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A hidden Rodinian lithospheric keel beneath Zealandia, Earth's newly recognized continent

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ABSTRACT

We present a data set of >1500 *in situ* O-Hf-U-Pb zircon isotope analyses that document the existence of a concealed Rodinian lithospheric keel beneath continental Zealandia. The new data reveal the presence of a distinct isotopic domain of Paleozoic–Mesozoic plutonic rocks that contain zircon characterized by anomalously low $\delta^{18}O$ values (median = +4.1‰) and radiogenic $\varepsilon_{Hf(t)}$ (median = +6.1). The scale (>10,000 km^2) and time span (>>250 m.y.) over which plutonic rocks with this anomalously low-$\delta^{18}O$ signature were emplaced appear unique in a global context, especially for magmas generated and emplaced along a continental margin. Calculated crustal-residence ages (depleted mantle model, T_{DM}) for this low-$\delta^{18}O$ isotope domain range from 1300 to 500 Ma and are interpreted to represent melting of a Precambrian lithospheric keel that was formed and subsequently hydrothermally altered during Rodinian assembly and rifting. Recognition of a concealed Precambrian lithosphere beneath Zealandia and the uniqueness of the pervasive low-$\delta^{18}O$ isotope domain link Zealandia to South China, providing a novel test of specific hypotheses of continental block arrangements within Rodinia.

INTRODUCTION

The Neoproterozoic amalgamation and subsequent breakup of the Rodinia supercontinent were significant events in Earth's history. However, despite consensus that Rodinia was assembled at ca. 1300–900 Ma and rifted apart ca. 800–600 Ma, debate continues as to the internal configuration of continent-sized blocks (e.g., Li et al., 1995, 2008; Cawood et al., 2013). Central to the Rodinia debate is the location of cratonic blocks to the east of the Australia–East Antarctica margin, with arguments that the margin was adjacent to the western Canadian Laurentian margin (Dalziel, 1991; Moores, 1991) or the western United States Laurentian margin (Karlstrom et al., 1999). Alternatively, it is also hypothesized that the South China block was positioned between Australia–East Antarctica and Laurentia (Li et al., 1999).

Recently recognized as a distinct continent, Zealandia—of which 94% is currently underwater—formed following Late Cretaceous breakup of the Gondwana supercontinent (Mortimer et al., 2017). Prior to its separation, the basement rocks of continental Zealandia were created by multiple episodes of terrane accretion and arc-related magmatism along the paleo-Pacific Gondwana margin from the Cambrian to Early Cretaceous (Mortimer, 2004). No Precambrian rocks are exposed onshore in New Zealand. The oldest basement rocks of Zealandia are divided into two provinces: the early Paleozoic Western province, comprising metasedimentary rocks and Paleozoic–Mesozoic intrusions, and the late Paleozoic–Mesozoic Eastern province, a series of plutonic-metasedimentary terranes accreted to the Gondwanan margin (Fig. 1) (Mortimer, 2004). The Median batholith, a long-lived arc once part of the active Gondwanan margin, sutures the two provinces (Mortimer, 2004). The inferred eastern limit of Gondwanan Paleozoic upper- to mid-crustal metasedimentary rocks in Zealandia is well defined by linked major ductile shear zones, marking a major crustal boundary (Fig. 1B) (Allibone and Tulloch, 2004; Scott et al., 2011; Klepeis et al. 2019). Previous isotopic studies focused on this boundary demonstrate that Mesozoic Zealandia consisted of separate crustal blocks that are isotopically distinct (Schwartz et al., 2021). In this study, we present *in situ* O-Hf-U-Pb isotopic zircon data for Cambrian–Cretaceous plutonic rocks throughout Zealandia that enable us to determine the middle- to lower-crustal source(s) of these diverse isotopic domains through time. Our results reveal for the first time that continental Zealandia is underlain by a broad Precambrian lithospheric keel, which allows us to place Zealandia into the greater Rodinia supercontinent puzzle.

ISOTOPIC FINGERPRINTING OF ZEALANDIA

Zircon is the foremost deep-time recorder of Earth's history, preserving a rich archive of isotope information that informs on magma parentage and crust-mantle evolution (Valley et al., 2005; Kemp et al., 2007). Unlike whole rocks, zircon is highly resistant to alteration and weathering, (Hoskin and Schaltegger, 2003), providing a robust record of the U-Pb age and O-Hf isotope composition of the melts from which it crystallized. Importantly, the $\delta^{18}O$ and Lu-Hf isotope composition of zircon is particularly sensitive in evaluating the interaction between crust and mantle reservoirs (Valley et al., 2005; Kemp et al., 2007). Mantle-like zircon has an $\delta^{18}O$ composition of +5.3‰ ± 0.8‰; deviation

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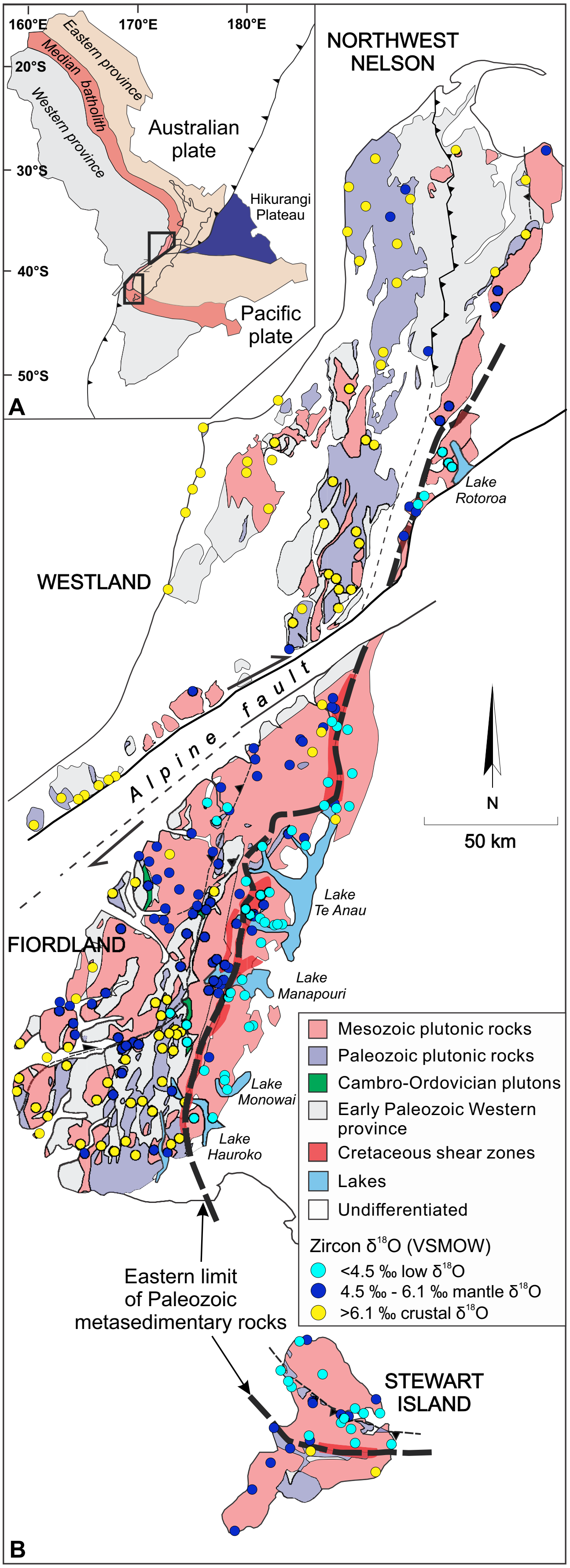

Figure 1. (A) Modern tectonic setting of New Zealand (thin black outlines) and spatial extent of Zealandia. Study area is delineated by thick black outlines. (B) Simplified geological map outlining the extent of early Paleozoic metasedimentary terranes and Phanerozoic plutonic rocks and their δ^{18}O zircon compositions (pre-Cretaceous reconstruction that addresses Cenozoic Alpine fault displacement). Eastern isotope domain includes all plutonic rocks emplaced east of the limit of Gondwanan Paleozoic upper- to mid-crustal metasedimentary rocks. VSMOW—Vienna standard mean ocean water.

of zircon δ^{18}O values above +6.1‰ reflects supracrustal recycling processes, whereas low zircon δ^{18}O values (<+4.5‰) require a source that has undergone high-temperature alteration or melting of source rocks that have interacted with fractionated meteoric waters at high paleolatitudes and/or paleo-elevations (Valley et al., 2005; Bindeman, 2008). The $\varepsilon_{Hf(t)}$ composition of zircon can be used to assess the relative contributions of primitive (mantle-derived) and continental crustal sources to magma petrogenesis and to calculate episodes of crustal extraction (Hf model age = T_{DM}) from a depleted mantle source (Vervoort and Blichert-Toft, 1999; Kemp et al., 2007).

To test the evolving nature of Zealandia's crustal architecture and the age and composition of the underlying lithosphere, we analyzed zircon from 169 samples that characterize the main episodes of plutonism in Zealandia's Western province. This new data set includes >1500 oxygen-isotope analyses (using secondary ion mass spectrometry) and >3550 Lu-Hf-U-Pb analyses (collected simultaneously using split stream laser-ablation–inductively coupled plasma–mass spectrometry [U-Pb] and multi-collector–inductively coupled plasma–mass spectrometry [Lu-Hf]). A full description of sample preparation, analytical protocols, and results is provided in the Supplemental Material[1] and raw data for all zircon analyses from individual plutonic samples, sample IDs, and location information is provided in the Petlab database (https://pet.gns.cri.nz/; Strong et al., 2016). To ensure analysis of a single domain representative of magmatic crystallization, all analyses were targeted to a single location of the zircon, guided by cathodoluminescence images (Fig. S1 in the Supplemental Material).

RECOGNITION OF A PERVASIVE LOW-Δ^{18}O ISOTOPE DOMAIN

Marked differences in δ^{18}O in zircon from Zealandia plutonic rocks highlight distinct lithospheric domains (Figs. 1B and 2A). Almost all plutonic rocks emplaced east of the limit of Paleozoic metasedimentary rocks have consistently low δ^{18}O values (Figs. 1B and 2A), with most within ±1‰ of the median δ^{18}O value of +4.1‰ (a range from −8.1‰ to +8.9‰). Plutonic rocks are Carboniferous to Cretaceous, with whole-rock SiO_2 from 50 to 77 wt%. Low intrasample δ^{18}O variability for most granitoid samples (Fig. 2A) supports isotopic homogenization in high-temperature melt-rich systems

[1]Supplemental Material. Detailed outline of analytical methods, raw data for all O-isotope and Lu-Hf-U-Pb isotope analyses for unknowns and standards, and sample location information. Please visit https://doi.org/10.1130/GEOL.S.14417615 to access the supplemental material, and contact editing@geosociety.org with any questions.

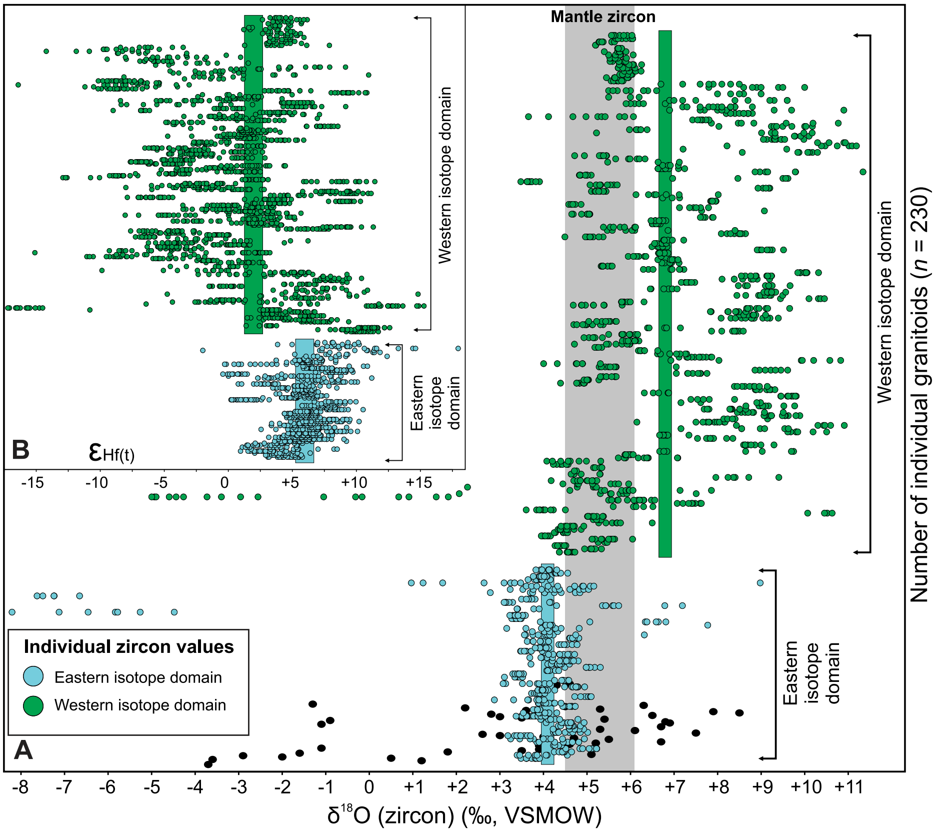

Figure 2. (A) Individual $\delta^{18}O$ values of zircon from Zealandia plutonic rocks from the eastern and western isotope domains. Black symbols are $\delta^{18}O$ zircon values from plutonic rocks of the South China block (Fu et al., 2013). VSMOW—Vienna standard mean ocean water. (B) Individual zircon $\varepsilon_{Hf(t)}$ values for Zealandia plutonic rocks. Median $\delta^{18}O$ and $\varepsilon_{Hf(t)}$ for each domain is represented by colored vertical bar; line thickness represents 1σ uncertainty (±0.15‰ for $\delta^{18}O$; ±0.7 for $\varepsilon_{Hf(t)}$). Analyses interpreted as metamorphic and inherited (based on spot U-Pb age) are not plotted. Samples (n = 169) analyzed in this study are supplemented with 61 additional $\delta^{18}O$ and $\varepsilon_{Hf(t)}$ values from Hiess et al. (2015), van der Meer et al. (2018), Schwartz et al. (2021).

in the lower crust and/or upper mantle (Bindeman, 2008). To the west of the limit of Paleozoic metasedimentary rocks, Cambrian-Ordovician to Cretaceous plutonic rocks have $\delta^{18}O$ values that range from −4.7‰ to +11.3‰ (median of +6.8‰; Figs. 1B and 2A) and whole-rock SiO_2 values between 47 and 78 wt%. I-type plutonic rocks from this western domain typically have mantle-like values (+5.3‰ ± 0.9‰) from melting of a sediment-modified mantle source and/or melting of subducted oceanic crust (i.e., Bolhar et al., 2008; Schwartz et al., 2021); conversely, S-type (peraluminous) and A-type (peralkaline) plutonic rocks have $\delta^{18}O$ values >>+6.1‰, consistent with significant crustal recycling (Hiess et al., 2015). For all plutonic rocks, no correlation is observed between $\delta^{18}O$ and fractionation indexes (i.e., SiO_2, Zr/Hf; Fig. S2), indicating that variability in O-Hf isotope compositions is not controlled by fractional crystallization. This new data set documents a widespread and internally homogeneous eastern isotope domain (EID) of plutonic rocks with anomalously low $\delta^{18}O$ values that extends for >10,000 km² (Figs. 1B and 2A). This contrasts with plutonic rocks emplaced in the western isotope domain (WID), which have mantle and crustal $\delta^{18}O$ values and almost no plutonic rocks with $\delta^{18}O$ zircon values <4.5‰.

Insights into the source(s) for the low-$\delta^{18}O$ EID come from considering zircon Hf isotope compositions. Plutonic rocks from the low-$\delta^{18}O$ EID have more radiogenic $\varepsilon_{Hf(t)}$ values (median $\varepsilon_{Hf(t)} = +6.1$) and are tightly clustered compared to those emplaced in the WID (median $\varepsilon_{Hf(t)} = +1.9$, broad range of values) (Fig. 2B). Coupled O-Hf zircon isotope compositions indicate that plutonic rock compositions from the low-$\delta^{18}O$ EID were controlled by melting of a relatively isotopically homogeneous mafic lower-crustal source (radiogenic $\varepsilon_{Hf(t)}$ values) that had experienced high-temperature hydrothermal alteration (responsible for the low-$\delta^{18}O$ signature). Plutonic rock compositions from the WID are controlled by melting of a mafic lower-crust and/or mantle source mixed with variable amounts of a metasedimentary source.

Magmas and zircon with $\delta^{18}O$ values lower than mantle are relatively rare in the geological record. Where present, they are primarily related to voluminous magmatism and elevated heat flux associated with hotspot and rift environments (Wang et al., 2011; Troch et al., 2020). Conversely, they are rarely reported from magmas emplaced within arc settings (Muñoz et al., 2012). Mesozoic plutonic rocks with low $\delta^{18}O$ (<<+4.5‰) have previously been reported in Fiordland, New Zealand (Bolhar et al., 2008; Schwartz et al., 2021), and attributed to an underthrust low-$\delta^{18}O$ source of unknown age. Our analysis of Cambrian-Ordovician and Carboniferous plutonic rocks with a low-$\delta^{18}O$ signature demonstrates that a source for these rocks is at least Cambrian and likely older.

To assess the age of the lower-crustal source(s) in the EID, we calculated crustal residence ages (T_{DM}) (Fig. 3). A broad range of model ages is observed for low-$\delta^{18}O$ plutonic rocks of the EID, with most T_{DM} ages between ca. 1300 and 500 Ma (Fig. 3). For WID plutonic rocks, T_{DM} ages range from >>2000 to 500 Ma (Fig. 3). We suggest that the T_{DM} age range and radiogenic $\varepsilon_{Hf(t)}$ values for the EID are indicative of a primitive lithospheric mafic source produced by melting of the depleted mantle at different periods between 1300 and 500 Ma. The isotopically homogeneous low $\delta^{18}O$ zircon values of the EID imply widespread high-temperature hydrothermal alteration of this primitive mafic source.

UNVEILING THE RODINIAN LITHOSPHERIC KEEL OF ZEALANDIA

We propose that Phanerozoic plutonic rocks emplaced within the low-$\delta^{18}O$ EID of Zealandia were produced by partial melting of a hydrothermally altered Precambrian lower-crustal mafic source. This accounts for calculated crustal residence ages between ca. 1300 and 500 Ma, radiogenic $\varepsilon_{Hf(t)}$, and low $\delta^{18}O$ zircon values (Fig. 2; Figs. S3 and S4). A three-stage process is evoked to explain the formation and subsequent alteration of the lower-crustal Precambrian source. In the first stage, melting of depleted mantle between ca. 1300 and 900 Ma produced mafic melts that ponded at the base of the crust. Magmatism during this period occurred along an active oceanic arc margin prior to final suturing and accretion of the Rodinia supercontinent (Fig. 4A) (Li et al., 2008). During the second stage, melting of depleted mantle between ca. 800 and 500 Ma produced additional mafic melts that also ponded in the lower crust. Mantle melting during this period was associated with Rodinian rifting events in response to a mantle superplume focused beneath Australia–East Antarctica and Western Laurentia (Fig. 4B) (Li et al., 1999, 2008). In the final stage, widespread hydrothermal alteration of the lower-crustal mafic material was synchronous with Rodinian rifting (800–500 Ma) due to high-temperature water-magma interaction during plume-driven magmatism (Wang et al., 2011). This would have been enough to impart the low-$\delta^{18}O$ signature (Wang et al., 2011). However, the involvement of glacier-derived waters

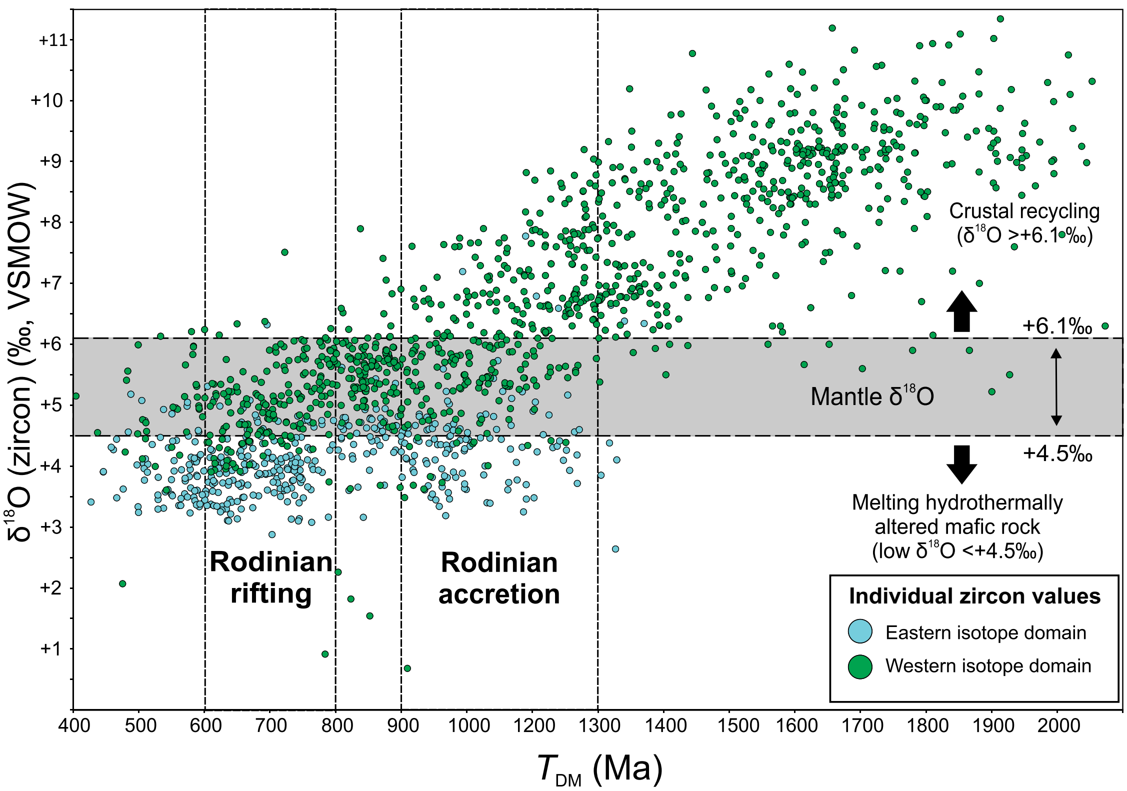

Figure 3. Calculated crustal residence ages (T_{DM}, depleted mantle model) versus δ^{18}O for individual zircon from Zealandia plutonic rocks. For clarity, analyses with T_{DM} >2000 Ma and few analyses with δ^{18}O values <0‰ are not plotted. VSMOW—Vienna standard mean ocean water.

along Rodinia rifting zones contributing to the low-δ^{18}O signature of the source cannot be ruled out (Zheng et al., 2004). In either case, the O-Hf isotope composition of Paleozoic–Mesozoic plutonic rocks in the low-δ^{18}O EID is directly tied to melting of this hydrothermally altered low-δ^{18}O mafic Rodinian keel.

The spatial extent of the Rodinian keel beyond the EID is difficult to establish. In the WID, any low-δ^{18}O signature is obscured by magmas contaminated by Phanerozoic continental crust. The lack of Phanerozoic plutonic rocks with low δ^{18}O values along the formerly contiguous Gondwana margin of southeastern Australia and Antarctica (Fig. 4C) (Kemp et al., 2007; Yakymchuk et al., 2013) suggests either that these segments of Gondwana are not underlain by the same Rodinian lithospheric keel as Zealandia or that that any low-δ^{18}O isotopic signal is also obscured by crustal contamination. Mantle xenoliths from the Waitaha domain (Fig. 4C) within Zealandia's Eastern province have Re-Os melt extraction ages that support an underlying Paleoproterozoic cratonic mantle (McCoy-West et al., 2013) but not a crustal keel of Rodinian age as revealed in this study.

ZEALANDIA IN RODINIA CONFIGURATION MODELS

The continent of Zealandia was once adjacent to western Tasmania in the Cambrian (Münker and Crawford, 2000). Our data, for the first time, also permit a Precambrian correlation to Tasmania and consequently Australia–East Antarctica. We suggest that Zealandia was part of (or proximal to) the Proterozoic microcontinental block VanDieland (which includes Tasmania) (Fioretti et al., 2005; Li et al., 2008; Cayley, 2011); the location of Zealandia in this context has implications for the position of South China (Fig. 4). In fact, the position of the South China block within Rodinia is controversial, with two main models proposed: (1) the South China block occupied an external position along a convergent margin adjacent to Western Australia and northern India (Karlstrom et al., 1999; Wang et al., 2017; Cawood et al., 2018), or (2) the South China block was located in the center of Rodinia between eastern Australia and Laurentia (Li et al., 1995, 1999, 2008). One of the pieces of evidence linking the South China block with northwestern India is the correlation of diverse Precambrian rocks from both blocks with anomalously low δ^{18}O values and the lack of any rocks with low δ^{18}O values in Australia–East Antarctica (Wang et al., 2017). The low-δ^{18}O EID in Zealandia, inherited from a low-δ^{18}O Precambrian mafic source, provides an alternative solution (Fig. 4) and a possible link to the South China block. Along with the VanDieland microcontinent, Zealandia may be the "linkage" terrane between East Gondwana, the South China block, and Laurentia.

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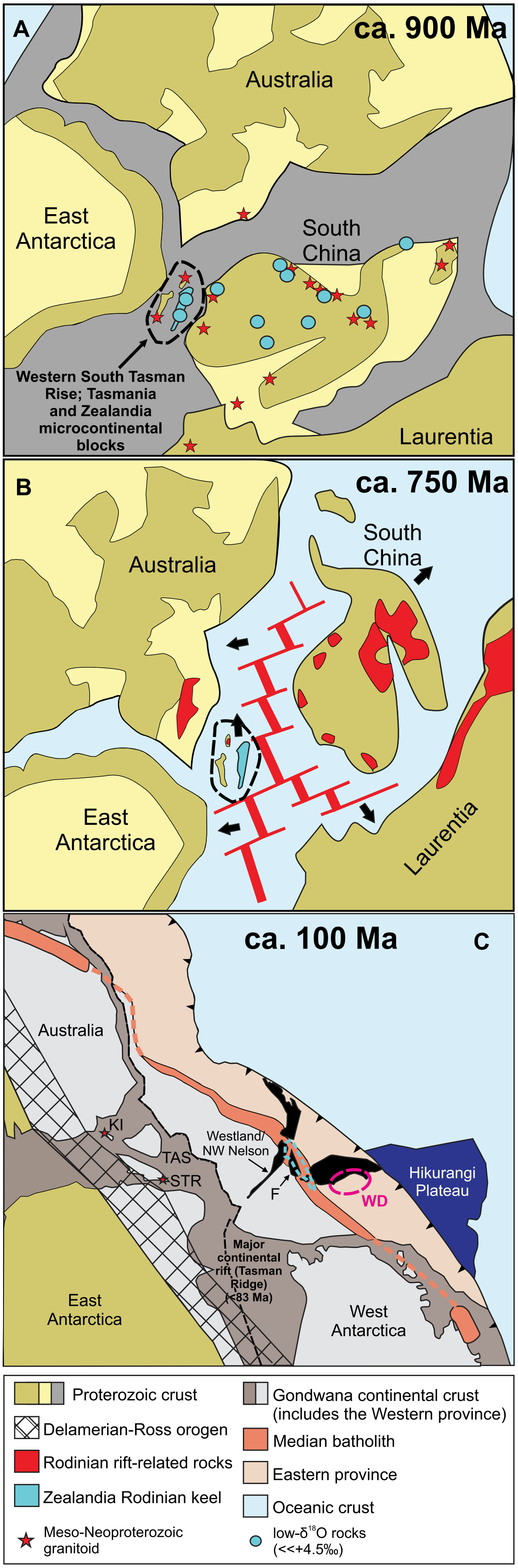

Figure 4. Schematic reconstructions. (A) Position of Zealandia lithospheric keel within Rodinia at the point of final supercontinent assembly at ca. 900 Ma. (B) Initiation of Rodinia rifting in response to underlying mantle superplume (which underlies the entire field of view) and likely location of Zealandia (highlighted in bright blue) proximal to the VanDieland microcontinent block at ca. 750 Ma. Red lines represent spreading ridges and black arrows show relative plate motions. (C) Reconstructed geological setting of Zealandia continental ribbon along the southeastern Gondwanan margin at ca. 100 Ma. Present-day exposed parts of New Zealand are in black. Pink ellipse represents the Waitaha domain (WD) of the Eastern province. F—Fiordland. Black dashed polygon in A and B represents the VanDieland microcontinent including Zealandia, South Tasman Rise (STR), Tasmania (TAS), and King Island (KI). Figures and information are adapted and sourced from Fioretti et al. (2005), Li et al. (2008), Tulloch et al. (2009), McCoy-West et al. (2013), and Cayley (2011).

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