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Phanerozoic record of mantle-dominated arc magmatic surges in the Zealandia Cordillera

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ABSTRACT

We integrated new and existing bedrock and detrital zircon dates from the Zealandia Cordillera to explore the tempo of Phanerozoic arc magmatism along the paleo-Pacific margin of southeast Gondwana. We found that episodic magmatism was dominated by two high-magma-addition-rate (MAR) events spaced ~250 m.y. apart in the Devonian (370–368 Ma) and the Early Cretaceous (129–105 Ma). The intervening interval between high-MAR events was characterized by prolonged, low-MAR activity in a geographically stable location for more than 100 m.y. We found that the two high-MAR events in Zealandia have distinct chemistries (S-type for the Devonian and I-type for the Cretaceous) and are unlikely to have been related by a repeating, cyclical process. Like other well-studied arc systems worldwide, the Zealandia Cordillera high-MAR events were associated with upper-plate deformation; however, the magmatic events were triggered by enhanced asthenospheric mantle melting in two distinct arc-tectonic settings—a retreating slab and an advancing slab, respectively. Our results demonstrate that dynamic changes in the subducting slab were primary controls in triggering mantle flare-up events in the Phanerozoic Zealandia Cordillera.

INTRODUCTION

Phanerozoic continental arcs are factories for the growth and refinement of modern continental crust (e.g., Rudnick, 1995; Hawkesworth and Kemp, 2006). In most well-studied continental arcs, the tempo of magmatism is episodic, and there is abundant evidence for alternating high-magma-addition-rate (MAR) events (or flare-ups) and magmatic lulls. These flare-ups are significant because they are responsible for the generation of the bulk of plutonic arc crust (~85%–90%) in geologically brief intervals (<20 m.y.; DeCelles et al., 2009; Ducea et al., 2015).

In continental arcs where long-lived records are available, high-MAR events are sometimes shown to have occurred at intervals of 30–70 m.y., with cycles repeating as many as three times over the course of ~150–250 m.y. (Ducea et al., 2015; Paterson and Ducea, 2015; Kirsch et al., 2016). However, there is currently no consensus regarding the mechanisms responsible for this episodic behavior and the causes of high-MAR events (e.g., Chapman and Ducea, 2019; Collins et al., 2020). In the case of the Sierra Nevada batholith and other segments of the American Cordillera, some researchers have proposed that plutonic rocks produced during repeated high-MAR events are linked to upper-plate compression leading to underthrusting of retroarc crust and widespread crustal melting beneath the arc (e.g., DeCelles et al., 2009; Ducea et al., 2015). However, others have noted that many arc segments do not display patterns of 30–70 m.y. high-MAR events (e.g., Kirsch et al., 2016), and in these cases, episodic magmatic surges may be driven instead by enhanced mantle melting rather than upper-plate deformation (e.g., Cecil et al., 2018). These conflicting views on the significance of episodic magmatic surges create an important and unresolved question in arc petrology: what processes drive the initiation of high-MAR events in continental arcs? Are they triggered by upper-plate compression and related phenomena, or are they triggered by mantle processes such as changes in subduction zone dynamics related to lower-plate geometry (e.g., slab rollback, slab tear, slab advance) and/or changes in volatile or melt contributions?

We addressed these questions by integrating >380 new and existing bedrock zircon ages with >2280 detrital zircon ages from 46 samples deposited on the Zealandia Cordillera to investigate the tempo of arc magmatism and the causes of high-MAR events (Figs. 1A and 1B). The Zealandia Cordillera, located along the Pacific margin of southeast Gondwana, was active for much of the Phanerozoic and encompasses an area that is 700 km long and 200 km wide (Fig. 2), comparable in scale to other well-studied arcs worldwide (e.g., the Sierra Nevada and Coast Mountains batholiths of North America). On the South Island of New Zealand, and Stewart Island, this paleo arc consists of lower-, middle-, and upper-crustal rocks from ~5 to 65 km paleodepth (Tulloch and Kimbrough, 2003; Allibone et al., 2009; De Paoli et al., 2009; Scott et al., 2011; Schwartz et al., 2017). These exposures offer a unique perspective from which to examine Phanerozoic arc magmatic tempos in southeast Gondwana for over 400 m.y.

GEOLOGY OF THE ZEALANDIA CORDILLERA

The Zealandia Cordillera was a Phanerozoic orogenic belt that extended over much of the 4.9×10^6 km^2 Zealandia continent, then part of southeast Gondwana (Figs. 1A and 1B) (Mortimer et al., 2017; Tulloch et al., 2019). Arc-related magmatism was nearly continuous from ca. 500 Ma to 100 Ma (Kimbrough et al., 1994; Tulloch and Kimbrough, 2003; Schwartz et al., 2017; Tulloch et al., 2009, 2019), and igneous and metamorphic rocks are best exposed in Fiordland, Nelson-Westland, and Stewart Island (Fig. 2). Studies of offshore samples have shown that the arc continues underwater for more than 1000 km eastward to the Bounty and Antipodes Islands (Tulloch et al., 2019), to the north and west of Nelson (Mortimer et al., 2017), and to likely correlatives in Queensland (Tulloch et al., 2010), for a total

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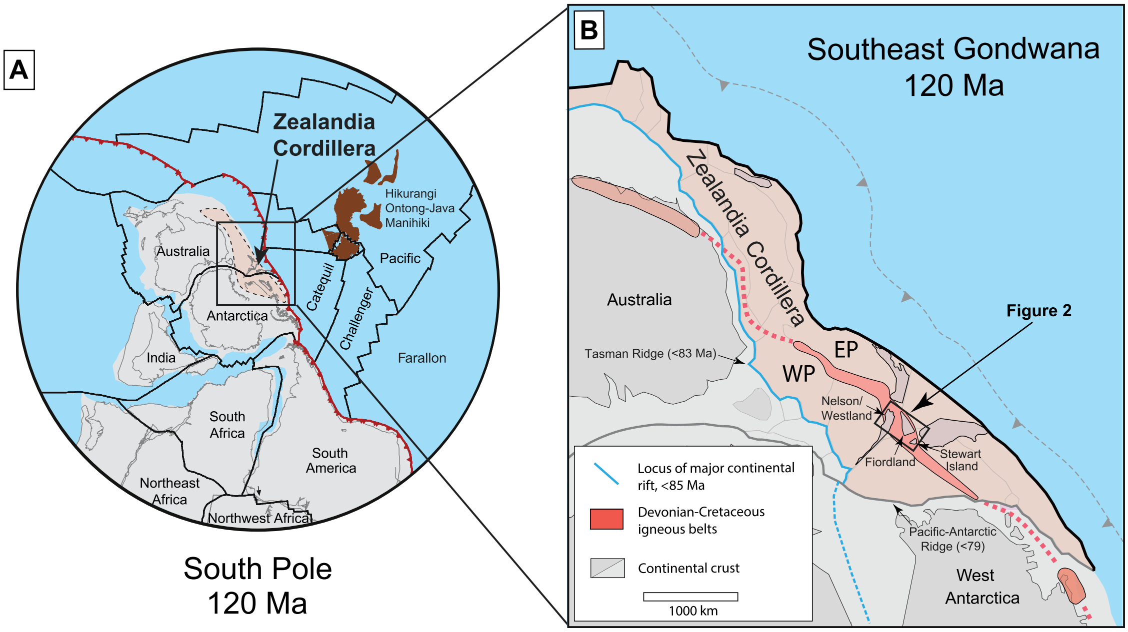

Figure 1. (A) Palinspastic reconstruction of the South Pole ca. 120 Ma, showing oceanic (blue) and continental (gray) plates (modified after Seton et al., 2012). (B) Reconstruction of Zealandia prior to 100 Ma (after Mortimer et al., 2017). Generalized arc axis is shown in red. Locations of major continental rifts are shown by blue fault lines. WP—Western Province, EP—Eastern Province.

arc length of ~4500 km (Fig. 1B). Prebatholithic rocks of the Zealandia Cordillera consist of variably metamorphosed and deformed rocks of the early Paleozoic Takaka and Buller terranes (Cooper, 1989), which are suggested to have amalgamated at ca. 387 ± 3 Ma (Turnbull et al., 2016). Construction of the Zealandia Cordillera primarily involved emplacement of arc-related igneous rocks into both terranes over >250 m.y. and included three main magmatic phases: (1) Devonian to Carboniferous plutons from 370 to 305 Ma, (2) Permian to Cretaceous Darran and Longwood Suite plutons from 260 to 130 Ma, and (3) Cretaceous Separation Point Suite and Rahu Suite plutons from 129 to 105 Ma (Fig. 2) (Kimbrough et al., 1994; Muir et al., 1998; Tulloch et al., 2009; Milan et al., 2017; Schwartz et al., 2017).

METHODS AND RESULTS

We compiled >380 U-Pb zircon ages, including 24 new dates, and we calculated new pluton area and volume estimates using digitized geologic maps of New Zealand, and paleocrustal thickness estimates after Mantle and Collins (2008) (see the Supplemental Material[1] for methods). Plutonic samples spanned the entire age range of magmatism in the Zealandia Cordillera, and we focused exclusively on arc-related magmatic rocks and excluded small-volume dikes and nonsubduction (i.e., alkaline intraplate) rocks. Our compilation of existing dates revealed a paucity of age information from the Mesozoic Darran Suite, and so we conducted additional U-Pb zircon geochronology to refine the tempo of Zealandia magmatism during this interval. Because the plutonic record is sometimes incompletely preserved, we also compared our bedrock zircon ages to >2280 detrital zircon dates from 46 samples (6 new) from sediments deposited on Zealandia for the purpose of examining the magmatic record preserved in detrital sediments. Analytical procedures, pluton and detrital zircon data, sample locations, standard information, and an explanation of age calculations are provided in the Supplemental Material.

TEMPO OF PHANEROZOIC MAGMATISM IN THE ZEALANDIA CORDILLERA

Our compilation of bedrock zircon dates allowed us to refine the tempo of arc magmatism over the ~400 m.y. life span of the Zealandia Cordillera, providing a complete history of a Phanerozoic arc outside the heavily studied North and South American Cordillera. Our data and volume addition rate calculations revealed that magmatism was nearly continuous for most of the Phanerozoic (Fig. 3A) and was dominated by two high-MAR pulses (Fig. 3B): one high-MAR event occurred in the Cretaceous (the Separation Point Suite pulse from 129 to 105 Ma; Tulloch and Kimbrough, 2003; Milan et al., 2017; Schwartz et al., 2017), and the other occurred in the Paleozoic (the Karamea Suite pulse from 370 to 368 Ma; Tulloch et al., 2009; Turnbull et al., 2016). Although Darran Suite and related magmatism (e.g., Longwood Suite) lasted for >100 m.y., we observed no high-MAR events during this time (see the discussion below). For the Cretaceous and Paleozoic high-MAR events, their duration was ~24 m.y. and 2 m.y., respectively, and estimated volume addition rates are as high as 40,000–45,000 km^3/m.y. (Fig. 3B). Milan et al. (2017) reached a similar conclusion for the Cretaceous event. These high-MAR durations are similar to other events in well-studied Cordilleran arcs, and the volume addition rates are comparable to some of the highest MAR events ever recorded (cf. Paterson and Ducea, 2015).

A unique aspect of the Zealandia Cordillera is that the time interval between high-MAR events (~250 m.y.) was characterized by an extended period of near-continuous, low-MAR subduction-related magmatism involving emplacement of minor late Paleozoic plutons, the Darran and Longwood Suites, along with minor accretion of fringing-arc terranes at ca. 270–265 Ma (Dun Mountain and Brook Street terranes) (Fig. 3A). The detrital record of sediments deposited on the Zealandia Cordillera also shows near-continuous magmatism throughout the Phanerozoic despite gaps in the plutonic record. This prolonged low-MAR interval is especially unique when compared to other well-studied magmatic arc segments; it is 3–4× longer than average magmatic cycles recognized in the Mesozoic American Cordillera (~60–70 m.y.) and 8–13 × longer than those recognized in the Cenozoic American Cordillera (~20–30 m.y.) (Haschke et al., 2006; DeCelles et al., 2009; DeCelles and Graham, 2015; Ducea et al., 2015; Paterson and Ducea, 2015; Kirsch et al., 2016).

Our new bedrock zircon ages also show that the relatively steady-state Darran Suite involved three low-MAR events (peaks at ca. 230, 148, and 138 Ma), but no high-MAR events are observed (Fig. 3B). This period of low-MAR activity is also documented in formerly adjacent sections of the southeast Gondwana

[1]Supplemental Material. Detailed analytical methods and U-Pb zircon geochronology results, zircon cathodoluminescence images, Tera-Wasserburg plots, and tables containing igneous and detrital zircon data and volume addition rate calculations. Please visit https://doi.org/10.1130/GEOL.S.14772789 to access the supplemental material, and contact editing@geosociety.org with any questions.

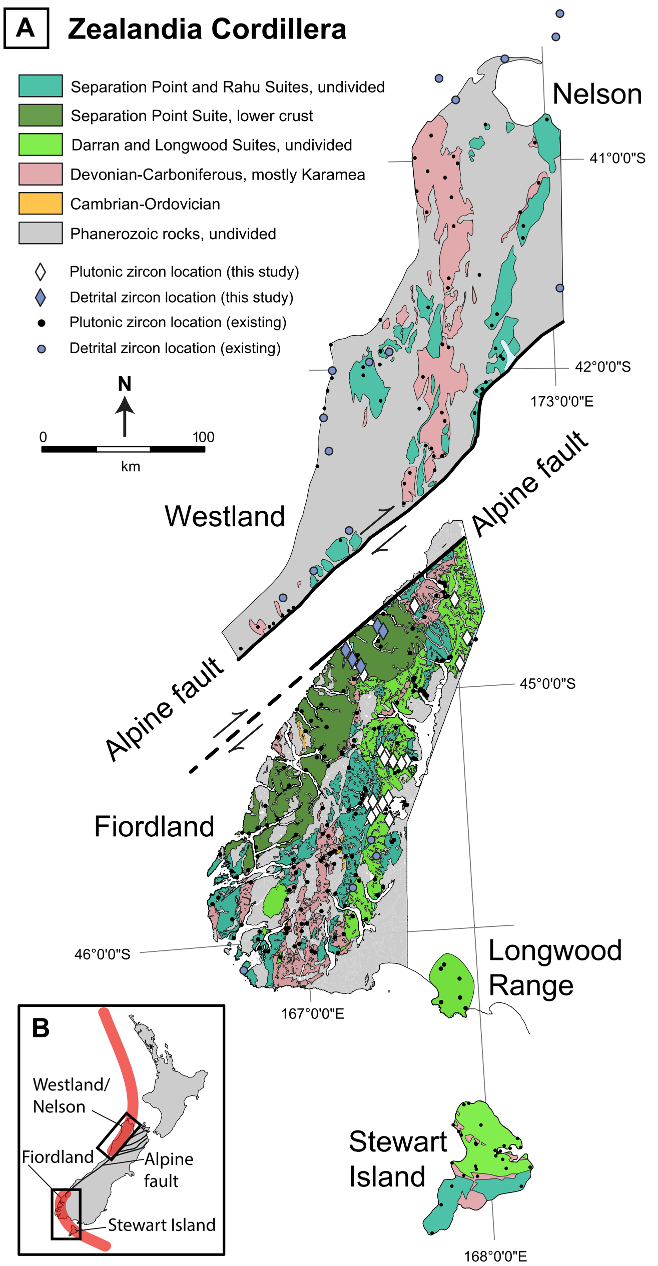

Figure 2. (A) Generalized geologic map of subaerially exposed Zealandia Cordillera. Restoration of movement along the Alpine fault illustrates north-south continuity of the arc prior to the Miocene after rifting from Australia and Antarctica. (B) Inset map of New Zealand. Thick red line indicates locus of the arc. Black boxes show location of Fiordland and Nelson blocks.

margin in West Antarctica (Tulloch et al., 2019) and eastern Australia, including within the Tasmanides (e.g., Jessop et al., 2019). In this along-strike arc segment, Paleozoic plutonic rocks show evidence for repeated patterns of slab advance and slab rollback behind a retreating arc (e.g., Collins, 2002). Estimated crustal addition rates for this period resemble average magmatic productivity at modern convergent plate boundaries (Kemp et al., 2009) and are lower than those estimated for the high-MAR events in the Zealandia Cordillera (Turnbull et al., 2016; Milan et al., 2017; Schwartz et al., 2017; this study). Therefore, the integrated record of both the Zealandia Cordillera and Paleozoic eastern Australia preserves evidence for only two high-MAR events with an intervening period of enigmatically prolonged, subduction-related, low-MAR events and minor terrane accretions (Fig. 3A).

CONTROLS ON HIGH-MAR EVENTS IN THE ZEALANDIA CORDILLERA

The presence of two high-MAR events spaced ~250 m.y. apart in the Zealandia Cordillera raises the question: what drivers were responsible for the two arc-magmatic surges? In both cases, there is strong evidence that lower-plate–triggered mantle-melting processes have dominated the Zealandia Cordillera for >400 m.y. In the case of the first documented high-MAR event in Zealandia (the Karamea Suite event), high-precision U-Pb geochronology and whole-rock geochemistry indicate that magma generation and batholith emplacement occurred during a period of extensional activity caused by slab rollback that occurred ~10 m.y. after an episode of orogenic crustal thickening at ca. 387 Ma (Figs. 3B, 4A, and 4B) (Tulloch et al., 2009; Turnbull et al., 2016). Slab rollback is interpreted to have triggered an episode of upper-plate extension, whereby thinning of the crust enabled hot asthenosphere to rise to shallow depths and facilitate rapid, widespread, and voluminous crustal melting (Fig. 4B). Whole-rock isotopic compositions indicate a crustal contribution between 35% and 90% and some contribution from a mantle source (Tulloch et al., 2009). Cessation of the brief high-MAR, S-type event by ca. 368 Ma is inferred to have been the result of depletion of the fertile metasedimentary source rocks due to significant partial melting and crustal thinning (Turnbull et al., 2016).

Structural and geochemical data from the Early Cretaceous Separation Point Suite also suggest that lower-plate processes were responsible for this high-MAR event (Figs. 3B, 4C, and 4D). Geochemical and in situ zircon Hf- and O-isotopic results show that the Cretaceous flare-up was primarily sourced from the underlying mantle, with limited contributions (0%–20%) from radiogenic crustal material (Muir et al., 1998; Decker et al., 2017; Milan et al., 2017; Schwartz et al., 2021). While the preceding low-MAR phase was geographically fixed and focused into a narrow 10–20-km-wide zone for over 100 m.y., the Separation Point Suite surge represents an abrupt and transient change in arc dynamics coincident with continentward migration of arc magmatism and widening of the active Early Cretaceous arc axis to ≥70 km (Scott et al., 2011; Schwartz et al., 2021). Evidence for underthrusting of melt-fertile continental crust beneath the arc is absent even in the lower crust (De Paoli et al., 2009), and the lack of evidence for a thick lithospheric root prior to the flare-up suggests that lithospheric foundering was an unlikely triggering mechanism for the Cretaceous high-MAR event (Klepeis et al., 2016; Chapman et al., 2017). Similarly, the strongly mantle-like O-isotope data in the lower crust preclude significant involvement of melt-fertile continental crust (Decker et al., 2017; Schwartz et al., 2021). The abrupt advance of the arc points to a fundamental change in the arc-tectonic setting from an extensional flare-up setting in the Paleozoic to a strongly contractional and advancing slab in the Early Cretaceous. Moreover, the mantle-dominated chemistry of the Early Cretaceous arc melts and their high zircon crystallization temperatures (>850 °C; Schwartz et al., 2017) indicate that asthenospheric mantle melting was the driver for the Early Cretaceous high-MAR event, and this enhanced melting event was likely triggered by a slab-tear or slab-window event (Fig. 4D).

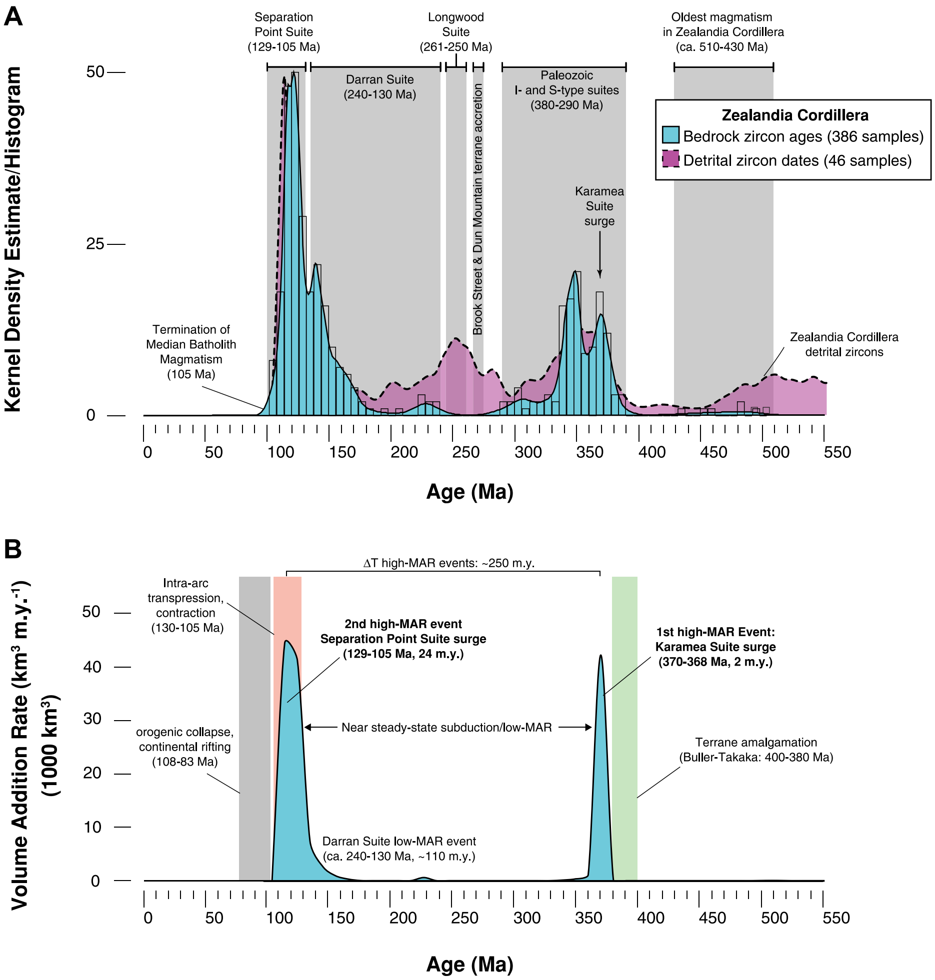

Figure 3. (A) Histogram and kernel density estimates for plutons and detrital zircons of the Zealandia Cordillera. (B) Calculated volume addition rates versus time form 10 m.y. bins. Major tectonic events associated with flare-up events are shown in green (terrane amalgamation) and red (intra-arc transpression). MAR—magma addition rate.

CONCLUSIONS

Our compilation of new and existing zircon dates from the Phanerozoic Zealandia Cordillera demonstrates that magmatism was episodic and characterized by two high-MAR events spaced ~250 m.y. apart. We observed no evidence for magmatic cyclicity, and geochemical data from the high-MAR events are difficult to attribute to similar, intra-arc processes in the upper plate because the dominant triggering mechanisms appear to have been different. Instead, our data point to external controls related to changes in lower-plate dynamics (slab retreat, slab advance, and/or slab tear) as the driving factors behind the two events. We conclude that the >400 m.y. magmatic record of the Zealandia Cordillera illustrates the importance of mantle-dominated processes in controlling magmatic flare-ups in some long-lived continental arcs.

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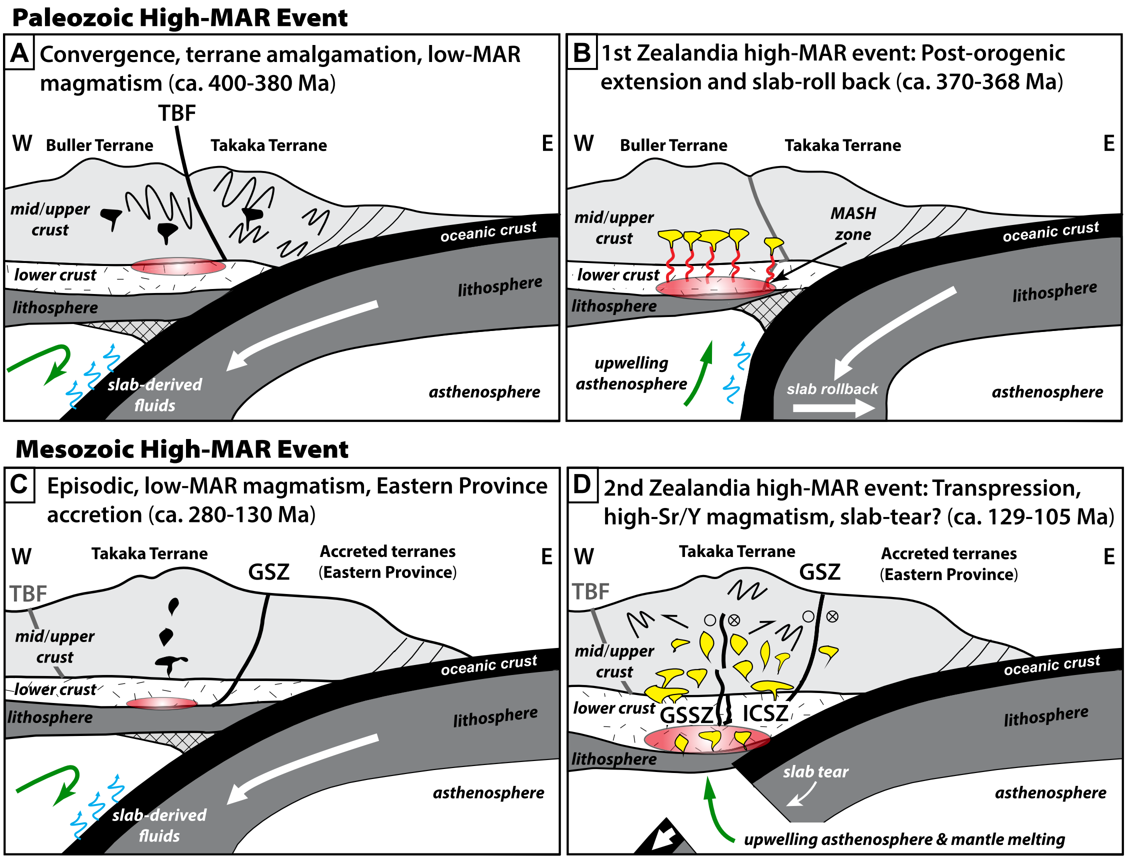

Figure 4. Schematic models for the evolution of the Zealandia Cordillera. (A) The first high-magma-addition-rate (MAR) event followed amalgamation of the Buller and Takaka terranes. (B) The event from 370 to 368 Ma was triggered by slab roll-back and asthenospheric upwelling. (C) Mesozoic magmatism involved >100 m.y. period of low-MAR activity. (D) The Separation Point Suite high-MAR event peaked during regional contraction/transpression. TBF—terrane-boundary fault, GSZ—Grebe shear zone, GSSZ—George Sound shear zone, ICSZ—Indecision Creek shear zone; MASH—melting, assimilation, storage, and homogenization.

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