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Late Cretaceous (99-69 Ma) basaltic intraplate volcanism on and around Zealandia: Tracing upper mantle geodynamics from Hikurangi Plateau collision to Gondwana breakup

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Abstract

Collision of a young, buoyant plateau fragment with an active continental margin can lead to subduction cessation, but can it also trigger continental breakup? It has been postulated that the collision of the Hikurangi Plateau with the Gondwana margin at ~110 Ma ago, caused subduction to cease, large-scale extension and ultimately breakoff of the Zealandia micro-continent from West Antarctica through seafloor spreading starting at circa 90 Ma. Here we report new geochemical (major and trace element and Sr-Nd-Pb-Hf isotope) data for Late Cretaceous (99-69Ma) volcanism from Zealandia. Four geographically-separated provinces of intraplate magmatism formed during this time interval: 1) Hikurangi Seamount Province

(99-86 Ma), 2) Marlborough Igneous Province (98-94 Ma), 3) Westland Igneous Province (92-69 Ma), and 4) Eastern Chatham Igneous Province (86-79 Ma). Each of the intraplate provinces forms binary mixing arrays on incompatible-element and isotope ratio plots between HIMU (requiring long-term elevated $\mu = {}^{238}U/{}^{204}Pb$) and either a depleted (MORB-source) upper mantle (DM) component or enriched continental crustal (EM) type component (located in the crust and/or upper mantle) or a mixture of both. St. Helena end member HIMU is the common component to all four provinces. Considering the uniformity in composition of the HIMU end member despite the type of lithosphere (continental, oceanic, oceanic plateau) beneath the igneous provinces, we attribute this component to a sublithospheric source, located beneath all volcanic provinces, and thus most likely a mantle plume. We propose that the plume rose beneath the active Gondwana margin and flowed along the subducting lithosphere beneath the Hikurangi Plateau and neighboring seafloor and through slab tears/windows beneath the Gondwana (later to become Zealandia) continental lithosphere. We conclude that both plateau collision, resulting in subduction cessation, and the opening of slab windows, allowing hot asthenosphere and plume material to upwell to shallow depths, were important in causing the breakup of Zealandia from West Antarctica.

Key Words: Zealandia continental breakup; Hikurangi Plateau collision; Gondwana subduction; major & trace element & isotope geochemistry; St. Helena HIMU mantle end member; mantle plume.

1. Introduction

A fundamental question in the Earth Sciences is what triggers continental breakup (e.g. Sleep, 1971; Condie, 2016). Many rifted margins are characterized by up to 15 km of underplated mafic crust and submarine seaward-dipping reflectors, which reflect subaerially-

51 erupted basaltic volcanism tilted during subsidence (e.g. Condie, 2016). They are generally
52 associated with flood basalt events (e.g. Menzies et al., 2002) formed during the initial (or
53 plume head) stage of a mantle plume (Richards et al., 1989). It is proposed that large plume
54 heads (up to 2000 km in diameter) impinge on the base of the lithosphere, causing
55 lithospheric mantle erosion and extension, both of which result in lithospheric thinning and
56 isostatic uplift, rifting and eventually seafloor spreading.
57 Far-field extensional plate tectonic forces are believed to govern the formation of non-
58 volcanic margins (Geoffroy, 2005). At some stage in their development, super continents are
59 surrounded by subduction zones. Rollback of the subducting slab along much of this
60 subduction network can lead to internal extension, resulting in continental breakup.
61 Progressive extension of cool, sediment-poor continental lithosphere far from a mantle
62 plume, for example the Iberian margin, has been proposed as a mechanism for generating
63 non-volcanic margins (Reston, 2007). Propagation of spreading centers, as is presently
64 occurring in the Woodlark Basin where spreading is propagating into and beginning to split
65 Papua New Guinea, provides another potential mechanism for causing continental breakup.
66 Alternatively, it has also been proposed that subduction of a spreading center or other change
67 in plate boundary forces can lead to continental breakup (e.g. Bradshaw, 1989).
68 Here we investigate one of the late breakup phases of the Gondwana supercontinent: One
69 of the most enigmatic continental breakup events in recent Earth history. This breakup event
70 resulted in the separation of pieces of the present Zealandia micro-continent from Marie Byrd
71 Land, West Antarctica (Mortimer et al., 2017). Proposed models to explain the breakup of
72 Zealandia from Antarctica include: 1) collision of the Pacific-Phoenix spreading center with
73 the Gondwana active margin (Bradshaw, 1989; Luyendyk, 1995; Storey et al., 1999; Tulloch
74 et al., 2009), 2) impingement of a mantle plume head at the base of the Gondwana margin
75 lithosphere at what is now Marie Byrd, Antarctica (Weaver et al., 1994; Storey et al., 1999),

3) collision of the Hikurangi Plateau with the Gondwana active margin (now the Chatham Rise) clogging the subduction system (e.g., Sutherland and Hollis, 2000; Davy et al., 2008; Hoernle et al., 2010; Reyners et al., 2011; Davy, 2014; Mortimer et al., 2019). A variation of model 3 involves normal faulting in the overlying basement along a SW continuation of the subducted western Wishbone Ridge (Mortimer et al., 2006). In most recent models, the collision of the Hikurangi Plateau, one of the three major fragments of the Ontong Java-Manihiki-Hikurangi superplateau (e.g., Taylor, 2006; Davey et al., 2008; Hochmuth et al., 2015), with the Gondwana active margin is invoked as the initial trigger of this breakup. Based on relocated seismicity, Reyners et al. (2017) postulate that the Hikurangi Plateau is underplated beneath much of the South Island of New Zealand terminating at the southern portion of the South Island. Major open questions include: What happens in the upper mantle during collision of an igneous oceanic plateau or Large Igneous Province (LIP) with an active continental margin? What role does such a collisional event play in causing continental breakup? Did a mantle plume play a role in triggering the breakup?

Here we will evaluate these questions using age and geochemical data from four different intraplate magmatic provinces (Fig. 1, 2): Hikurangi Igneous Seamount Province (99-84 Ma; Hoernle et al., 2010) - consisting of alkalic seamounts on the Hikurangi Plateau, formed after collision of Hikurangi Plateau with the Gondwana margin, 2) Marlborough Igneous Province (98-94 Ma; Baker et al., 1994; Tappenden, 2003; McCoy-West et al., 2010; Mortimer et al., 2019) - alkalic volcanism on the northern South Island east of the South Alpine Fault, including Lookout, Gridiron, Mandamus and Tapuaenuku Igneous complexes, 3) Westland Igneous Province (92-69 Ma; van der Meer et al., 2016; van der Meer et al., 2017; Mortimer et al., 2019) - tholeiitic to lamprophyric Westland and Hohonu dikes on the northern South Island west of the Alpine Fault, and 4) East Chatham Volcanic Province (86-78 Ma; Panter et al., 2006; Homrighausen et al., 2018; Mortimer et al., 2019) - transitional to alkalic lavas on

Chatham Island and seamounts on the East Chatham Rise and the surrounding seafloor. We use the temporal evolution of these four intraplate volcanic provinces to reconstruct processes occurring within the subducted lithosphere and within the mantle beneath the former Zealandia active margin until breakup, including the early history of seafloor spreading between Zealandia and West Antarctica.

2. Samples and Analytical Methods

For the present study, volcanic rocks were dredged from five submerged volcanoes on the eastern Chatham Rise, one from DSDP Site 595, 30 locations from the Marlborough volcanic province (Mandamus Igneous complex, Lookout and Gridion volcanics), 10 locations from the Westland province (Hohonu Dikes), 28 locations from the Mount Somers volcanic group (including two sites from the Torlesse metasediments) (Figure 1). At all sites discussed here, the angular shape of the rocks, freshly broken surfaces, and the homogeneity of rock types indicate an in-situ (not ice-rafted) origin for the dredged rocks. Sampling localities are summarized in Supplementary Table 1.

Analytical methods are reported in Supplementary File 1.

3. Results

We present new geochemical (major and trace element and Sr-Nd-Hf-Pb isotope; Supplementary Tables 1 & 2) data on volcanism from the Marlborough, Westland and Mt. Somers Igneous Provinces and seamounts on and near the eastern Chatham Rise, collected by dredging on the R/V SONNE SO168 and SO246 expeditions (Table 1). $^{40}Ar/^{39}Ar$ ages and additional background information for many of the samples are reported in Mortimer et al. (2019) and Homrighausen et al. (2018). We combine our new results with those from published studies (Hoernle et al., 2006; Mortimer et al., 2006; Panter et al., 2006; McCoy-

West et al., 2010; Timm et al., 2010; Homrighausen et al., 2018; van der Meer et al., 2010, 2016) to reconstruct the evolution of intraplate volcanism on and around Zealandia from ~100-70 Ma.

Alteration has affected many of these samples, in particular considering their Late Cretaceous age and the submarine history of some of the samples. With decreasing MgO, both SiO_2 and Al_2O_3 (until ~5wt.% for East Chatham and Mt. Somers samples) roughly increase, whereas CaO (until ~7wt.% MgO) and FeO^t (total iron until ~5wt.% MgO) remain roughly constant and then begin to decrease. TiO_2 and P_2O_5 increase initially and begin to decrease at MgO ~5wt.% (except for Westland samples). The observed trends are consistent with fractionation of the observed major phenocryst phases in the samples in the sequence olivine, clinopyroxene, Fe-Ti oxides, ± plagioclase and apatite (Tappenden, 2003; Panter et al., 2006; McCoy-West et al., 2010; van der Meer et al., 2010, 2016).

Considering that the alkalis have been mobilized in many samples, we use the Nb/Y vs. Zr/Ti plot (after Pearce, 1996) to classify the rocks (Fig. 3a), which relies on ratios of immobile incompatible elements. The intraplate samples range from tholeiites (Southern Volcanics from Chatham Island) to alkali basalts (most samples) through alkali rhyolites to foidites through phonolites (primarily Westland rocks), whereas the Mt. Somers rocks range from andesite to dacite - rhyolite - trachyte. On the Nb/Yb vs. Th/Yb and TiO_2/Yb diagrams (Fig. 3b,c) after Pearce (2008), most of the intraplate igneous rocks have alkalic ocean-island basalt (OIB) affinities. The Hikurangi, Marlborough, Westland and East Chatham province igneous rocks form arrays that extend from the OIB domain to lower Nb/Yb ratios with some samples plotting within the mantle array in the direction of mid-ocean-ridge basalts (MORBs) and other samples plotting above the mantle array in the volcanic arc and crustal field. The Mt. Somers volcanic rocks with subduction and/or continental geochemical affinities (Tappenden, 2003) plot well above the mantle array clustering around typical

Torlesse metasediments from Canterbury. On multi-element diagrams showing incompatible elements for the freshest samples with highest MgO and most radiogenic Pb isotope ratios, to minimize the effects of alteration, differentiation and crustal assimilation (Fig. 4), the Hikurangi, Marlborough, Westland and East Chatham volcanic rocks display positive Nb and Ta anomalies and negative K and Pb anomalies characteristics of OIB, whereas the Mt. Somers rocks display clear negative Nb, Ta and positive K, Pb anomalies characteristic of subduction-related volcanism and crustal rocks.

Isotope correlation diagrams can be used to evaluate the sources from which igneous rocks are derived (Fig. 5). On the uranogenic Pb ($^{206}Pb/^{204}Pb$ vs $^{207}Pb/^{204}Pb$) isotope diagram (Fig. 5A), the 99-69 Ma intraplate igneous rocks form a broad array with positive slope between St. Helena end member HIMU (high time-integrated $\mu = {}^{206}Pb/^{204}Pb$) and the low-$\mu$ enriched mantle (EM), represented by Mt. Somers and Hikurangi Plateau basement rocks. On the $^{206}Pb/^{204}Pb$ vs. $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ isotope diagrams (Fig. 5B,C), the four intraplate provinces form binary arrays that converge on the St. Helena HIMU field at radiogenic Pb isotope ratios. The Hikurangi Province samples form a roughly horizontal array, extending to the Hikurangi Plateau basement at the end with unradiogenic Pb isotope ratios. The Westland samples form a crude negatively-sloped array trending towards MORB at its unradiogenic end, and the Marlborough and East Chatham provinces form concave-down hyperbolas, ending near the Mt. Somers samples at their ends with unradiogenic Pb isotope ratios.

4. Discussion

During much of the Mesozoic, present-day Zealandia formed part of the southern Gondwana active continental margin, located adjacent to what is presently Marie Byrd Land, West Antarctica. At ~120-125 Ma ago, the Ontong Java Nui, the largest known Phanerozoic volcanic event on Earth, formed in the western Pacific, covering more than 1% of Earth's

surface (Taylor, 2006; Davy et al., 2008; Hoernle et al, 2010; Timm et al., 2011; Hochmuth et al., 2015). Shortly after its formation, this super plateau broke apart into at least three major plateau fragments: 1) Ontong Java, 2) Manihiki and 3) Hikurangi. The Hikurangi and Manihiki Plateaus rifted apart between 115-120 Ma along the Osbourn Trough spreading system (Mortimer et al., 2006; Hochmuth et al., 2015). Thereafter the Hikurangi Plateau drifted southwards from the Manihiki Plateau until it collided with the Gondwana active margin at ~110-105 Ma (e.g. Bradshaw, 1989; Mortimer et al., 2006; Davy et al., 2008). The buoyant (then ~15-20 Ma old) Hikurangi Plateau clogged the Gondwana subduction zone, causing cessation of subduction along the northern edge of what is now the Chatham Rise (e.g., Sutherland and Hollis, 2000; Davy et al., 2008; Reyners et al., 2011; Davy, 2014; Mortimer, 2019).

4.1 Formation of four intraplate volcanic provinces after Hikurangi Plateau collision

Four different mafic intraplate volcanic provinces (~99-69 Ma) formed on Gondwana continental crust (now Zealandia), the Hikurangi Plateau and the surrounding seafloor shortly after the Hikurangi Plateau collided with the Gondwana margin. The four intraplate volcanic provinces form distinct binary arrays on trace element and isotope diagrams (Fig. 3-5) that converge on a common composition. Below we will first discuss the binary arrays formed by each volcanic province, and then the common component involved in all four of the provinces.

The oldest ages come from the Hikurangi and Marlborough Provinces. The seamounts on the Hikurangi Plateau record ages of 99-86 Ma (Hoernle et al., 2010). The seamounts have a distinct composition from the Hikurangi basement. The basement has an EM type trace element (relatively flat incompatible element patterns on multi-element diagrams) and Sr-Nd-Pb isotopic composition similar to the main plateau-building stage on Ontong Java formed by

the Kwaimbaita/Kroenke lavas (Hoernle et al., 2010). The dominant Kwaimbaita lavas represent differentiates of the mafic Kroenke lavas, which have identical Sr-Nd-Pb-Hf isotopic compositions. The Hikurangi seamounts, on the other hand, have more enriched incompatible element abundances and fractionated heavy rare earth elements, forming patterns with a negative slope on multi-element diagrams. The seamounts form an array on incompatible-element and isotope ratio diagrams, extending from the St. Helena HIMU end member field to the EM-type plateau basement field (Fig. 5). The array can most easily be explained by mixing of HIMU melts with EM melts from the Hikurangi Plateau basement or underlying lithosphere, overprinted with a similar composition during emplacement of the LIP. Although a HIMU-type component (but not with end member St. Helena type composition) has been found in the ~125 Ma Manihiki basement (Timm et al, 2011; Golowin et al. 2018), no evidence for the presence of a St. Helena type HIMU end member component has been found within the basement of the Hikurangi Plateau. The most radiogenic Manihiki basement lavas only have $^{206}Pb/^{204}Pb_{in}$ of ~19.7 and both $^{207}Pb/^{204}Pb_{in}$ and $^{208}Pb/^{204}Pb_{in}$ are lower in the Manihiki basement lavas at a given $^{206}Pb/^{204}Pb_{in}$ than in the Hikurangi Seamount lavas, indicating that this HIMU-like component has a different composition than St. Helena and Cook-Austral end member HIMU. Accordingly, it is unlikely that the St. Helena end member HIMU component in the Hikurangi seamount lavas was derived from the Hikurangi Plateau basement or lithospheric mantle overprinted by the melts forming the plateau basement. Since the Hikurangi Plateau is believed to have formed on young ocean crust near a spreading center (Hochmuth et al., 2015), the pre-existing lithosphere is also an unlikely source for the HIMU component. Therefore, we favor an asthenospheric source for the HIMU component in the Hikurangi seamount lavas.

The intraplate Marlborough Igneous Province (98-94 Ma; Baker et al., 1994; Tappenden, 2003; McCoy-West et al., 2010; Mortimer et al., 2019) on the northern South Island and the

calc-alkaline, Mt. Somers volcanic rocks, located in the central South Island, were both located in the forearc of the Gondwana subduction zone, north (or trench-wards) of the 232-105 Ma Median Batholith (e.g., Tappenden, 2003; van der Meer et al., 2018). On incompatible-element and isotope ratio diagrams (Fig. 3, 5), the Marlborough intraplate rocks form an array from the St. Helena HIMU mantle end member towards an enriched composition, which has more radiogenic Sr and less radiogenic Nd, Hf and Pb isotope ratios than the HIMU end member. The Sr-Nd-Pb-Hf isotopic variations in the Marlborough igneous rocks could be explained by assimilation of up to ~25% crustal rocks, but generally <10%, from the Early Cretaceous Pahau terrane rocks (Tappenden, 2003; McCoy-West et al., 2010). We however do not see any clear correlations between indices of differentiation (e.g. SiO_2 or MgO) with Sr-Nd-Pb isotope ratios in our data (not shown), but rather each isotope ratio forms relatively flat trends on diagrams of isotope ratios versus an index of differentiation. Therefore, if these trends are caused by crustal assimilation, they are not coupled to differentiation, i.e. assimilation during fractional crystallization (AFC). Although oxygen isotopic disequilibrium between clinopyroxene cores and rims suggests phenocrysts interacted with meteoric water in shallow magma chambers (McCoy-West et al., 2010), this will not necessarily show up in radiogenic isotope systems, especially not for immobile elements such as Nd and Hf.

The calc-alkaline Mt. Somers rocks also have enriched isotopic compositions that could serve as the enriched end member for the Marlborough Province intraplate rocks. Due to low Pb concentrations and low Nd/Pb ratios, mixing of mafic Marlborough melts with Mt. Somers rocks would generate concave down mixing curves that can also explain the observed Marlborough array.

The calc-alkaline Mt. Somers volcanic rocks display typical incompatible-element characteristics of subduction zone volcanism, such as relative depletion in Nb, Ta and relative

enrichment in K and Pb, compared to other elements with similar degrees of incompatibility (Fig. 4). Tulloch et al. (2009) have argued that, because of their 96 Ma age, the Mt Somers lavas are actually intraplate continental tholeiites, indistinguishable from subduction-related suites on the basis of their whole rock chemistry. This remains an open issue. Whatever their origin, these incompatible-element characteristics are opposite to those of the intraplate Marlborough igneous rocks, which show relative enrichment in Nb, Ta and relative depletion in K and Pb. The major and trace element characteristics of the Mt. Somers rocks are consistent with the melts having been influenced by the mantle wedge of the Gondwana subduction zone, implying that the isotopic composition of the parental melts also represent those of the Gondwana mantle wedge (asthenosphere and lithosphere) located beneath the South Island in the mid Cretaceous. Although the mantle wedge could have an upper mantle type composition, represented by normal MORB, this is unlikely considering that marine sediments, as evidenced in the accreted forearc sequence, subducted beneath the Gondwana margin. Nevertheless, with the present database, it is not possible to distinguish the exact composition of the mantle-derived melts and the amount of crustal assimilation that has taken place. In conclusion, the Marlborough Province mixing array could be explained by interaction of HIMU mantle melts with the enriched Pahau terrane crustal rocks and/or potentially enriched (Mt. Somers-type) mantle wedge.

Although it has been argued that the source of the HIMU end member may have been located in the lithospheric portion of the mantle wedge, reflecting metasomatism by subduction-related silicate melts (e.g. Panter et al., 2006), we note that subduction-related rocks are characterized globally by Pb enrichment and low U/Pb ratios. They are also characterized by enrichment in other fluid mobile incompatible elements, as well as relative depletions in Nb and Ta. These characteristics are distinct from intraplate volcanic rocks, so it is not clear how a HIMU-type source could be created in the lithosphere above a

subducting slab. Furthermore, no HIMU-type melts have been found on the South Island with an age >98 Ma. Considering the longevity of subduction along the Gondwana margin, why would HIMU compositions suddenly start erupting at 98 Ma if they are formed in the subduction zone environment? For the aforementioned reasons, we do not favor a lithospheric mantle source for the Marlborough intraplate HIMU melts, but rather a deep, ancient source as will be discussed in more detail below.

After cessation of Marlborough volcanism at ~94 Ma, volcanism moved to the Westland Igneous Province, which includes northern and central Westland and the Hohonu mafic dikes (92-69 Ma; van der Meer et al., 2016; van der Meer et al., 2017; Mortimer et al., 2019). At the time of the Westland magmatism, this region was located south of the Median Batholith and thus in the back-arc region, hundreds of kilometers south of the Marlborough and Mt. Somers volcanic provinces. The basement beneath this province consists of an amalgamation of Cambrian to Ordovician volcanic arc, passive margin and forearc turbidite assemblages, which were collectively metamorphosed to greenschist facies in the late Ordovician and subsequently intruded by Mesozoic granites, making up 50% of the present basement (van der Meer et al., 2018). The mafic volcanic rocks were erupted in two distinct phases becoming younger to the south: 1) northern Westland and Hohonu dikes (~92-83 Ma), 2) central Westland dikes (~72-69 Ma) (van der Meer et al., 2016). This confirms a southern progression in intraplate volcanism on the overriding plate after cessation of subduction at ~100 Ma from the Marlborough Province to northern Westland/Hohonu to central and southern Westland. These volcanic rocks have OIB-type incompatible element abundances (Fig. 3,4), displaying relative Nb enrichment and K and Pb depletions (van der Meer et al., 2016; van der Meer et al., 2017). They also form a crude array on isotope diagrams between a HIMU-like component and a depleted upper mantle MORB source (Fig. 5b). The overall less radiogenic Pb isotope ratios for the Westland samples with the most radiogenic Pb

301 ($^{206}Pb/^{204}Pb_{90Ma} \leq 19.4$) could reflect greater dilution of HIMU type mantle melts with
302 depleted upper mantle ± enriched mantle wedge material and/or crust in the mafic Westland
303 igneous rocks.
304 Contemporaneous with the Westland and Hohonu magmatism, the Eastern Chatham
305 Province, including the Chatham Islands and seamounts on the eastern Chatham Rise, were
306 active from ~86-79 Ma (Panter et al., 2006; Mortimer et al., 2006; Mortimer et al., 2019).
307 Two intraplate seamounts north of the easternmost Chatham Rise and east of the West
308 Wishbone Ridge, located on the mid Cretaceous (98-92 Ma; Mortimer et al., 2019) Pacific
309 ocean crust, have similar ages of 86 Ma (Chicken Seamount) and 81 Ma (Pukeko Seamount)
310 to the East Chatham Rise volcanism (Homrighausen et al., 2018; Mortimer et al., 2019). The
311 East Chatham rocks have incompatible element characteristics that extend from the OIB field
312 to both subduction and EMORB-type compositions (Fig. 3). Chicken Seamount volcanic
313 rocks have St. Helena end member composition with more radiogenic $^{206}Pb/^{204}Pb_{90Ma}$ than all
314 of the East Chatham Province intraplate volcanic rocks, including those from Chatham Island
315 that also fall within the end member St. Helena HIMU compositional field (Panter et al.,
316 2006; Homrighausen et al., 2018), overlapping with the Hikurangi and Marlborough rocks
317 with the most radiogenic Pb on the isotopic diagrams (Fig. 5). The East Chatham isotope data
318 can be explained by mixing HIMU mantle melts with low-μ components ranging from
319 enriched Mt. Somers mantle wedge and/or crustal Takahe granite (Mortimer et al., 2006) type
320 compositions to a normal MORB type composition.
321
322 4.2 A common HIMU end member for the Late Cretaceous intraplate volcanism
323 Four different mafic intraplate volcanic provinces (99-69 Ma) formed on contiguous
324 Gondwana continental crust (now Zealandia), the Hikurangi Plateau and the surrounding
325 seafloor shortly after the Hikurangi Plateau collided with the Gondwana margin. The four

intraplate volcanic provinces form distinct arrays on trace element and isotope diagrams (Fig. 3-5). As discussed above, the low μ end of the mixing arrays can be explained by interaction of a common HIMU type component with the widely differing types of overlying lithosphere and possibly also shallow asthenosphere. The Hikurangi seamounts formed on the oceanic Hikurangi Plateau after it was transported nearly 3000 km southwards from where it formed together with the Manihiki and possibly Ontong Java Plateaus at ~120 Ma on Late Jurassic or Early Cretaceous oceanic crust (Taylor, 2006; Davey et al., 2008; Hoernle et al., 2010; Timm et al., 2011; Hochmuth et al., 2015). The Westland, Marlborough and East Chatham volcanic provinces formed largely on different age and types of continental lithosphere, which overlay the subducting Pacific oceanic lithosphere. Several seamounts belonging to the East Chatham Province (e.g. Chicken and Pukeko seamounts) are, however, located on Cretaceous (~98-92 Ma; Mortimer et al., 2019) Pacific ocean crust. Despite the variation in the age and nature (oceanic crust and plateau versus continental crust) of the overlying lithosphere, the trace element and isotope ratios from each volcanic province form arrays that converge on a common end member (Fig. 5).

The common end member in the Late Cretaceous intraplate lavas has radiogenic Pb, relatively radiogenic Nd and Hf, and unradiogenic Sr isotope ratios, falling within the range of end member HIMU compositions from St. Helena, which has a similar isotopic composition to the Cook-Austral Islands, but with higher $^{207}Pb/^{204}Pb$ at a given $^{206}Pb/^{204}Pb$ isotope ratio (e.g. Chaffey et al., 1989; Hanyu et al., 2011; Nebel et al. 2013). The common end member is also characterized by enrichment of highly and moderately incompatible elements, and displays relative enrichment in Nb and Ta and relative depletion of K and Pb compared to elements with similar incompatibility (Fig. 4). Although the depletion in K and Pb have been used to argue for amphibole in the source of the Late Cretaceous New Zealand lavas and thus for a subcontinental lithospheric mantle source (SCLM; e.g. Panter et al.,

2008; McCoy-West et al., 2016; van der Meer et al., 2017), we note that the classic end member HIMU localities (St. Helena, Mangaia and Tubuaii Islands) with these trace element and isotopic characteristics were erupted on oceanic lithosphere and thus cannot be derived directly from subcontinental lithospheric mantle (SCLM). Although Archean and Early Proterozoic subcontinental lithospheric mantle (SCLM) can have HIMU type compositions, intraplate lavas not located on continental crust of this age could be derived from ocean crust or SCLM recycled through the lower mantle via subduction and mantle plumes (e.g., Hofmann and White, 1982; Weis et al., 2016; Homrighausen et al., 2018). The most compelling argument that the HIMU end member component is related to mantle plumes is that at both type localities (St. Helena and Cook-Australs) mantle plumes can be imaged beneath the hotspots to the base of the lower mantle (e.g. Montelli et al., 2006; French and Romanowicz, 2015).

A popular model for the formation of the HIMU component in Zealandia lavas invokes derivation from relatively young (no more than a few hundred million years old) metasomatized lithospheric mantle (e.g. Panter et al., 2006; McCoy-West et al., 2016; van der Meer et al., 2017). This model, however, is unrealistic for the common HIMU end member observed in the Late Cretaceous Zealandia/Hikurangi volcanic provinces, because 1.0-3.2 Ga are needed to form end member HIMU from St. Helena and the Cook-Austral Islands based on Pb isotope model ages (e.g. Hofmann, 1997; Hanyu et al. 2011; Nebel et al. 2013; Homrighausen et al., 2018). Numerical simulations of the source evolution and mixing relationships, on the other hand, suggest a minimum formation age for HIMU of 2.0-2.5 Ga (Kimura et al., 2016). In order to explain the negative $\Delta^{33}S$ isotope ratios in olivines from Cook-Austral HIMU, it has been argued that the source has to be ≥2.45 Ga in age (Cabral et al., 2013). Although high $^{206}Pb/^{204}Pb$ isotope ratios of end member HIMU can be produced by very high $^{238}U/^{204}Pb$ ratios on the scale of a few hundred million years, high $^{207}Pb/^{204}Pb$

cannot be generated in such a short time span in the present earth from recycled normal MORB type ocean crust or in the depleted upper mantle, because most of the ^{235}U with a half-life of ~0.7 Ga has decayed since Earth formation, such that in today's Earth there is ~138 times as much ^{238}U as ^{235}U.

Other problems also exist with the proposition that subduction-related melts metasomatized the overlying subcontinental lithospheric mantle (SCLM) to form the HIMU type compositions. First, there is no evidence that subduction ever occurred beneath the Hikurangi oceanic lithosphere, either before or after formation of the plateau, and beneath the lithosphere on which the Chicken and Pukeko seamounts are located. Furthermore, subduction zone melts generally have very low μ, reflecting greater mobility of Pb in hydrous fluids and melts than U. To our knowledge, there is no evidence of HIMU type compositions having been formed in the Gondwana supra-subduction setting. Finally, metasomatism generally creates very heterogeneous sources, which is inconsistent with the convergence of the Cretaceous intraplate volcanism on a fairly narrow isotopic compositional range similar to that of St. Helena lavas. Instead, the uniform composition of the common HIMU component must be derived from a well-mixed sublithospheric source in the convecting mantle that could generate melts beneath oceanic (normal MOR type crust and oceanic plateau crust) and diverse continental lithosphere. In conclusion, we favor derivation of the HIMU end member from a deep homogeneous reservoir and that the different igneous provinces were fed by a mantle upwelling (plume) or upwellings (plumes) from this reservoir.

In contrast to the Late Cretaceous Volcanic Provinces, Cenozoic intraplate volcanism on Zealandia requires an end member with radiogenic $^{206}Pb/^{204}Pb_{90Ma}$, in some cases within the end member HIMU range, but with lower $^{207}Pb/^{204}Pb_{90Ma}$ and slightly higher $^{143}Nd/^{144}Nd_{90Ma}$ (Fig. 5; Timm et al., 2010). Derivation of the Cenozoic intraplate volcanism from SCLM is

401 possible. The Gondwana SCLM is likely to have consisted of depleted upper mantle (DM)
402 that was partially metasomatized by subduction zone fluids and melts containing a subducted
403 sediment component (and thus EM type composition). Ascending Cretaceous HIMU melts
404 would have overprinted the lithosphere forming SCLM representing a mixture of St. Helena
405 HIMU with DM and EM type components. Mantle xenoliths from the southern South Island
406 largely fall on an array between a Cretaceous-type HIMU end member and depleted (DM)
407 and/or enriched (EM) type upper mantle on Pb isotope diagrams (Fig. 4c in McCoy-West et
408 al., 2016). Nevertheless, many of the xenoliths have isotopic compositions shifted to the right
409 of this mixing array, i.e. to more radiogenic $^{206}Pb/^{204}Pb$. These samples however have
410 $^{207}Pb/^{204}Pb$ lower than HIMU. The shift to the right of the HIMU - DM+EM mixing array can
411 be explained by short-term (99-69 Ma) radiogenic ingrowth of mantle with elevated μ ratios,
412 since little ^{235}U (which decays to ^{207}Pb) remains on Earth at the present. Such an ingrowth
413 model could explain not only the composition of the xenoliths but also the greater
414 heterogeneity in the Cenozoic lavas and the lower $^{207}Pb/^{204}Pb$ (and slightly higher
415 $^{143}Nd/^{144}Nd$) at a given $^{206}Pb/^{204}Pb$ than observed in the Cretaceous lavas.
416 Based on studies of dikes from Marie Byrd Land, Antarctica with $^{40}Ar/^{39}Ar$ ages of 107±5
417 Ma, it has been proposed that a HIMU-type plume head beneath Marie Byrd Land may also
418 have served as the trigger for the final phase of Gondwana breakup (Weaver et al., 1994;
419 Storey et al., 1999). We note, however, that none of the dikes have classic HIMU trace
420 element (lacking pronounced relative Nb and Ta enrichments and K and Pb depletions;
421 Storey et al., 1999) or radiogenic Pb isotopic compositions (e.g. $^{206}Pb/^{204}Pb > 20.5$, as is the
422 case for St. Helena, Tubuaii and Mangaia end member HIMU islands and the Late
423 Creataceous Zealandia, Hikurangi and nearby seafloor volcanism; e.g. Zindler and Hart,
424 1986). The Pb isotope ratios of the dikes ($^{206}Pb/^{204}Pb$ = 18.74-19.02, $^{207}Pb/^{204}Pb$ = 15.61-
425 15.63 and $^{208}Pb/^{204}Pb$ = 38.53-38.78) are instead typical of Antarctic Peninsula crust (Fig. 7

426 in Storey et al., 1999), either reflecting extensive crustal assimilation or source contamination
427 by subducted sediments with a similar composition to the Antarctic Peninsula crust.
428 Furthermore, it was assumed that the Hikurangi Plateau was formed at the same time as the
429 Antarctica dikes and to have a HIMU composition (Storey et al., 1999), we now know that
430 the Hikurangi Plateau formed contemporaneous with the Ontong Java and Manihiki Plateaus,
431 thousands of kilometers to the north of the Gondwana margin and that the basement has a
432 EM (rather than HIMU) type composition similar to the Kwaimbaita/Kroenke lavas from
433 Ontong Java (Taylor et al., 2006; Davies et al., 2008; Hoernle et al., 2010). Finally, the SE
434 margin of Zealandia (the Campbell Plateau) and conjugate margin in Marie Byrd Land
435 (Tulloch et al., 2019), Antarctica aren't volcanic type margins. Therefore, there is no
436 compelling evidence for the emplacement of a HIMU type plume head beneath Marie Byrd
437 Land at ~107 Ma; in contrast to the evidence for a HIMU plume(s) ascending beneath
438 Zealandia and the Hikurangi Plateau between ~99-69 Ma.
439 Some evidence exists for a deep reservoir that could have fed mantle plumes beneath the
440 Gondwana margin upon subduction cessation. Anomalous basement topography (0.5-1.2 km)
441 centered beneath the West Antarctic margin and anomalously high Paleogene subsidence
442 rates (total subsidence 0.5-0.9 km) of the Campbell Plateau greater than expected from rift
443 basin models points to long-lived (>80 Ma) mantle upwelling below the Antarctic margin
444 (Sutherland et al., 2010). It is suggested that subduction death allowed a broad low-velocity
445 anomaly that is presently located at 400-1000 km depth to rise from 700-1500 km depth. This
446 low-density anomaly must have had an original horizontal dimension of several thousands of
447 kilometers and could be explained by an average temperature anomaly of 150-200°K
448 (Sutherland et al., 2010). This large-scale low-density anomaly may be the source of the Late
449 Cretaceous HIMU end member and collision of the Hikurangi Plateau with the Gondwana
450 margin at ~110 may have triggered its upwelling (Sutherland et al., 2010). Although it was

speculated that this anomaly resulted from metasomatism of the mid-mantle by subducting slabs over the last 400 Ma, we note that this is not a sufficient amount of time to derive the high $^{207}Pb/^{204}Pb$ isotopic signatures of the HIMU end member from a MORB source (1.0-3.2 Ga) as discussed above. Therefore, this anomaly may ultimately tap a source in the lower mantle containing substantially older recycled ocean crust and/or SCLM.

4.3 A model to explain Late Cretaceous HIMU Intraplate volcanism

We now present a model to explain the interaction of upwelling HIMU type mantle plume(s) with the Gondwana subduction zone jammed by the Hikurangi Plateau collision. Upwelling plume mantle beneath the Gondwana margin would be deflected upwards along the base of the slab until it arrived beneath the Hikurangi Plateau. Although it was no doubt difficult for magmas to ascend through the thickened plateau lithosphere, explaining why many show contamination by enriched (EM type) Hikurangi lithosphere, deep lithospheric fractures and faults formed during the collision of the plateau with the Gondwana margin at ~110-105 Ma (e.g. Davey et al., 2008; Barrett et al., 2018) could have facilitated the rise of the plume-derived magmas.

An important question is why extensive intraplate volcanism took place in Marlborough between 98-94 Ma, because the plume material would have likely been blocked from upwelling to shallow depths by the recently-subducted lithosphere beneath the Torlesse accretionary wedge. Interestingly, the Marlborough Igneous Province was located close to the subducted western margin of the Hikurangi Plateau. The west side of the Hikurangi Plateau is likely to have been bounded by a major transform fault/fracture zone (Mortimer et al., 2019). A sharp transition in thickness in the subducting crust along a tectonic lineament, such as a fracture zone, is a likely place for a slab tear to form, allowing plume mantle to flow into the mantle wedge. Formation of a slab tear along the western edge of the partially subducted

476 Hikurangi Plateau at ~100 Ma would have facilitated upwelling of HIMU plume material
477 beneath the Marlborough area of the South Island and its interaction with enriched (Mt.
478 Somers-type) mantle wedge, as well as forearc crust that is expected to have a similar
479 composition.
480 In the Late Cretaceous, the Westland igneous province could have been located ~500 km
481 SW of the Marlborough igneous province. The geochemical characteristics of the Westland
482 igneous rocks are consistent with increased dilution of the HIMU end member as the plume
483 material flowed through a progressively deeper slab tear below the arc/backarc region,
484 resulting in greater contamination of the melts with enriched (EMORB type) mantle wedge.
485 Interestingly, the southern progression of intraplate volcanism appears to have occurred along
486 what in the future (at ~45 Ma) would become the Pacific-Australia plate boundary,
487 suggesting that the Alpine Fault's location may have initially been influenced or even
488 controlled by a slab tear at the western margin of the subducted portion of the Hikurangi
489 Plateau (Reyners et al., 2011). The slab tear is likely to have propagated down dip with the
490 plateau edge. As a result, hot plume mantle could have streamed through an elongate slab
491 tear, thermally weakening the overlying lithosphere. Therefore, a precursor fault to the
492 Alpine Fault may have formed in the Late Cretaceous (e.g., van der Meer et al., 2016).
493 Considering the similarity in isotopic composition, the East Chatham HIMU end member
494 is likely to be derived from the same source (plume) that feed the Hikurangi, Marlborough
495 and Westland volcanism. A SW propagating detachment of the subducting slab, possibly
496 along an extension of the NE-SW-trending Western Wishbone Ridge, which has been
497 interpreted to be a fracture zone or a major dextral strike-slip fault system (e.g. Mortimer et
498 al., 2006; Barrett et al., 2018), or along the eastern boundary of the thick Hikurangi Plateau,
499 could explain the opening of a slab window beneath the SE Chatham Rise margin. This
500 window would have allowed plume material to upwell into and interact with the former

wedge mantle and the overlying continental crust. The opening of a slab window would have facilitated the upwelling of hotter, deeper asthenosphere, including hot plume mantle, to shallow depths, thermally eroding and weakening the overlying lithosphere and possibly triggering extension and rifting along the southern margin of the Chatham Rise and the Bounty Trough. Once significant thinning of the Gondwana continental lithosphere had occurred, including formation of the Bounty Trough (~90 Ma; Eagles et al., 2004), upwelling plume material could have melted by decompression to form the large intraplate seamounts, many being guyots (former ocean island volcanoes), and the extensive Cretaceous southern Chatham Island volcanism. The volcanism shortly preceded and was concurrent with seafloor spreading that initiated prior to 83 Ma in the mouth of the Bounty Trough (Davy, 2006).

Although the HIMU plume type volcanism along the rifted southeastern Chatham Rise margin is extensive, there is no evidence for the existence of seaward dipping reflectors or for a HIMU type flood basalt province. The lack of excess volcanism is not consistent with this being a volcanic rifted margin formed by interaction of a mantle plume head with the base of a continent. Instead we propose that the margin is a hybrid type that initially formed as non-volcanic margin and then became volcanically active in an intermediate to final stage of its evoluction by interaction of "plumelets" (secondary plumes) from a HIMU type plume head stalled in the transition zone.

5. Conclusions

Four Late Cretaceous intraplate igneous provinces (Hikurangi, Marlborough, Westland and East Chatham) located on oceanic and diverse continental crust form crude binary mixing arrays between a common St. Helena-type HIMU component and depleted and enriched components located in the former Gondwana mantle wedge and the overlying lithosphere. A mantle plume has been imaged to the base of the lower mantle beneath the St. Helena

526 hotspot, providing evidence for a deep mantle plume source for St. Helena HIMU mantle. In
527 contrast to most continental breakup events, there are no flood basalts associated with the
528 final phase of Gondwana breakup separating Zealandia from Antarctica, as expected from a
529 starting plume head (Richards et al., 1989), and no evidence for seaward-dipping reflectors at
530 the rifted Chatham Rise margin. A possible source for the HIMU end member was the 700-
531 1000 km deep, several thousand kilometers in size, mid-mantle low-density anomaly (with
532 possible excess temperature of 150-200°K) postulated by Sutherland et al. (2010). The
533 formation of one large plume or possibly multiple smaller plumes may have been triggered
534 by the Hikurangi Plateau collision and subduction cessation, since for example subduction
535 may have previously dragged such mantle downwards not allowing it to rise or detachment /
536 change of subduction angle may have allowed the slab to destabilize the low-velocity
537 anomaly allowing it to rise. Upwelling HIMU material from the mid mantle began to feed
538 intraplate volcanism at ~100 Ma north and south of the Gondwana margin, lasting for ~30
539 Ma. Rise of this plume material beneath the Gondwana continental margin was facilitated by
540 the formation of a slab tear on the western side of the partially subducted Hikurangi Plateau
541 (between ~98-69 Ma), followed by the opening of a slab window as a result of slab breakoff
542 on the SE side of the subducted plateau (beginning at ~86 Ma). We propose that the
543 upwelling hotter HIMU mantle from mid mantle depths and hotter upper mantle from below
544 the slab upwelling through the slab window played a fundamental role in thermally
545 weakening and extending the overlying lithosphere, first causing rifting in the Bounty Trough
546 and Chatham Rise-Amundsen Sea sector (100-90 Ma) and then breakup and seafloor
547 spreading along the SE margin of the Chatham Rise at ≤85 Ma, which propagated southwards
548 to split the Campbell Plateau from West Antarctica. At ~65 Ma, there was a slight shift in the
549 flavor of the HIMU end member composition towards less radiogenic $^{207}Pb/^{204}Pb$ and more
550 radiogenic $^{143}Nd/^{144}Nd$, as is the case for the HIMU end member in the Cenozoic Zealandia

lavas. The Cenozoic HIMU-type compositions are derived from a distinct source, either from SCLM metasomatized by Cretaceous plume activity or from a different plume source. In closing, we conclude that both Hikurangi Plateau collision and HIMU plume activity were essential in causing the separation of Zealandia from Gondwana.

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Appendix. Supplementary material

Supplementary material related to this article can be found on-line at http://dx.doi.org/10.1016/j.epsl.....

Figure Captions

Figure 1: Bathymetric map (after Smith and Sandwell, 1997), showing Zealandia and the Hikurangi Plateau. Also shown are the four Cretaceous (99-69 Ma) intraplate igneous provinces (Hikurangi in yellow, Marlborough in green, Westland in blue and East Chatham in red), including sample locations within them, and the location of the Mt. Somers subduction-related volcanism (~98 Ma). The black line marks the plate boundary between the Pacific and Indo-Australian Plates. UFZ = Udintsev Fracture Zone; BFZ = Bollons Fracture Zone; PFZ = Pahemo Fracture Zone.

Figure 2: Major element diagrams of MgO vs. a) SiO_2, b) CaO, c) Al_2O_3, d) FeO^t = total iron as FeO, e) TiO_2 and f) P_2O_5. Data sources: Eastern Chatham Rise = Mortimer et al. (2019), Homrighausen et al. (2018); Chatham Island Southern Volcanic rocks = Panter et al. (2006); Hikurangi Province = Hoernle et al. (2010); Osbourn Trough = Worthington et al. (2006); DSDP Site 595 = Mortimer et al. (2019); Marlborough = this study; McCoy-West et al. (2010); Mount Somers volcanic group = this study; Westland Province = this study; van der Meer et al. (2016), van der Meer et al. (2017); Cenozoic intraplate lavas = Hoernle et al. (2006); Timm et al. (2009); Timm et al. (2010).

Figure 3: Diagram panels showing a) Nb/Y versus Zr/Ti after Pearce (1996), and b) Nb/Yb versus Th/Yb and c) Nb/Yb versus TiO_2/Yb after Pearce (2008). Only samples with MgO>6 wt.% are shown in c) to minimize the effect to magnetite-ilmenite fractionation. Data sources are as follows: Hikurangi Seamount Province = yellow circles (Hoernle et al., 2010); Marlborough Igneous Province = green triangles: Lookout Volcanics (this study; McCoy-West et al., 2010), Gridiron Volcanics (this study), Mandamus Igneous Complex (this study); Eastern Chatham Igneous Province: seamounts = red squares (this study; Homrighausen et al., 2018); Chatham Islands Southern Volcanic rocks (Panter et al., 2006); Westland Igneous

Province = blue hexagons (this study; van der Meer et al., 2016, van der Meer et al., 2017). Grey diamonds represent published data from Cenozoic Volcanic centers (age of <60 Ma) (sources as in figure 2).

Figure 4: Representative multi-element patterns for the freshest and most mafic samples with the most radiogenic Pb isotope ratios (most HIMU type composition): A) Hikurangi Seamount Province (Hoernle et al., 2010; filters used: MgO>3wt%. LOI<3wt.%; $^{206}Pb/^{204}Pb$>19.95), B) Westland Volcanic Province (filters used: MgO>5wt%; LOI<3.5wt%; $^{206}Pb/^{204}Pb$>19.19), C) Marlborough Volcanic Province (filters used: MgO>4wt%; $^{206}Pb/^{204}Pb$>20.4), D) Eastern Chatham Province (LOI<3wt%; $^{206}Pb/^{204}Pb$>19.6), and E) Mt. Somers (MgO>5.5wt%). Data sources are as listed in Fig. 2 captions. Average N-MORB are after Sun and McDonough, (1989) and average St.Helena pattern are from data in Chaffey et al. (1989) and Hanyu et al. (2011).

Figure 5: Plots of initial A) $^{206}Pb/^{204}Pb$ vs $^{207}Pb/^{204}Pb$, B) $^{206}Pb/^{204}Pb$ vs $^{143}Nd/^{144}Nd$ and C) $^{206}Pb/^{204}Pb$ vs $^{87}Sr/^{86}Sr$ isotope ratios for samples from this study and published data (see below), assuming an average age of 90 Ma for all Late Cretaceous samples. The St. Helena HIMU (Chaffey et al., 1989; Kawabata et al., 2011), Cook Austral HIMU (Kawabata et al., 2011; Hanyu et al., 2011) and Cenozoic Zealandia and Pacific MORB fields have been projected to 90 Ma, using the same parent/daughter ratios as employed by Homrighausen et al. (2018 and references therein). Sm = 6.5 ppm and Nd = 20 ppm were assumed for the DSDP 595 $^{143}Nd/^{144}Nd$ age correction. Mantle endmembers are from Zindler and Hart (1986). Data sources are: this study; McCoy-West et al. (2010); McCoy-West et al. (2016), Hoernle et al. (2010); Panter et al. (2006); Homrighausen et al. (2018); Mortimer et al. (2006); van der Meer et al. (2016); Hoernle et al. (2006); Timm et al. (2009) and Timm et al.

(2010). Late Cretaceous ocean crust, sampled at Bollons Gap (~77-85 Ma; Mortimer et al., 2019) and DSDP Site 595 (~84 Ma; Mortimer et al., 2019) has a depleted composition, pointing to a primarily depleted composition for the upper mantle in this area.

Figure 6: Conceptual model showing the evolution of the Zealandian continental margin during three different time periods (A = ~110-100 Ma; B = ~100-90 Ma and C ≤ 85 Ma). (A) At ~ 110 Ma, the Hikurangi Plateau collided with the Gondwana margin triggering rise of HIMU plume mantle to the base of the subducting Pacific Plate. (B) At ~100 Ma, upwelling plume material flows along the base of the subducting slab until it reaches the base of the Hikurangi Plateau, melting by decompression to form the Hikurangi Seamounts (yellow triangles). Mt. Somers volcanism (white triangle) takes place in the Gondwana forearc at ~98-96 Ma. A slab tear opened along the western, presumably fracture zone boundary, of the subducted portion of the Hikurangi Plateau. This tear allowed plume material to upwell to the base of the Gondwana lithosphere, also partially melting by decompression to form the Marlborough Igneous Province at 98-94 Ma and begin forming the Westland mafic igneous rocks (small blue triangles) beginning at ~92 Ma. (C) At ~85 Ma, a slab tear began at the eastern boundary of the Hikurangi Plateau (possibly at the Wishbone Fracture Zone) and propagated to the SW eventually resulting in slab detachment. The slab window allowed HIMU plume material to flood into the former Gondwana margin mantle wedge, triggering extension to form the Bounty Trough (~90-80 Ma), seafloor spreading (≤85 Ma) and formation of the East Chatham and SE Chatham Volcanic Province rocks (86-79 Ma).

Supplementary Materials

Supplementary File 1: Analytical methods.

Supplementary Table 1: Major and trace element and Sr, Nd and Pb radiogenic isotope data.

Supplementary Table 2: Standard data for XRF and ICPMS analyses.

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Figure 1

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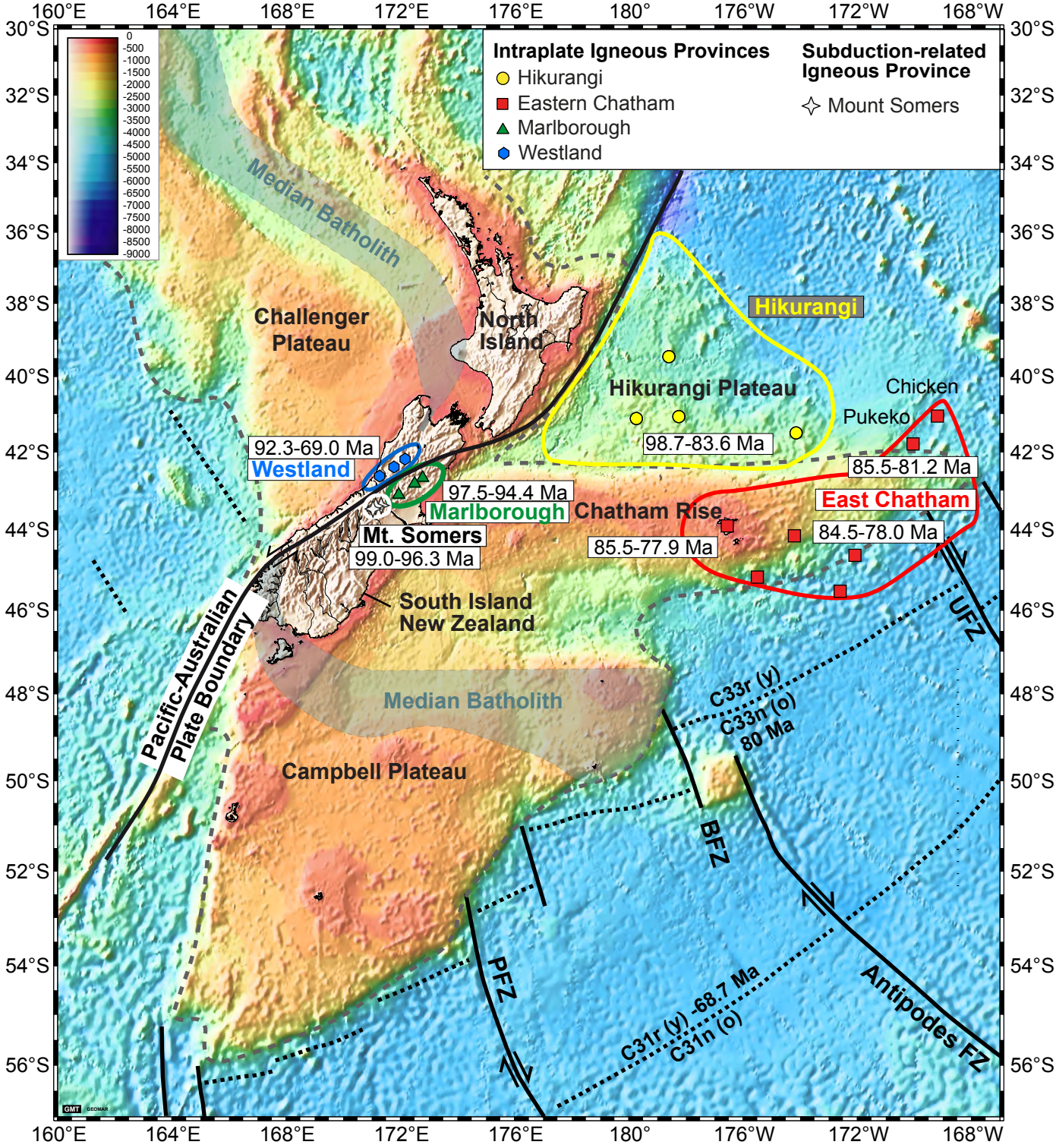

Figure 2

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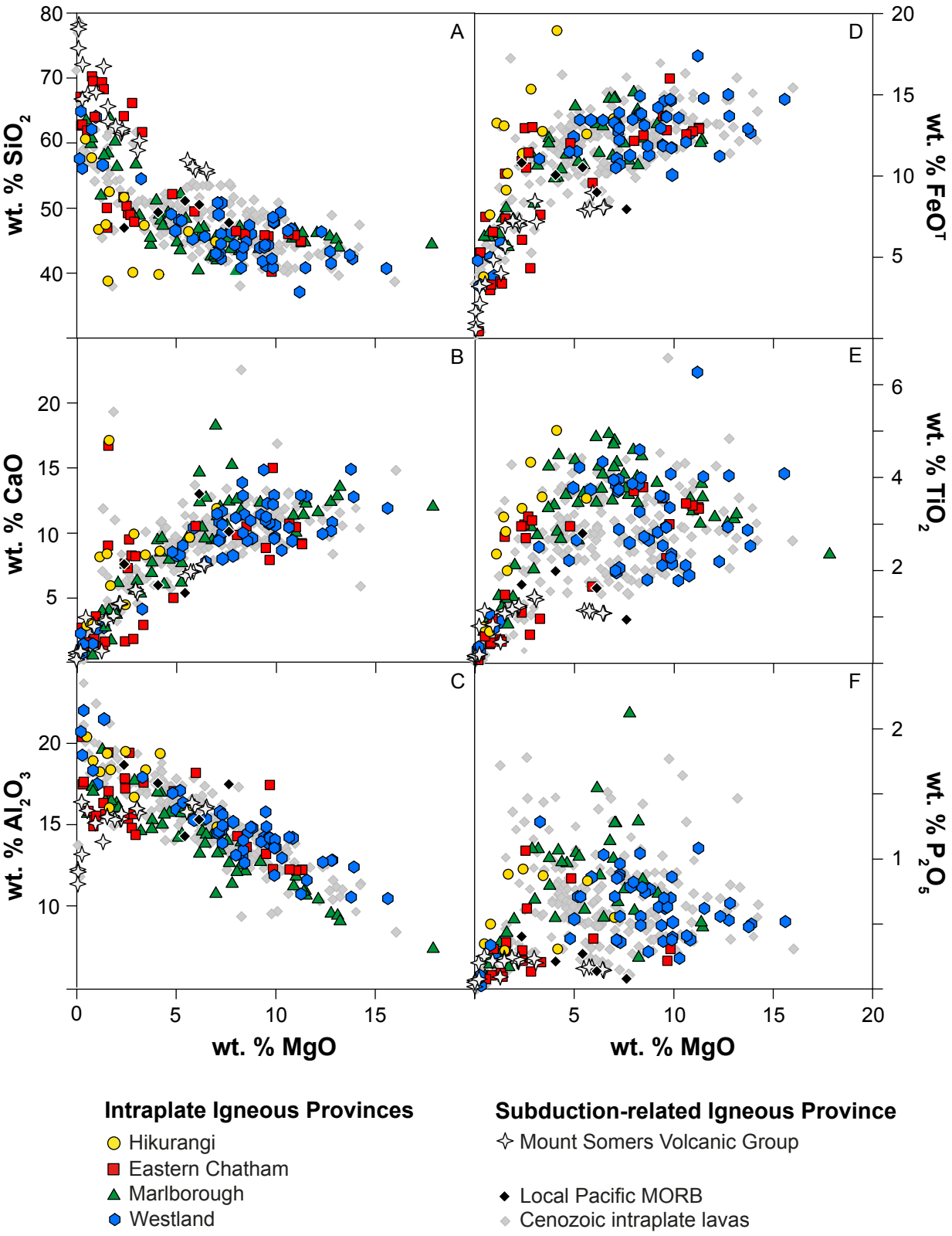

Figure 3

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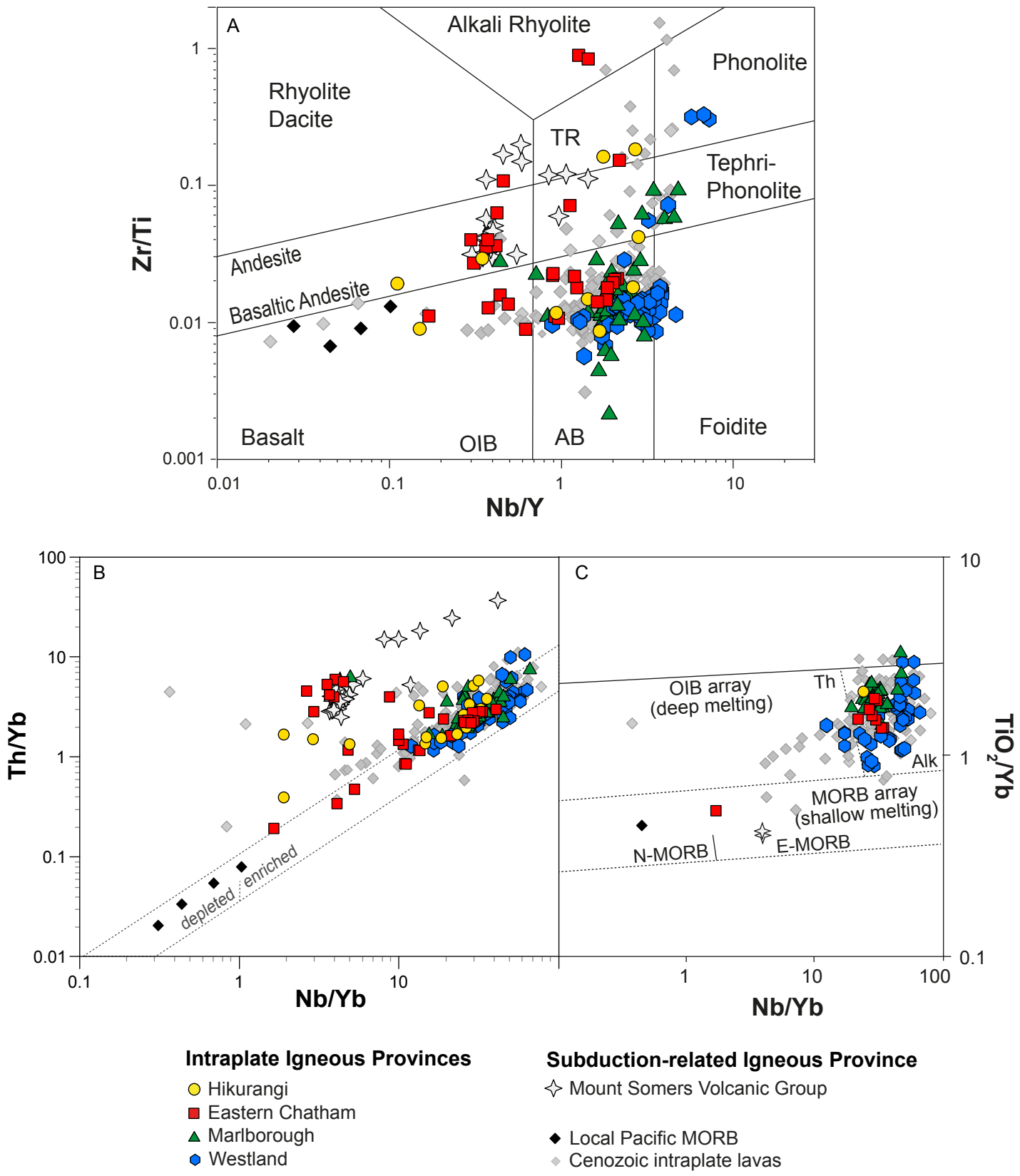

Figure 4

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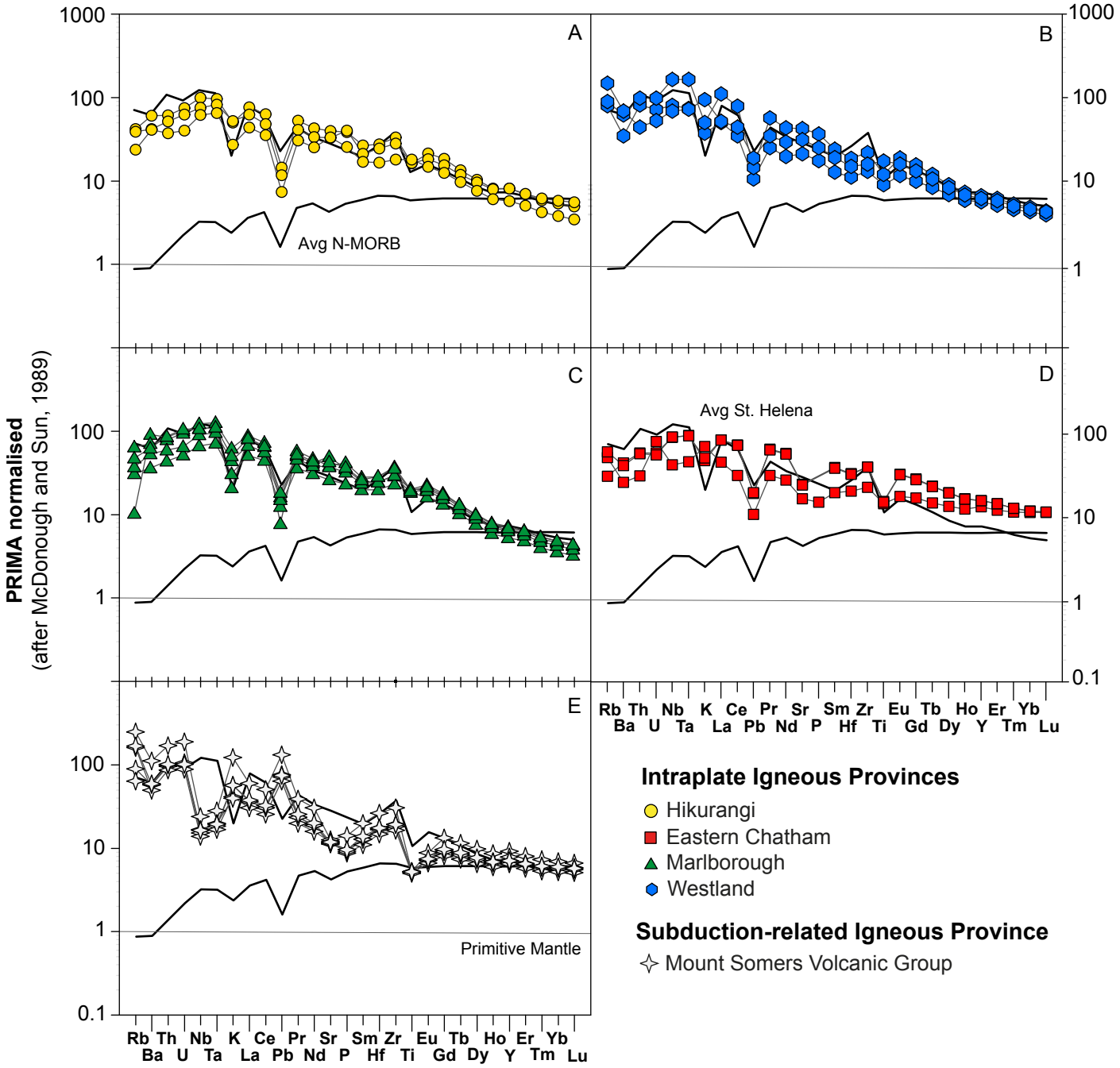

Figure 5

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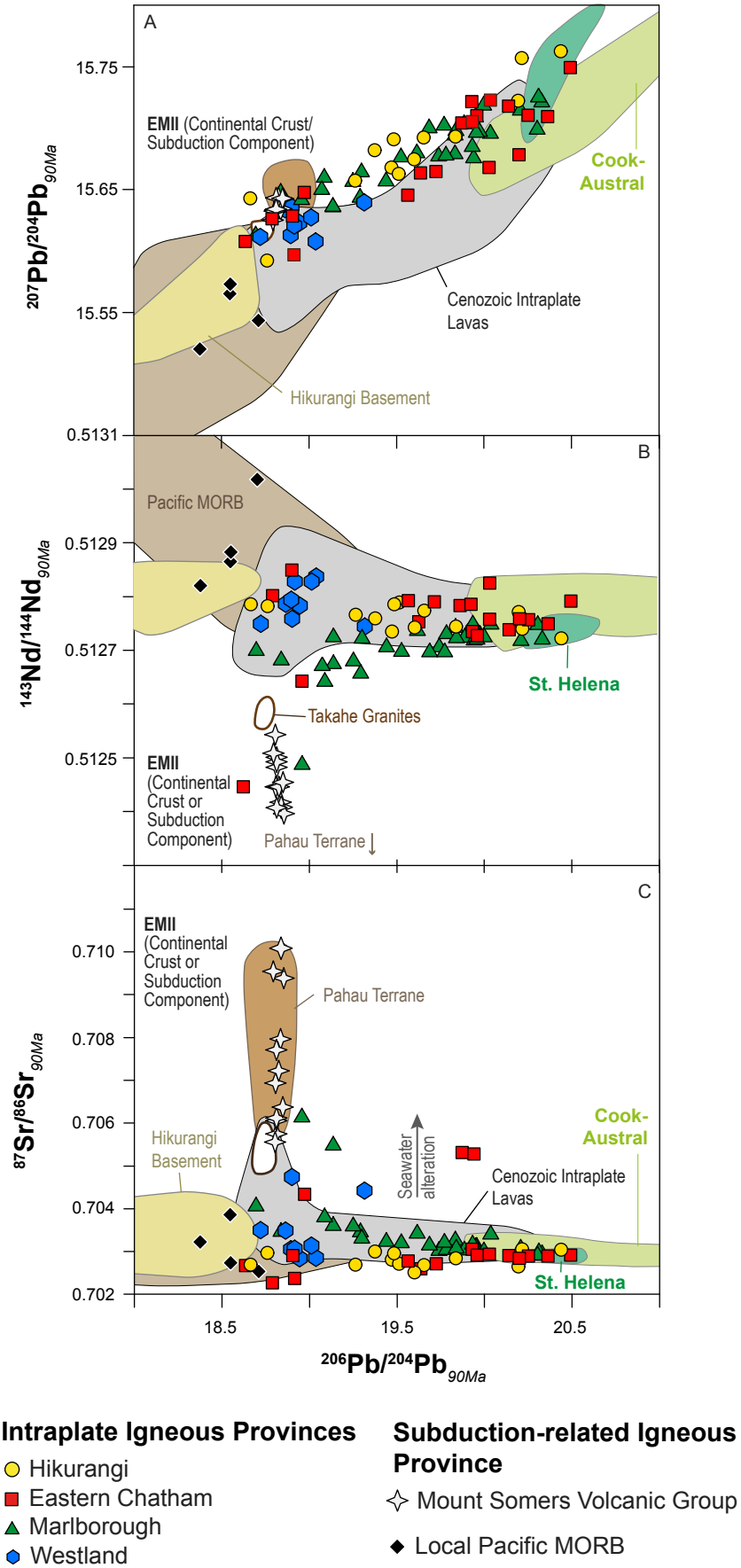

Intraplate Igneous Provinces

- Hikurangi
- Eastern Chatham
- Marlborough
- Westland

Subduction-related Igneous Province

- Mount Somers Volcanic Group
- Local Pacific MORB

Figure 6

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