Continent stabilisation by lateral accretion of subduction zone-processed depleted mantle residues; insights from Zealandia

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Abstract

To examine how the mantle lithosphere stabilises continents, we present a synthesis of the mantle beneath Zealandia in the SW Pacific Ocean. Zealandia, Earth's "8th continent", occurs over 4.9 M km^2 and comprises a fore-arc, arc and back-arc fragment rifted from the Australia-Antarctica Gondwana margin 85 Myr ago. The oldest extant crust is ~500 Ma and the majority is Permian-Jurassic. Peridotitic rocks from most known locations reveal the underpinning mantle to comprise regional domains varying from refractory (Al_2O_3 < 1 wt%, olivine Mg# > 92, spinel Cr# up to 80, Pt/Ir < 1) to moderately depleted (Al_2O_3 = 2-4 wt%, olivine Mg# ~90.5, spinel Cr# < ~ 60). There is no systematic distribution of these domains relative to the former arc configuration and some refractory domains underlie crust that is largely devoid of magmatic rocks. Re-depletion Os model ages have no correlation with depletion indices but do have a distribution that is very similar to global convecting mantle. Whole rock, mineral and isotopic data are interpreted to show that the Zealandia mantle lithosphere was constructed from isotopically heterogeneous convecting mantle fragments swept into the sub-arc environment, amalgamated, and variably re-melted under low-P hydrous conditions. The paucity of mafic melt volumes in most of the overlying crust that could relate to the depleted domains requires melting to have been followed by lateral accretion either during subduction or slab rollback. Recent Australia-Pacific convergence has thickened portions of the Zealandia mantle to > 160 km. Zealandia shows that the generation of refractory and/or thick continental lithosphere is not restricted to the Archean. Since Archean cratons also commonly display crust–mantle age decoupling, contain spinel peridotites with extreme Cr# numbers that require low-P hydrous melting, and often have a paucity of mafic melts relative to the extreme depletion indicated by their peridotitic roots, they too may - in part - be compilations of peridotite shallowly melted and then laterally accreted at subduction margins.

Keywords: lithosphere, peridotite, Os isotopes, continent, depleted mantle, lateral accretion, Zealandia

1. Introduction

The compositions of cratonic peridotite xenoliths have led to models in which the mantle roots to Earth's early continents formed by high-*P* melting induced by plumes (e.g., Griffin et al., 2003; Arndt et al., 2009; Aulbach, 2012), polybaric decompression melting beneath oceanic plates (e.g., Bernstein et al., 2006; Rollinson, 2010; Herzberg and Rudnick, 2012) and/or low-P hydrous melting in sub-arc environments (e.g., Parman et al., 2004; Pearson and Witting, 2008). The intrinsic buoyancy of depleted lithospheric peridotite compared to the convecting mantle promotes long-term lithosphere stability (e.g., Jordan, 1978). The difficulty of deciphering the process of ancient lithosphere formation in part stems from the lack of consensus on when global subduction began, since subduction implies the presence of arcs, and arcs are synonymous with modern sites of hydrous melting, continent accretion and growth.

Whereas there are a plethora of geological, geochemical and dynamic modelling studies examining the factors leading to the stabilisation of Archean continents, relatively few focus in the same way on the role played by peridotitic lithosphere in forming Earth's younger continents. To understand the formation of young continental lithospheres, we present the results of an extensive survey, using almost all known mantle sample locations, of the composition and age of the lithospheric mantle underpinning central-southern Zealandia (**Fig. 1**). Zealandia is a 4.9 M km^2 Phanerozoic continent in the southwest Pacific Ocean and represents Earth's most recently stabilised continental masses (Mortimer et al., 2017). It is an ideal place to examine the formation of a continental-scale modern lithosphere because (1) it was unequivocally assembled as a result of Phanerozoic subduction along the margin of Gondwana; and (2) there are numerous exhumed fragments of its lithospheric mantle keel, in the form of ultramafic massifs and mantle xenoliths in volcanic rocks, that span the former Gondwanan Mesozoic fore-arc, arc and back-arc areas. We draw on an extensive mineral, whole rock and Os isotopic database to generate a model for how the mantle roots underpinning this young continent established and became stable. We find that Re-depletion Os model ages have little or no association with the stabilisation age, and suggest that, despite many billions of years of interim Earth evolution, there are similarities in the process of continental root assembly of Earth's youngest and oldest continents.

2. Zealandia's geological context

Zealandia is a largely submarine continent occurring over 4.9 million km^2 in the SW Pacific Ocean that comprises a near-intact fragment of the Mesozoic Gondwana arc margin (**Fig. 1**). The oldest crust is Late Cambrian and the continent is predominantly composed of younger meta-sedimentary terranes and arcs that were progressively accreted to the subduction margin throughout the Phanerozoic (**Fig. 2**) (Mortimer,

2004). Unlike formerly contiguous Antarctica and Australia, neither surficial nor deeply exhumed crust (e.g., Beyssac et al. 2015; Jacob et al., 2017) or zircon U–Pb–Hf isotope systematics in igneous rocks (e.g., Bolhar et al., 2008) provide evidence that Zealandia has an Archean or even Proterozoic crustal core.

The continental terrane assemblage of Zealandia preserves the Early Cretaceous subduction margin fore-arc, arc and back-arc configuration of Gondwana (**Fig. 2**). Subduction ceased at ~105 Ma when the Hikurangi oceanic plateau (**Fig. 2**), a significant fragment of the Ontong Java - Manihiki large igneous province, collided with the Gondwana margin. The Hikurangi Plateau was too buoyant to subduct, and this is inferred to have resulted in a shallow dipping fore-running oceanic lithosphere rolling back towards the trench and ceasing the long-lived Phanerozoic convergence (Jacob et al., 2017). This process ultimately led to the defining evolutionary stages that culminated in Zealandia's continent status: Late Cretaceous to Early Eocene development of the oceanic crust-floored Tasman Sea during separation of Zealandia from Australia, and Late Cretaceous to present day formation of oceanic crust in the Southern Ocean between Zealandia and Antarctica (e.g., Tulloch and Kimbrough, 1989; Mortimer et al., 2017).

The orogenic peridotites, xenoliths in alkaline basalts, and the ultramafic bases to ophiolites represent fragments of Zealandia mantle lithosphere (**Fig. 1, 2**). The Dun Mountain Ophiolite Belt – type locality of dunite – stretches for > 1000 km and represents a depleted slice of Permian oceanic lithosphere accreted in the Mesozoic (Coombs et al., 1976). The Anita Peridotite in SW New Zealand is a 15 km long by up to 1 km wide refractory body that provides a snapshot of the Cretaceous sub-arc spinel facies mantle lithosphere (Czertowicz et al., 2016). The main insights into the Zealandia lithosphere, however, have come from Cretaceous to Miocene peridotite xenoliths entrained by alkaline basalts. Limited whole rock Os data (McCoy-West et al., 2013; Liu et al., 2015) and clinopyroxene Hf (Scott et al., 2014b) has revealed that peridotite suites from the West Otago and East Otago mantle domains (**Fig. 1**) contain depletion ages that span Archean to modern times. The ancient material has been interpreted to represent long-lived stable lithosphere (McCoy-West et al., 2013) or material accumulated during young lithosphere assembly (Scott et al., 2014b; Liu et al., 2015); we further address this topic in the current paper. Regardless of which model is preferred, the Zealandia mantle lithosphere records Cretaceous metasomatism by CO_2-bearing silicate and carbonatitic magmas that have imparted a HIMU-like Sr-Nd-Pb $\pm$ Hf-like isotopic signature (Scott et al., 2014a, b; McCoy-West et al., 2016; Scott et al., 2016a, b; Dalton et al., 2017; van der Meer et al., 2017). Shortening across the Australia-Pacific plate boundary in the last ~7 Ma has thickened the present-day lithosphere beneath West Otago and interpretation of

geophysical survey results indicates that the mantle root beneath the Southern Alps now extends to > 160 km (e.g., Stern et al., 2000; Sutherland et al., 2000; Reyners et al., 2017).

3. Methods

3.1. Whole rock geochemistry

Peridotite whole rock powders were prepared by cutting samples into narrow plates and removing alteration. Sample surfaces were then cleaned with carborundum paper, washed and dried. Rocks were placed in several plastic bags and gleefully smashed with a hammer until fragments were < 1 cm. Material was then pulverised in an agate mill. A pure quartz sand was run between samples, and the mill cleaned thoroughly twice between analyses. Powders were dispatched and then processed for major and trace elements by X-ray fluorescence at Franklin & Marshall College in the United States of America or SpectraChem Analytical in New Zealand. Major elements were measured on lithium tetraborate disks containing 0.4 grams (Franklin & Marshall College) or 0.5 grams (SpectraChem Analytical) of homogenised powder. Trace elements were measured on dried powders (110^{o}C) converted to pressed powder pellets comprising 7.0 grams of rock powder and 1.4 grams of copolywax. Elements were measured on a PANalytical 2404 X-ray fluorescence vacuum spectrometer equipped with a 4 kW Rh super sharp X-ray tube. Loss on ignition was calculated by weighing aliquots before and after being subjected to 950^{o}C for one hour.

3.2. Os isotopes and PGE

Whole rock PGE (Os, Ir, Pt, Pd and Re) concentrations and Os isotope ratios were obtained using isotope dilution at the University of Alberta. Approximately 1 gram of whole-rock powder, in combination with an appropriate amount of mixed HSE spikes (^{185}Re, ^{190}Os, ^{191}Ir, ^{194}Pt, and ^{106}Pd), was attacked by inverse Aqua Regia (3.5 ml of Teflon-distilled concentrated HCl and 6 ml of sparged Teflon-distilled concentrated HNO_3) in a high-pressure Asher (HPA-S, Anton Paar; *P* = 130 bar) for ~16 h at ~260°C. Osmium was extracted immediately from the acid solution by solvent extraction into $CHCl_3$, back extracted into HBr and further purified via micro-distillation using a H_2SO_4–dichromate solution into 15 µl of concentrated HBr. Osmium isotope ratios were measured as OsO_3^- using multiple Faraday collectors and amplifiers equipped with 10^{12} Ω resistors by a Thermo Scientific Triton Plus thermal ionization mass spectrometer (TIMS) at the University of Alberta. Typical intensities of mass 240 (mainly $^{192}Os^{16}O_3^-$) were 0.1-0.4 V (10^{11} Ω amplifier equivalent signals; 0.001 V is equivalent to ~62500 counts per second) with 50 ratios taken at 8 seconds integration per ratio. Raw ratios were first corrected for gain and baseline,

followed by oxygen correction using $^{17}O/^{16}O = 0.0003749$ and $^{18}O/^{16}O = 0.0020439$ and spike correction, and finally by instrumental mass fractionation correction using $^{192}Os/^{188}Os = 3.083$ via the exponential law. Internal precision on $^{187}Os/^{188}Os$ ratios was typically better than 0.05% (2σ). During the analytical campaign, repeated measurements of 0.5-2.5 ng loads of Os reference materials yielded $^{187}Os/^{188}Os$ of 0.160927 ± 0.000173 (2σ, n=14) for DrOsS and 0.113796 ± 0.000022 (2σ, n=10) for the University of Maryland Johnson Matthey Os Standard; these ratios are within 0.01% of the accepted values.

HSE were separated and purified from the remaining acid solution using cation exchange column chromatography and BPHA solvent extraction. Cation exchange chromatography was implemented to reduce the concentrations of interfering elements such as Y, Cd, Rb, Zn, Cu and Ni, with BPHA solvent extraction used to remove Zr, Mo, Hf, and W. The solution remaining after Os extraction was evaporated to dryness, and the residues were dissolved in 5 ml of 6 mol L^{-1} HCl. Following this 1 ml of 30% H_2O_2 was slowly added to reduce Cr^{VI} to Cr^{III}, and the solution was dried down again. The residue was dissolved in 10 ml of 0.1 mol L^{-1} HCl and loaded onto the cation exchange columns (AG50W-X8, 200-400 mesh, 16 mm x 240 mm column with a 50 ml reservoir). Before sample loading, the columns were cleaned with 60 ml 6 mol^{-1} HCl, and conditioned with 80 ml of 0.1 mol L^{-1} HCl. After sample loading, an additional 11 ml of 0.1 mol L^{-1} HCl was eluted and collected. The resulting ~21 ml solution was then dried down and 80 ml of 6 mol L^{-1} HCl was used to clean the columns. The residues were dissolved in 2 ml of 0.5 mol L^{-1} HCl and 300 μL of fresh 0.025 mol L^{-1} BPHA (Tokyo Chemical Industry: P0158-25G) $CHCl_3$ was added to the solution, which was vigorously shaken for 5 minutes then centrifuged. The solvent extraction was completed three times, after which the 2 ml of 0.5 mol L^{-1} HCl was pipetted off and analyzed for HSE in a single cut via ICP–MS. All HSE column cuts were measured in low-resolution mode on a Nu instruments Attom at the University of Alberta. Given that the $^{175}Lu^+$ and $^{178}Hf^+$ signals were less than 10000 and 1000 counts per second, respectively, in the sample solutions, Lu and Hf oxide isobaric interference corrections for Ir and Pt were negligible. For Pd analysis, the zirconium (^{90}Zr) standard solution was measured to determine the oxide production rate (ZrO^+/Zr^+) and found to be < 1% during the analytical measurements. The isobaric interference correction of $^{90}ZrO^+$ on mass 106 was < 0.1%. Instrumental mass fractionation was corrected for by periodic measurements of in-house standard (GP-13; usually one per four sample analyses) using the standard bracketing method and resulted in a typically less than 1% correction.

4. Results

4.1. Zealandia's mantle geochemistry

In the context of interpreting the formation of the peridotitic root to a continent, a key feature of Zealandia is the relative abundance of mantle peridotite that has been erupted or exhumed across the Mesozoic crustal configuration of a fore-arc, arc and back-arc (**Fig.1, 2**; summarised in **Supplementary Table 1**). Although many of the rocks are variably metasomatised (McCoy-West et al., 2013; Scott et al., 2014a, b; Czertowicz et al., 2016; Scott et al., 2016a, b), bulk rock peridotite Al_2O_3 concentrations show the dataset to be divisible into geographical domains that, relative to primitive upper mantle (PUM), are moderately depleted (Auckland Island, Canterbury, Dun Mountain Ophiolite Belt, East Otago) through to refractory (Anita Peridotite, Chatham Island, West Otago, Lake Moana in Westland) (**Fig. 3**; dataset summarised in **Supplementary Table 2**). The refractory domains show no systematic distribution relative to the Cretaceous arc configuration. With the exception of Auckland Island and East Otago, most of the investigated Zealandia suites are generally more depleted in incompatible major elements than abyssal peridotites, with the refractory peridotites comparable to the most depleted residues of any known age documented on Earth: fore-arc mantle, depleted ophiolite and the least metasomatised cratonic mantle compositions (e.g., Tanzanian Craton and the West and East Greenland portions of the North Atlantic Craton) (**Fig. 3**). When the refractory domain Al_2O_3 compositions are compared experimental residues that have undergone 30% anhydrous melt extraction at 5, 3 and 2 GPa (Walter, 2003), the Zealandia residues plot in the realm of low-*P* (< 3 GPa) melting. Melting at higher pressure (7 GPa) stabilises garnet to very high melt extraction levels (~50%) and effectively rules out a high-P residue origin for most of these residues.

Like Al_2O_3, peridotite Mg# (100*Mg/(Fe+Mg)) is a well-known indicator of the degree of melt extraction. Of the refractory suites, the West Otago, Chatham Island, and Lake Moana peridotites have averaged bulk rock Mg# ranging between 90.7 and 91.8. Since it is difficult to obtain a whole rock analysis from a small xenolith, and the bulk rock analyses can be compromised by Fe-enrichment from the host melt, the composition of the most abundant peridotite mineral phase, olivine, provides more robust information with which to test the geographical extent of the Zealandia mantle domains and further assess their levels of depletion. When olivine Mg# data for 263 peridotites from 26 localities are plotted, it is evident that the moderately depleted (olivine Mg# ~90.0**–**91.5) to refractory (olivine Mg# $\geq$ 91.5 but typically 92.5) domains are regional in scale (**Fig. 4; Supplementary Table 4**). The high mean and median olivine Mg# of olivine from the Anita Peridotite, Lake Moana (Westland) and the Mt Alta, Lake Wanaka and MacFarlane Stream (West Otago) locations are equivalent to or only slightly less depleted than typical Archean peridotites (e.g., Bernstein et al., 2007) (**Fig. 4**). As with the bulk Al_2O_3 values,

olivine Mg# values provide minima for melting estimates because many xenoliths have been metasomatised and experienced some Fe addition.

Spinel is the main host to Cr in spinel facies peridotites, and high Cr# (100*Cr/(Cr+Al)) equates to high degrees of melting in the shallow mantle (e.g., Dick and Bullen, 1984). Spinel Cr# versus olivine Mg# shows the Zealandia peridotites to span compositions from close to PUM (olivine Mg# = 89.2; spinel Cr# = 7) to forsterite-rich olivine (Mg# > 92) coexisting with chromite (Cr# > 65) equivalent to some of the most refractory spinel facies cratonic peridotite suites (**Fig. 5**). The Al-spinel and Cr-spinel-bearing East Otago and Auckland Island suites cluster at the less depleted end of the spectrum and partially overlap with the abyssal peridotite field. The Chatham Island peridotites, which come from beneath the partially subducted Hikurangi Plateau, have high olivine Mg# for their generally moderate Cr# and mostly plot at compositions that overlap the Archean peridotite field (**Fig. 5**). The Dun Mountain Ophiolite Belt peridotites plot slightly to the right of the main Zealandia trend but within the field of supra-subduction zone peridotites. The chromite-bearing Anita Peridotite, Lake Moana and West Otago samples overlap our compilations of the fields for chromite-bearing garnet-free Archean peridotites, modern supra-subduction zone peridotites, and hydrous melting experiments. A distinct feature of the olivine-spinel trends in Al-spinel to Cr-spinel-bearing rocks is that the Zealandia peridotites have lower olivine Mg# for equivalent Cr# compared to Archean xenoliths (**Fig. 5**).

4.2. Os isotope and platinum group element data

Osmium isotopes and platinum group elements (PGE) have been measured in 70 peridotites from the Mesozoic back-arc (Auckland Islands, n = 8 analyses; Lake Moana, n = 9), arc (Anita Peridotite, n = 10), and from beneath the fore-arc (Chatham Island; n = 19; Dun Mountain Ophiolite Belt; n = 24). When supplemented with 5 analyses from Canterbury, 14 from East Otago, 2 from the Chatham Islands (McCoy-West et al., 2013), and 21 from West Otago (Liu et al., 2015), all from the fore-arc area, the Zealandia sample suite represents one of the largest global non-cratonic continental Os isotope and PGE datasets (**Supplementary Table 1**).

Zealandia peridotite Os model ages (T_{MA}) correlate poorly with Re-depletion Os model ages (T_{RD}) in the xenoliths (**Supplementary Table 1, Fig. 1**). This is likely due to late-stage Re addition during xenolith entrainment and transport, since the T_{MA} versus T_{RD} agreement is better for the orogenic Anita Peridotite. The Os isotope compositions and their resulting T_{RD} ages indicate that the Zealandia lithospheric mantle is extremely isotopically heterogeneous. T_{RD} ages span Archean to modern times but contain the striking feature that most ages are significantly older than the Zealandia crust (**Fig. 6**). The

very broad T_{RD} peak centred at 1.2 Ga is analogous to that observed in the global abyssal peridotite dataset and Pt-alloys from ophiolites (e.g., Pearson et al., 2007) and quite distinct from, for example, Archean cratons (**Fig. 6**). As with bulk rock chemistries and mineral chemistries, there is no correlation between peridotite T_{RD} age and geographical distribution.

Aside from a subset of samples that exhibit Pd/Ir > PUM, such as those of the fore-arc Dun Mountain Ophiolite Belt and the back-arc Auckland Island peridotites, Zealandia peridotites with low Pd/Ir correspond to low bulk rock Al_2O_3 (**Fig. 7A**). These compositions also extend to those of cratonic peridotites, although low Pd/Ir is not necessarily indicative of Archean processes because if the PGE are mainly bound up in sulphides and alloys then Pd/Ir should not change greatly after sulphide/alloy consumption (~20-25% melting; Aulbach et al., 2016) and any refractory residue should have low Pd/Ir. A key feature of the Zealandia HSE is the broadly sub-vertical $^{187}Os/^{188}Os$ versus Pd/Ir arrays at low Pd/Ir in the most refractory suites (**Fig. 7B**). The sub-vertical Os array was first noted for Zealandia peridotites by Liu et al. (2015) in the West Otago suite but the new Chatham Islands, Lake Moana and Anita Peridotite suites data confirm this to be a continental-scale trend.

5. DISCUSSION

5.1. Decoupling of Os isotopes and bulk rock and mineral chemistries

The Zealandia peridotite $^{187}Os/^{188}Os$ values are generally far too radiogenic to be the result of widespread Archean depletion and not radiogenic enough to represent only depletion during Paleozoic and Mesozoic crust formation. The sub-vertical Os isotope vs Pd/Ir arrays, which cannot be regressed though PUM (**Fig. 7B**), require the Zealandia peridotite Os isotopes and bulk rock chemistries to be decoupled. One interpretation of the large range in Re-depletion Os model ages (**Fig. 6**) is that the small number of Archean ages indicates that the underpinning Zealandia mantle is very old and that the Os systematics have been heavily modified by metasomatism and addition of Re. Although many Zealandia peridotites show chemical signatures of having been metasomatised (Scott et al., 2014a, b; McCoy-West et al., 2016; Scott et al., 2016a, b; Dalton et al., 2017), the lack of systematic Os versus HSE trends (**Fig. 7A, 7B**) is inconsistent with the overall isotopic range being caused by this process. The lack of correlation between Os isotopes and depletion indices (where the lowest Al_2O_3 and Pd/Ir and highest olivine Mg# samples can have either Archean or Phanerozoic model ages) belies the relationship observed in cratonic peridotites where the most depleted peridotites preserve the oldest ages (e.g., Luguet et al., 2015). Furthermore, a long-lived mantle lithosphere scenario would require a particularly complex geodynamic model that permits a large lithospheric mantle platform to remain stable for billions

of years through numerous cycles of accretion of Phanerozoic oceanic crustal (**Fig. 2**) and yet experience total replacement of any Archean crust. As a measure of how likely this is, the mantle lithosphere beneath eastern Australia, immediately adjacent to the Gawler Craton, contains no vestige of Archean heritage (Handler et al., 1997).

An alternative explanation for the Os data is that the Zealandia lithosphere domains represent amalgamations of peridotite fragments with a spectrum of depletion ages. A key point here is that the Zealandia lithospheric mantle demonstrably contains small-scale Os isotope heterogeneities. The best example of this comes from the orogenic Anita Peridotite, for which samples within 100s of m to 1 km of one another have T_{RD} ages from 0.1-1.5 Ga (**Supplementary Fig. 2**) yet show no systematically distinguishable chemistry or mineralogy (**Figs. 5, 7**). Although this exact relationship cannot be confidently stated for the peridotite xenolith suites because they have lost their source reference frame, 16 xenolith analyses from a single diatreme in West Otago yielded T_{RD} ages of 0.51-2.75 Ga but all are extremely refractory and do not define a trend that intersects PUM (Liu et al., 2015). Similar trends occur in the Chatham Island and Lake Moana datasets (**Fig. 7B**), and together the data point to lithospheric columns of Zealandia mantle containing extreme Os heterogeneity that cannot be accounted for by variable degrees of melting in a single event.

Abyssal and ophiolitic peridotite suites and ophiolite suite demonstrate that the convecting mantle is highly heterogeneous and also must contain small-scale Os heterogeneities (e.g., Parkinson et al., 1998; Brandon et al., 2000; Schulte et al., 2009). An important observation is that the Zealandia Os isotope range falls within the spectrum defined by abyssal peridotites (**Fig. 6**), which must globally underpin Jurassic or younger oceanic crust. Although Archean residues have not been obtained from abyssal peridotites, the removal of Archean mantle lithosphere, as well known for example in the North China Craton, requires that the convecting mantle contains some ancient components. Therefore, while there is a broad peak in the Zealandia depletion ages at 1.2 Ga, there is no evidence that this represents the “stabilisation” age of this lithosphere. In summary, three key points are: (1) the Zealandia Os model ages appear to have little or no temporal or genetic association with the overlying continental crust; (2) there is no apparent long-lived Archean-Proterozoic core to the continent, although there is no doubt that there are some ancient residues embedded within the mantle lithosphere; and (3) the Zealandia lithospheric mantle broadly preserves the inherent Os isotopic variability observed in Phanerozoic convecting mantle and is mostly likely young.

5.2. A model for continental root formation

Zealandia's oldest crustal rocks are Late Cambrian but the continent only formed as an entity free from Australia and Antarctica 85 Myr ago when the paleo-Pacific subduction margin of Gondwana fragmented and the Tasman Sea and Southern Ocean opened (**Fig. 1**). Any model for the formation and stabilisation of the Zealandia lithosphere needs to address how Phanerozoic continental crust can be underlain by a mantle lithosphere containing regional domains that: (1) vary from moderately depleted to highly refractory, (2) commonly have T_{RD} ages decoupled from PGE systematics and major element compositions, and (3) have histories extending to billions of years before crust formation. We propose that these three features can be explained by the lithospheric mantle having been constructed from mixing of an array of heterogeneous peridotite fragments swept together beneath the Gondwana subduction margin, variably re-melted, and then laterally accreted.

In our model, the refractory peridotite domains represent previously depleted mantle with minimal remaining Re – and hence unradiogenic Os – that underwent re-melting in some cases to generate the extremely low Al_2O_3, high olivine Mg# and high spinel Cr# harzburgitic to dunitic residues (**Fig. 8A**). It is very unlikely that the highly refractory parts of this lithosphere could have been produced *in situ* by, for instance, plume residue accretion. This is because there is no geological or geophysical evidence for the presence of plume-related magmatic rocks anywhere in the Zealandia crust except for the Hikurangi Plateau in the northeast (**Fig. 1, 2**) and because there is a clear crust-mantle age decoupling in most areas (**Fig. 6**). The high olivine Mg# in the most depleted Zealandia peridotite suites requires $\geq$ 30% melt extraction, which is the point of orthopyroxene exhaustion (Bernstein et al., 2006, 2007). These levels of depletion, coupled with the low bulk Al_2O_3 (**Fig. 3**) and the very high spinel Cr# have been shown to be achievable only via low-P melting of peridotite in the presence of modest amounts of water (e.g., Mitchell and Grove, 2015; **Supplementary Table 5**). Peridotites with low Al_2O_3 and high olivine Mg# and spinel Cr# occur in modern arc lithospheres, as indicated, for example, in the SW Pacific Ocean by the widespread occurrence of young boninitic arc magmas (Crawford, 1989), depleted peridotite from mantle lithosphere such as the Mariana arc (Parkinson et al., 1992), and refractory mantle associated with ophiolite belts such as exemplified by Papua New Guinea (Jaques et al., 1980; Kaczmarek et al., 2015), and, to a lesser degree, the Dun Mountain Ophiolite belt (**Fig. 3**).

The low-P hydrous melting of already Re-depleted peridotite may have occurred along the Gondwana subduction margin in the part of the asthenospheric mantle wedge influence by corner flow, as has been invoked to explain the refractory residues at the Mariana trench (e.g., Parkinson et al., 1998), which have Os model ages and bulk compositions similar to the range of the Zealandia peridotites. Mantle residues may be trapped by corner-flow and extensively flux melted by fluid sourced

from dehydration of serpentinite that forms above the subducting slab, giving rise to even more refractory compositions. On the other hand, the moderately depleted mantle lithospheric domains such as beneath the Auckland Islands, East Otago, and Canterbury, may represent oceanic peridotite that was brought to the subduction margin but not subjected to high degrees of sub-arc hydrous re-melting, thus explaining their mildly depleted bulk compositions (**Fig. 3**) with spinel-olivine relations that closely mirror the abyssal peridotite trend (**Fig. 5**). In the Zealandia example, one exception for arc-melting may be the depleted Chatham Island xenoliths. These originate from beneath the Hikurangi Plateau and by comparison with peridotites erupted through the once contiguous Ontong Java Plateau (Ishikawa et al., 2011) could represent portions of oceanic mantle that re-melted during Early Cretaceous plume interaction (**Fig. 8B**).

Progressive lateral accretion of variably aged and depleted mantle fragments during the Phanerozoic assembly of Zealandia generated a sub-continental lithospheric mantle comprising domains that do not relate genetically to the overlying crust (**Fig. 8B)**. This result is exemplified by the refractory West Otago mantle domain that underpins a thick meta-sedimentary crustal pile that is almost devoid of igneous rocks as indicated by exposures of lower crustal rock exhumed along the Alpine Fault (e.g., Beyssac et al., (2016) or as crustal xenoliths (e.g., Jacob et al., 2017). However, even the moderately depleted East Otago and Canterbury domains (e.g., **Fig. 4**) are overlain by crust that contains minimal magmatic rocks. Subduction margins provide an excellent site for the lateral accretion of mantle lithosphere, since these are prime sites of separation of crust from mantle during subduction, or extensive lateral modification during slab-rollback events. A consequence of the observations and model is that any oceanic crust accreted along with the lithosphere must have been removed by density settling during eclogite-formation (e.g. Percival and Pysklywec, 2007; Lee et al. 2011), which is consistent with the absence of eclogite xenoliths in the Zealandia mantle suites. We conclude that the widespread occurrence of refractory residues in the Zealandia mantle has led to a continental root that is more depleted and therefore more buoyant than the convecting mantle and this resulted in stabilisation of this continental mass.

Zealandia is not the only stable post-Archean continental area to be underlain by an array of complex and variably depleted residues with histories distinct from the overlying crust. Another example comes from peridotite xenoliths from Patagonia and southern Argentina, which have moderately depleted to refractory compositions with Os isotope compositions that broadly mimic the convecting mantle, have little or no correlation with bulk rock depletion indices, and are age-distinct from the overlying crust (e.g., Schilling et al., 2008; Mundl et al., 2016). While the spread in Os isotope compositions are argued to have been affected by melt percolation (Mundl et al., 2016), an alternate view, by analogy with Zealandia,

could be that the southern South America lithospheric mantle is younger than thought and composed of heterogeneous residues compiled at the Gondwanan subduction margin and then laterally displaced from their melt locations. The moderate to refractory lithospheric mantle beneath southeast Australia (e.g., Handler et al., 1997), Antarctica (Handler et al., 2003) and the Canadian Cordillera (e.g., Peslier et al., 2000), all located on Paleozoic and Mesozoic subduction margins, also have late Proterozoic Os model ages older than their known overlying crust. Either lateral accretion has played a key role in juxtaposing crust and mantle, and/or the underlying mantle records the Os isotope history of the convecting mantle at the time of stabilisation. In either case, the data re-enforce the conclusions (1) that peridotite Os age data in some post-Archean continental areas may have little significance in defining the "stabilisation" of lithosphere, and (2) subduction margins play a fundamental role in accumulating and accreting mantle residues.

5.3. Implications for the formation of ancient continents

Should the Zealandia lithosphere thicken, it would develop a garnet-bearing peridotite keel that would in many places be compositionally similar to common Archean mantle lithosphere but with much younger Re-depletion Os model ages (**Fig. 8C)**. Upon becoming thickened, the high-Cr spinels in the Zealandia lithosphere should react with orthopyroxene to make high-Cr low-Ca garnets of the type documented in many Archean peridotite suites and proposed to originate by metamorphism of lower pressure chromite-bearing peridotites (e.g., Brey and Shu, 2018). In fact, crust and mantle lithospheric thickening due to plate boundary convergence has already occurred beneath the western portion of the South Island in New Zealand adjacent to the Australia-Pacific plate boundary in the last ~7 Ma. From seismic detection of a high-velocity zone beneath the Southern Alps, the mantle lithosphere there is now interpreted to extend to > 160 km depth in some places (e.g., Stern et al., 2000; Sutherland et al., 2000).

The cause of the thickened Zealandia lithosphere remains debated, being attributed to a west-dipping subducted slab (Sutherland et al., 2000), an east-dipping subducted oceanic plateau (Reyners et al., 2017) or plate boundary contraction (Stern et al., 2000). Regardless of which model is preferred, since the Miocene-wide southern Zealandia lithosphere was only 70-80 km thick (Scott et al., 2014a, b), this means that the West Otago refractory mantle that was sampled ~25 Myr ago from beneath the future Southern Alps prior to thickening occurred, has now likely been displaced to greater depths. Sampling of a present-day root beneath the Southern Alps, or a putatively continent-wide thickened Zealandia mantle lithosphere, would reveal the presence of a mixture of moderately depleted to refractory subduction zone residues along with plume residues from beneath the Hikurangi Plateau broadly resembling Archean

cratonic mantles compositions. A difference would be that Archean cratonic mantle residues would include higher degrees of depletion due to the higher ambient mantle potential temperature. The Zealandia mantle composition therefore reinforces the concept that generation of refractory mantle residues and extreme thickening of lithosphere is not restricted to Archean processes. The seismically imaged mantle beneath the Tibetan Plateau has been interpreted as an analogue for Archean cratonic mantle formation via tectonic thickening (McKenzie and Priestley, 2016). Although pre-Miocene mantle there was sampled by basaltic volcanism, the lack of very recent deep-seated volcanism penetrating this actively forming 200 km-thick root means that refractory mantle – if present – has yet to be documented.

Peridotite melting calculations (e.g., Canil, 2004; Lee and Chin, 2014), geochemical parameters (e.g., Pearson and Wittig, 2008) and the occurrence of high-Cr low Ca garnets in cratonic peridotites (e.g., Brey and Shu, 2018) also indicate that Archean cratonic mantle lithospheres may have formed at low-P and were thickened to great depths. The near-invariant olivine composition versus wide-ranging spinel Cr# in Archean garnet-free peridotites is, however, distinct from the over-arching Zealandia trend at the low Cr# end (**Fig. 5**). This Archean trend has been interpreted to represent polybaric anhydrous melting (Bernstein et al. 2006, 2007) but experimental data on anhydrous melting of typical mantle compositions indicate that the highest residual spinel Cr# possible by this mechanism is only ~ 60 (**Supplementary Figures 3-4**).

While the low spinel Cr# at high olivine Mg# trend of cratonic peridotites defined in **Fig. 5** may be generated by other processes compared to more modern refractory residues (e.g., Archean spinel compositions could represent melting first in the garnet field to obtain high Mg# (in olivine) but retain Cr (in garnet), followed by decompression and re-equilibration in the spinel facies accompanied by hydrous melting to shift refractory bulk compositions to lower Al/Cr), the only experimentally determined method for formation of chromite compositions in peridotite at mantle conditions involves wet melting. For example, spinel Cr# of ~70 to 80 coexisting with olivine Mg# > 92 has been experimentally attained at ~ 40% melting at < 2 GPa (e.g., Hirose and Kawamoto, 1995; Mitchell and Grove, 2015; **Supplementary Figures 5-6**). The formation of garnet-free Archean peridotites with high Cr-spinel/chromite could therefore share a melting stage with the most depleted subduction-modified residues beneath Zealandia – that is, via melt extraction at low-P in a hydrous sub-arc environment. Moreover, like Zealandia, Archean cratons commonly comprise an amalgamation of distinct crustal blocks representing juxtaposed terranes distributed with remarkable similarity to terranes accreted at Phanerozoic subduction margins (e.g., the Superior Craton; Percival et al., 2006).

A feature of Zealandia is the decoupling of mantle depletion ages and the overlying crust age, and such decoupling is also hinted at in Archean cratons. Global compilations of Os isotope Re-depletion ages and U-Pb zircon data indicate that there is a general coupling of melting events in the crust and mantle (Pearson et al., 2007; Pearson and Wittig, 2008; Lee et al., 2011); however, Meso- to Eoarchean crustal units that occur in most cratons do not correlate with mantle melting events. In addition, Archean crustal rocks have a distinct scarcity in komatiite and basalt compared to the widespread abundance of underlying refractory residues (e.g., Parman et al., 2004). By analogy with Zealandia, these features may be explained by the cratonic mantle having undergone high levels of depletion – potentially by a variety of mechanisms in different tectonic settings but likely including wet melting at low-P – before being laterally displaced from the melting. The result of re-melting of such refractory mantle lithosphere would be boninite-equivalent high-MgO rocks, which is consistent with some occurrences in cratons (e.g., Polat et al., 2001; Parman et al., 2004). Subsequent thickening of the Archean root by convergence will then displace the residues to great depth and lead to garnet-bearing refractory peridotite lithosphere (e.g., Jordan, 1978; McKenzie and Priestley, 2016; Wang et al., 2018). By analogy with the formation of Earth's youngest continent, subduction margins would be prime locations for this series of processes to have occurred to stablise ancient continents.

6. Conclusions

Examination of mantle peridotites from many locations across Zealandia, a Late Cretaceous rifted fragment of the Gondwana margin and Earth's most recently stabilised continent, reveals that it is underlain by a compositionally and isotopically heterogeneous mantle lithosphere. There is no systematic distribution to moderately depleted to refractory domains. Re-depletion Os isotope model ages, which are extremely variable within individual sample suites and do not correlate with depletion indices, give dates that range as far back as Archean but have a broad peak at ~ 1.2 Ga similar to the modern convecting mantle. The Zealandia mantle lithosphere is interpreted to have been constructed from isotopically heterogeneous oceanic mantle fragments swept into the Gondwana sub-arc environment, compiled, variably re-melted under hydrous conditions at low-P to generate the refractory residues, and then laterally accreted to displace the residues from the melting location. Subsequent thickening associated with the present-day Australia-Pacific plate boundary has displaced portions of the lithospheric mantle to > 160 km (e.g., cratonic depths). This example, and that of the Himalaya, indicates that the formation of depleted residues and displacement to near craton-equivalent depths is not restricted to Archean times. Some Archean cratonic peridotites also have extreme spinel Cr# that appear to be only achievable by

hydrous melting, whereas others possess high-Cr garnet that could have formed via metamorphism at elevated P of high Cr-bearing spinel. Because the Archean crust often lacks sufficient mafic melts to explain the extremely depleted peridotitic roots, Archean lithospheric mantle may also be accumulations of variably depleted peridotite that was re-melted at a subduction margin to give high spinel Cr# and olivine Mg#, laterally accreted, and then thickened to high-P to form garnet. The stabilisation of the root to Earth's old continents may therefore have formation processes in common with Earth's youngest continents.

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Figure 1. Make-up of the 4.9 M km^2 continent of Zealandia in the SW Pacific Ocean. This continent, of which the islands of New Zealand form ~ 6 % by area above water, represents a rifted portion of the fore-arc, arc and back arc to the Australia–Antarctica–New Zealand Mesozoic subduction margin of Gondwana (inset). Mesozoic fore-arc mantle is represented by xenoliths in Cretaceous–Cenozoic basalts in Canterbury, Chatham Island, East Otago, and West Otago, as well as along the > 2000 km long Permian Dun Mountain Ophiolite Belt. Arc mantle is represented by the orogenic Anita Peridotite. Back-arc mantle was sampled by Cretaceous and Miocene basalts at Lake Moana in Westland and on Auckland Island, respectively. The size of the stars indicates the extent of the different peridotite suites.

Figure 2. Zealandia is composed of an array of accreted terranes, here shown according to their Cretaceous back-arc, arc and fore-arc positions. Terrane relative ages and main compositions are indicated on the lower diagram. Terrane information is taken from the summary provided in Mortimer (2004).

Figure 3. Box and whisker plots of peridotite bulk rock Al_2O_3, normalised to 100 wt.% anhydrous. These data illustrate the heterogeneity in the Zealandia lithospheric mantle and show that the refractory Zealandia peridotites are comparable to depleted fore-arc (Marianna Arc, Kamchatka Arc), depleted ophiolite (Luobusa, Papua New Guinea) and least metasomatised cratonic mantle (North Atlantic Craton, Tanzania Craton and the Murowa location in the Zimbabwe Craton). Comparison of the refractory Zealandia peridotites (Westland, Anita, West Otago) with experimentally determined Al_2O_3 contents of a residue after 30 % partial melting at 5, 3 and 2 GPa (Al_2O_3 concentrations from the experiments of Walter, 2003) implies that they reached their low Al_2O_3 contents at $P \leq 3$ GPa. PUM is from Meisel et al. (2001). Data sources for suites are in **Supplementary Tables 2 and 3**.

643 **Figure 4**. Summary of olivine Mg# data for 263 Zealandia peridotites. Boxes show the median values
644 and the 1st and 3rd quartiles for each dataset. Some Zealandia samples have experienced Fe addition
645 that has lowered their olivine Mg#, such as from the Burke River and Moeraki locations in West Otago
646 and Cape L'Evique and Ohira Bay from Chatham Island (see Scott et al., 2014a, b, 2016a, b for
647 discussion), and Hohonu Westland suite. Data are summarised in **Supplementary Tables 4** and **6**. .
648 Average Archean cratonic compositions are from the compilations of Bernstein et al. (2006, 2007) and
649 Pearson & Wittig (2008).
650
651 **Figure 5**. Spinel Cr# versus olivine Mg# for the Zealandia peridotites compared to global fields of abyssal
652 peridotite, supra-subduction zone peridotite, Archean peridotites and the results of peridotite anhydrous
653 and hydrous melting experiments. The Supplementary File provides references for these large datasets,
654 and an up-to-date compilation of Archean spinel facies peridotites and experimental melting
655 compositions. The orthopyroxene-out and clinopyroxene-out for low-P melting are estimated from
656 Bernstein et al. (2006, 2007) and Scott et al. (2016b), respectively.
657
658 **Figure 6**. Summary of whole rock Re-depletion Os model ages for Zealandia (McCoy-West et al., 2013;
659 Liu et al., 2015; this study). The T_{RD} ages indicate that many peridotites experienced Re depletion > 0.4
660 Ga before formation of the Zealandia crust, which is Late Cambrian at its oldest but dominantly
661 Mesozoic. Ages for duplicates are not included. Dominantly refractory classification refers to peridotite
662 suites with olivine Mg# mostly > 91. The global abyssal trend represents the Os isotopic composition of
663 the convecting mantle and is from Pearson et al. (2007), and the Kaapvaal Craton compilation example is
664 from Pearson and Wittig (2008); note that the abyssal and Kaapvaal curves are relative probability
665 distributions and do not correlate to the Y-axis (number of analyses for histogram).
666
667 **Figure 7.** Depletion indices versus platinum group elements. **7A.** Bulk rock Pd/Ir versus Al_2O_3. The most
668 refractory samples, as judged by bulk rock Al_2O_3 normalised to anhydrous conditions, generally
669 correspond to lowest Pd/Ir. There is some evidence for P-PGE enrichment in the Pd/Ir > PUM, as is seen
670 in most Dun Mountain Ophiolite and Auckland Island samples. **7B.** The lack of $^{187}Os/^{188}Os$ linear arrays
671 projected from PUM indicate that the Os isotopes record a history that involves decoupling of the PGE
672 abundances from the Re-depletion events. Archean mantle Pd/Ir range is from Aulbach et al. (2016).
673

Figure 8. Formation of a modern continent. **8A.** Variably aged peridotitic material is brought into a subduction margin, amalgamated, and melted at low pressure (< 3 GPa) in the presence of water to generate refractory residues. Melting causes decoupling of Os isotopes from depletion indices. Some new domains undergo little or no re-melting and retain (or gain) moderately depleted compositions. The variably depleted peridotites are then progressively laterally accreted to the sub-arc lithosphere, which results in crust underpinned by autochthonous mantle. **8B**. Once subduction ceases, a buoyant platform comprising heterogeneous crust and variably depleted mantle lithosphere is formed. **8C.** If this lithosphere were thickened by compression, refractory portions of the root would chemically resemble Archean mantle lithosphere, as has occurred under the Southern Alps of New Zealand over the last ~7 Ma. This figure also shows the distribution of terranes forming modern Zealandia (see also Fig. 2); DMOB, Dun Mountain Ophiolite Belt.

Figure 1

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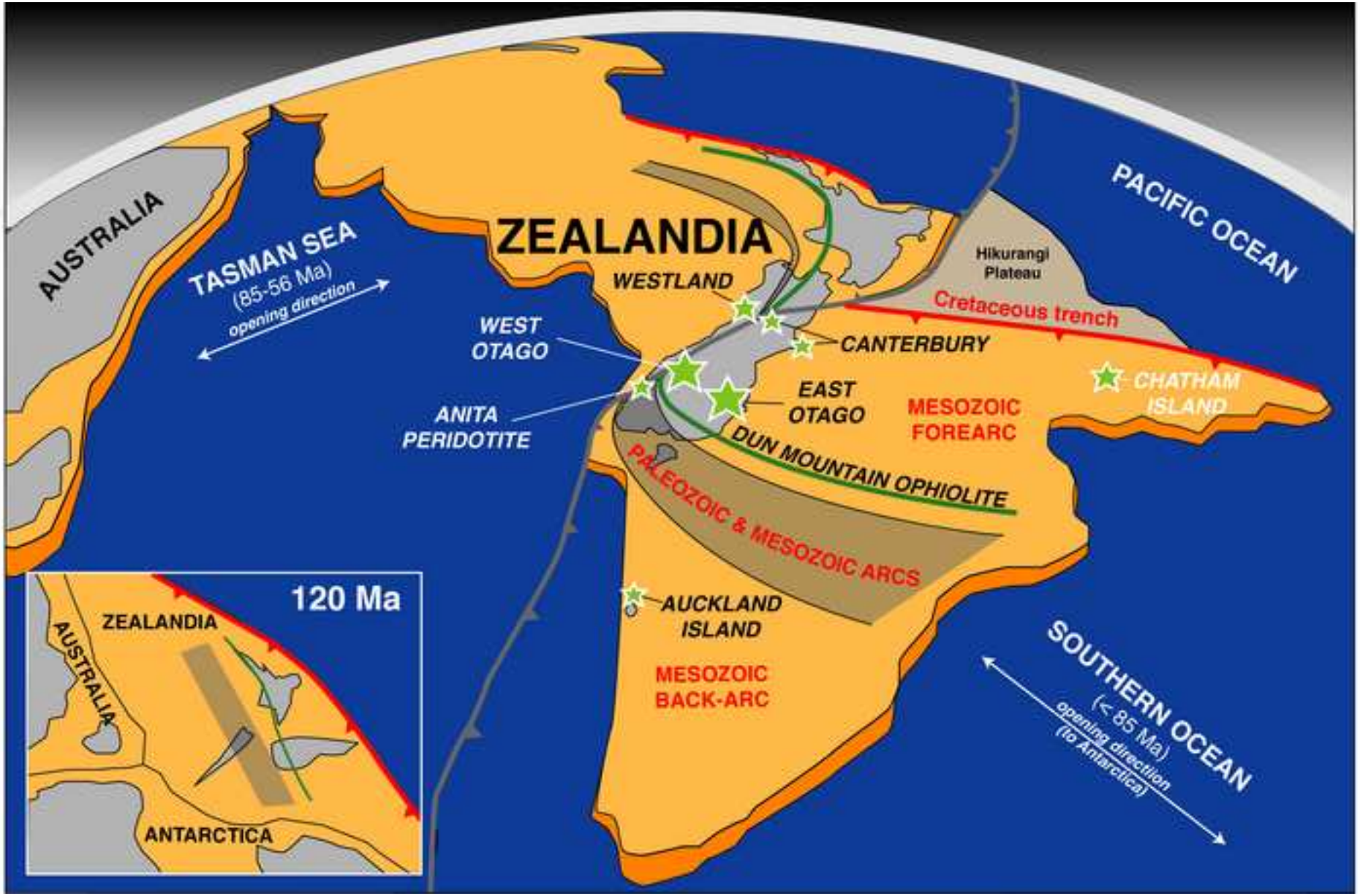

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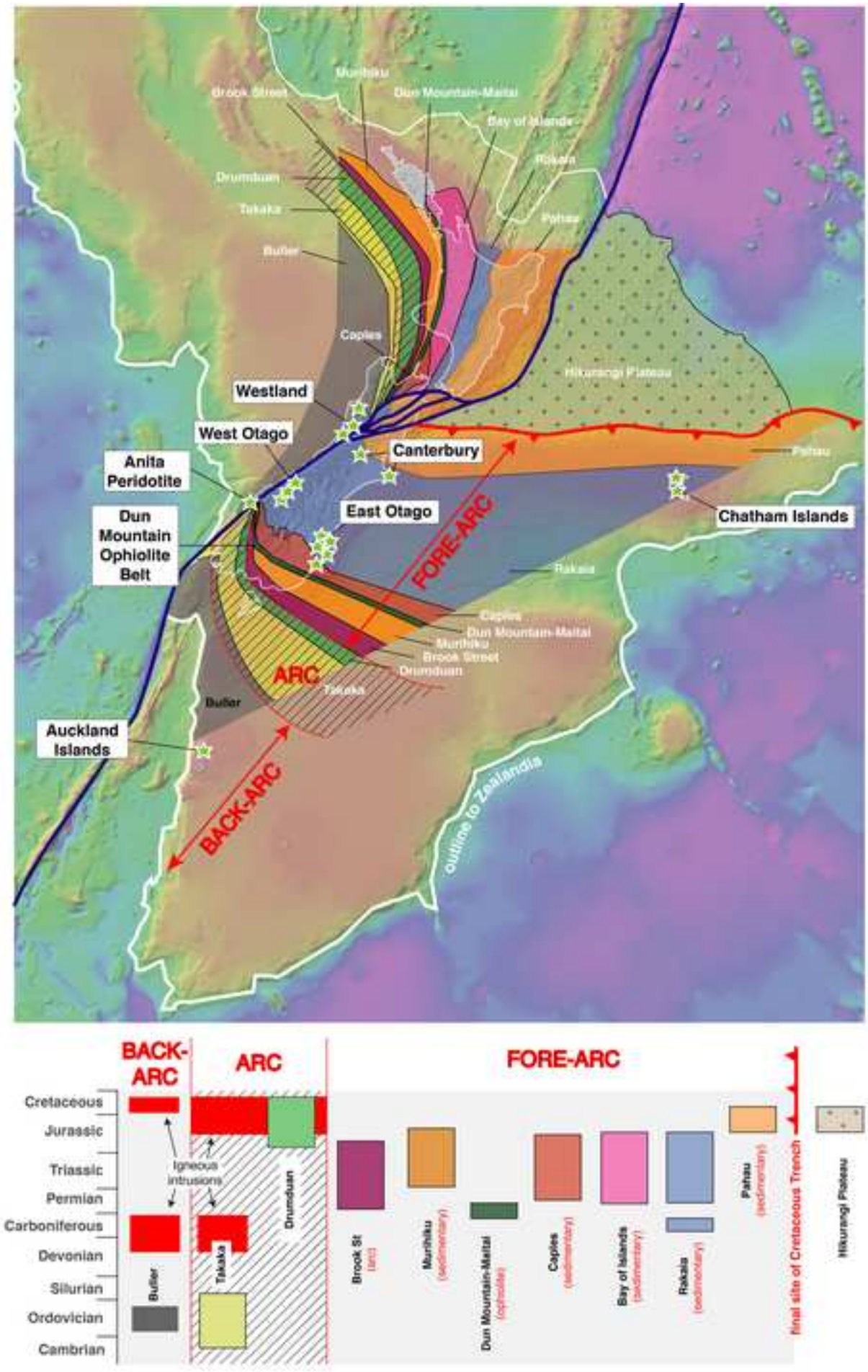

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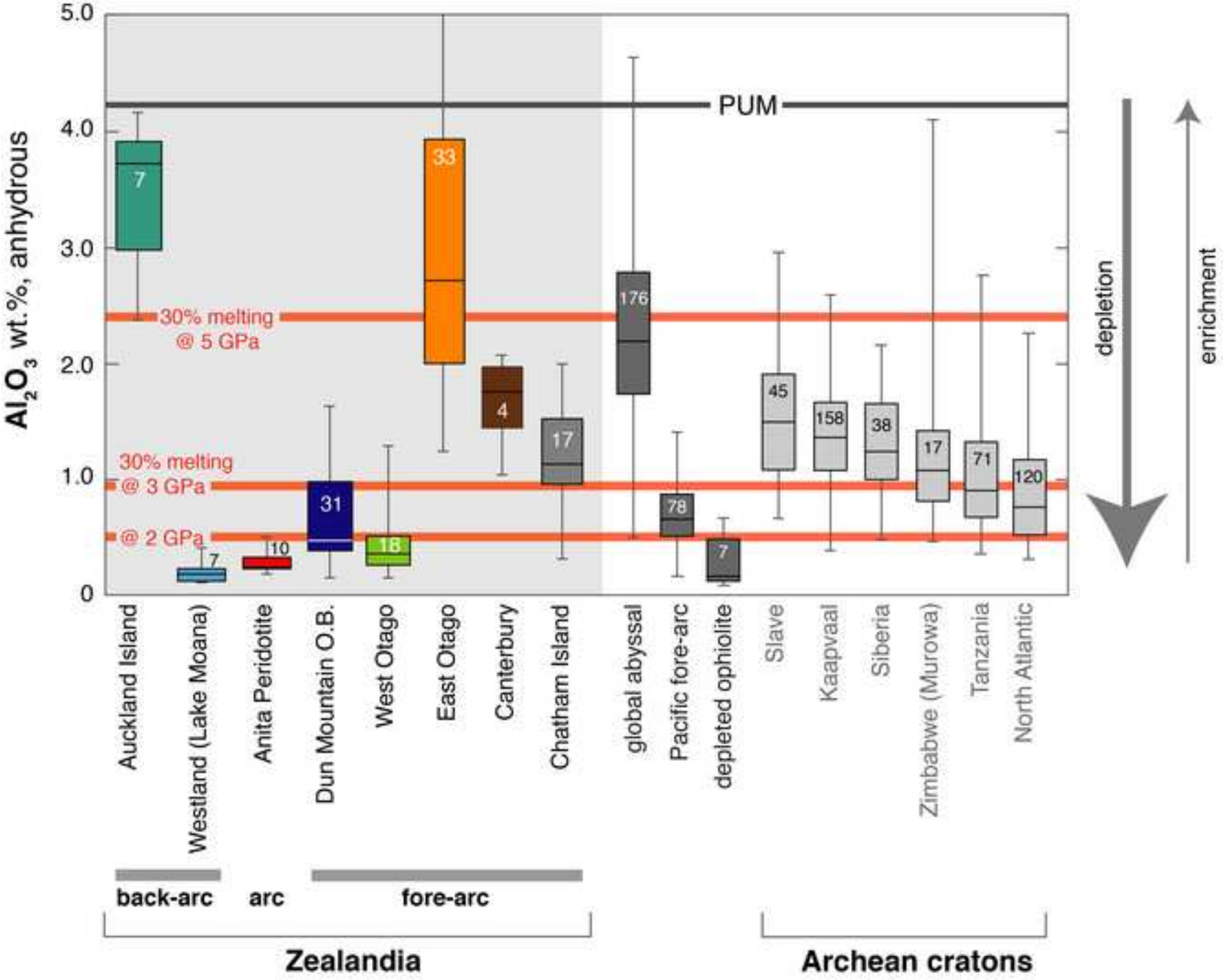

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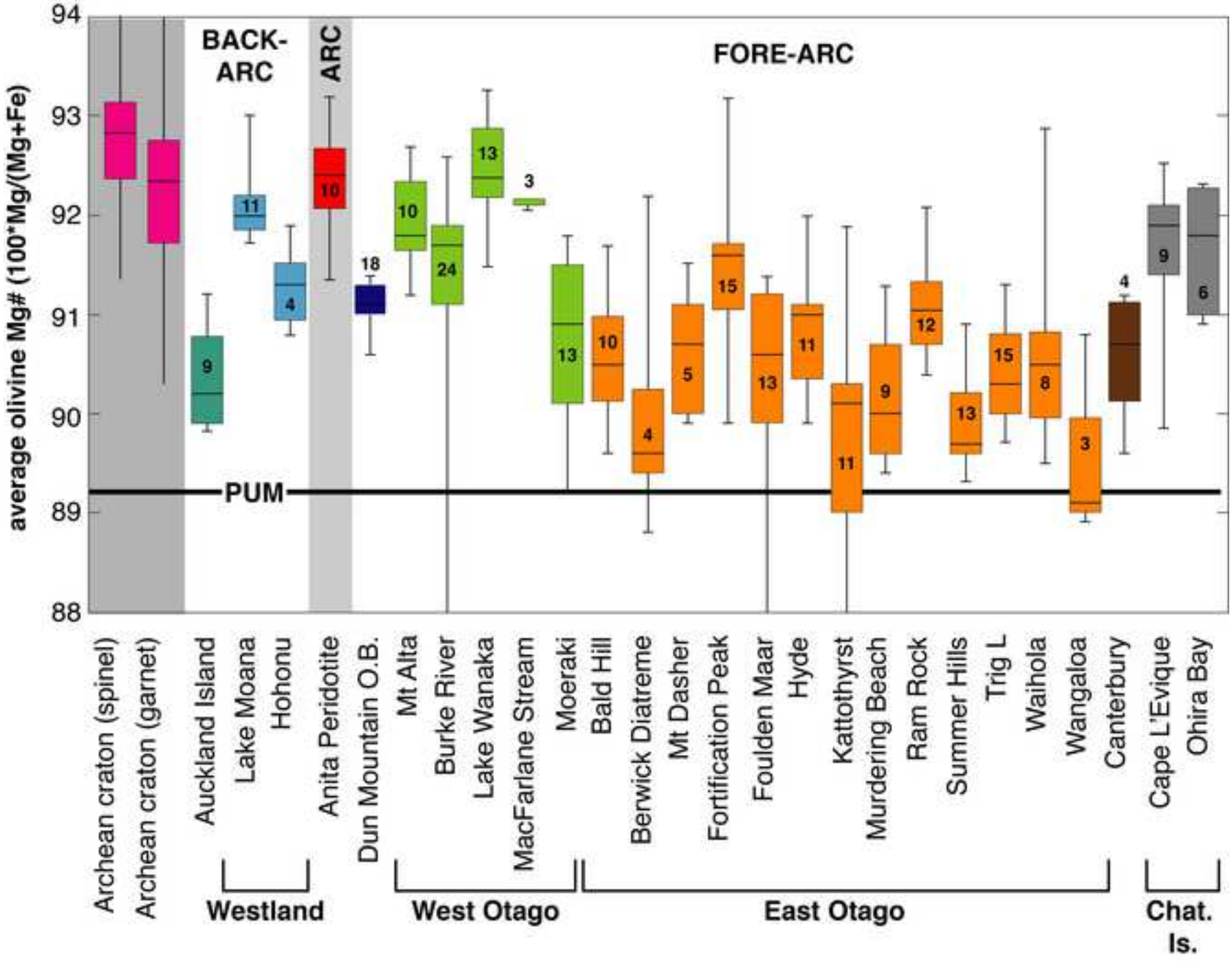

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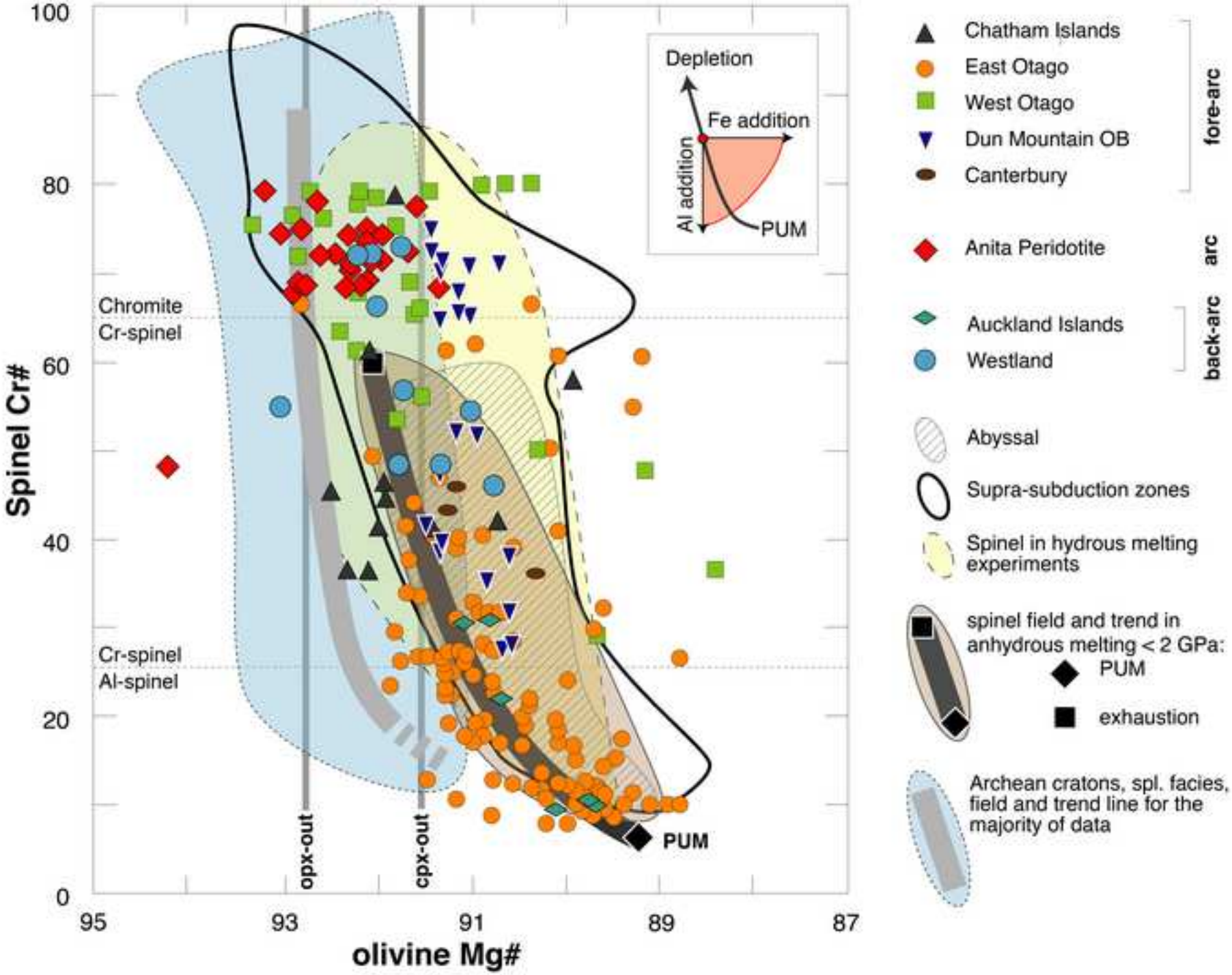

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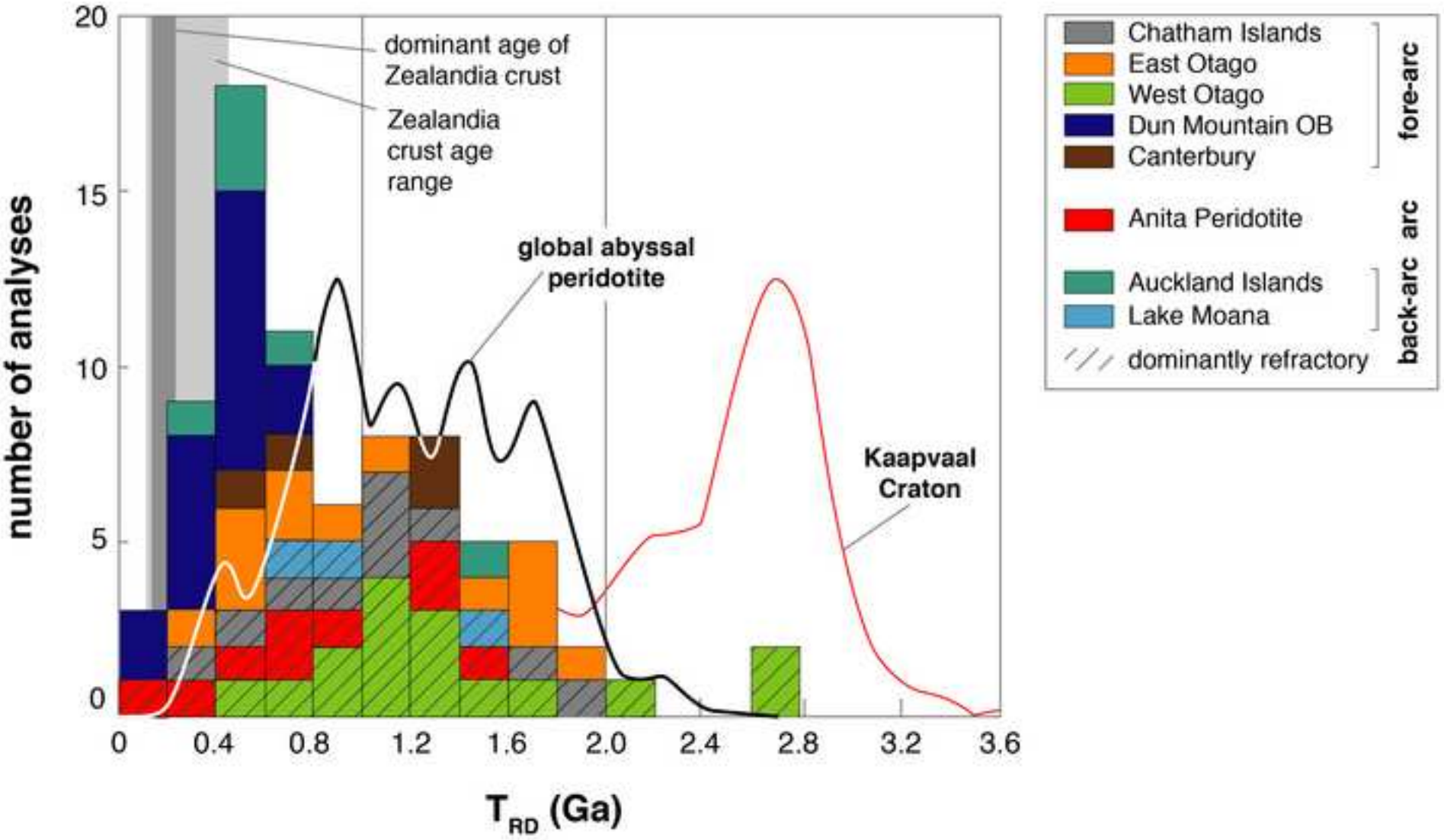

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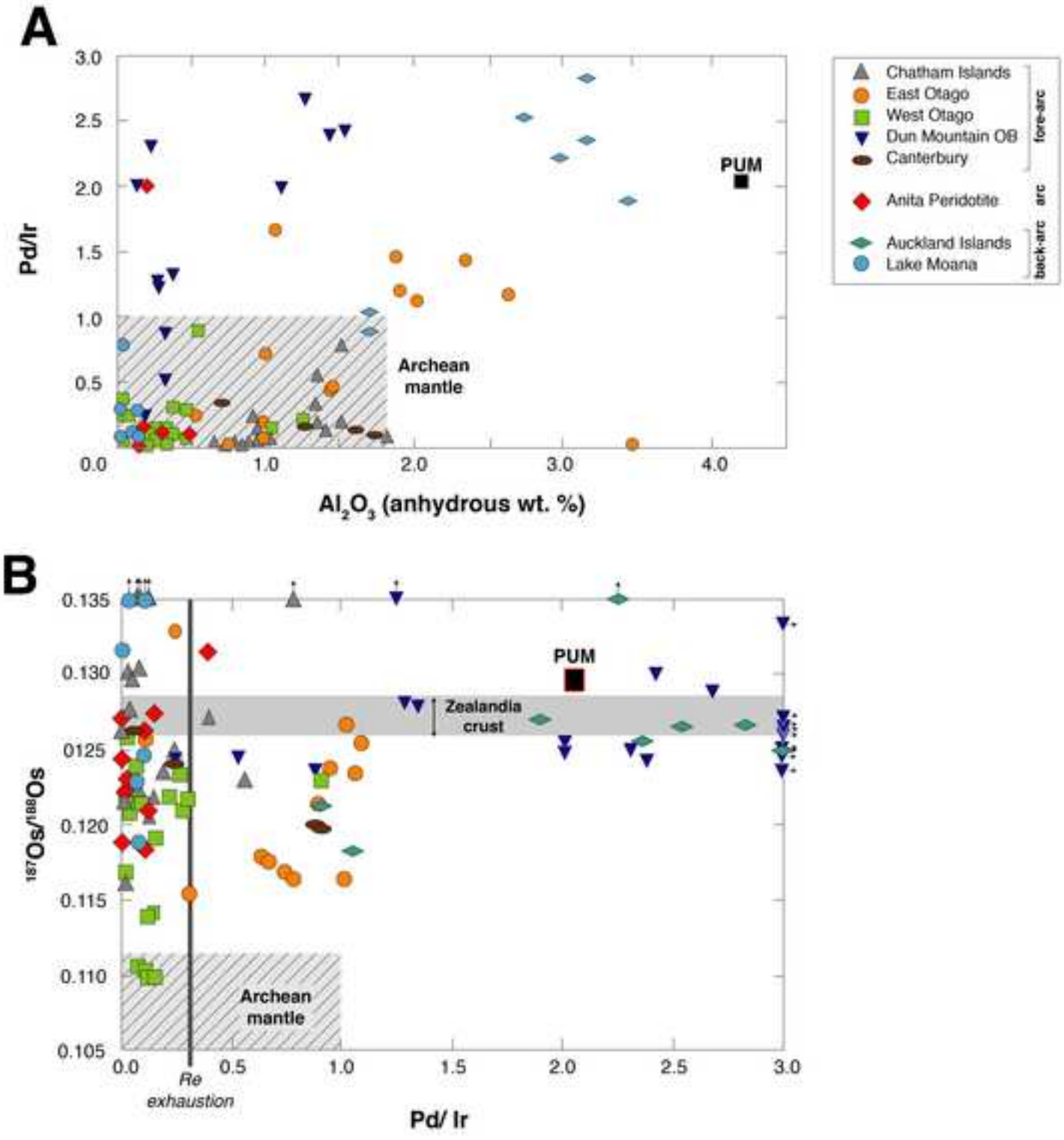

Figure 8

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