for grains >1000 Ma are considered in our interpretations.

To test if Western Tasmania Terrane-like crust would have melted during the Devonian at its inferred depth in the Selwyn Block (Figure 1B), we constructed a pressure-temperature (P-T) pseudosection for a representative pelite from the Mesoproterozoic Rocky Cape Group, which is the most widespread Proterozoic lithology in the Western Tasmania Terrane (Figure 1A). The pseudosection was calculated using an average whole-rock XRF composition of 136 representative pelite samples from the Rocky Cape Group units within the Mineral Resources of Tasmania geochemical database (https://www.mrt.tas.gov.au/products/database_searches/samples_and_geochemistry). Calculations were performed using THERMOCALC v 3.50 (*Powell and Holland*, 1988), with the *Holland and Powell* (2011) internally consistent thermodynamic dataset 6.2 (updated 6 Feb 2012), and metapelitic mineral activity-composition models in the system NCKFMASHTO (Na_2O - CaO - K_2O - FeO - MgO - Al_2O_3 - SiO_2 - H_2O - TiO_2 - FeO_2O_3; within "tc-mp50NCKFMASHTO", updated 23 Jan 2022; *White et al.*, 2014). The XRF bulk composition was converted to molar oxide %. H_2O was set to the minimum amount required to saturate assemblages at the solidus. Redox compositions were estimated at $Fe^{3+}/[Fe^{3+} + Fe^{2+}] = 0.3$ based on XRF analyses that calculated FeO by titration.

4 Results

4.1 Western Tasmanian Terrane pelite melt fertility

The seismic section for the Melbourne Zone suggests that the Selwyn Block occurs at depths of ∼12-36 km (equivalent to pressures of ∼3.2-9.7 kbar; Figure 3). The P-T pseudosection was therefore calculated over a pressure range of 3-10 kbar and a temperature range of 650-900 °C (Figure 3). For the representative Western Tasmanian Terrane pelite composition, the wet solidus is modelled to occur at temperatures of ∼660-670 °C at pressures above 3 kbar. The model is contoured for melt abundance in modal % (Figure 3).

Regional thermal gradients in the southern Lachlan orogen during the early Paleozoic are not well constrained, as regional metamorphic rocks are relatively low grade and diagnostic metamorphic assemblages are mostly related to contact metamorphism in the upper crust (*Gray*, 1997; *Offler et al.*, 1998). However, the Devonian granitoids in the Melbourne Zone are proposed to have intruded during back-arc extension in the late stages of the Tabberabberan Orogeny, with heat provided by emplacement of mantle-derived magmas deep in the crust (*Keay et al.*, 1997; *Collins*, 2002; *Gray and Foster*, 2004; *Clemens and Buick*, 2019; *Clemens et al.*, 2023). Previous P-T estimates at the melt source of the Devonian magmas have suggested melting occurred at 775-900 °C and 6-9 kbar, corresponding to elevated thermal gradients in the range ∼850-1450 °C/GPa (*Clemens and Buick*, 2019). At a thermal gradient of ∼850 °C/GPa, the solidus of the Western Tasmanian Terrane pelite is modelled to occur at 7.9 kbar, equivalent to depths of ∼30 km (Figure 3). Heating to 900 °C along a thermal gradient of ∼850 °C/GPa in a closed system produces ∼45% melt at pressures of 10.5 kbar (∼37 km). At thermal gradients of 1000 °C/GPa and 1500 °C/GPa, the solidus occurs at pressures of 6.7 kbar (∼24 km) and 4.4 kbar (∼16 km), respectively. Heating to 900 °C in a closed system along a thermal gradient of 1000 °C/GPa produces > 45% melt at pressures of 9 kbar (∼33 km). Heating to 900 °C along a thermal gradient of 1500 °C/GPa produces >55% melt at pressures of 6 kbar (∼22 km).

4.2 Inherited Zircons

Before presenting inherited zircon ages from Devonian granitoids in the Western Tasmania Terrane and the Melbourne Zone, we briefly summarise the detrital zircon age signatures of the sedimentary rocks hosting these granitoids. The detrital zircon signature of Mesoproterozoic sedimentary rocks in the Western Tasmania Terrane is characterised by prominent age peaks at ca. 1450 Ma and 1600–1800 Ma with a minor distribution of early Paleoproterozoic and Archean ages (Figure 4A and 4B; *Berry et al.*, 2001; *Black et al.*, 2004; *Halpin et al.*, 2014; *Mulder et al.*, 2018a,b). The detrital zircon signature of Neoproterozoic strata in the Western Tasmania Terrane shares major age populations with the underlying Mesoproterozoic strata but also includes smaller ca. 1300–1100 Ma and ca. 640 Ma populations (Figure 4A and 4B; *Mulder et al.*, 2020). The detrital zircon signature of these strata differ from the nearest Proterozoic strata in southeast Australia, exposed in the Neoproterozoic Adelaidean Superbasin (Figure 4A; *Lloyd et al.*, 2020). The most important difference is the prominent detrital zircon age populations at 1600–1500 Ma and 1100–1000 Ma in the Adelaidean strata (*Lloyd et al.*, 2020, 2022, 2024), which are rare in Western Tasmania Terrane strata (Figure 4A). The Western Tasmania Terrane therefore has a distinct zircon signature that can be distinguished from other potential Proterozoic basement provinces in eastern Australia.

Paleozoic sedimentary rocks in the Lachlan orogen have a distinct 'Pacific Gondwanan' detrital zircon signature characterised by prominent age populations at ca. 650–500 Ma and 1200–900 Ma (Figure 4D and

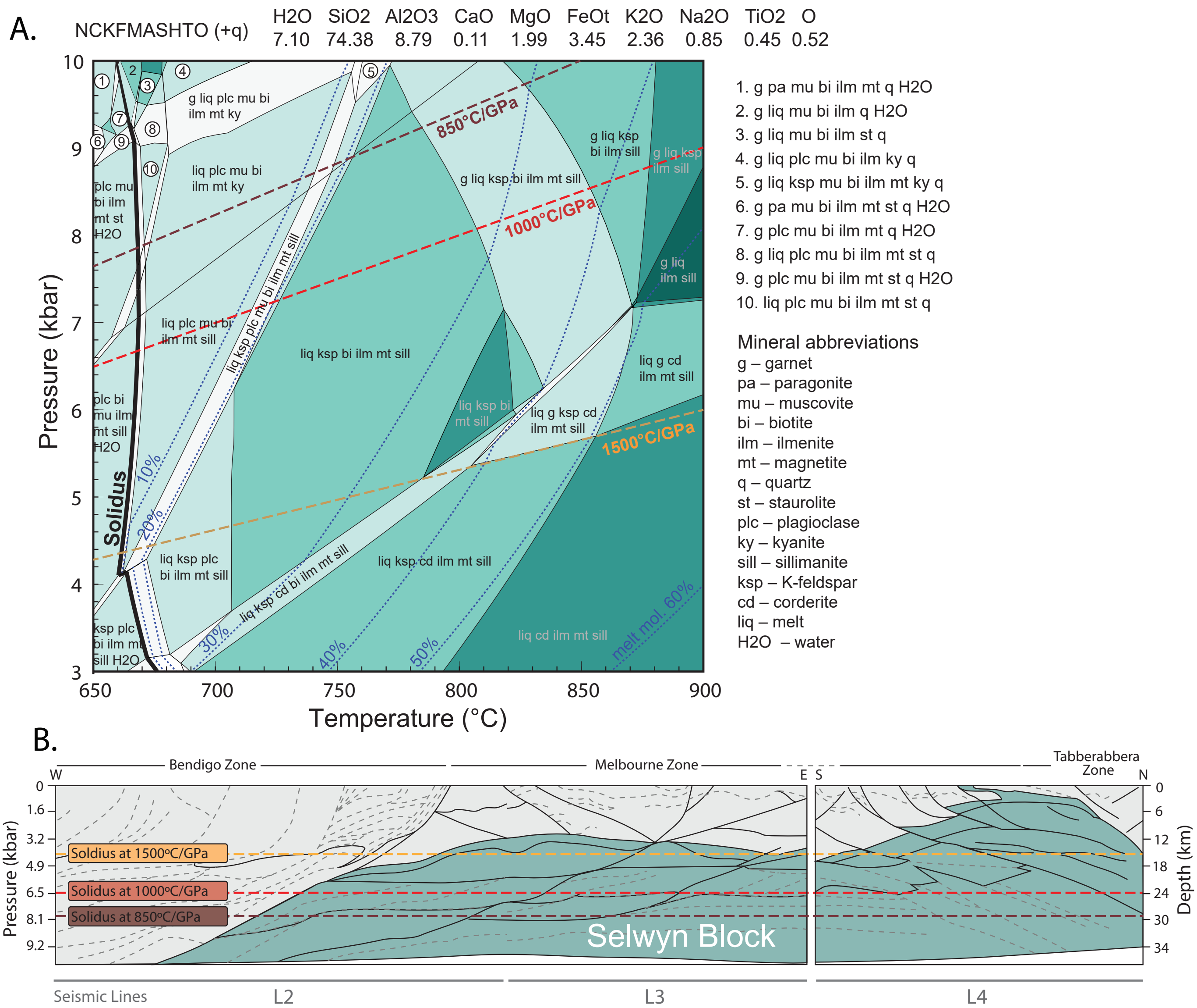

Figure 3 – P-T pseudosection modelling of Tasmanian Proterozoic sedimentary rocks in the Selwyn Block. **A)** Pressure-temperature pseudosection of a representative Mesoproterozoic pelite from the Western Tasmania Terrane. The solidus is highlighted by a thick black line. Blue dashed lines correspond to melt modes in modal%. Brown, red, and orange lines mark apparent thermal gradients of 850 °C/GPa, 1000 °C/GPa and 1500 °C/GPa, respectively. **B)** Simplified geological interpretation of the Selwyn Block showing distribution of inferred Proterozoic and Cambrian crust (green) and Paleozoic cover (grey). Dashed horizontal lines show the depth of the solidus of the representative Tasmanian pelite modelled in panel A at inferred Devonian geothermal gradients of 850 °C/GPa, 1000 °C/GPa and 1500 °C/GPa. Crust below the solidus is a plausible melt source for Devonian granitoids in the Melbourne Zone.

4E; *Squire et al.*, 2006; *Glen et al.*, 2017). Although there are differences in the relative size and the position of age peaks within these two populations between individual samples, the Pacific Gondwanan signature is remarkably consistent in Paleozoic strata across the entire orogen, including western Tasmania (*Berry et al.*, 2001; *Habib et al.*, 2021). For example, the variability in detrital zircon age peaks between samples from the same stratigraphic interval is comparable to the variation observed between samples from opposite sides of the orogen (*Glen et al.*, 2017). To better characterise the Pacific Gondwanan detrital zircon signature, we combine the comparatively small detrital zircon dataset available from the Melbourne Zone with compiled data from Paleozoic strata elsewhere in the Lachlan orogen (Figure 4D and 4E).

The inherited zircon ages for granitoids in the Western Tasmania Terrane are summarised in Figure 4A and Supplementary File 4. The oldest inherited zircons are rare Neoarchean grains (n = 3). Paleoproterozoic inherited zircons are the most abundant (60% of total population) and form a large 1800–1600 Ma population with prominent age peaks at ca. 1750 and ca. 1610 Ma. Mesoproterozoic inherited zircon grains comprise 30% of the total population and form a large age population centred on 1430 Ma. The youngest inherited zircons form a positively skewed population (6% of total population) spanning 600–450 Ma centered on an age peak at ca. 510 Ma. There is no notable difference in the inherited zircon age populations between individual plutons or between I-type and S-type varieties (Figure 4C; Supplementary File 4).

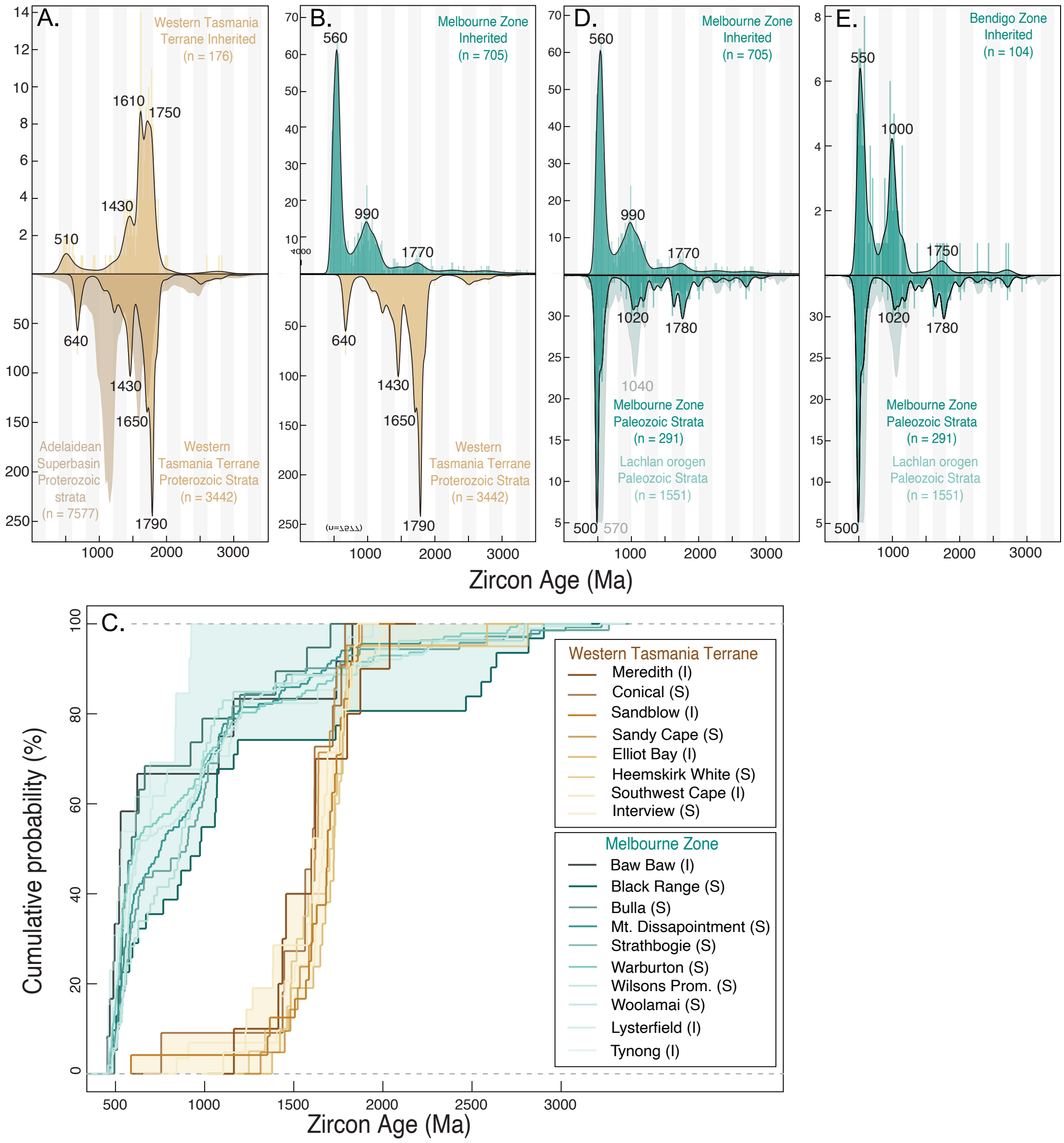

Figure 4 – Kernel Density Estimates and histograms of U-Pb ages of inherited zircon grains in Devonian granitoids (top panels) and detrital zircon grains from host sedimentary rocks (bottom panels). **A)** Tasmanian granitoid inheritance vs. Tasmanian Proterozoic strata detrital zircons. Compiled ages from Proterozoic strata of the Adelaidean superbasin are also shown for comparison to highlight the distinct detrital zircon signature of the Western Tasmania Terrane strata. **B)** Melbourne Zone granitoid inheritance vs. Tasmanian Proterozoic strata detrital zircons. **C)** Cumulative age distribution of inherited zircons from individual Western Tasmania Terrane and Melbourne Zone granitoids. I-type and S-type varieties are designated (I) and (S), respectively. **D)** Melbourne Zone granitoid inheritance vs. Lachlan Orogen Paleozoic strata detrital zircons. **E)** Bendigo Zone granitoid inheritance vs. Lachlan Orogen Paleozoic strata detrital zircons. Detrital zircon data are from *Black et al.* (2004), *Halpin et al.* (2014), *Mulder et al.* (2015a, 2018a,b, 2020), *Squire et al.* (2006), *Glen et al.* (2017), *Lloyd et al.* (2020), and *Habib et al.* (2022).

The inherited zircon signature of granitoids in the Melbourne Zone is summarised in Figure 4B, Figure 4D, and Supplementary File 5. Apart from a minor (6%) spread of Early Paleoproterozoic and Archean ages (3500–2000 Ma), most inherited zircon grains from the Melbourne Zone are distributed between two age populations at ca. 560 Ma and ca. 990 Ma. In detail, the ca. 560 Ma population spans ca. 600–450 Ma and includes 42% of inherited zircon grains. The older population (32%) spans ca. 1300–700 Ma and contains an age peak at ca. 990 Ma and a shoulder at ca. 1100 Ma. There is no notable difference in the inherited zircon age populations between plutons in the Melbourne Zone or between I-type and S-type varieties, although the latter typically yield more inherited grains (Figure 4C; Supplementary File 5). The inherited zircon distribution of granitoids from the adjacent Bendigo Zone (Figure 1A) are also summarised in Figure 4E and are discussed in Section 5.2, below.

4.3 Hafnium Isotope Data

Individual magmatic zircon U-Pb ages span ca. 360–380 Ma for the granitoids analysed in this study (Supplementary File 3). For ease of comparison, we calculate all zircon initial Hf isotope compositions at an assumed crystallisation age of 370 Ma. Calculating

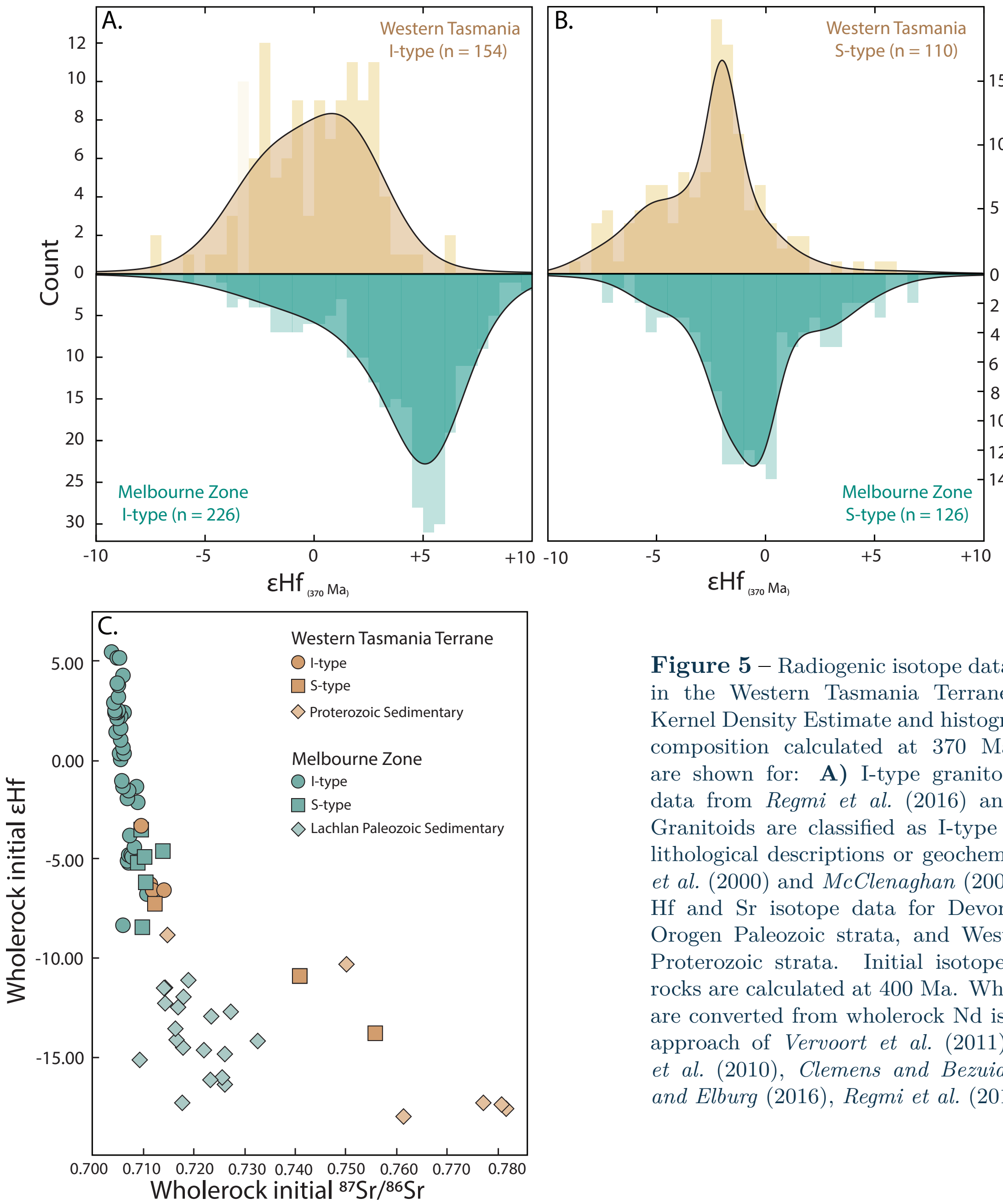

Figure 5 – Radiogenic isotope data for Devonian granitoids in the Western Tasmania Terrane and Melbourne Zone. Kernel Density Estimate and histogram of initial εHf isotopic composition calculated at 370 Ma for magmatic zircons are shown for: **A)** I-type granitoids (including published data from *Regmi et al.* (2016) and **B)** S-type granitoids. Granitoids are classified as I-type or S-type based on the lithological descriptions or geochemical data in *VandenBerg et al.* (2000) and *McClenaghan* (2006). **C)** Wholerock initial Hf and Sr isotope data for Devonian granitoids, Lachlan Orogen Paleozoic strata, and Western Tasmanian Terrane Proterozoic strata. Initial isotope values for sedimentary rocks are calculated at 400 Ma. Wholerock Hf isotope values are converted from wholerock Nd isotope data following the approach of *Vervoort et al.* (2011). Data are from *Black et al.* (2010), *Clemens and Bezuidenhout* (2014), *Clemens and Elburg* (2016), *Regmi et al.* (2016).

initial Hf isotope compositions at the actual age calculated for individual spots does not change our interpretations. We present results from I-type and S-type granitoids separately. This allows us to compare the zircon Hf signature of granitoids containing a significant contribution from their sedimentary host rocks (S-type granites) to less contaminated I-type granitoids, which may better sample deeper crustal sources (*Collins*, 1996; *Keay et al.*, 1997).

Figure 5A shows histograms and kernel density estimates of $\varepsilon Hf_{(i)}$ values calculated for magmatic zircons from the Western Tasmania Terrane and the Melbourne Zone. The range of $\varepsilon Hf_{(i)}$ values generally overlaps for I-type and S-type granites from Western Tasmania Terrane and the Melbourne Zone but differ in their respective modes. The $\varepsilon Hf_{(i)}$ of magmatic zircons from I-type granitoids from Western Tasmania Terrane spans +7 to -7 with a peak at +1 epsilon unit and a shoulder at -2 epsilon unit (Figure 5A). Approximately 48% of the population has subchondritic Hf isotope values. In comparison, the $\varepsilon Hf_{(i)}$ of magmatic zircons from I-type granitoids in the Melbourne zone are generally more positive (-5 to +10; 15% subchondritic) and define a negatively skewed population with a mode at +5 epsilon units (Figure 5A). The $\varepsilon Hf_{(i)}$ of magmatic zircons from S-type granitoids in both the Western Tasmania Terrane and Melbourne Zone are generally more evolved than their S-type counterparts. Approximately 88% of the magmatic zircons from S-type granitoids in the Western Tasmania Terrane have subchondritic $\varepsilon Hf_{(i)}$ and define a population spanning -7 to + 6 with a prominent peak at -4 and a shoulder at -5 epsilon units (Figure 5B). The $\varepsilon Hf_{(i)}$ of magmatic zircons from S-type granitoids in the Melbourne Zone is generally less evolved (62% subchondritic) and defines a population with a peak at -2 and shoulders at -5 and + 3 epsilon units (Figure 5B).

5 Discussion

5.1 Evidence for Proterozoic Continental Crust in the Selwyn Block

The significant volume of Devonian magmatism in the Melbourne Zone has been used as evidence that the source rocks were low metamorphic grade and melt-fertile prior to the magmatic event (*Clemens and Buick*, 2019). Consistent with this inference, the representative Western Tasmania Terrane pelite modelled in Figure 3 is predicted to produce large volumes of melt (~30–55% melt volume) at the P-T conditions estimated for Devonian melt generation in the Melbourne Zone. Modelled melt volumes in a closed system are likely to be overestimated, as episodic melt loss in natural systems results in increasingly residual bulk compositions that decrease the cumulative amount of melt that can be produced (*Yakymchuk and Brown*, 2014a; *Morrissey et al.*, 2016). However, for a thermal gradients ≥1000 °C, the modelled volume of melt from the representative pelite composition produced at 850 °C significantly exceeds the Melt Escape Threshold (20-25% melt volume) and the Rigid Percolation Threshold of 50-55% melt volume (*Arzi*, 1978; *van der Molen and Paterson*, 1979; *Wickham*, 1987). These high volumes should enable zircon entrainment into the melt and melt removal from the source region to form granitoid plutons (*Bea et al.*, 2021). Therefore, the P-T modelling highlights that if the pelitic rocks that make up most of the exposed geology of the Western Tasmania Terrane are present at depth in the Selwyn Block, they would have melted and contributed to the inherited zircon signature of Devonian granitoids in the Melbourne Zone (Figure 3).

5.1.1 Inherited Zircons

Granitoids in the Western Tasmania Terrane contain major inherited zircon age populations at 1430 Ma and 1800–1600 Ma, which mirror the characteristic detrital zircon age peaks of Proterozoic strata in the Western Tasmania Terrane (Figure 4A). The smaller distribution of 1300–1000 Ma inherited zircons may have been derived from local Neoproterozoic or Paleozoic strata (Figure 4A); the latter are also a suitable source for the uncommon ca. 500 Ma inherited zircon grains (*Habib et al.*, 2021).

The new inherited zircon data confirm that granitoids emplaced within the Western Tasmania Terrane inherited its distinct zircon age signature (Figure 4A), providing a comparative dataset for recognising the presence of similar crust in the Selwyn Block. This comparison is presented in figures 4B and 4C, which demonstrates that the inherited zircon age signature of granitoids in the Melbourne Zone differs markedly from Western Tasmania Terrane granitoids. Instead, the inherited zircon signature of the Melbourne Zone granitoids closely reflects the detrital zircon age signature of their Paleozoic sedimentary host rocks (Figure 4D). Notably, the zircon age populations at ca. 1450 Ma and 1800–1600 Ma that are characteristic of Proterozoic strata in the Western Tasmania Terrane form only a minor component of the inherited zircon population of Melbourne Zone granitoids (1500–1400 Ma inherited grains = 1% of total inherited population; 1800–1600 Ma = 4%).

5.1.2 Radiogenic Isotope Data

Contrasting sources of Devonian granitoids in the Western Tasmania Terrane and Melbourne Zone is also evident in the radiogenic Hf isotope signature of magmatic zircons from each area (Figure 5A and 5B). As I-type granitoids generally have a low contribution of melt from sedimentary sources (*Chappell and White*, 1992, 2001; *Collins*, 1996), the radiogenic Hf isotopic composition of magmatic zircon from these granitoids are more likely to reflect melt sources other than their upper crustal sedimentary host rocks. The comparison in Figure 5A shows that Devonian I-type granitoids in the Western Tasmania Terrane have more evolved magmatic zircon $\varepsilon\text{Hf}_{(i)}$ than those from the Melbourne Zone. This observation is consistent with the interpretation that the Western Tasmania Terrane I-type granitoids sampled a more isotopically evolved, and hence likely older, source than I-type granitoids in the Melbourne Zone.

Unlike I-type granitoids, the $\varepsilon\text{Hf}_{(i)}$ of magmatic zircons from S-type granites in the Western Tasmania Terrane and the Melbourne Zone are broadly similar (Figure 5B). This observation could suggest that S-type granitoids in the Western Tasmania Terrane and Melbourne Zone share a common sedimentary source. However, this interpretation is difficult to reconcile with dissimilar inherited zircon ages from these two areas (Figure 4A and 4B). The interpretation of a common sedimentary source for these S-type granitoids is also complicated by the observation that Paleozoic sedimentary rocks in the Melbourne Zone have time-integrated radiogenic Hf isotopic compositions that are only slightly less evolved than Proterozoic sedimentary rocks in the Western Tasmania Terrane (Figure 5C). As there are few wholerock radiogenic Hf isotope analyses from sedimentary rocks in southeast Australia to compare to our new magmatic zircon Hf isotope data, we convert published wholerock εNd values from sedimentary rocks to their corresponding εHf using the equation of *Vervoort et al.* (2011):

$$\varepsilon Hf = 1.55 \times \varepsilon Nd + 1.21 \tag{1}$$

This conversion yields εHf (400Ma) values of -11.2 to -17.4 (mean = -13.4, n = 19) for Paleozoic sedimentary rocks in the Lachlan orogen. In comparison, the εHf (400Ma) of Proterozoic strata from the Western Tasmania Terrane are generally only slightly more evolved at -9.0 to -18.0 (mean = -15.4, n = 7).

Although Paleozoic sedimentary rocks in the Lachlan orogen and Proterozoic sedimentary rocks in the Western Tasmania Terrane have comparable radiogenic Nd and Hf isotope compositions, these potential sources rocks are more clearly distinguished by their radiogenic Sr isotope compositions. Published wholerock radiogenic Sr isotope data from Paleozoic sedimentary rocks in the Lachlan orogen define a field spanning $^{87}Sr/^{86}Sr$ = 0.715–0.735 (Figure 5C). In comparison, published $^{87}Sr/^{86}Sr$ for Proterozoic sedimentary rocks from the Western Tasmania Terrane are higher (0.715–0.86), with all but one sample yielding $^{87}Sr/^{86}Sr$ values > 0.75 (Figure 5C). This contrast in $^{87}Sr/^{86}Sr$ composition of local sedimentary rocks is also reflected in the $^{87}Sr/^{86}Sr$ of S-type granitoids in the Melbourne Zone and Western Tasmania Terrane (*Gray*, 1990; *Black et al.*, 2010). S-type granitoids from the Melbourne Zone generally have a narrow range of $^{87}Sr/^{86}Sr$ (0.705–0.715), which is similar or lower than S-type granitoids elsewhere in the Lachlan orogen (*Gray*, 1990). The more limited dataset (n = 3) from S-type granitoids form the Western Tasmania Terrane includes only one granitoid with $^{87}Sr/^{86}Sr$ comparable to the Melbourne Zone granitoids with the remaining granitoids inheriting the highly radiogenic Sr isotopic signature of local Proterozoic sedimentary rocks (Figure 5C). Post-crystallisation alteration is unlikely to explain the different radiogenic Sr isotope systematics between Devonian granitoids of the Melbourne Zone and Western Tasmania Terrane as both regions share comparable post-Devonian geological histories (Figure 2A). Therefore, we argue that the different radiogenic Sr isotopic signature of granitoids between the Melbourne Zone and Western Tasmania Terrane reflects distinct crustal melt sources in these regions, which is supported by their contrasting zircon inheritance patterns.

5.2 Inferences on the Age and Composition of the Selwyn Block

The main conclusion of this study is that the inherited zircon age signature of Devonian granitoids in the Melbourne Zone provides no compelling evidence that the underlying Selwyn Block contains Proterozoic continental crust comparable to that exposed in the Western Tasmania Terrane (Figure 4B). Instead, we argue that the inherited zircon age signature of Melbourne Zone granitoids is indistinguishable from the detrital zircon age signature of the Paleozoic sedimentary rocks they intrude, at least at the resolution of the available data (Figure 4D). This interpretation differs from the study of Victorian granitoid inheritance by *Clemens et al.* (2023) who obtained inherited zircon age signatures comparable to those presented in this study but suggest local Paleozoic sedimentary rocks were not a significant source component of the granitoids based on differences in the size and position of zircon age populations between Paleozoic sedimentary host rocks, metasedimentary enclaves, and granitoid inheritance. However, these age population offsets are generally small (< 50 Ma) and comparable to the typical 2SE uncertainty of zircon U-Pb analyses, indicating that they are not statistically significant. Furthermore, the apparent differences in the zircon age spectra presented by *Clemens et al.* (2023) could reflect under-sampling, particularly of granitoids and enclaves (n = < 50 analyses). As outlined in Section 4.2, when the variability in the detrital zircon age signature of Palaeozoic sedimentary rocks in the Lachlan orogen is considered more broadly (*Glen et al.*, 2017), these rocks can account for the zircon inheritance of Melbourne Zone granitoids (Figure 4B).

We consider two scenarios to explain the exclusively upper crustal source of inherited zircons in the Devonian granitoids of the Melbourne Zone: (1) All zircon was dissolved during partial melting of the deeper crustal sources within the Selwyn Block, or (2), the Selwyn Block comprises zircon-poor lithologies that did not transfer any zircon inheritance to Devonian granitoids.

In considering the first scenario, thermodynamic modelling of suprasolidus metasedimentary rocks–like those inferred to make up large parts of the Selwyn Block (*Moore et al.*, 2016)–demonstrates that zircon solubility decreases as melt is lost from the system during prograde metamorphism (*Kelsey et al.*, 2008; *Kelsey and Powell*, 2011; *Yakymchuk and Brown*, 2014b; *Kohn et al.*, 2015). This relationship results in the complete dissolution of zircon being rarely, if ever, achieved during typical crustal metamorphism (*Kelsey et al.*, 2008; *Kohn et al.*, 2015). Therefore, the first scenario, in which all inherited zircon was dissolved during partial melting of the Selwyn Block is unlikely. The second scenario in which the Selwyn Block comprises zircon-poor lithologies is consistent with the predominantly mafic and ultramafic (meta)igneous rocks that make up most of the exposed geology of the block. Although current interpretations of the seismic structure of the Selwyn Block imply that at least some of the exposed mafic and ultramafic rocks form a thin thrust sheet emplaced over Proterozoic continental crust of the Western Tasmania Terrane (*Cayley et al.*, 2011; *Moore et al.*, 2016), this interpretation is difficult to reconcile with our inherited zircon data (Figure 4B). Instead, we suggest that the seismically defined units occupying the lower parts of the Selwyn Block (Figure 1B) are also zircon-poor, mafic and ultramafic rocks, comparable to those exposed at the surface (Figure 2D).

In using the lack of a distinct inherited zircon fingerprint to infer a predominantly mafic composition for the Selwyn Block, it is instructive to compare our new results to the inherited zircon signature of Paleozoic granitoids elsewhere in the Lachlan orogen where a mafic lower and middle crust is better established. The Bendigo Zone, immediately west of the Melbourne Zone (Figure 1A), provides a suitable comparison as a relatively homogenous lower and middle crust can be traced on seismic reflection profiles to surface exposures of Cambrian oceanic crust along major fault zones (Figure 1B). The inherited zircon signature of Paleozoic granitoids in the Bendigo Zone is summarised in Figure 4E and is a close match to the inherited zircon signature of Devonian granitoids in the Melbourne Zone (Figure 4D). We suggest these comparable inherited zircon signatures imply a broadly similar crustal composition for the Melbourne and Bendigo zones. This composition is characterised by an upper crust of Paleozoic sedimentary rocks and a predominantly mafic lower and middle crust, the latter of which contributed no clearly recognisable inherited zircon signature to the Paleozoic granitoids of either zone.

We propose that the simplest interpretation that satisfies both outcrop evidence and the new inherited zircon data is that the Selwyn Block mostly comprises zircon-poor, mafic and ultramafic (meta)igneous rocks. The distinct suprasubduction zone affinity of the exposed parts of the Selwyn Block, including boninites, arc-type tholeiites, and strongly depleted ultramafic rocks, together with the low degree of crustal contamination inferred from radiogenic isotope data imply an origin in an intra-oceanic island arc (*Crawford et al.*, 2003; *Foster et al.*, 2009). The onset and duration of this hypothesised intra-oceanic island arc are poorly constrained but available geological evidence are consistent with a middle Cambrian age. Exposures of the Selwyn Block at Dookie suggest the arc was active at ca. 514–502 Ma (*Spaggiari et al.*, 2003; *Habib et al.*, 2022). A post-collisional origin for the Jamieson and Licola volcanics (*Crawford et al.*, 2003) suggests arc magmatism had ceased by 500 ± 8 Ma (*Spaggiari et al.*, 2003). Arc-shut down by ca. 500 Ma is consistent with field relationships at Waratah Bay, which demonstrate that mafic and ultramafic rocks of the Selwyn Block were uplifted and eroded prior to deposition of the unconformably overlaying ca. 480 Ma Digger Island Marlstone (*Cayley et al.*, 2011).

The interpretation of the Selwyn Block as the remnants of a Cambrian intra-oceanic island arc, rather than a Proterozoic microcontinent, is still consistent with most geological and geophysical data previously used to define the block (*Cayley et al.*, 2011). The interpreted geology of the Selwyn Block shown in Figure 1B follows *Moore et al.* (2016) who used inverse modelling of regional gravity and magnetic data to correlate seismically defined units in the Selwyn Block with Proterozoic units in the Western Tasmania Terrane. However, the density and magnetic susceptibility of the Tasmanian Proterozoic rocks used in this modelling overlap with many of the rock types in the Melbourne Zone, including the surface exposures of the Selwyn Block itself (*Moore et al.*, 2016). Indeed, *McLean et al.* (2010) modelled comparable regional magnetic and gravity data from the Selwyn Block as Cambrian arc-related rocks equivalent to the Jamieson and Licola volcanics and more deeply buried ultramafic bodies. Inferences from the structural and sedimentary record of the Melbourne Zone that suggest the Selwyn Block acted as a mechanically rigid substrate and a topographic high in the Paleozoic (*Cayley et al.*, 2002) are still valid in our interpretation because neither require that the Selwyn Block is made of Proterozoic continental crust. For example, intra-oceanic island arcs can be incorporated into orogens as coherent and mechanically rigid terranes provided they are suitably thick (*Boutelier et al.*, 2003). Although not a focus of this study, wholerock chemical and isotopic data of Devonian granitoids in the Melbourne Zone are also consistent with the interpretation of the Selwyn Block as a Cambrian intra-oceanic island arc. In their single component petrogenetic model of S-type granitoids in the Melbourne Zone, Clemens and Buick (2019) favoured a melt source including arc-related dacite, basalt, andesite, and volcaniclastic rocks. Similarly, multi-component petrogenetic models for granitoids in the Lachlan orogen require a significant melt component derived from arc-related mafic rocks (*Collins*, 1996; *Keay et al.*, 1997; *Gray and Kemp*, 2009). Radiogenic isotope data imply that this arc-related mafic source component is no older than Ediacaran (*Collins*, 1996; *Keay et al.*, 1997; *Rossiter and Gray*, 2008; *Foster et al.*, 2009).

5.3 Refining the Cambrian Orogenic Architecture and Tectonic Evolution of Southeast Australia

Interpreting the Selwyn Block as a Cambrian intra-oceanic arc provides a new opportunity to understand its broader tectonic context by evaluating possible correlations with other Cambrian arc remnants in southeast Australia (Figure 6A). The Macquarie Arc in western New South Wales is generally interpreted as a dismembered intra-oceanic arc that developed outboard of the Pacific margin of Gondwana (*Crawford et al.*, 2007; *Glen et al.*, 2007; *Kemp et al.*, 2020, but see *Quinn et al.* (2014) for an alternative interpretation). Although most magmatism in the Macquarie Arc is late Ordovician and Silurian, the arc appears to have been built on an earlier Cambrian arc substrate (*Forster et al.*, 2011; *Kemp et al.*, 2020; *Leslie*, 2021). Evidence for this Cambrian arc basement includes ca. 503 Ma gabbro (Kemp et al., 2020) and ca. 488–515 Ma inherited zircon grains in younger magmatic units (*Leslie*, 2021). Both the Cambrian inherited zircons and the magmatic zircons from ca. 503 Ma gabbro have isotopically juvenile initial Hf isotopic compositions, consistent with an intra-oceanic arc setting (*Kemp et al.*, 2020; *Leslie*, 2021). Other exposures of this Cambrian arc could include mafic and ultramafic rocks in the Coolac Serpentinite belt to the south of the Macquarie Arc (*Bodorkos et al.*, 2013; *Bruce*, 2018) and exotic blocks of ca. 530–500 Ma (meta)igneous rocks in the Peel-Manning Fault System to the northwest (Figure 6A; *Phillips et al.*, 2015; *Manton et al.*, 2017; *Milan et al.*, 2021).

Middle Cambrian arc-related rocks are also exposed in the Stavely Complex, Glenelg River Complex, and Koonenberry Belt in the far western Tasmanides (Figure 6A). These isolated exposures are interpreted as remnants of the once contiguous continental Stavely Arc that developed on the thinned leading edge of the Pacific margin of Gondwana (*Kemp et al.*, 2002; *Kemp*, 2003; *Crawford et al.*, 2003; *Greenfield et al.*, 2011; *Gibson et al.*, 2015; *Johnson et al.*, 2016; *Lewis et al.*, 2016; *Foden et al.*, 2020). Direct correlation of the continental Stavely Arc with the intra-oceanic Macquarie Arc is difficult given their differing tectonic settings. This distinction is particularly evident in the contrasting radiogenic Hf and Nd isotopic signatures of the two arcs, with Stavely Arc rocks generally being isotopically evolved, reflecting extensive reworking of ancient continental crust, contrasting with

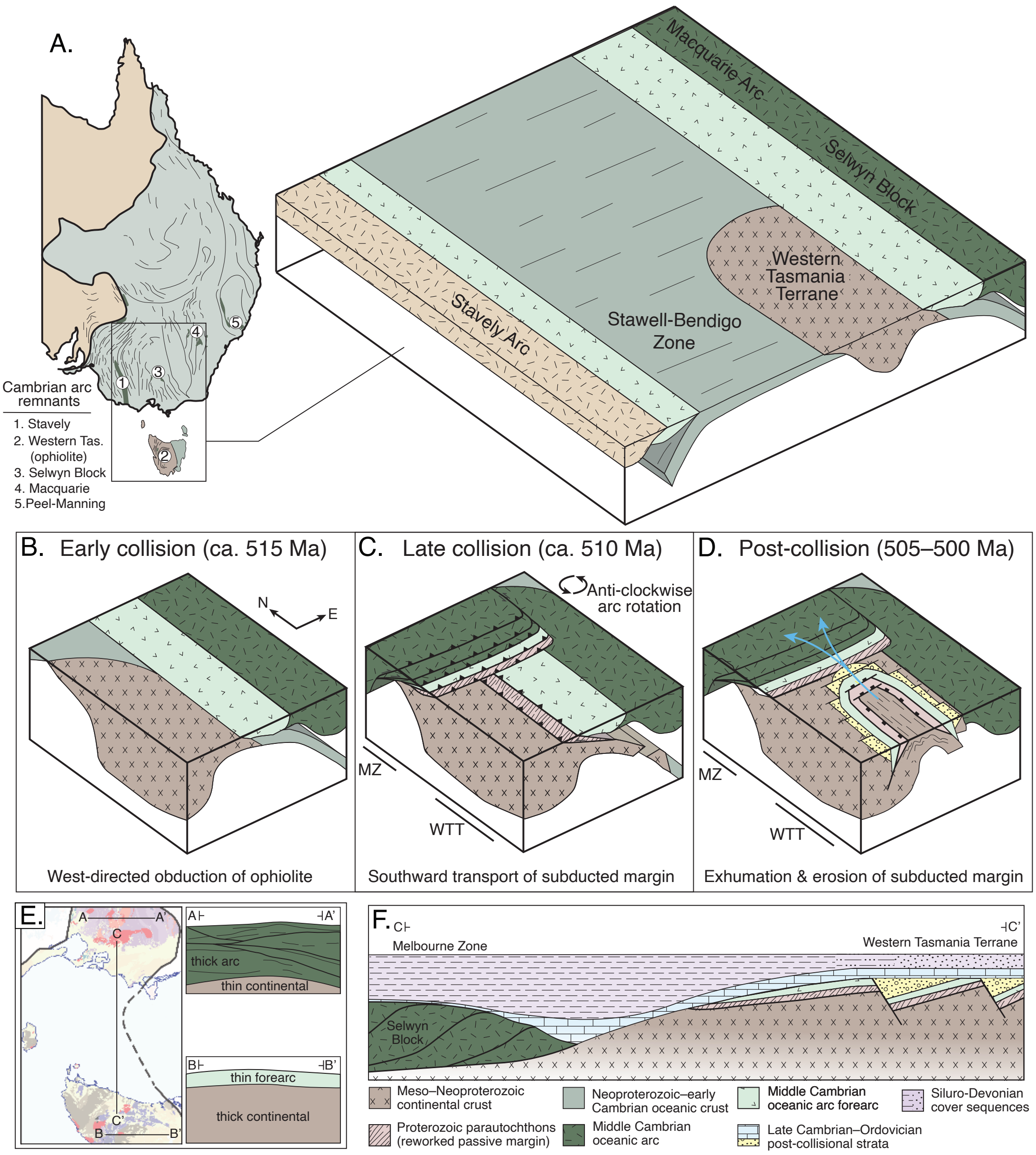

Figure 6 – Refined model for the Cambrian orogenic architecture and tectonic evolution of southeast Australia. **A)** Regional context of Western Tasmania Terrane and Selwyn Block within the southern Tasmanides. Map highlights the location of Cambrian arc-related rocks. Block model summarising the correlation of Selwyn Block with the Cambrian phase of Macquarie Arc and the location of the Selwyn Block-Macquarie Arc intraoceanic arc system and the Western Tasmania Terrane outboard of the continental Stavely Arc. **B)** Early stages of Tyennan Orogeny involving collision of the Western Tasmania Terrane with Selwyn Block intra-oceanic arc. **C)** Late stages of the Tyennan Orogeny showing inferred rotation of colliding arc. Relative positions of Melbourne Zone (MZ) and Western Tasmania Terrane (WTT) shown next to block diagram. **D)** Late Tyennan Orogeny, involving post-collisional uplift and erosion of subducted Proterozoic continental crust, which shed detritus into late Cambrian-Early Ordovician sedimentary basins in the Western Tasmania Terrane and the Melbourne Zone (*Habib et al.*, 2022). **E)** Schematic east-west cross sections showing possible orogenic architecture of the Melbourne Zone and the Western Tasmania Terrane. **F)** Schematic north-south cross section showing possible orogenic architecture across the Melbourne Zone and the Western Tasmania Terrane.

the depleted mantle-like signature of the intra-oceanic Macquarie Arc (*Kemp et al.*, 2009, 2020; *Foden et al.*, 2020). Geochronological and isotopic data are therefore consistent with two broadly contemporaneous Cambrian arcs along the Pacific margin of Gondwana- the continental Stavely Arc and the outboard intra-oceanic Macquarie Arc. The predominance of isotopically juvenile mafic rocks making up the Selwyn Block (*Crawford et al.*, 2003; *Foster et al.*, 2009; *Habib et al.*, 2022) suggests a close affinity to the latter, outboard intra-oceanic arc system.

In addition to the possible correlation of the Selwyn Block with the Cambrian phase of the Macquarie Arc, suitably aged intra-oceanic arc rocks also occur in ophiolitic mafic-ultramafic complexes in the Western Tasmania Terrane (Figures 1A and 2A). These ophiolitic complexes include boninites, low-Ti basalts, and strongly melt-depleted ultramafic cumulates (*Crawford and Berry*, 1992), which are compositionally similar to exposures of the Selwyn Block (*Crawford et al.*, 2003; *Birch and Andrew*, 2024).The ophiolite complexes are typically <2 km thick and are interpreted to represent slices of the fore-arc of a middle Cambrian intra-oceanic arc that was obducted onto the Neoproterozoic passive margin of the Western Tasmania Terrane during the Tyennan Orogeny (*Berry and Crawford*, 1988; *Crawford and Berry*, 1992; *Meffre et al.*, 2000; *Mulder et al.*, 2016; *Gray et al.*, 2023). If middle Cambrian arc-related rocks are correlative between the Selwyn Block and the Western Tasmania Terrane, we suggest the thicker (20–30 km) crust defining the Selwyn Block represents the main body of the intra-oceanic arc that collided with the Western Tasmania Terrane (Figure 6A). In this context, the ophiolite complexes in the Western Tasmania Terrane represent the comparatively thin fore-arc of the colliding Cambrian arc now preserved in the Selwyn Block and possibly further afield in the Macquarie Arc.

The advantage of our new correlation is that it explicitly places the enigmatic geology of the Selwyn Block into the well-established geological framework of Cambrian orogenesis in the Western Tasmania Terrane (Tyennan Orogeny). Figure 6B–D outlines our new Cambrian tectonic model for southeast Australia, which reconciles the interpretation of Selwyn Block as an intra-oceanic arc with the record of arc-microcontinent collision in the Western Tasmania Terrane during the Tyennan Orogeny (*Berry and Crawford*, 1988; *Meffre et al.*, 2000; *Chmielowski and Berry*, 2012; *Mulder et al.*, 2016; *Brown et al.*, 2021; *Gray et al.*, 2023).

The initial stages of the Tyennan Orogeny occurred outboard of the Pacific margin of Gondwana, prior to the arrival of the Western Tasmania Terrane and the Selwyn Block into their present-day position with respect to southeast Australia (Figure 6A; *Berry et al.*, 2008). Unlike the continent-dipping (west-dipping) subduction recorded elsewhere along the Pacific margin of Gondwana (i.e., the Stavely Arc; *Foden et al.*, 2020), arc-microcontinent collision during the Tyennan Orogeny was facilitated by an east-dipping subduction zone (Figure 6A and 6B). This opposite sense of subduction polarity is required by the west-directed kinematic indicators from the metamorphic sole of the ophiolite complexes in western Tasmania (*Berry and Crawford*, 1988; *Mulder et al.*, 2016). A minimum age for the colliding intra-oceanic arc is provided by magmatic zircon U-Pb ages from the ophiolite complexes in the Western Tasmania Terrane, which include tonalite dated at 509 ± 4 (*Habib et al.*, 2022), 510 ± 6 (*Turner et al.*, 1998), and 513 ± 5.0 Ma (*Black et al.*, 1997) and gabbro dated at 516.0 ± 0.9 Ma (*Mortensen et al.*, 2015), 512 ± 5 Ma and 513 ± 5 (*Habib et al.*, 2022). These ages are comparable to zircon U-Pb ages from exposures of the Selwyn Block in the Dookie inlier, which include arc-related gabbros dated at 502 ± 0.7 (*Spaggiari et al.*, 2003) and 514 ± 2.5 Ma (*Habib et al.*, 2022).

During the collisional stage of the Tyennan Orogeny, parts of the Neoproterozoic passive margin of the Western Tasmania Terrane were subducted beneath the Cambrian intra-oceanic arc and locally reached eclogite facies conditions (> 60 km depth) by ca. 510 Ma (Figure 6C; *Turner and Bottrill*, 2001; *Meffre et al.*, 2000; *Chmielowski and Berry*, 2012; *Mulder et al.*, 2015b; *Brown et al.*, 2021). Kinematic indicators from overthrust passive margin units mostly record syn-collisional transport to the south (*Holm and Berry*, 2002; *Berry*, 2014), contrasting with the initial west-directed obduction of the ophiolite complexes (*Berry and Crawford*, 1988; *Mulder et al.*, 2016). This record of significant rotation (∼90°) is typical of the complex structural evolution of arc collisions from the more recent geological record (e.g., *Wallace et al.*, 2009). Plate kinematic data and numerical models demonstrate that collisional choking of subduction zones causes along-strike changes in the rate of convergence, which induces a strong rotational component to the stress field during collision (*Wallace et al.*, 2005; *Moresi et al.*, 2014). We speculate that the transition from west- to south-directed transport during the collisional phase of the Tyennan Orogeny reflects an anti-clockwise rotation of the colliding arc following congestion of the subduction zone by the Western Tasmania Terrane microcontinent (Figure 6C). Given that the collisional phase of the Tyennan Orogeny lasted approximately 10 Ma (ca. 515–505 Ma), the transition from west- to south-direct transport can be explained by the typical arc rotation rates of ∼5–9°/ Ma observed in Cenozoic arc collisions in the southwest Pacific such as those in Papua New Guinea and New Caledonia (*Wallace et al.*, 2009). Importantly, this inferred syn-collisional rotation can explain why the Selwyn Block–interpreted here as the main body of the colliding arc–is preserved along strike from its obducted fore-arc in the Western Tasmania Terrane (Figure 6C).

The collisional phase of the Tyennan Orogeny terminated shortly after ca. 510 Ma with slab-break off and rapid exhumation of the deeply subducted passive margin (Figure 6D). By ca. 505 Ma, parts of the subducted passive margin had been exhumed and were shedding detritus into adjacent sedimentary basins, including those developed on the Selwyn Block (Berry Gully Chert; *Habib et al.*, 2021). Post-collisional volcanism is recorded by the ca. 508–496 Mount Read Volcanics in the Western Tasmania Terrane (*Mortensen et al.*, 2015) and the possibly correlative 500 ± 8 Ma Jamieson and Licola volcanics in the Selwyn Block (*Spaggiari et al.*, 2003; *Crawford et al.*, 2003). The final stage of the Tyennan Orogeny involved a latest Cambrian phase of east-west compression, which may document the accretion of the combined Western Tasmania Terrane and Selwyn Block onto the Pacific margin of Gondwana in their present-day relative position with respect to southeast Australia (*Holm and Berry*, 2002; *Berry et al.*, 2008; *Cayley*, 2011; *Glen and Cooper*, 2021). The post-accretion architecture of the Selwyn Block and Western Tasmania Terrane is summarised schematically in Figure 6E and 6F. Late Cambrian accretion of the Western Tasmania Terrane-Selwyn Block was likely followed by re-establishment of an outboard subduction zone as recorded by early Ordovician magmatism in the

Macquarie Arc (*Glen*, 2013; *Kemp et al.*, 2020), signalling a new cycle of accretion and outward growth of the Tasmanides.

6 Conclusions

The Selwyn Block is a prominent feature of the Paleozoic orogenic architecture of southeast Australia and has previously been interpreted to represent a northern extension of the Western Tasmania Terrane Proterozoic microcontinent. We tested the proposed continuation of Proterozoic continental crust of the Western Tasmania Terrane into the Selwyn Block by comparing the inherited zircon age distribution of Devonian granitoids in both regions. The inherited zircon signature of granitoids in the Western Tasmania Terrane closely matches the detrital zircon age signature of widespread Mesoproterozoic and Neoproterozoic strata in western Tasmania with large age populations at ca. 1430 Ma and 1800–1600 Ma. Phase equilibria modelling indicates that if equivalent Proterozoic strata are present at depth within the Selwyn Block, they would have crossed their solidus in the Devonian and contributed melt and inherited zircon grains to granitoids in the Melbourne Zone. However, Devonian granitoids in the Melbourne Zone preserve little evidence for zircon inheritance from Western Tasmania Terrane-like crust. Instead, these granitoids apparently inherited all pre-magmatic zircon grains from the Paleozoic sedimentary cover of the Selwyn Block.

The generally lower wholerock $^{87}Sr/^{86}Sr$ and higher magmatic zircon initial $\varepsilon Hf_{(i)}$ of Devonian granitoids in the Melbourne Zone compared to their counterparts in the Western Tasmania Terrane also support distinct melt sources between these areas. Based on these findings, we argue that the majority of the Selwyn Block comprises Cambrian arc-related mafic and ultramafic rocks, comparable to those forming the rare surface exposures of the block. The Selwyn Block is potentially correlative with Cambrian arc-related rocks in the Macquarie Arc of New South Wales and a Cambrian forearc ophiolite in western Tasmania, which may collectively be remnants of an intra-oceanic island arc located outboard of the Pacific margin of Gondwana. Prior to accreting onto the margin of southeast Australia, this intra-oceanic island arc collided with the Western Tasmania Terrane microcontinent during the middle Cambrian Tyennan Orogeny. Our new model offers a refined view of the Cambrian orogenic architecture of southeast Australia and the early history of accretionary tectonics along the Pacific margin of Gondwana.

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Author contributions

JM: Conceptualisation, Data curation, Formal analysis, Investigation, Writing. **JH**: Conceptualisation, Formal analysis, Investigation. **LM**: Conceptualisation, Formal analysis, Investigation. **YZ**: Formal analysis, Investigation. **JE**: Formal analysis, Resources. **SM**: Conceptualisation, Investigation. **MH**: Formal analysis, Resources. **ON**: Formal analysis, Resources. **PC**: Formal analysis, Funding acquisition.

Data availability

The following supplementary files are available at: https://doi.org/10.5281/zenodo.16418547

- Supplementary File 1: Sample details
- Supplementary File 2: Zircon U-Pb data
- Supplementary File 3: Zircon U-Pb-Hf data
- Supplementary File 4: Inter-sample comparison of Western Tasmania Terrane inheritance
- Supplementary File 5: Inter-sample comparison of Melbourne Zone inheritance

Competing interests

The authors declare no competing interests.

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