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# Slab-Triggered Arc Flare-up in the Cretaceous Median Batholith and the Growth of Lower Arc Crust, Fiordland, New Zealand

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## ABSTRACT

The Mesozoic continental arc in Fiordland, New Zealand, records a *c.* 110 Myr history of episodic, subduction-related magmatism that culminated in a terminal surge of mafic to intermediate, high-Sr/Y, calc-alkalic to alkali-calcic magmas. During this brief, 10–15 Myr event, more than 90% of the Cretaceous plutonic arc root was emplaced; however, the source of these rocks and the degree to which they represent lower crustal mafic and/or metasedimentary recycling versus the addition of new lower arc crust remain uncertain. We report whole-rock geochemistry and zircon trace element, O-isotope and Hf-isotope analyses from 18 samples emplaced into lower arc crust (30–60 km depth) of the Median Batholith with the goals of (1) evaluating the processes that triggered the Cretaceous arc flare-up event and (2) determining the extent to which the Cretaceous arc flare-up resulted in net addition of lower arc crust. We find that $\delta^{18}$O (Zrn) values from the Western Fiordland Orthogneiss range from 5·2 to 6·3‰ and yield an error-weighted average value of 5·74 ± 0·04‰ (2SE, 95% confidence limit). Laser ablation multicollector inductively coupled plasma mass spectrometry results yield initial εHf (Zrn) values ranging from –2·0 to + 11·2 and an error-weighted average value of + 4·2 ± 0·2. We explore the apparent decoupling of O- and Hf-isotope systems through a variety of mass-balance mixing and assimilation–fractional crystallization models involving depleted- and enriched-mantle sources mixed with supra-crustal contributions. We find that the best fit to our isotope data involves mixing between an enriched, mantle-like source and up to 15% subducted, metasedimentary material. These results together with the homogeneity of $\delta^{18}$O (Zrn) values, the high-Sr/Y signature, and the mafic character of Western Fiordland Orthogneiss magmas indicate that the Cretaceous flare-up was triggered by partial melting and hybridization of subducted oceanic crust and enriched subcontinental lithospheric mantle. We argue that the driving mechanism for the terminal magmatic surge was the propagation of a discontinuous slab tear beneath the arc, or a ridge–trench collision event, at *c.* 136–128 Ma. Our results from the Early Cretaceous Zealandia arc contrast with the strong crustal signatures that characterize high-flux magmatic events in most shallow to mid-crustal, circum-Pacific orogenic belts in the North and South American Cordillera and the Australia Tasmanides; instead, our results document the rapid addition of new lower arc crust in <<15 Myr with lower crustal growth rates averaging 40–50 km$^3$ Ma$^{-1}$ arc-km$^{-1}$ from 128 to 114 Ma, and peaking at 150–210 km$^3$ Ma arc-km$^{-1}$ from 118 to 114 Ma when ~70% of the arc root was emplaced. Our results highlight the significant role of Cordilleran arc flare-up events in the rapid, net generation of continental crust through time.

**Key words**: arc flare-up; lower arc crust; zircon; oxygen isotopes; Hf isotopes; high-Sr/Y melts

## INTRODUCTION

Continental arcs are often considered factories for crustal growth, whereby partial melting of the mantle adds to the growth of the evolving continental crust (Tatsumi & Stern, 2006; Scholl & von Huene, 2007; Hawkesworth *et al*., 2010; Voice *et al*., 2011). In circum-Pacific orogens, the long-term (>100 Myr) magmatic evolution of continental arcs is dominated by mantle-derived magmatism (Collins *et al*., 2011); however, the pace of magmatism in arcs has long been recognized to be non-steady state, characterized by episodic periods of high-volume magmatic pulses, termed high magma addition rate (MAR) events, that occur within a background of lower-volume activity (Armstrong, 1988). These high-MAR events represent short-term (<20 Myr) excursions from long-term magmatic trends, yet they overwhelmingly dominate arc magma addition rates (Ducea & Barton, 2007; Scholl & von Huene, 2007; Ducea *et al*., 2015*a*, 2017; Paterson and Ducea, 2015). Their cause(s) and the degree to which they contribute to the net addition of new continental crust are fundamental and yet unresolved problems in understanding geodynamic controls on continental crustal growth through time.

In well-studied Phanerozoic continental arcs, geochemical and isotopic data suggest that high-MAR events involve significant reworking of pre-existing crust, and evidence for significant volumes of mantle-derived melts is often conspicuously absent (e.g. Ducea, 2001; Saleeby *et al*., 2003; Lackey *et al*., 2005; Ducea & Barton, 2007; Paterson *et al*., 2011; Paterson and Ducea, 2015; Ducea *et al*., 2015*a*). This problem is underscored in various circum-Pacific arc segments of the North and South American Cordillera and the Australian Tasmanides where high-MAR events are particularly well documented. For example, in the eastern Peninsular Ranges batholith, voluminous tonalitic to granodioritic magmas of the La Posta Pluton (94–91 Ma) display elevated $\delta^{18}O$ values (9–12·8‰) and radiogenic isotope signatures that reflect significant contributions from ancient crustal sources (Taylor & Silver, 1978; Silver *et al*., 1979; Kistler *et al*., 2014). In other shallow to mid-crustal batholiths, such as the Cretaceous Sierra Nevada batholith, geochemical and isotopic studies demonstrate that ~50% or more of the magmatic budget was derived from pre-existing, upper-plate crustal material (Ducea, 2001; Lee *et al*., 2006; Ducea & Barton, 2007; Lackey *et al*., 2008, 2012; Ducea *et al*., 2015*b*). On the opposite side of the Pacific basin in the Australian Tasmanides, repeated arc retreat followed by closure of oceanic back-arc basins produced widespread melting of craton-derived turbiditic metasedimentary rocks and the generation of 'classic' S-type granites (Kemp *et al*., 2009). Taken as a whole, geochemical and isotopic patterns from large portions of circum-Pacific magmatic belts reveal complex tectonic reorganizations through time and the reworking of pre-batholithic basement and supra-crustal rocks in the generation and modification of arc crust during voluminous magmatic surges (e.g. Ducea & Barton, 2007; Lackey *et al*., 2008; DeCelles *et al*., 2009; Chapman *et al*., 2013).

A key problem in understanding crustal growth processes in circum-Pacific magmatic belts is that much of our information is dominated by studies of shallow to mid-crustal plutons that may have undergone significant assimilation of wall-rocks during magma ascent through the crustal column, and/or hybridization of original mantle-derived magmas at depth in lower crustal melting, assimilation, storage and homogenization (MASH) zones (Hildreth & Moorbath, 1988). This problem is particularly acute in over-thickened continental arcs where the crustal column may reach a thickness of 70–75 km (Beck *et al*., 1996). The involvement of mantle-derived melts in high-MAR events has long been noted in whole-rock and mineral isotopic data (Cui & Russell, 1995; Kemp *et al*., 2007, 2009; Appleby *et al*., 2010; Shea *et al*., 2016); however, the significance of mantle processes in triggering high-MAR events remains controversial, in part owing to a lack of exposure of deep portions of the crust generated during voluminous arc magmatism (Ducea, 2001; de Silva *et al*., 2015; Paterson & Ducea, 2015; Ducea *et al*., 2017).

Here, we investigate a deep-crustal flare-up along the Mesozoic, paleo-Pacific margin of SE Gondwana, now isolated and preserved in the largely submerged continent 'Zealandia' (Mortimer *et al*., 2017) with the goals of (1) evaluating the processes that triggered the voluminous surge of mafic to intermediate magmatism and (2) determining the extent to which the Cretaceous arc flare-up resulted in the addition of new lower continental crust. We focus on the western Fiordland sector of the Mesozoic Median Batholith (Fig. 1) because it exposes a section of lower continental arc crust (1·0–1·8 GPa, or 35–65 km paleo-depth: Allibone *et al*., 2009*a*, 2009*b*; De Paoli *et al*., 2009) generated in a high-flux magmatic episode during which the entire Mesozoic plutonic arc root was emplaced in ~14 Myr from 128 to 114 Ma (Schwartz *et al*., 2017). This unique lower crustal exposure allows us to investigate the geochemical and isotopic composition of lower arc rocks that have not been significantly modified by transport through the crustal column during ascent.

Results from our study indicate that $\delta^{18}O$ (Zrn) values from the Cretaceous arc root give uniformly mantle-like

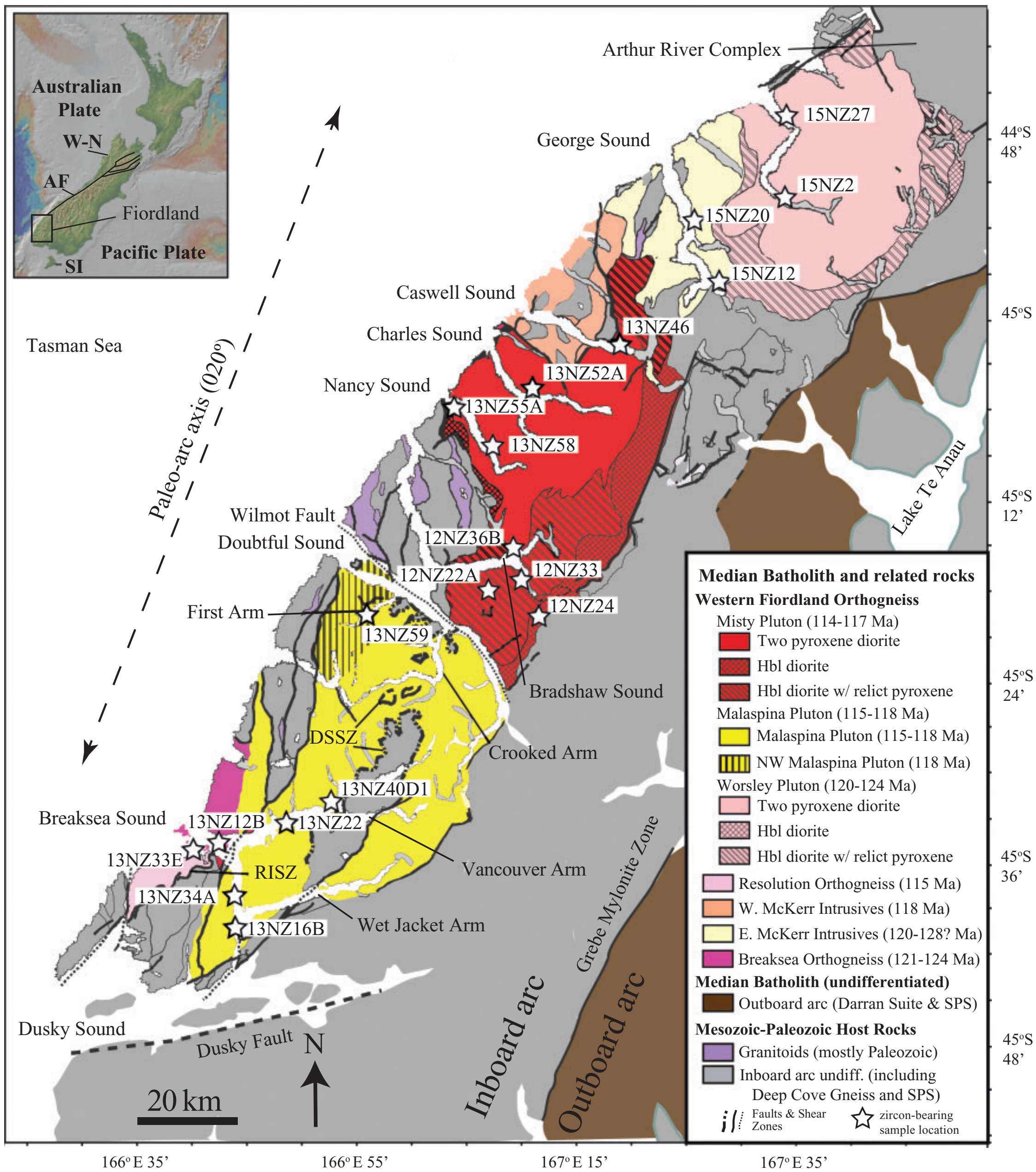


**Fig. 1.** A simplified geological map of the study area in Fiordland [adapted from Allibone *et al.* (2009*a*)]. Samples for zircon O- and Hf-isotope analyses are shown with white stars. Inboard Median Batholith consists of Western Fiordland Orthogneiss, which was emplaced during an arc flare-up event from 124 to 114 Ma. Inset shows location of Fiordland in New Zealand. W-N = Westland-Nelson region; AF = Alpine fault; SI = Stewart Island, DSSZ = Doubtful Sound shear zone; RISZ = Resolution Island shear zone.

values ranging from 5·2 to 6·3‰ and yield an error-weighted average value of 5·74 ± 0·04‰ (2SE; $n = 126$). These results indicate that the surge of lower crustal arc magmas was primarily sourced from the underlying mantle, with only limited contributions from upper plate materials. We present a model whereby the arc flare-up was triggered by widespread partial melting of metasomatized, subcontinental lithospheric mantle with contributions from partially melted, subducted eclogite-facies metasedimentary rocks and oceanic crust. Our isotopic results reveal that the terminal Cretaceous flare-up resulted in the rapid addition of new continental crust to the base of the Median Batholith in $<<$15 Myr with crustal production rates averaging ~40–50 km$^3$ Ma$^{-1}$ arc-km$^{-1}$ from 128 to 114 Ma, and peaking at ~150–210 km$^3$ Ma$^{-1}$ arc-km$^{-1}$ from 118 to 114 Ma.

## GEOLOGICAL FRAMEWORK

### The Median Batholith in Fiordland

The Median Batholith crops out over 10 000 km$^2$ and is located within the Western Province of New Zealand (Mortimer *et al.*, 1999, 2014; Tulloch & Kimbrough, 2003). It consists of two margin-parallel plutonic belts, which are compositionally distinct: an older, low-Sr/Y (<40), outboard arc, located primarily in eastern Fiordland, and an inboard plutonic belt of high-Sr/Y character (>40) located primarily in central and western Fiordland. Collectively, these belts preserve a record of episodic magmatism active over >150 Myr along the southeastern Gondwana margin from 260 to 114 Ma. Arc magmatism resulted in at least two recognized surges of low- and high-Sr/Y magmas at *c.* 147–136 Ma and 128–114 Ma, respectively, each of which occurred over *c.* 10–15 Myr (Schwartz *et al.*, 2017). The latter surge of magmatism resulted in emplacement of the Separation Point Suite (SPS) shortly before termination of arc magmatism and the initiation of extensional orogenic collapse beginning at 108–106 Ma (Schwartz *et al.*, 2016). The boundary between the inboard and outboard arcs is marked by the Grebe Mylonite zone (Fig. 1) (Allibone *et al.*, 2009*a*; Scott *et al.*, 2009, 2011; Scott, 2013) and other major subvertical contractional to transpressional shear zones (Klepeis *et al.*, 2004; Marcotte *et al.*, 2005).

### *Outboard arc*

The primary Mesozoic component of the outboard arc is the low-Sr/Y Darran Suite (Muir *et al.*, 1995; Tulloch & Kimbrough, 2003). Darran Suite magmatism occurred on or near the paleo-Pacific margin of southern Gondwana from 230 to 136 Ma, with peak magmatic activity taking place between 147 and 136 Ma (Kimbrough *et al.*, 1994; Muir *et al.*, 1998; Schwartz *et al.*, 2017, and references therein). It is characterized by mafic and felsic (gabbroic to granitic) I-type plutonic rocks, probably derived from mantle wedge melting and/or mafic sources (Muir *et al.*, 1998). Whole-rock $\delta^{18}$O values in the Darran Suite range from 4·6 to 5·4‰, with an average value of 5·03‰ ($n = 12$; Blattner & Williams, 1991). Decker (2016) reported that some Darran Suite rocks emplaced from 169 to 135 Ma have low $\delta^{18}$O (Zrn) values ranging from 3·8 to 4·9‰. The Early Cretaceous Largs Group volcanic rocks located in NE Fiordland also display anomalously low whole-rock (WR) $\delta^{18}$O values ranging from +3·3 to –12·3‰ ($n = 26$), indicating hydrothermal alteration by heated meteoric fluids at high latitudes or high paleo-elevations (Blattner & Williams, 1991; Blattner *et al.*, 1997). Initial Hf isotope (Zrn) values from Darran Suite plutons give values ranging from +8 to +11 (Scott *et al.*, 2011; Decker, 2016). Whole-rock initial $\varepsilon$Nd values range from +3 to +4 (Muir *et al.*, 1998), and initial $^{87}$Sr/$^{86}$Sr ratios range from *c.* 0·7037 to 0·7049.

Darran Suite magmatism terminated at *c.* 136 Ma and was followed by the emplacement of high-Sr/Y tonalites and granodiorites of the SPS from 128 to 105 Ma at depths of *c.* 0·2–0·7 GPa (Muir *et al.*, 1995, 1998; Tulloch & Challis, 2000; Tulloch & Kimbrough, 2003; Allibone & Tulloch, 2004, 2008; Bolhar *et al.*, 2008). Although the SPS plutonic belt mostly lies inboard of the Darran Suite plutonic belt, intrusions into the outboard Darran Suite are also common and have been extensively studied (Muir *et al.*, 1998; Tulloch & Kimbrough, 2003; Bolhar *et al.*, 2008). Both Darran and SPS plutonic suites are calc-alkalic to alkali-calcic in composition (Tulloch & Kimbrough, 2003). Muir *et al.* (1998) reported that SPS plutons display a small range of positive, whole-rock initial $\varepsilon$Nd values of *c.* +3, and low $^{87}$Sr/$^{86}$Sr initial ratios of *c.* 0·7038. Bolhar *et al.* (2008) reported initial $\varepsilon$Hf (Zrn) values ranging from +8·1 to +11·8 from the same plutonic rocks east of the Grebe Mylonite Zone. Zircon $\delta^{18}$O values for the same rocks range from 1·0 to 5·2‰. Bolhar *et al.* argued that SPS magmas east of the Grebe Mylonite zone were primarily sourced from remelted mafic arc crust (e.g. Darran Suite rocks) and assimilated small amounts of hydrothermally altered, low $\delta^{18}$O crust at the level of emplacement.

### *Inboard arc, including the Separation Point Suite*

Mesozoic magmatism in the inboard belt is dominated by Cretaceous SPS and related plutons (Muir *et al.*, 1995, 1998; Tulloch and Kimbrough, 2003). Tonalites and granodiorites west of the Grebe Mylonite zone occur in central and southwestern Fiordland and give zircon crystallization dates ranging from 120·8 to 116·3 Ma (Scott & Palin, 2008; Ramezani & Tulloch, 2009). No isotopic data are reported from tonalitic to granodioritic rocks west of the Grebe Mylonite zone.

In western Fiordland, deep-crustal plutons of the SPS were emplaced at 1·0–1·8 GPa and formed the Western Fiordland Orthogneiss (Allibone *et al.*, 2009*a*, 2009*b*; De Paoli *et al.*, 2009). These lower crustal rocks are the focus of this study and include seven major plutons: Worsley, McKerr Intrusives (Western and Eastern), Misty, Malaspina, Breaksea Orthogneiss, and Resolution Orthogneiss. The plutonic rocks are primarily diorites and monzodiorites and locally intruded the Deep Cove Gneiss at 128–114 Ma (Mattinson *et al.*, 1986; Hollis *et al.*, 2003; Tulloch & Kimbrough 2003; Allibone *et al.*, 2009*a*; Schwartz *et al.*, 2017). The Deep Cove Gneiss is a heterogeneous unit chiefly consisting of quartzo-feldspathic paragneiss, marble, calc-silicate, and hornblende–plagioclase gneiss (Oliver, 1980; Gibson, 1982). Emplacement of the Western Fiordland Orthogneiss was synchronous with regional transpression and contractional deformation in northern Fiordland (Pembroke Valley and Mt. Daniel) and in the Caswell Sound fold-and-thrust belt in western Fiordland (Daczko *et al.*, 2001, 2002a; Klepeis *et al.*, 2004; Marcotte *et al.*, 2005). Subsequent granulite- to upper amphibolite-facies metamorphism occurred from 116 to 102 Ma and overlapped with the initiation of extensional orogenic collapse in the deep crust at 108–106 Ma (Hollis *et al.*, 2003; Flowers *et al.*, 2005; Stowell *et al.*, 2014; Klepeis *et al.*, 2016; Schwartz *et al.*, 2016). For deformation and metamorphic descriptions of the Western Fiordland Orthogneiss the reader is referred to the studies by Oliver (1976, 1977), Gibson & Ireland (1995), Clarke *et al.* (2002), Daczko *et al.* (2002b), Hollis *et al.* (2004), Klepeis *et al.* (2004, 2007, 2016), Allibone *et al.* (2009*b*) and Stowell *et al.* (2014).

Plutonic rocks from the Western Fiordland Orthogneiss are characterized by low $SiO_2$ (<50–60 wt %), Y (<20 ppm) and heavy rare earth element (HREE) concentrations (Yb <2·0 ppm) and high $Al_2O_3$ (>18 wt %), $Na_2O$ (4·0 wt %), Sr (>1000 ppm), and Sr/Y and La/Yb values (>50 and >15, respectively) (McCulloch *et al.*, 1987). They display steeply fractionated light REE (LREE)/HREE patterns and lack positive or negative europium anomalies. Relative to normal mid-ocean ridge basalt (N-MORB), they display large ion lithophile element (LILE) enrichment with pronounced positive Pb and Sr anomalies, and negative Rb, Nb and sometimes Zr anomalies (McCulloch *et al.*, 1987). Isotopically, they display weak enrichment in $^{87}Sr/^{86}Sr$ initial ratios of 0·70380–0·70430, and weakly negative to positive $\varepsilon$Nd values ranging from –0·4 to +2·7 (McCulloch *et al.*, 1987; Muir *et al.*, 1998). Geochemical modeling of Western Fiordland Orthogneiss magmas from the Malaspina Pluton demonstrates that the variation in major element chemistry reflects fractional crystallization of low-silica phases including garnet, clinopyroxene and plagioclase (Chapman *et al.*, 2016). Although Western Fiordland Orthogneiss plutonic rocks bear strong similarities to high-Sr/Y granitic plutons in eastern and central Fiordland, their low $SiO_2$ concentrations and more evolved radiogenic isotope values distinguish them from their shallower level counterparts. Similar composition lavas are commonly known as adakites, and Archean analogues are referred to as tonalite–trondhjemite–granodiorites (TTGs) [see comprehensive review by Moyen (2009)]. However, we prefer the term 'high-Sr/Y plutonic rocks' to describe the Western Fiordland Orthogneiss as the term avoids genetic connotations [see discussion by Tulloch & Kimbrough (2003)]. Western Fiordland Orthogneiss plutonic rocks bear strong similarities to a subclass of high-Sr/Y rocks termed 'low-silica adakites' (Martin *et al.*, 2005) that are commonly interpreted to have formed from interactions between slab melts and peridotitic mantle (e.g. Rapp *et al.*, 1999; Kelemen *et al.*, 2003, 2014). We return to this idea and the petrogenesis of the Western Fiordland Orthogneiss in the Discussion section.

## METHODS

### Whole-rock geochemistry

Whole-rock samples were powdered in an alumina ceramic shatter box and major and trace element analyses were conducted at Pomona College. Oxygen isotope analyses were conducted at the University of Wisconsin–Madison by laser fluorination as described by Valley *et al.* (1995) and Spicuzza *et al.* (1998*a*, 1998*b*). All $\delta^{18}O$ values are reported relative to Vienna Standard Mean Ocean Water (VSMOW).

### Zircon trace element geochemistry

Zircon trace element geochemical data were collected simultaneously with U–Pb isotopes; age data for these zircons have been reported by Schwartz *et al.* (2017). Detailed descriptions of the methods used are given in the Supplementary Data (SD), and sample locations are provided in SD Appendix Table 1 (supplementary data are available for downloading at http://www.petrology.oxfordjournals.org). Analyses for U–Pb and trace elements were performed on the sensitive high-resolution ion microprobe with reverse geometry (SHRIMP-RG) at the USGS–Stanford laboratory, utilizing an $O^{2-}$ primary ion beam, varying in intensity from 4·3 to 6·4 nA, which produced secondary ions from the target that were accelerated at 10 kV. The analytical spot diameter was between ~15 and 20 μm and the depth was 1–2 μm for each analysis performed in this study. Prior to every analysis, the sample surface was cleaned by rastering the primary

**Table 1**: Summary of zircon U–Pb, O and Lu–Hf isotope data for the Western Fiordland Orthogneiss, Median Batholith, Zealandia Cordillera

| Pluton | Field sample number | P-number | Pb/U Zrn age (Ma) (2SE)* | $SiO_2$ (WR) | $\delta^{18}O$ (WR) (‰)# | $\delta^{18}O$ (WR) (‰)† | Zrn $\delta^{18}O$ range (‰) | $\delta^{18}O$ (Zrn) mean (‰) | ±2 SD | *n* | Zrn $\varepsilon$Hf (initial) range | Zrn $\varepsilon$Hf (initial) mean | ±2 SD | *n* | Ti-in-zircon temperature (°C)‡ | ±1 SD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Breaksea | 13NZ33E | P83729 | 123·2 ± 1·3 | 54·7 | 6·05 | 6·15 | 5·2–5·4 | 5·30 | 0·23 | 6 | 2·7–6·5 | 4·8 | 3·5 | 20 | n.d. | n.d. |
| E. McKerr | 15NZ20 | P85715 | 120·1 ± 2·8 | 55·1 | 5·92 | 6·64 | 5·5–6·0 | 5·77 | 0·27 | 6 | (–)2·0–5·7 | 3·8 | 3·1 | 20 | 777 | 57 |
| Malaspina | 13NZ16B | P83712 | 118·0 ± 2·1 | 56·0 | 5·52 | 6·67 | 5·5–5·9 | 5·74 | 0·27 | 7 | 2·1–5·6 | 4·2 | 3·1 | 20 | 776 | 43 |
| Malaspina | 13NZ22 | P83718 | 116·9 ± 1·6 | 56·1 | 4·53 | 6·60 | 5·5–5·9 | 5·67 | 0·37 | 5 | 3·0–6·2 | 4·3 | 3·4 | 17 | 812 | 31 |
| Malaspina | 13NZ34A | P83730 | 118·0 ± 1·8 | 55·2 | 6·36 | 6·62 | 5·5–6·0 | 5·74 | 0·39 | 7 | 1·2–4·6 | 2·9 | 3·3 | 20 | 792 | 31 |
| Malaspina | 13NZ40D1 | P83733 | 116·4 ± 1·3 | 52·6 | 6·21 | 6·46 | 5·4–5·9 | 5·74 | 0·37 | 9 | 1·9–5·3 | 3·6 | 3·3 | 17 | 780 | 31 |
| Malaspina | 13NZ59 | P83750 | 117·5 ± 1·0 | 54·9 | 5·96 | 6·61 | 5·7–5·8 | 5·75 | 0·27 | 6 | 1·9–6·5 | 4·3 | 3·1 | 20 | 788 | 29 |
| Misty | 12NZ22a | P83650 | 114·7 ± 1·1 | 59·2 | 6·11 | 6·80 | 5·5–5·8 | 5·68 | 0·17 | 7 | 1·3–10·8 | 4·7 | 3·4 | 20 | n.d. | n.d. |
| Misty | 12NZ24 | P83652 | 115·8 ± 2·1 | 53·5 | 6·05 | 6·52 | 5·6–6·0 | 5·75 | 0·12 | 6 | 2·9–6·0 | 3·9 | 3·3 | 20 | n.d. | n.d. |
| Misty | 12NZ33 | P83661 | 114·3 ± 2·1 | 52·9 | 6·12 | 6·29 | 5·4–5·6 | 5·56 | 0·23 | 8 | 2·0–5·7 | 4·0 | 3·6 | 20 | n.d. | n.d. |
| Misty | 12NZ36b | P83664 | 114·2 ± 1·3 | 52·6 | 5·34 | 6·50 | 5·5–5·9 | 5·78 | 0·20 | 5 | 2·8–4·9 | 3·9 | 3·4 | 20 | n.d. | n.d. |
| Misty | 13NZ46 | P83738 | 116·9 ± 1·2 | 54·5 | 6·28 | 6·70 | 5·6–6·0 | 5·87 | 0·17 | 8 | 2·6–11·2 | 4·4 | 3·1 | 20 | 795 | 21 |
| Misty | 13NZ52A | P83743 | 116·8 ± 1·6 | 55·5 | 6·37 | 6·95 | 5·8–6·2 | 6·05 | 0·38 | 5 | 2·5–5·4 | 3·9 | 2·9 | 20 | 776 | 26 |
| Misty | 13NZ55A | P83746 | 115·2 ± 1·9 | 60·2 | 6·76 | 7·06 | 5·7–6·1 | 5·87 | 0·40 | 7 | 2·1–7·7 | 4·4 | 2·9 | 20 | 773 | 48 |
| Misty | 13NZ58 | P83749 | 115·3 ± 1·5 | 52·0 | 6·12 | 6·74 | 5·7–6·2 | 6·06 | 0·27 | 7 | 1·4–5·4 | 4·3 | 2·9 | 20 | 735 | 32 |
| Resolution | 12NZ12b | P83640 | 115·1 ± 2·1 | 51·0 | 6·35 | 6·47 | 5·3–6·1 | 5·85 | 0·25 | 7 | 2·2–7·9 | 4·0 | 3·2 | 20 | n.d. | n.d. |
| Worsley | 15NZ02 | P85716 | 121·6 ± 1·9 | 55·3 | 5·61 | 6·34 | 5·2–5·6 | 5·46 | 0·38 | 8 | 3·5–6·9 | 4·9 | 3·3 | 20 | 745 | 17 |
| Worsley | 15NZ27 | P85717 | 123·2 ± 1·6 | 54·4 | 5·58 | 6·78 | 5·6–6·2 | 5·95 | 0·45 | 10 | 2·6–6·1 | 5·0 | 3·1 | 20 | 781 | 24 |

*U–Pb zircon data reported by Schwartz *et al.* (2017), except 13NZ33E, which was reported by Klepeis *et al.* (2016).
#Data refer to measured whole-rock values. When $\delta^{18}O$ (measured whole rock) is lower than $\delta^{18}O$ (calculated from zircon), we interpret the whole rock, rather than zircon, to have experienced subsolidus alteration.
†Calculated using equation reported by Lackey *et al.* (2008): $\delta^{18}O(\text{WR-Zrn}) = 0{\cdot}0612(SiO_2) - 2{\cdot}50‰$.
‡Ti-in-zircon temperatures calculated following Ferry & Watson (2007) assuming $aSiO_2 = 1$ and $aTiO_2 = 0{\cdot}6$ and P = 1 GPa.
SE, standard error; SD, standard deviation; n.d., not determined.

beam for 60–120 s, and the primary and secondary beams were auto-tuned to maximize transmission. The duration of this procedure typically required 2·5 min prior to data collection. The acquisition routine included $^{89}Y^+$, nine REE ($^{139}La^+$, $^{140}Ce^+$, $^{146}Nd^+$, $^{147}Sm^+$, $^{153}Eu^+$, $^{155}Gd^+$, $^{163}Dy^{16}O^+$, $^{166}Er^{16}O^+$, $^{172}Yb^{16}O^+$), a high mass normalizing species ($^{90}Zr_2{}^{16}O^+$), followed by $^{180}Hf^{16}O^+$, $^{204}Pb^+$, a background measured at 0·045 mass units above the $^{204}Pb^+$ peak, $^{206}Pb^+$, $^{207}Pb^+$, $^{208}Pb^+$, $^{232}Th^+$, $^{238}U^+$, $^{232}Th^{16}O^+$, and $^{238}U^{16}O^+$. Measurements were made at mass resolutions of $M/\Delta M = 8100$–8400 (10% peak height), which eliminated interfering molecular species, particularly for the REE. For some samples, the analysis routine was the same as above, but also included masses $^{30}Si^{16}O^+$, $^{48}Ti^+$, $^{49}Ti^+$, and $^{56}Fe^+$. Measurements for these samples were performed at mass resolutions of $M/\Delta M = 9000$–9500, which were required to separate fully the $^{48}Ti^+$ peak from the nearby $^{96}Zr^{2+}$ peak. Analyses consisted of five peak-hopping cycles stepped sequentially through the run table. The duration of each measurement ranged between 15 and 25 min on average. Count times for most elements were between 1 and 8 s, with increased count times ranging from 15 to 30 s for $^{204}Pb$, $^{206}Pb$, $^{207}Pb$, and $^{208}Pb$ to improve counting statistics and age precision. Similar to previous studies, U concentrations were fairly low (roughly <200 ppm) for zircons from mafic to intermediate composition rocks. Zircon standard R33 was analyzed after every 3–5 unknown zircons. Average count rates of each element were ratioed to the appropriate high mass normalizing species to account for any primary current drift, and the derived ratios for the unknowns were compared with an average of those for the standards to determine concentrations. Spot-to-spot precisions (as measured on the standards) varied according to elemental ionization efficiency and concentration.

For the zircon standards MAD-green (4196 ppm U, Barth & Wooden, 2010) and MADDER (3435 ppm U), precision generally ranged from about ±3% for Hf to ±5–10% for Y and HREE, typically ±10–15%, but up to ±40% for La, which was present most often at the ppb level (all values at 2σ). Trace elements (Y, Hf, REE) were measured briefly (typically 1–3 s per mass) immediately before the geochronology peaks in mass order. All peaks were measured on a single EPT® discrete-dynode electron multiplier operated in pulse counting mode. Analyses were performed using five scans (peak-hopping cycles from mass 46 to 254), and counting times on each peak were varied according to the sample age as well as the U and Th concentrations to improve counting statistics and age precision. Chondrite-normalized plots were calculated using values from McDonough & Sun (1995).

## Zircon secondary ion mass spectrometry O isotopes

Zircon oxygen isotope analyses were conducted at the University of Wisconsin–Madison using the CAMECA IMS 1280 ion microprobe, following the procedures outlined by Kita *et al.* (2009) and Valley & Kita (2009). All mounts were polished using 6, 3, and 1 μm diamond lapping film to expose the surface of the zircons just below the bottom of the existing pits from U–Pb SHRIMP-RG analysis. Where U–Pb pits were visible after polishing, they were avoided so that O-implantation from SHRIMP-RG analyses did not affect oxygen isotope ratios. Zircons were imaged by reflected light and by SEM-cathodoluminescence (CL) at California State University Northridge (CSUN) to aid in the selection of oxygen isotope analysis spot locations. Mounts were cleaned using a series of ethanol and deionized water baths in an ultrasonic cleaner, then dried in a vacuum oven at ~40°C for 1 h, and gold-coated in preparation for secondary ionization mass spectrometry (SIMS) analysis. Zircon mounts were mounted with the KIM-5 oxygen isotope standard (Valley, 2003, $\delta^{18}O = 5{\cdot}09$‰ VSMOW). Extra care was taken to achieve a smooth, flat, low-relief polish. A focused, 10 kV $^{133}Cs^+$ primary beam was used for analysis at 1·9–2·2 nA and a corresponding spot size of 10–12 μm. A normal incidence electron gun was used to aid charge compensation. The secondary ion acceleration voltage was set at 10 kV and oxygen isotopes were collected in two Faraday cups simultaneously with $^{16}O^1H$. Ratios of OH/O provide a monitor of 'water', which can identify domains of metamict zircon or inclusions (Wang *et al.*, 2014). Four consecutive measurements of zircon standard KIM-5 were analyzed at the beginning and end of each session, and every 8–10 unknowns throughout each session. The average values of the standard analyses that bracket each set of unknowns were used to correct for instrumental bias. The average precision (reproducibility) of the bracketing standards for this study ranged from ±0·12 to ±0·44 and averaged ±0·28‰ (2SD). After the oxygen isotope analysis was complete, ion microprobe pits were re-imaged by the SEM at CSUN to ensure that there were no irregular pits or inclusions.

## Zircon LA-MC-ICP-MS Lu–Hf isotopes

Hafnium isotopes were analyzed via laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) at the University of California Santa Barbara in analytical sessions on 6 and 7 August 2015. Whenever possible, O-isotope spot locations were resampled for Hf isotopes to target the same chemical domain. Mounts were polished between U–Pb, O, and Hf analysis such that the original U–Pb spot was no longer visible. Careful documentation of the CL images allowed for accurate placement of spots during analysis. A 50 μm beam diameter, 3·5 mJ energy (*c.* 80 nm per pulse), and a 10 Hz repetition rate were used for all ablations. Analyses were conducted over a 30 s ablation period with a 45 s washout between measurements. Masses 171–180 (Yb, Hf, Lu) were measured simultaneously on an array of 10 Faraday cups at 1 a.m.u. spacing. Data reduction was preformed using Iolite 2.3 (Paton *et al.*, 2011).

The MC-ICP-MS system is not able to differentiate between $^{176}Yb$, $^{176}Lu$, and $^{176}Hf$; therefore, the $^{176}Hf$ intensity must be corrected for isobaric interferences. Natural

$^{173}Yb/^{171}Yb = 1{\cdot}123575$ was used to calculate the Yb mass bias factor and Lu mass bias (Thirlwall & Anczkiewicz, 2004), and $^{179}Hf/^{177}Hf = 0{\cdot}7325$ was used to calculate the Hf mass bias (Patchett & Tatsumoto, 1980; Vervoort *et al.*, 2004). $^{176}Yb/^{173}Yb = 0{\cdot}786847$ and $^{176}Lu/^{175}Lu = 0{\cdot}02656$ were used to subtract isobaric interferences on $^{176}Hf$ (Patchett & Tatsumoto, 1980; Thirlwall & Anczkiewicz, 2004; Vervoort *et al.*, 2004). A variety of zircon hafnium standards with known hafnium compositions were analyzed before and after ~10 unknowns, and yield weighted averages within uncertainty of their accepted values (see SD Appendix file).

## RESULTS

### Sample descriptions

Geochemical data consist of 56 new whole-rock samples collected from >2300 km$^2$ of lower crust in Western Fiordland (Fig. 2). Our data span ~130 km parallel and ~30 km perpendicular to the strike of the paleo-arc axis, which is roughly approximated by the present-day western Fiordland coastline. Samples for isotopic analysis consist of a subset and include eight samples from the Misty Pluton, five samples from the Malaspina Pluton, two samples from the Worsley Pluton, one sample from the Resolution Orthogneiss, one sample from the Breaksea Orthogneiss, and one sample from the Eastern McKerr Intrusives (Fig. 1). Oxygen and Hf isotope measurements were conducted on the same chemical domain as U–Pb isotope determinations where possible (see Fig. 3). Zircon trace element, $\delta^{18}O$ and initial εHf isotope values are shown in Figs 4–9.

### Whole-rock geochemical data

Rocks from the Western Fiordland Orthogneiss range in composition from trachybasalts to trachyandesites (Fig. 2a). They are magnesian, calc-alkalic to alkali-calcic, and metaluminous (Fig. 2b–d), similar to plutonic rocks in other Cordilleran plutons and batholiths (Frost *et al.*, 2001). Molar Mg#s range from 56 to 43, and display fractional crystallization trends consistent with removal of high-pressure mineral assemblages including clinopyroxene + garnet (Chapman *et al.*, 2016). All plutonic rocks from the Western Fiordland Orthogneiss display high average $Al_2O_3$ (18·6 wt %), $Na_2O$ (4·9 wt %), Ni (26 ppm), Cr (83 ppm), Sr (1300 ppm) and Sr/Y values (128), and low average Y (14 ppm) and HREE concentrations (Yb = 1·4 ppm) ($n = 175$). Compared with N-MORB, the plutonic rocks have pronounced positive Ba, K, Pb, and Sr anomalies, and negative Nb and Zr anomalies. Measured $\delta^{18}O$ (WR) ranges from 5·3 to 6·8‰, with one sample as low as 4·5‰ (13NZ22). The mean value of all $\delta^{18}O$ (WR) values (excluding the outlier) is 6·0 ± 0·4‰ (Table 1).

### Zircon trace element geochemistry

Zircons from the Western Fiordland Orthogneiss are distinguished from continental arc and mid-ocean ridge (MOR) zircons by strongly enriched U/Yb values at low Hf concentrations (Fig. 4a). Misty Pluton zircons show the highest Hf concentrations of all zircons. Western Fiordland Orthogneiss zircons are also characterized by high Gd/Yb and low Yb values, reflecting strongly fractionated middle REE (MREE)/HREE concentrations and depletions in HREE concentrations (Fig. 4b–e). Western Fiordland Orthogneiss zircons are also characterized by high Ti concentrations, which reflect high average crystallization temperatures using the Ferry & Watson (2007) calibration [typically > 750°C assuming $a_{SiO2} = 1$ and $a_{TiO2} = 0{\cdot}6$; see Schwartz *et al.* (2017) for zircon-thermometry details] (Fig. 4d and e). Western Fiordland Orthogneiss zircons also display enrichments in Ce/Yb (Fig. 4c). Using the calibration of Trail *et al.* (2011), Ce/Ce* values from Western Fiordland Orthogneiss zircon data give an average $fO_2$ of ~5·0 log units above the value defined by the fayalite–magnetite–quartz (FMQ) buffer (±3·2 log units).

### Zircon oxygen isotope ratios

Individual zircon $\delta^{18}O$ values in the Western Fiordland Orthogneiss range from 5·2 to 6·3‰ (Table 1; Supplementary Data). The mean value of all zircons is 5·76 ± 0·46‰ (2SD), and the error-weighted average is 5·74 ± 0·04‰ (2SE, 95% confidence limit) (Fig. 5a). In samples where we measured internal and external domains, we see no measurable difference in $\delta^{18}O$ values (e.g. 15NZ27; Fig. 3). Within samples, measured values tightly cluster and yield standard deviations ranging from 0·08 to 0·59‰ (2SD). Intra-pluton $\delta^{18}O$ standard deviations are also small, <0·6‰. From north to south, mean intra-pluton values and 2SD are 5·73 ± 0·59‰ (Worsley Pluton), 5·77 ± 0·35‰ (Eastern McKerr Intrusives), 5·82 ± 0·39‰ (Misty Pluton), 5·73 ± 0·29‰ (Malaspina Pluton), 5·85 ± 0·59‰ (Resolution Orthogneiss), and 5·30 ± 0·59‰ (Breaksea Orthogneiss). All single zircon and mean intra-pluton values for the Western Fiordland Orthogneiss lie within analytical SIMS error of the high-temperature mantle value for zircon from SIMS analyses (5·3 ± 0·80‰: 2SD; Valley, 2003). There are no temporal or latitudinal trends in $\delta^{18}O$ (Zrn) values (Fig. 6a and b).

Calculated WR values from measured $\delta^{18}O$ (Zrn) using the equation of Lackey *et al.* (2008) generally agree with measured $\delta^{18}O$ whole-rock; however, several samples display deviations towards lower $\delta^{18}O$ (WR) values (Fig. 7; Table 1), presumably due to subsolidus alteration of feldspars and other easily exchanged minerals. Samples with the largest deviations include two samples from the Malaspina Pluton [13NZ22, which also has the lowest $\delta^{18}O$ (WR) value, and 13NZ16B], the two Worsley Pluton samples (15NZ02 and 15NZ27), and one sample from the Misty Pluton (12NZ36b).

### Zircon Lu–Hf isotopes

Initial εHf values in the Western Fiordland Orthogneiss range from –2·0 to + 11·3; the error-weighted average for all zircons is +4·2 ± 0·2 (MSWD = 0·6; $n = 354$) (Fig. 5b). From north to south, weighted average initial εHf values for plutons are + 5·0 ± 0·5 for the Worsley

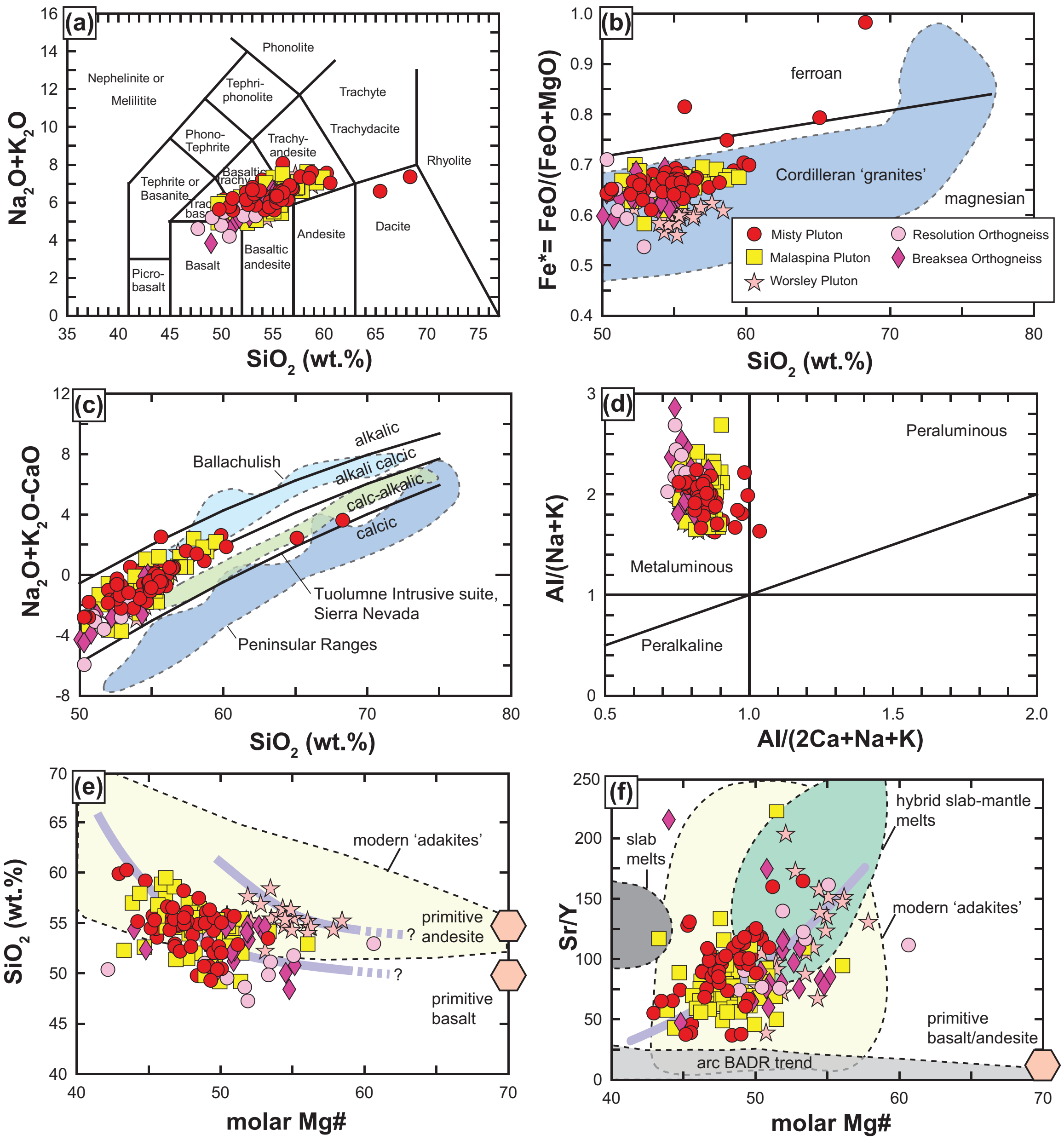


**Fig. 2.** Bivariate plots of whole-rock data showing the geochemical characteristics of the Western Fiordland Orthogneiss (this study and J. Wiesenfeld & J. Schwartz, unpublished data). (a) Samples range from ~47 to 60 wt % $SiO_2$ and are classified as basalt/trachybasalt to trachyandesite. Western Fiordland Orthogneiss samples are largely magnesian (b), calc-alkalic to alkali-calcic (c) and metaluminous (d). (e) Molar Mg#s range from 42 to 60 consistent with fractionation of high-density assemblages including garnet + clinopyroxene from a primitive basalt or primitive andesite. (f) Western Fiordland Orthogneiss samples have high-Sr/Y values (>40) indicating the presence of garnet and/or amphibole as residual or fractionating phases. The high-Sr/Y character is present and highest in the most primitive samples (Mg# > 50), indicating that the high-Sr/Y signature is a feature of the source and not related to crystal fractionation processes. Fields in (b) and (c) are from Frost *et al.* (2001), Frost and Frost (2008).] Fields in (e) and (f) are compiled from Rapp *et al.* (1999) and Moyen (2009). BADR, basalt–andesite–dacite–rhyolite arc trend.

Pluton (MSWD = 0·3; $n$ = 40), +3·8 ± 0·7 for the Eastern McKerr Intrusives (MSWD = 1·1; $n$ = 20), +4·2 ± 0·2 for the Misty Pluton (MSWD = 0·5; $n$ = 160), +3·9 ± 0·3 for the Malaspina Pluton (MSWD = 0·6; $n$ = 94), +3·9 ± 0·7 for the Resolution Orthogneiss (MSWD = 0·5; $n$ = 20), and +4·6 ± 0·7 for the Breaksea Orthogneiss (MSWD = 0·4; $n$ = 20). In general, Western Fiordland Orthogneiss values are significantly more evolved than Cretaceous depleted mantle (~+15); our results overlap with existing results from the Western Fiordland Orthogneiss (Bolhar *et al.*, 2008; Milan *et al.*, 2016).

## DISCUSSION

### Zircon geochemical constraints on lower crustal magma sources

Zircons from the Western Fiordland Orthogneiss are distinguished from arc and N-MORB zircons by

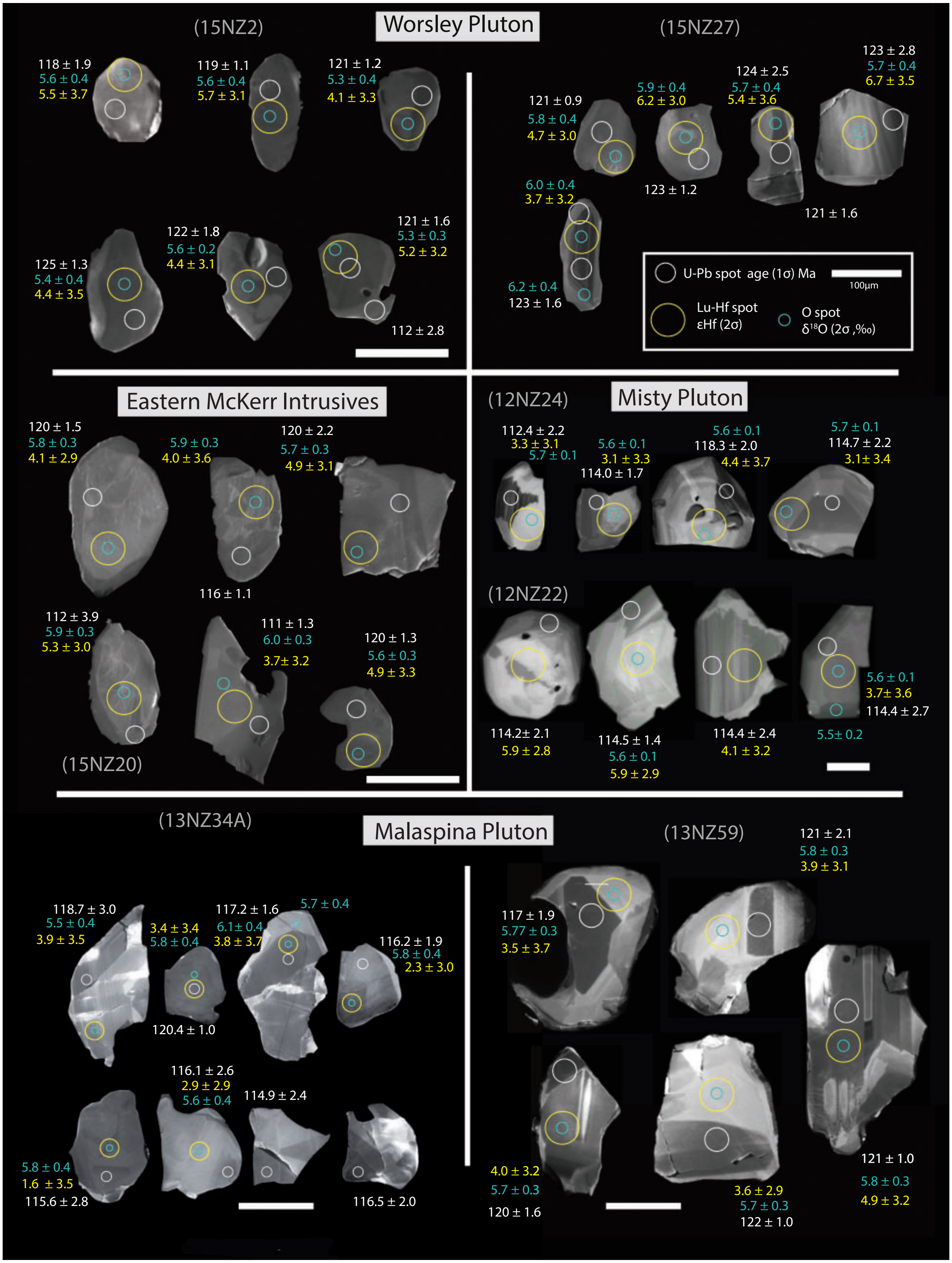


**Fig. 3.** Cathodoluminescence images of representative zircons from the Western Fiordland Orthogneiss. Locations of ion microprobe and laser ablation spots are shown (U–Pb in white, oxygen in teal, and Hf in yellow) along with data from each spot. Scale bars represent 100 µm.

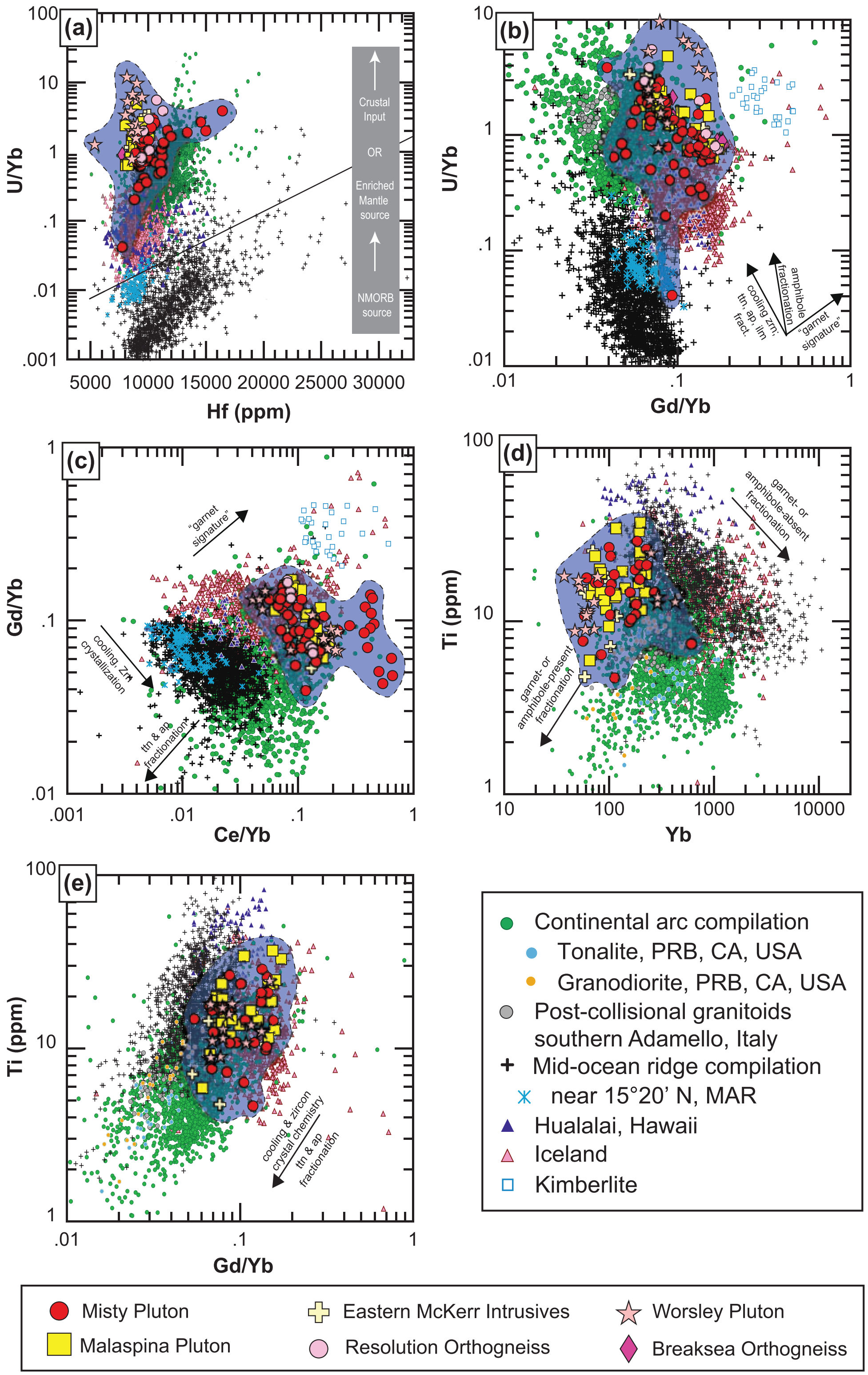


**Fig. 4.** Bivariate plots of Western Fiordland Orthogneiss zircon trace element data compared with a global compilation of zircons from various tectonic environments by Grimes *et al.* (2015, and references therein). (a) U/Yb vs Hf (ppm), showing enrichment in U/Yb for Western Fiordland Orthogneiss zircons relative to continental arc zircons, suggesting either strong crustal input or an enriched mantle source. (b) U/Yb vs Gd/Yb, illustrating the strong garnet signature relative to continental zircons, especially the Worsley and Malaspina Plutons and Breaksea Orthogneiss. Negative trends are consistent with fractional crystallization during cooling. (c) Gd/Yb vs Ce/Yb. Western Fiordland Orthogneiss zircons display enrichment in both Ce/Yb and Gd/Yb, indicating relatively oxidizing magmas relative to MOR, intra-plate and other continental zircons. Only zircons from kimberlites have higher average Gd/Yb values. (d) Ti vs Yb, showing relatively high Ti concentrations (and high crystallization temperatures) at low average Yb concentrations relative to other continental arc zircons. Weak trends towards decreasing Yb are consistent with garnet and/or late-stage amphibole crystallization. (e) Ti vs Gd/Yb. Western Fiordland Orthogneiss zircons plot at the high-temperature (Ti) end of the continental arc spectrum, with high Gd/Yb values consistent with a garnet signature. Weak cooling trends are present, reflecting either garnet or apatite fractionation. PRB, Peninsular Ranges batholith; MAR, Mid-Atlantic Ridge.

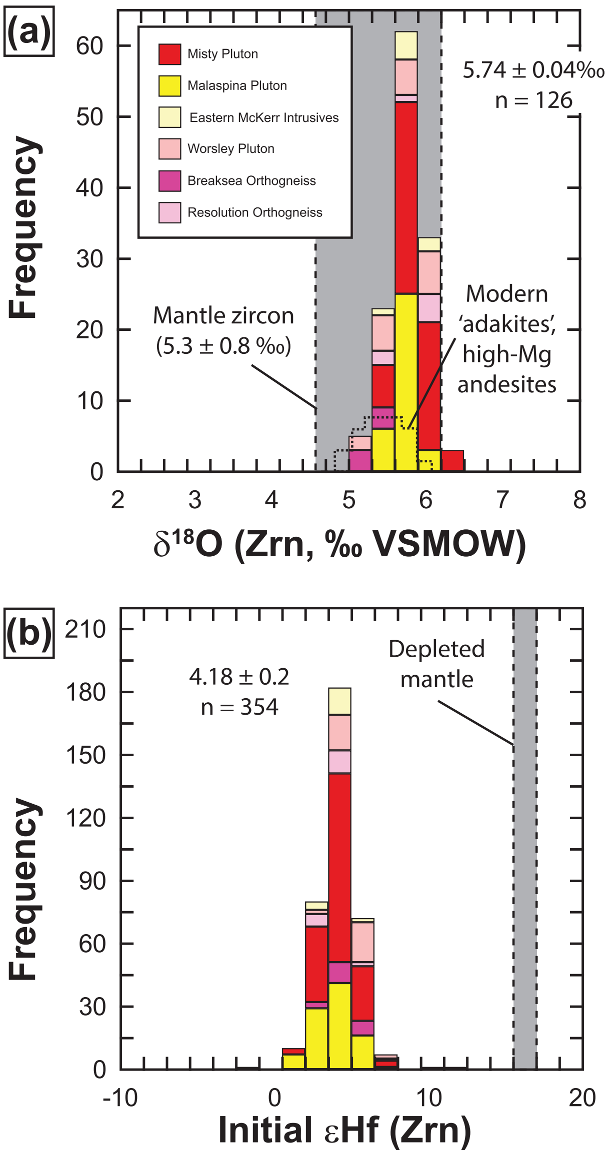


**Fig. 5.** (a) Histogram showing $\delta^{18}O$ (Zrn) values for the Western Fiordland Orthogneiss. Grey bar reflects the $\delta^{18}O$ composition of high-temperature mantle (Valley *et al.*, 2005). The weighted-average $\delta^{18}O$ value for all Western Fiordland Orthogneiss zircons is $5{\cdot}74 \pm 0{\cdot}04$‰ ($2\sigma$). Dashed area shows modern 'adakites' and high-Mg andesites from the global compilation of Bindeman *et al.* (2005). (b) Histogram showing initial εHf (Zrn) for the Western Fiordland Orthogneiss. The weighted-average value for all Western Fiordland Orthogneiss zircons is $+4{\cdot}2 \pm 0{\cdot}2$ ($2\sigma$). Grey bar reflects the composition of depleted mantle at *c.* 120 Ma (Vervoort & Blichert-Toft, 1999).

enrichment in U/Yb, suggesting either significant crustal input or derivation from an enriched mantle source (Fig. 4a). Mantle-like $\delta^{18}O$ values for all zircons in this study (see discussion below and Figs 5 and 6) preclude significant, if any, crustal input, and imply that the source of elevated trace element contents is an enriched mantle source. Strongly fractionated MREE/HREE ratio and depletions in HREE concentrations (Fig. 4b and c) further indicate the presence of garnet as a fractionating and/or residual phase in the source region. These features also characterize Hawaiian and Icelandic zircons. Weak trends in Ti–Yb space can be indicative of either garnet and/or late-stage amphibole crystallization (Fig. 4d); however, even the most primitive zircons with the highest Ti contents show strong depletions in Yb concentration, indicating that the Western Fiordland Orthogneiss magmas were depleted in HREE, probably a consequence of residual garnet in the source region, prior to zircon crystallization.

Western Fiordland Orthogneiss also display enrichments in Ce/Yb relative to MOR, intra-plate and other continental zircons (Fig. 4c), suggesting crystallization from relatively oxidizing magmas. These features are consistent with high average calculated $fO_2$ values (~5·0 log units above the value defined by the FMQ buffer) and the petrological observations of Bradshaw (1989, 1990), who noted that Western Fiordland Orthogneiss oxide assemblages are characterized by intergrowths of exsolved ilmenite and hematite, indicating relatively oxidizing conditions during crystallization. Collectively, zircon trace element data indicate that zircons crystallized from trace element enriched, mafic magmas that were relatively oxidizing, and depleted in HREE.

## Zircon O and Hf isotope constraints on lower crustal magma sources

Zircons from the lower crust of the Median Batholith are characterized by uniformly low $\delta^{18}O$ values with all analyses lying within analytical SIMS error of high-temperature mantle values (Fig. 5a) indicating equilibration between Western Fiordland Orthogneiss zircons and mantle-like melts. Whole-rock $\delta^{18}O$ data for the same rocks are also characterized by mantle-like values; however, several samples display evidence for modest open-system exchange after magmatic crystallization (Fig. 7; Table 1). We therefore base our interpretations primarily on $\delta^{18}O$ (Zrn), which is highly retentive of magmatic $\delta^{18}O$, even in rocks that have undergone subsolidus exchange and hydrothermal alteration (Valley, 2003; Lackey *et al.*, 2006, 2008; Page *et al.*, 2007).

In addition to their mantle-like character, the analysed zircons display very little intra- and inter-sample variation in $\delta^{18}O$ values, consistent with the lack of measurable differences between internal and external domains (Fig. 3). This observation is remarkable given the wide geographical distribution of our samples, which span >2300 $km^2$ of lower arc crust (Fig. 1). Together, the homogeneity of $\delta^{18}O$ (Zrn) values, the mantle-like $\delta^{18}O$ character of both zircons and whole-rocks, and the low $SiO_2$ whole-rock contents of Western Fiordland Orthogneiss rocks in this study ($54{\cdot}7 \pm 2{\cdot}3$ wt %: 1SD) support the interpretation that Western Fiordland Orthogneiss magmas were derived from partial melting of a high-temperature mantle or mantle-like sources.

In contrast to the mantle-like $\delta^{18}O$ zircon and whole-rock values, initial εHf (Zrn) values range from –2·0 to +11·2 with a mean of +4·2 (Table 1; Fig. 6b). These

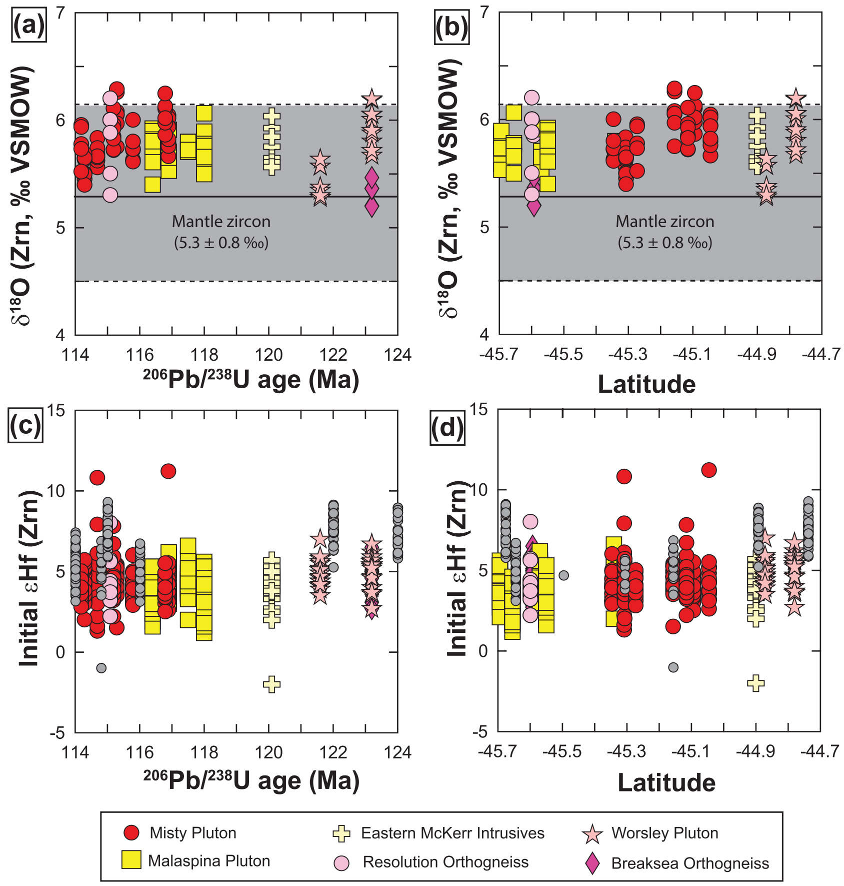


**Fig. 6.** Bivariate plots of O-isotope and initial εHf values vs zircon Pb/U age and latitude. (a) $^{206}Pb/^{238}U$ zircon age vs $\delta^{18}O$ (Zrn). (b) $\delta^{18}O$ (Zrn) vs latitude. (c) $^{206}Pb/^{238}U$ age vs initial εHf (Zrn). (d) Initial εHf (Zrn) vs latitude. Grey field in (a) and (c) reflects the $\delta^{18}O$ composition of zircon in equilibrium with high-temperature mantle (Valley *et al.*, 2005). All Western Fiordland Orthogneiss O-isotope data lie within SIMS analytical error of the mantle field. Grey circles are Western Fiordland Orthogneiss zircons reported by Milan *et al.* (2016) filtered for $^{206}Pb/^{238}U$ zircon dates between 110 and 130 Ma—the age range of the Western Fiordland Orthogneiss defined by high-precision zircon dates [see Schwartz *et al.* (2017) and references therein].

values are significantly lower than those for Cretaceous depleted MORB mantle (~15; Vervoort & Blichert-Toft, 1999) and average modern island-arc values (~13; Dhuime *et al.*, 2011). Because the Hf budget of crustal rocks is largely contained within zircon, contamination from pre-existing zircon-bearing sources is likely to strongly affect the distribution of Hf-isotope values. A curious feature of the Western Fiordland Orthogneiss zircons is that their strong mantle-like $\delta^{18}O$ values and lack of xenocrystic zircon cargo appear inconsistent with significant crustal contamination.

We explore possible explanations for the decoupling of O- and Hf-isotopes by considering a variety of mixing and assimilation–fractional crystallization (AFC) scenarios involving wall-rocks, subducted metasedimentary rocks, and various depleted- and 'enriched'-mantle sources. Here we use 'enriched' to describe εHf values significantly lower than those for Cretaceous depleted mantle (+15). Epsilon Hf values for the assimilated wall-rock were calculated from the average εNd values of Takaka metasedimentary rocks given by Tulloch *et al.* (2009b) using the Vervoort *et al.* (1999) 'crustal' Hf–Nd relationship. The average Takaka value (εNd = –7·9) is similar to that of a metasedimentary rock reported from George Sound (εNd = –9: McCulloch *et al.*, 1987) and either value is considered viable. Epsilon Hf values and Hf concentrations for subducted sediment were selected from average pelagic sediments reported by Vervoort *et al.* (1999). Hf concentrations were selected from average values of metasedimentary rocks from western Fiordland (J. Wiesenfeld & J. Schwartz, unpublished data) and average values of arc lavas from the Mariana arc reported by Tollstrup & Gill (2005).

Results of binary mixing models are illustrated in Fig. 8a and b, and AFC models are shown in Fig. 8c and d. In all scenarios, mixing and AFC scenarios involve <20% interaction with Deep Cove Gneiss (Fig. 8a and c), and <10% interaction with pelagic sediments (Fig. 8b and d). Two important features of our data are also illustrated in Fig. 8: (1) in both mixing and AFC scenarios, no single model adequately describes the distribution of Western Fiordland Orthogneiss zircon isotope data; (2) Western Fiordland Orthogneiss zircons show no apparent mixing trends, but instead they plot in a clustered field within the mantle array centered at εHf = +4. We also observe that models with a depleted mantle end-member

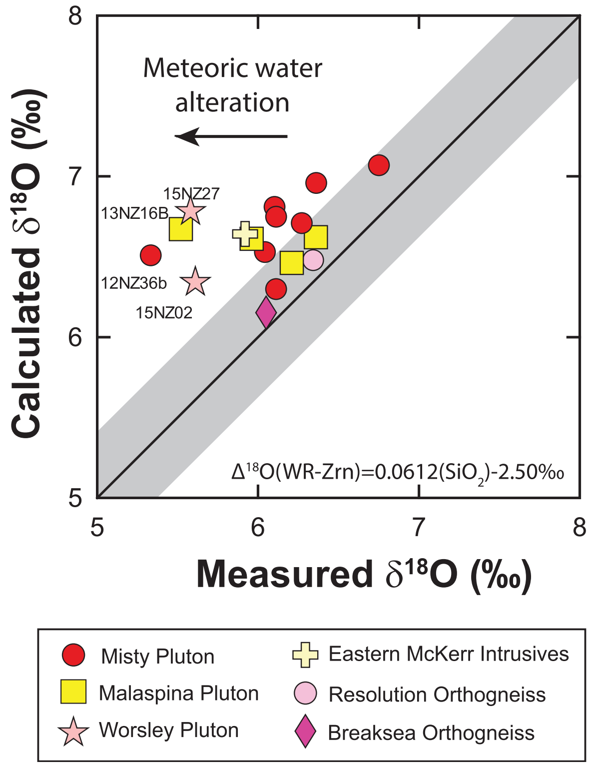


**Fig. 7.** Comparison of calculated and measured $\delta^{18}O$ (WR). Calculated values were determined from zircon O-isotopes and $SiO_2$ concentrations following the equation of Lackey *et al.* (2008). The grey field bounding the equilibrium line is 3SD of analytical uncertainty wide. Samples that lie off that line are interpreted to have interacted with low-$\delta^{18}O$ (marine or meteoric) water.

($\varepsilon Hf = +15$) fail to describe the distribution of the tightly clustered Western Fiordland Orthogneiss data. Similarly, the average modern island arc source ($\varepsilon Hf = +13$) is a poor fit in both mixing and AFC models. Models that involve an 'enriched' mantle end-member ($\varepsilon Hf +3$ to $+9$) intersect the majority of the data; however, as mentioned above, our data lack obvious evidence for mixing trends. These observations suggest that probablly neither mixing nor AFC processes involving supra-crustal sources in the lower crust are the primary explanation for O and Hf enrichment in the Western Fiordland Orthogneiss; instead, Hf isotopic enrichment is a primary feature of the Western Fiordland Orthogneiss, reflecting derivation from an enriched source region.

## Evaluating triggering mechanisms for the Zealandia high-MAR event

Zircon trace element and isotopic data for the lower crust of the Median Batholith underscore the role of an enriched mantle-like source region with limited supra-crustal interaction in the petrogenesis of the Western Fiordland Orthogneiss from 128 to 114 Ma. The mantle-like oxygen isotope signatures of the Western Fiordland Orthogneiss, in particular, distinguish the terminal Zealandia flare-up from other Phanerozoic flare-ups, especially those in the North and South American Cordillera where widespread partial melting and/or devolatilization of fertile crustal material is commonly invoked to explain the isotopically evolved character of the magmatic rocks (e.g. Ducea, 2001; Haschke *et al.*, 2002, 2006; Kay *et al.*, 2005; Ducea & Barton, 2007; DeCelles *et al.*, 2009; Ramos, 2009; Chapman *et al.*, 2013; Ramos *et al.*, 2014; DeCelles & Graham, 2015). Existing whole-rock Pb-isotope data also rule out triggering of the flare-up by interaction with a HIMU plume (McCoy-West *et al.*, 2016) as Western Fiordland Orthogneiss magmas have low $^{206}Pb/^{204}Pb$ signatures that are distinct from those of later Cretaceous intraplate lavas (Mattinson *et al.*, 1986). Lithospheric foundering is also unlikely as a triggering mechanism as there is no evidence for significant Jurassic or Early Cretaceous magmatism or a geochemical signature of a thick lithospheric root (e.g. high Sr/Y, low HREE concentrations) in western Fiordland prior to the Cretaceous flare-up.

In considering other possible triggering mechanisms, we note that petrological models must address both the high-Sr/Y and calc-alkaline signature of the Western Fiordland Orthogneiss (Fig. 2). High-Sr/Y values and low HREE concentrations, particularly Yb and Lu in Western Fiordland Orthogneiss whole-rocks and zircons, are characteristic features and signify the presence of garnet in the source or as a fractionating phase (McCulloch *et al.*, 1987; Muir *et al.*, 1998; Chapman *et al.*, 2016). In contrast, calc-alkaline signatures reflect melting of a mantle source that was previously enriched in LILE by a hydrous fluid phase or a melt in equilibrium with garnet (Kelemen *et al.*, 2003, 2014). To explain both of these features, we consider two potential scenarios including (1) partial melting of an amphibole-rich lower crust (Muir *et al.*, 1995, 1998; Tulloch & Kimbrough, 2003) and/or (2) partial melting and hybridization of eclogite-facies metasedimentary rocks and basalt from a subducting slab with mantle-derived melts from the subcontinental lithospheric mantle.

Before considering these petrological scenarios, we note that the brief surge of magmatism from 128 to 114 Ma was linked to distinctive tectonic and magmatic features that provide insights into the geodynamic setting during the flare-up event. These features include the following: (1) transpression and regional thrusting from *c.* 130 to 105 Ma (Daczko *et al.*, 2001, 2002a; Klepeis *et al.*, 2004; Marcotte *et al.*, 2005; Allibone & Tulloch, 2008); (2) crustal thickening and possibly loading of the Western Fiordland Orthogneiss in Northern Fiordland from 128 to 116 Ma (Brown, 1996; Scott *et al.*, 2009, 2011); (3) a transition from dominantly low-Sr/Y magmatism from 230 to 136 Ma to voluminous, high-Sr/Y magmatism at 128–114 Ma (Mattinson *et al.*, 1986; Muir *et al.*, 1998; Tulloch & Kimbrough, 2003; Hollis *et al.*, 2004; Bolhar *et al.*, 2008; Scott & Palin, 2008; Schwartz *et al.*, 2016), (4) an apparent gap in magmatism from 136 to 128 Ma (Tulloch & Kimbrough, 2003; Tulloch *et al.*, 2011); (5) the initiation of early granulite-facies metamorphism synchronous with magmatism at *c.* 134 Ma, peaking at *c.* 120–112 Ma (Gibson & Ireland,

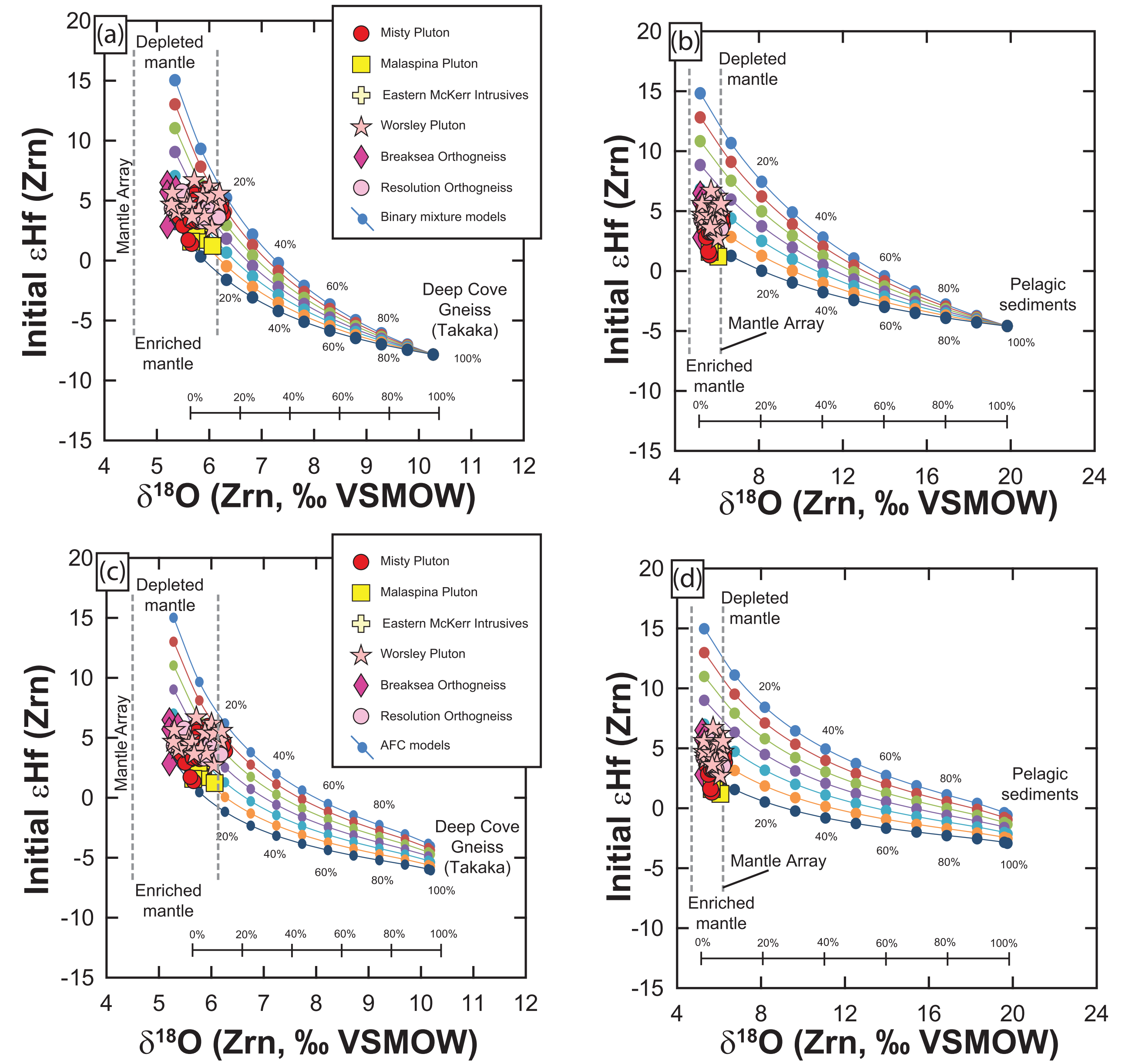


**Fig. 8.** Results of bulk mixing (a, b) and assimilation–fractional crystallization (c, d) models for zircon $\delta^{18}O$ vs initial εHf (Zrn) (colored curves). Black, horizontal lines at the bottom of (a)–(d) show the results of oxygen isotope bulk mass-balance mixing models. All models involve a variety of mantle-derived melts. Models in (a) and (c) use average Deep Cove Gneiss, whereas models in (b) and (d) use average pelagic sediments (after Vervoort *et al.*, 1999). Ticks and percentages indicate relative proportions of assimilant. In general, models involving Cretaceous depleted mantle (εHf = +15) and average arc (εHf = +13) fail to describe the variation in the Western Fiordland Orthogneiss data. Best-fit models involve 'enriched' mantle sources (mixing curves with εHf = +7 to +3 as end-member compositions). Results permit bulk mixing and/or assimilation of up to 15% Deep Cove Gneiss and up to 10% pelagic sediment; however, the lack of apparent assimilation or mixing trends suggests that the isotopic composition of the Western Fiordland Orthogneiss magmas was acquired in the source region rather than by crustal assimilation at the level of emplacement. Mantle arrays after Patchett & Tatsumoto (1980) and Valley *et al.* (2005).

1995; Hollis *et al.*, 2004; Flowers *et al.*, 2005; Stowell *et al.*, 2010, 2014; Tulloch *et al.*, 2011; Klepeis *et al.*, 2016; Schwartz *et al.*, 2016); (6) migration of magmatism towards Gondwana (Tulloch & Kimbrough, 2003); (7) northward drift of the Pacific Plate relative to Gondwana during the Aptian (125–112 Ma) (Davy *et al.*, 2008). These features collectively point to a major transition in subduction-zone dynamics along the SE Gondwana margin during the interval from 136 to 128 Ma, which preceded the extensional orogenic collapse of Zealandia starting at 108–106 Ma. Below we explore the possible petrological and geodynamic scenarios that may explain these features and our geochemical and isotopic data.

### *Partial melting of mafic lower crust*

McCulloch *et al.* (1987) and Muir *et al.* (1995, 1998) proposed that the Cretaceous surge of high-Sr/Y magmas in the Western Fiordland Orthogneiss and SPS resulted from partial melting of basaltic lower crust leaving behind an eclogite to garnet amphibolite root. In the McCulloch *et al.* (1987) model [later refined by Tulloch & Kimbrough (2003)], the Western Fiordland Orthogneiss originated from partial melting of an LREE-enriched, low-Rb/Sr, mid- to late Paleozoic crustal protolith equivalent to the Darran Leucogranite ($SiO_2 = 51{\cdot}0$–$53{\cdot}6$ wt %). Muir *et al.* (1995, 1998) presented a similar model in which trenchward-directed, retroarc underthrusting of a putative back-arc beneath the arc triggered widespread partial melting of mafic crust resulting in the surge of Separation Point Suite magmatism. Geological mapping of western Fiordland has not identified either mid- to late Paleozoic Darran Suite rocks or remnants of a mafic back-arc basin beneath the Western Fiordland Orthogneiss. Instead, the deepest portions of the arc root consist of complexly interlayered granulite-facies metadiorite and eclogite, the latter of which is interpreted to represent high-pressure magmatic cumulates produced by fractional crystallization of the Western Fiordland Orthogneiss magmas (De Paoli *et al.*, 2009; Chapman *et al.*, 2016).

Existing petrological models involving melting of mafic crust also have considerable difficulty in reproducing the geochemical and isotopic features of the Western Fiordland Orthogneiss. Data from this study and data compiled from the literature (Fig. 2a) show that $SiO_2$ values extend to as low as 47·2 wt %. These low values cannot be attributed to partial melting of amphibole-rich source rocks at reasonable partial melting percentages (e.g. 10–30%), which would produce high $SiO_2$ (55 to $>$70 wt%) and low Mg# (20–45) melts (Rapp & Watson, 1995). This point is illustrated in Fig. 2f by comparing melts derived from partial melting of mafic crust (grey field labeled 'slab melts') with the distribution of Western Fiordland Orthogneiss data. It should be noted that Western Fiordland Orthogneiss data show decreasing Sr/Y with decreasing Mg# (purple line), indicating the likely fractionation of both a high-MgO and an HREE-enriched phase. Mass-balance numerical simulations of elemental data show that the diversity in Western Fiordland Orthogneiss compositions can be successfully modeled by fractionation of assemblages involving garnet + clinopyroxene from a basaltic to trachybasaltic parental magma (Fig. 2a and e) (Chapman *et al.*, 2016). Layered igneous garnet pyroxenites at the base of the Western Fiordland Orthogneiss in the Breaksea Orthogneiss are probably cumulates generated by such a process, and provide strong support for the existence of an extensive ultramafic arc root beneath the Western Fiordland Orthogneiss, consistent with observed high seismic velocities ($V_p > 7{\cdot}5\,km\,s^{-1}$) (Eberhart-Phillips & Reyners, 2001). Isotopic data for the Darran Leucogranite also preclude it as a source for the Western Fiordland Orthogneiss as it is characterized by low $\delta^{18}O$ (Zrn) values of $3{\cdot}97 \pm 0{\cdot}32‰$, and radiogenic initial $\varepsilon$Hf (Zrn) values of $8{\cdot}4 \pm 3{\cdot}1$ (2SD; Decker, 2016) that are unlike the Western Fiordland Orthogneiss. Thus, geochemical and isotopic considerations appear to rule out melting of underthrust mafic rocks as the primary source for the Western Fiordland Orthogneiss.

Further, experimental studies also highlight difficulties in producing the large volumes of mafic to intermediate magmas over the timescales that we observe in the Western Fiordland Orthogneiss. Clemens & Vielzeuf (1987) have demonstrated that fluid-undersaturated melting of amphibolites yields relatively low-melt volumes compared with melting of pelites and quartzo-feldspathic rocks, and melt volumes decrease with increasing depth. Melt volumes are also strongly dependent on the fertility of the source rock, which is controlled by the modal abundance of hydrous phases (e.g. muscovite, biotite and amphibole). In lower arc crust, voluminous andesitic melts are unlikely to be generated by melting of underplated basaltic source rocks unless they experienced low-grade, fluid-present metamorphism resulting in a significant modal increase in amphibole content (Clemens & Vielzeuf, 1987). As discussed above, no back-arc basin rocks have been identified beneath the Western Fiordland Orthogneiss, and hydrous metasedimentary host-rocks show little evidence for melting except within the immediate contact aureole of the Western Fiordland Orthogneiss (Allibone *et al.*, 2009*b*; Daczko *et al.*, 2009). The mantle-like $\delta^{18}O$ (Zrn) values for the Western Fiordland Orthogneiss also preclude significant involvement of high-$\delta^{18}O$ sources such as the Deep Cove Gneiss ($\sim$10·4‰) or putative underthrust, hydrothermally altered mafic crust (7–15‰: Gregory & Taylor, 1981; Alt *et al.*, 1986; Staudigel *et al.*, 1995). Numerical simulations of amphibolite partial melting based on repeated injection of basalt into the lower crust also conclude that voluminous magma chambers are not likely to form from basaltic protoliths (Petford & Gallagher, 2001; Dufek & Bergantz, 2005). Direct field and geochemical observations from the lower crust of the Famatinian arc, Argentina, also show little evidence for dehydration melting of amphibole, and instead emphasize the role of fractional crystallization of mantle-derived melts in the diversification of lower and mid-crustal crustal arc rocks (Walker *et al.*, 2015). In Fiordland, the sustained production of Separation Point Suite magmas from 128 to 105 Ma, and especially the production of voluminous mafic to intermediate melts in the Western Fiordland Orthogneiss from 118 to 114 Ma, also points to a mantle heat source in triggering the terminal Zealandia flare-up.

### *Partial melting of the subducted crust and hybridization with the mantle*

Another possibility is that the distinctive chemistry of the Western Fiordland Orthogneiss reflects interaction of partially melted, subducted, eclogite-facies metabasalt and/or metasedimentary rocks with the overlying mantle wedge. Slab-derived melts are thought to occur from partial melting of young crust ($\sim$5–10 Ma: Defant

& Drummond, 1990; Peacock *et al.*, 1994), or where torn subducted plates are exposed to mantle flow (Yogodzinski *et al.*, 2001). Thermal models that incorporate temperature-dependent viscosity, and/or non-Newtonian viscosity, predict temperatures in the wedge and the top of the slab higher than the fluid-saturated solidus for both basalt and sediment (e.g. Johnson & Plank, 2000) at normal subduction rates and subducting plate ages (van Keken *et al.*, 2002; Kelemen *et al.*, 2003, 2014). Thus, partial melts of eclogite-facies metasedimentary rocks and metabasalts probably make up an important component of arc magmas, particularly in high-Mg# andesites (>50), and are abundant features in unusually hot subduction zones where 'tears' and/or young subducting plates yield a larger proportion of eclogitic partial melt relative to the overlying mantle wedge (Kelemen *et al.*, 2003, 2014; Moyen, 2009).

Magmas generated by partial melting and hybridization of subducted oceanic crust with mantle peridotite have distinctive geochemical features that allow us to compare them with Western Fiordland Orthogneiss compositions. Slab melts are typically andesitic to dacitic in composition with high Sr/Y (>100) and $Al_2O_3$ (>15 wt %) contents, and steeply fractionated REE patterns suggestive of an eclogite residue (e.g. Rapp & Watson, 1995). Primitive andesites (Mg# > 60) and high-Mg# andesites (Mg# > 50) with high-Sr/Y signatures typically have high Cr (>36 ppm) and Ni (>24), features that are interpreted to reflect hybridization of $H_2O$-rich, low-temperature melts with the high-temperature mantle wedge (Yogodzinski & Kelemen, 1998; Yogodzinski *et al.*, 2001; Kelemen *et al.*, 2014). Slab melts are also characterized by enrichments in fluid-mobile elements relative to REE (e.g. high U/Yb, Ce/Yb, Ba/La, and Sr/Nd), signatures that are commonly attributed to an aqueous fluid component with the isotopic characteristics of hydrothermally altered MORB (e.g. $^{87}Sr/^{86}Sr \sim 0{\cdot}7035$, $^{143}Nd/^{144}Nd \sim 0{\cdot}5132$, and $^{208}Pb/^{204}Pb$ down to 38) (Rapp *et al.*, 1999). However, melting of sedimentary rocks may also be an important factor in controlling the geochemical budgets of fluid-immobile elements such as Nd, Pb, Hf, and Th (Johnson & Plank, 2000; Plank, 2005), and lavas with potentially large components of slab melt (*c.* 10%) are reported from some arcs (e.g. Setouchi, Japan; Shimoda *et al.*, 1998; Hanyu *et al.*, 2002; Tatsumi *et al.*, 2003). Despite evidence in slab melts for potentially significant contributions from high-$\delta^{18}O$ sources such as low-temperature hydrothermally altered MOR crust and sedimentary rocks, olivine from slab melts typically displays only weak, <1‰, enrichment in $\delta^{18}O$ values over MORBs (see stippled region in Fig. 5a). Bindeman *et al.* (2005) proposed that the weak enrichment in slab melts may result from partial oxygen isotope equilibration between slab melts and mantle peridotite, and/or efficient mixing between partial melts from several different parts of the slab such that higher- and lower-$\delta^{18}O$ components average out to have no net difference from average mantle.

Data from the Western Fiordland Orthogneiss display strong similarities to hybridized slab melts described above. A distinctive feature of the Western Fiordland Orthogneiss is that high Mg# (>50) rocks have high-Sr/Y signatures (Fig. 2f) and high Cr and Ni contents that probably reflect reaction of hydrous, eclogite-facies partial melts with peridotite during their transport through the mantle wedge. Deep emplacement of some, if not all, of the Western Fiordland Orthogneiss at pressures ≥1·4 GPa (Allibone *et al.*, 2009*b*) is high enough for igneous garnet to be stable on the liquidus (Green & Ringwood, 1967, 1968; Green, 1972; Chapman *et al.*, 2016); however, primitive Western Fiordland Orthogneiss rocks (e.g. Mg# > 50) also have high-Sr/Y signatures, which preclude trace element enrichment by fractional crystallization alone. Zircon trace element data support this conclusion, as early crystallizing zircons with high Ti contents show both HREE depletions and high Gd/Yb values relative to other continental arc zircons (Fig. 4d and e). Thus, the high-Sr/Y (WR) signature, high Gd/Yb (Zrn), and distinctive trace element and isotopic features of high-Mg# rocks from the Western Fiordland Orthogneiss reflect primitive melt compositions, and are not features produced exclusively by fractional crystallization. Moreover, these features support the interpretation that garnet was not only a fractionating phase but also a residual phase in the source region.

A series of bulk mixing curves for a variety of sources including adakitic melts (A), mantle wedge melts (W), crustal melts (C) and sediment (S) is shown in Fig. 9. In Fig. 9a and b, Western Fiordland Orthogneiss samples consistently plot at lower Sr/Y and La/Yb values than expected from pure slab melts ('A' in Fig. 9) consistent with their major element chemistry (e.g. Fig. 2f). Western Fiordland Orthogneiss rocks also lie near or between bulk-mixing curves for adakite–mantle wedge melts and adakite–sediment melts. In this regard, the Western Fiordland Orthogneiss are similar to lavas from the Aleutians, where previous workers have argued for mixing and/or hybridization of slab melts with eclogite-facies metasedimentary rocks and mantle wedge melts (Yogodzinski & Kelemen, 1998; Yogodzinski *et al.*, 2001). A distinguishing feature of our data is that at low $\delta^{18}O$ melt values, Western Fiordland Orthogneiss rocks have higher average $^{87}Sr/^{86}Sr$ values compared with modern slab melts and they plot along the bulk mixing trend between slab melts and metasedimentary rock melts together with lavas from Setouchi, Japan (Fig. 9c). The bulk mixing curve with a sediment end-member in Fig. 9c yields a sediment input amount of ~4–5%, which is similar to values calculated for the modern Kermadec–Hikurangi margin (Gamble *et al.*, 1996), but is less than values observed in Setouchi lavas.

Kelemen *et al.* (2014) modeled the trace element composition of melts and fluids in equilibrium with eclogite, and observed that modern, high-Mg# andesites display trends that are consistent with eclogite-facies sediment melt input in both 'typical' arcs and

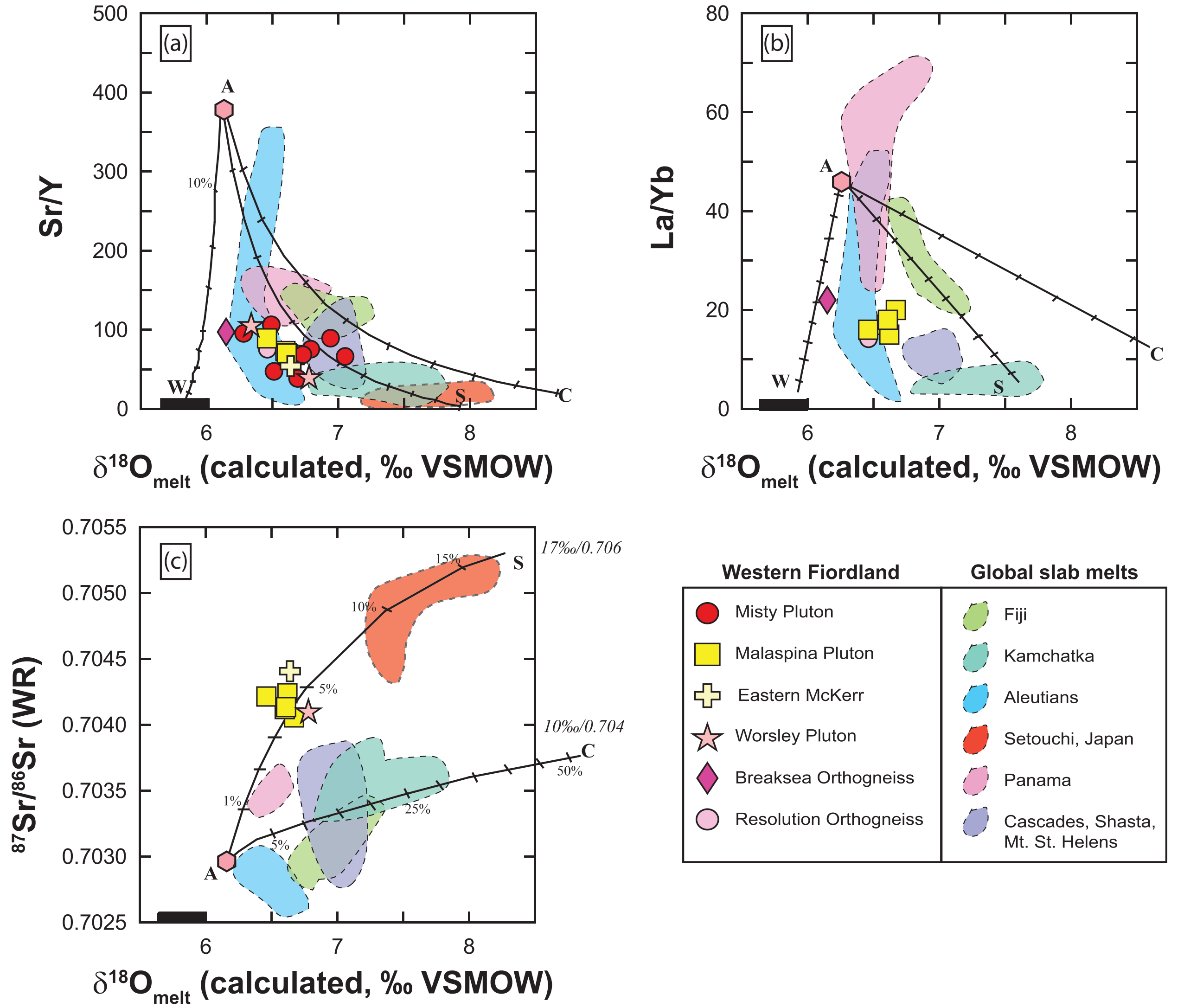


**Fig. 9.** Bivariate plots of $\delta^{18}O$ melt calculated from zircon values vs whole-rock trace element ratios and initial $^{87}Sr/^{86}Sr$. (a) Sr/Y vs $\delta^{18}O$ melt. (b) La/Yb vs $\delta^{18}O$ melt. (c) Initial $^{87}Sr/^{86}Sr$ vs $\delta^{18}O$ melt (J. Wiesenfeld, unpublished data). Thick black bars in each graph show the accepted range of $\delta^{18}O$ for mantle-derived basaltic melts. Curves represent bulk mixing of end-member compositions after Bindeman *et al.* (2005): A, adakitic (slab) melts; W, mantle wedge melts; C, crustal melts; S, sediment melts ± fluids. Fields for global slab melts after Bindeman *et al.* (2005) and references therein. No La/Yb data are reported for Setouchi, Japan (Fig. 9b). Trace element data from the Western Fiordland Orthogneiss overlap the field defined by the Aleutians and lie between bulk mixing curves for adakite–mantle wedge melts and adakite–sediment melts. Radiogenic isotope data plot along the bulk mixing curve for adakite–sediment melt, and indicate ~4–5% sediment input. Low-Sr/Y lavas from Setouchi, Japan lie along the same bulk mixing curve with higher amounts of sediment input.

those where slab melts have been observed (Fig. 10). Compared with modeled compositions, Western Fiordland Orthogneiss rocks consistently plot between fluid and melt in equilibrium with eclogite, implying contributions from both components during melting and melt transport. The Worsley Pluton has the highest Th concentrations of Western Fiordland Orthogneiss rocks and consistently overlaps or plots near modeled eclogite-facies sediment melt compositions. Closer inspection of immobile trace elements in Fig. 11 shows that high-Mg# rocks from the Western Fiordland Orthogneiss are characterized by two distinct groups that define: (1) a low Th/La (<0·1) trend including most Western Fiordland Orthogneiss plutons (Breaksea and Resolution Orthogneisses, Malaspina and some Worsley) and modern MORB; (2) a high Th/La (~0·3) trend that characterizes high-Th Worsley rocks and arc rocks from the Antilles and Aleutians (Plank, 2005). Both subducted Kermadec–Hikurangi sediments (Gamble *et al.*, 1996) and lower crustal sedimentary rocks in the Median Batholith (grey diamonds) are potential sources for the high Th/La signature; however, the lack of observed assimilation or mixing trends in our isotopic data (Fig. 8) argues for subducted metasedimentary melt in the source region rather than crustal contamination at the level of emplacement.

Oxygen isotope signatures in zircons from the Western Fiordland Orthogneiss are also remarkably

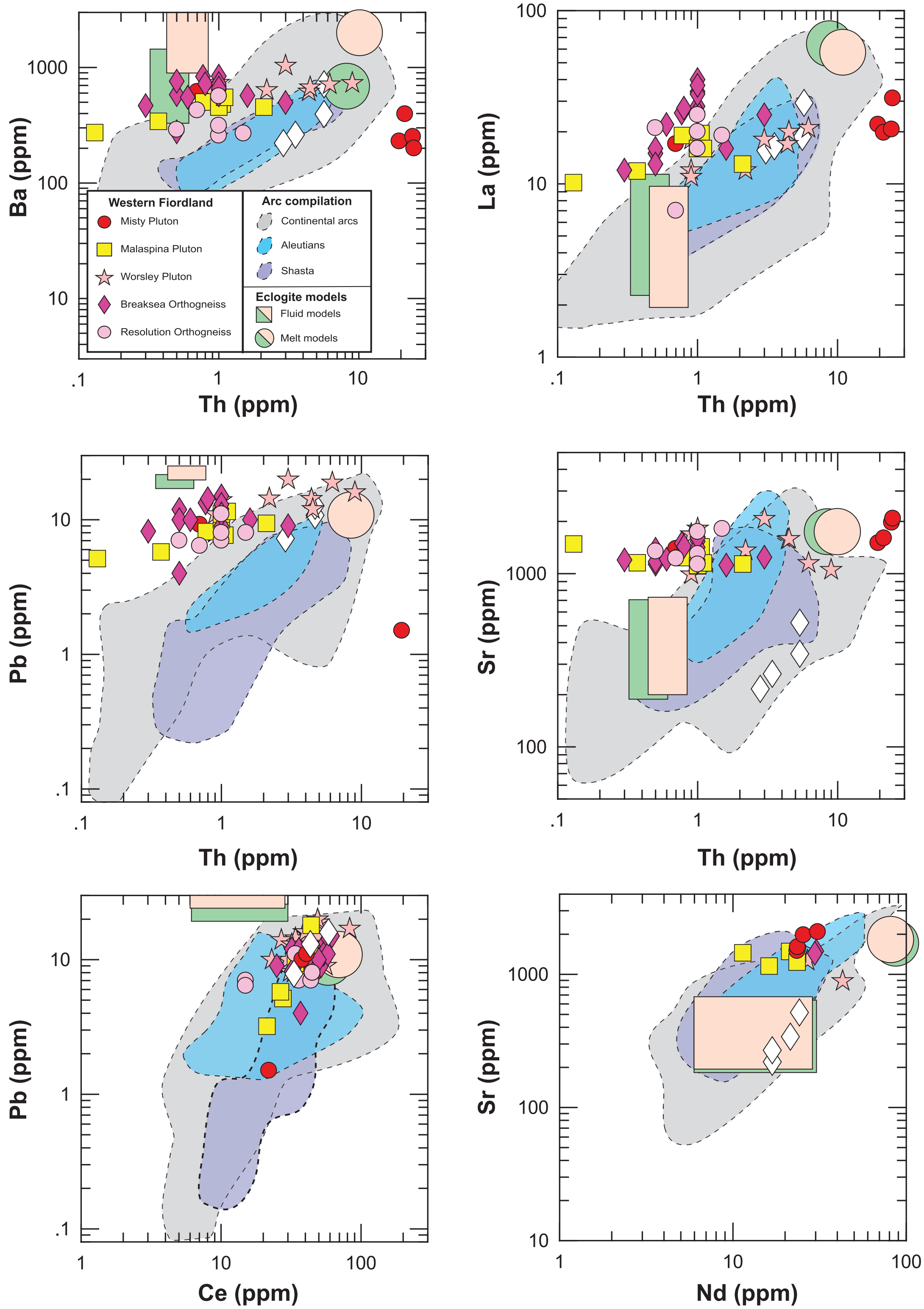


**Fig. 10.** Bivariate trace element plots for Western Fiordland Orthogneiss samples filtered to show only high-Mg# basalts and andesites (Mg# > 50). In general, Western Fiordland Orthogneiss samples show strong enrichment in Th, Ba, La, Pb, Ce, Sr and Nd, and largely plot within fields defined by other high-Mg# andesites [fields after Kelemen *et al.* (2014)]. Large symbols show estimated compositions of fluid (rectangles) and melt (circles) in equilibrium with eclogite for Marianas (green) and Aleutians (peach) at 2 wt % fluid or melt extracted (Kelemen *et al.*, 2014). Data from the Western Fiordland Orthogneiss plot between eclogite fluid and melt compositions, suggesting contributions from both sources during melting and melt transport. Relative to bulk continental crust (white diamonds), Western Fiordland Orthogneiss is more enriched in Ba and Sr, and somewhat lower in Th. Estimated bulk continental crust values from Weaver & Tarney (1984), McLennan & Taylor (1985), Christensen & Mooney (1995) and Rudnick & Fountain (1995), including Archean estimate of Taylor & McLennan (1995).

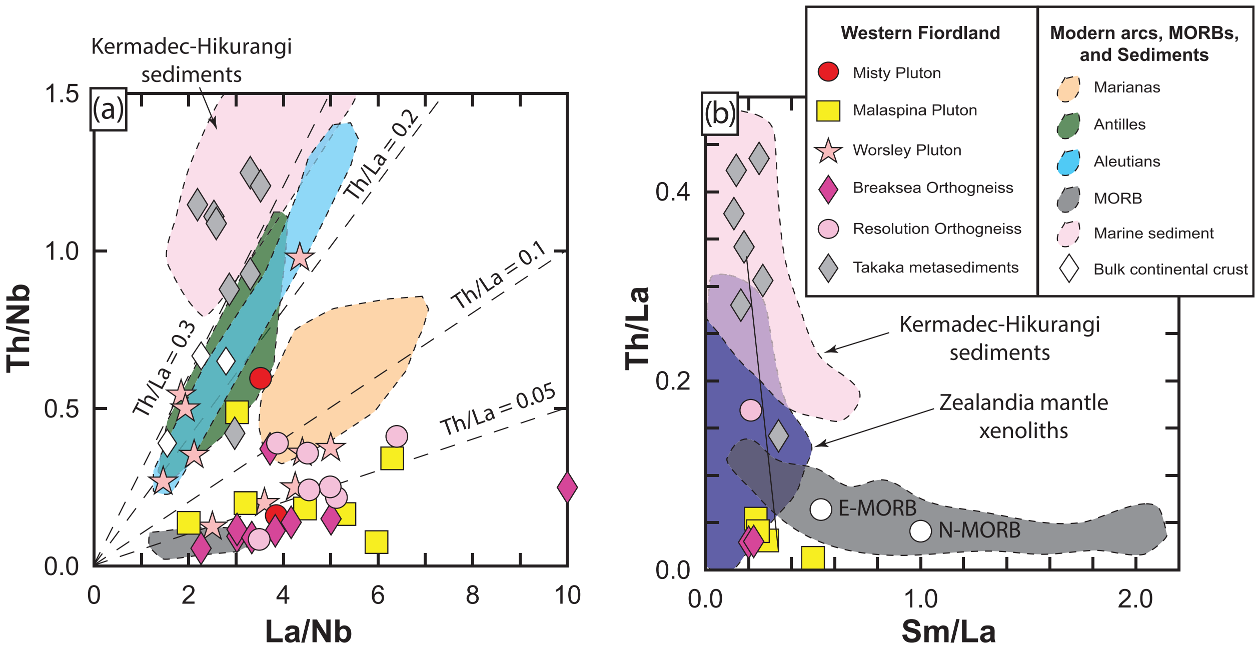


**Fig. 11.** Bivariate plots of (a) Th/Nb vs La/Nb and (b) Th/La vs Sm/La for high-Mg# basalts and andesites (Mg# > 50). Fields show modern arc lavas and mid-ocean ridge basalts (MORB), and sediments from the Kermadec–Hikurangi arc. (a) Western Fiordland Orthogneiss data show two trends: (1) a low Th/La (<0·1) source that characterizes the Breaksea and Resolution Orthogneisses, the Malaspina Pluton, some of the Worsley Pluton, and MORB; (2) a high Th/La (~0·3) source that characterizes a sub-group of the high-Th, Worsley samples. The high Th/La source is consistent with subducted, Kermadec–Hikurangi sediments (Gamble *et al.*, 1996). (b) Western Fiordland Orthogneiss rocks are characterized by low Sm/La, a feature that also defines ocean island basalt (OIB), enriched (E)-MORB and mantle xenoliths from greater Zealandia (Sun & McDonough, 1989; McCoy-West *et al.*, 2015). Western Fiordland Orthogneiss rocks trend from low Th/La to higher values consistent with interaction with high-Th sediment. The black line shows a bulk mixing trend between a high-Th sedimentary component and a low Sm/La mantle component. Arc and MORB fields after Plank (2005). Average E-MORB and N-MORB compositions after Sun & McDonough (1989).

similar to those for olivine from modern slab melts (Fig. 5a) with both datasets lying within error of high-temperature mantle. Although not conclusive, $\delta^{18}O$ values in Western Fiordland Orthogneiss zircons are consistent with mixing of slab melts with contributions from eclogite-facies metasediment ± fluids in the source region (Figs 10c and 11). Coupled with the lack of obvious mixing or AFC trends (Fig. 8), we speculate that efficient homogenization and hybridization with mantle or mantle melts occurred in the source region and/or during transport, prior to emplacement at the base of the crust.

## A petrogenetic flare-up model for the Separation Point Suite

Large abundances of high-Sr/Y rocks are atypical in modern arc environments, except in unusually hot subduction zones characterized by either subduction of young oceanic crust, very slow convergence rates allowing heating and melting of the slab, and/or discontinuous 'tears' that enhance mantle convection below the subducting plate and allow conductive heating from the side, top and bottom (e.g. de Boer *et al.*, 1988, 1991; Defant & Drummond, 1990; Yogodzinski *et al.*, 1994, 1995, 2001; Kelemen *et al.*, 2014). Enhanced mantle melting can also be achieved by 'melt-fluxed melting' in which reaction between hydrous partial melts of subducting metasedimentary rock and/or metabasalt and overlying mantle peridotite leads to increasing melt mass, producing a hybrid 'primary melt' in which more than 90% of the compatible elements (Mg, Fe, Ni, Cr) are derived from the mantle, whereas most of the alkalis and other incompatible elements come from small degrees of partial melting of subducted crust (e.g. Myers *et al.*, 1985; Kelemen, 1986, 1990, 1995; Kelemen *et al.*, 1993, 2003; Yogodzinski *et al.*, 1995; Yogodzinski & Kelemen, 1998). Melt-fluxed melting may also be facilitated beneath arcs as melts decompress through the mantle column and dissolve mantle minerals, thereby increasing the resulting melt mass (Kelemen, 1986, 1990, 1995; Kelemen *et al.*, 1993, 2014). We speculate that the hybrid 'Cordilleran' arc and high-Sr/Y composition of the Western Fiordland Orthogneiss reflects this process.

In addition to melt-fluxed melting, the development of discontinuous 'tears' (e.g. slab-tears or ridge–trench collisions) beneath long-lived continental arcs hold the potential to release large volumes of melts if hot, upwelling asthenosphere is exposed to metasomatized subcontinental lithosphere similar to that postulated to have existed during the Mesozoic beneath the Median Batholith (Panter *et al.*, 2006; McCoy-West *et al.*, 2010, 2015, 2016; Timm *et al.*, 2010; Scott *et al.*, 2014; Czertowicz *et al.*, 2016). Field and geochemical studies in mantle rocks thought to have underlain the Median

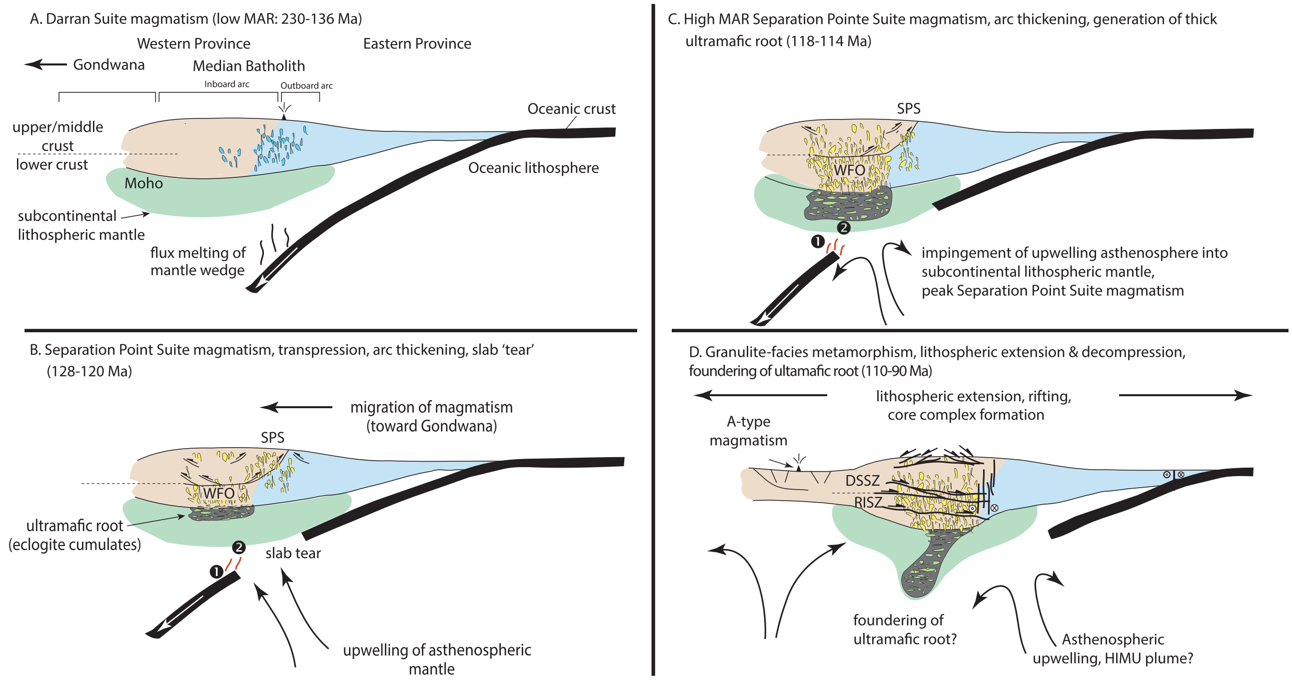


**Fig. 12.** Schematic model for the development of the Fiordland sector of the Gondwana margin from the Triassic to Early Cretaceous. (a) Arc-related magmatism in the outboard arc (Darran Suite) from *c.* 230 to 136 Ma. Magmatism is characterized by low-Sr/Y plutons with depleted mantle radiogenic isotope values. (b) Development of a 'tear' or ridge–trench collision after *c.* 136 Ma results in the opening of a slab window and upwelling of asthenospheric mantle. High-Sr/Y melts are generated from (1) partial melting of subducted, eclogite-facies sedimentary rocks and oceanic crust. Subsequent hybridization occurs by (2) mixing of high-Sr/Y melts with metasomatized subcontinental mantle lithosphere and/or basaltic melts derived from partial melting of the same mantle lithosphere. (c) Peak high-MAR event occurs as upwelling asthenospheric mantle continues to melt subducted, eclogite-facies oceanic crust and impinges on hydrous subcontinental lithospheric mantle igniting the Cretaceous flare-up. (d) Waning high-Sr/Y magmatism, and granulite- to amphibolite-facies metamorphism in the lower to middle crust (Stowell *et al.*, 2014). Decompression in the lower crust initiates at *c.* 108–106 Ma during regional extension and A-type magmatism (Tulloch *et al.*, 2009b; Klepeis *et al.*, 2016; Schwartz *et al.*, 2016). Possible foundering of thick ultramafic root produced during high-Sr/Y flare-up event. SPS, Separation Point Suite; WFO, Western Fiordland Orthogneiss; DSSZ, Doubtful Sound shear zone; RISZ, Resolution Island shear zone.

Batholith show that mantle enrichment occurred during a two-stage, metasomatic process involving reactive percolation of small amounts of mafic silicate melt and subsequent fluxing by an OH-rich fluid during Mesozoic magmatism beneath the arc (Czertowicz *et al.*, 2016). We postulate that the surge of high-Sr/Y melts in the Median Batholith resulted from partial melting of this enriched mantle source in an unusually hot subduction zone where a 'tear' or slab window produced from a ridge–trench collision allowed for upwelling asthenosphere to interact with and melt the subducted plate and the hydrous subcontinental lithospheric mantle.

The plate-tectonic configuration of the Median Batholith prior to Zealandia break-up during the Cretaceous is difficult to know as much of the Cretaceous oceanic crust has been subducted. Existing palinspastic reconstructions vary greatly; however, all involve subduction of either the Phoenix or Moa plate beneath eastern Gondwana in the Early Cretaceous (e.g. Bradshaw, 1989; Luyendyk, 1995; Sutherland & Hollis, 2001; Mortimer *et al.*, 2006). Bradshaw (1989) proposed that extensional break-up of Zealandia resulted from collision of the Phoenix–Pacific spreading center. Based on radiolarian faunal data, Sutherland & Hollis (2001) suggested that a previously unrecognized plate, the Moa plate, subducted beneath the Median Batholith in the Early Cretaceous and obliquely collided with the eastern Gondwana margin, resulting in dextral strike-slip motion. We speculate that collision of either the Phoenix–Pacific or Phoenix–Moa ridge with the eastern Gondwana margin, or the development of a slab tear within the subducting plate, may have been responsible for inducing hot asthenospheric upwelling beneath the downgoing slab, resulting in partial melting of eclogite-facies metasedimentary rocks and metabasalt along the plate edge (Fig. 12). Although speculative, a ridge–trench collision or slab tear model provides a mechanism to explain several of the enigmatic tectonomagmatic features of the Cretaceous Median Batholith including the following: (1) the transition of 'normal', low-Sr/Y arc magmatism to high-Sr/Y magmatism from 136 to 132 Ma (Fig. 12a and b); (2) the rapid generation of large volumes of low-silica, high-Sr/Y melts with mantle-like $\delta^{18}O$ (Zrc) signatures in the Western Fiordland Orthogneiss from 128 to 114 Ma (Fig. 12b and c); (3) the anomalous high-temperature (>900°C) eclogite- to granulite-facies metamorphic event in the lower crust of the Western Fiordland Orthogneiss, initiating in the host-rocks at *c.* 134 Ma and peaking between 116 and 112 Ma (Fig. 12d) (Hollis *et al.*, 2003; Flowers *et al.*, 2005; Tulloch *et al.*, 2011; Stowell *et al.*, 2014; Schwartz *et al.*, 2016); (4) the linear nature of high-Sr/Y plutonism along the axis of the Median Batholith (Tulloch & Kimbrough, 2003); (5) the development of transpression and dextral strike-slip motion in Fiordland and along the Gondwana margin after *c.* 132 Ma (Daczko *et al.*, 2001, 2002a; Sutherland & Hollis, 2001; Klepeis *et al.*, 2004; Marcotte *et al.*, 2005; Allibone & Tulloch, 2008). Foundering of the subducted plate beneath Zealandia and subsequent enhanced mantle upwelling may be related to rapid vertical motions in the crust and collapse of the orogen beginning at 108–106 Ma (Fig. 12d) (Klepeis *et al.*, 2007, 2016). An implication of this model is that subduction-related, asthenospheric wedge melting ceased to be the primary mechanism for generating melts and transfer of thermal energy to the Median Batholith by *c.* 136 Ma [see the discussion by Tulloch *et al.* (2009)].

## Do high-MAR events contribute to the addition of new continental crust?

Our geochemical and isotopic results from the lower crust of the Median Batholith reveal that the high-MAR event was primarily driven by mantle melting with important, but volumetrically minor, additions of subducted arc sediment and oceanic crust. As such, we argue that >95% of the exposed Western Fiordland Orthogneiss represents new continental crust added to Gondwana from 128 to 114 Ma, most of which was emplaced between 118 and 114 Ma (Schwartz *et al.*, 2017). Given the exposed areal extent of the Western Fiordland Orthogneiss (~2350 km$^2$), a minimum paleothickness of ~30 km, derived from structural and metamorphic pressure data (Klepeis *et al.*, 2007, 2016), and an arc segment length of ~80 km during peak flare-up (118–114 Ma) and 125 km during the entire duration of the flare-up, we calculate a time-averaged lower crustal magma addition rate of $\geq$38 km$^3$ Ma$^{-1}$ arc-km$^{-1}$ from 128 to 114 Ma, and a peak rate of $\geq$152 km$^3$ Ma$^{-1}$ arc-km$^{-1}$ from 118 to 114 Ma during the interval when ~70% of the arc root was emplaced (see the Supplementary Data for a summary of geochronology and flux rate calculations). When integrated for the entire crustal column, total crustal (0–65 km) magma addition rates are 70 km$^3$ Ma$^{-1}$ arc-km$^{-1}$ during the surge of magmatism from 128 to 114 Ma. As the Western Fiordland Orthogneiss shows little if any evidence for crustal interaction, magma addition rates are approximately equal to continental crustal production rates. These rates, however, are minima as they do not include the effects of lateral arc migration during the flare-up interval, a feature that is obscured by the truncation of Western Fiordland by the Alpine Fault. Following Ducea *et al.* (2015a, 2017), we assume an average arc migration rate of ~4 km Ma$^{-1}$, and calculate a reconstructed time-averaged lower crustal magma addition rate of $\geq$54 km$^3$ Ma$^{-1}$ arc-km$^{-1}$ from 128 to 114 Ma, and a peak rate of $\geq$210 km$^3$ Ma$^{-1}$ arc-km$^{-1}$ from 118 to 114 Ma. Comparable magma addition rates have been determined for thick Andean-type arcs where rates average between 10 and 150 km$^3$ Ma$^{-1}$ arc-km$^{-1}$ (Ducea *et al.*, 2017). In those cases, half of the total magmatic products are estimated to be mafic additions to the crust, in contrast to the Western Fiordland Orthogneiss, which is nearly entirely new mantle addition. Compared with other thickened Andean arcs, peak magmatic production rates in the lower crust of the Median Batholith are equal to and/or exceed the highest reported magma addition rates in other Cordilleran arcs, a feature that we attribute to enhanced mantle melting during propagation of a slab tear or window beneath the arc.

Ducea *et al.* (2017) noted that modern and ancient island arcs and thin continental arcs (e.g. Famatinian arc in the Sierra Valle Fértil–Sierra de Famatina; Ducea *et al.*, 2017) are characterized by much faster magma addition rates that reach 300–400 km$^3$ Ma$^{-1}$ arc-km$^{-1}$. As such, they proposed that thin arcs are primary factories for the rapid production of continental crust whereby fast to ultrafast magma addition rates are produced by high arc migration rates across the trench. In the case of the Famatinian arc, ultrafast magmatic buildup included ~50% mafic additions from the mantle, resulting in a continental crust production rate of ~180 km$^3$ Ma$^{-1}$ arc-km$^{-1}$ (Ducea *et al.*, 2017), which is similar to our calculated crustal production rates in the lower crust of the Median Batholith. In addition, the dominantly 'andesitic' lower crust of the Median Batholith and its trace element composition approximates bulk lower continental crust (see white diamonds in Fig. 10). Thus, we suggest that high-MAR events involving slab tears or windows may be an efficient means of generating continental crust in thickened Cordilleran arcs without requiring further modification (see Kelemen & Behn, 2016). In addition, our isotopic data demonstrate that high-MAR events do not necessarily represent isotopic excursions from dominantly mantle-addition trends (Collins *et al.*, 2011); instead, high-MAR events, particularly those involving lower plate triggering processes, may be important in the rapid generation of new lower arc crust along destructive plate margins.

# CONCLUSIONS

Geochemical and Hf- and O-isotopic results from the deep crustal root of the Median Batholith, New Zealand, show that the Cretaceous surge in high-Sr/Y magmatism was primarily sourced from the underlying mantle. We suggest that the high-MAR event was caused by a discontinuous 'tear' or ridge collision event. Development of a slab window and asthenospheric upwelling resulted in widespread partial melting of an isotopically enriched and metasomatized subcontinental lithospheric mantle beneath the Median Batholith, with contributions from subducted, eclogite-facies metasedimentary rocks and metabasalt. We propose that the slab tear or window initiated between *c.* 136 and 128 Ma, at the end of low-Sr/Y arc magmatism and prior to the onset of voluminous high-Sr/Y magmatism. If this proposal is correct, ridge subduction may be linked to regional transpression and local contraction that commenced at *c.* 130 and continued to 105 Ma. Propagation of the putative slab window beneath Zealandia may also explain the apparent gap in magmatism from 136 to 128 Ma, and the continentward migration of high-Sr/Y magmatism throughout Zealandia. Our isotopic results reveal that the terminal Cretaceous flare-up resulted in the rapid addition of $>$2350 km$^2$ of new lower arc crust with time-averaged crustal production rates of $\sim$40–50 km$^3$ Ma$^{-1}$ arc-km$^{-1}$ from 128 to 114 Ma, and peak rates of 150–210 km$^3$ Ma$^{-1}$ arc-km$^{-1}$ from 118 to 114 Ma when $\sim$70% of the arc root was emplaced. Compared with bulk continental crust, the lower crust of the Median Batholith is remarkably similar in trace element composition, suggesting that high-MAR events involving slab tears or ridge–trench collisions may be an efficient means of generating lower continental crust from hybridization of mantle and subducted slab components, and may not require second-stage processes such as relamination (Kelemen & Behn, 2016).

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## SUPPLEMENTARY DATA

Supplementary data for this paper are available at *Journal of Petrology* online.

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