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Detrital isotopic record of a retreating accretionary orogen: An example from the Patagonian Andes

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ABSTRACT

U-Pb zircon geochronology and isotopic records have played an influential role in our understanding of convergent margin dynamics. Orogenic cyclicity models link tectonic regimes with magmatic isotopic signatures in advancing orogens, relating compressional regimes with evolved signatures and extension with juvenile signatures; however, such frameworks may not apply for retreating orogens, which commonly produce substantial crustal heterogeneities during backarc rifting and ocean spreading. We explore the Mesozoic to Cenozoic Patagonian Andes tectonic evolution, combining U-Pb zircon ages, bulk rock εNd, and new detrital zircon εHf from the retroarc basin to understand the associated magmatic arc evolution during retreat and advance of the margin. Our results reveal a protracted phase of isotopically juvenile magmatism between 150 and 80 Ma, which began during backarc extension and persisted long after the margin switched to a contractional regime. We propose that the prolonged juvenile isotopic trend started mainly due to trenchward migration of the arc during backarc extension (150–120 Ma) and persisted due to partial melting of underthrusted juvenile attenuated and oceanic crust during backarc basin closure (120–80 Ma). This interpretation implies that tectonic stress alone does not predict isotopic trends, and factors like assimilation or the composition of underthrusted crust are important controls on magmatic isotopic composition, especially in retreating and transitional orogens.

INTRODUCTION

The combined utility of U-Pb geochronology and isotopic signatures of zircon provides a time-integrated window into the genesis of magmatic arcs, making it a powerful tool for studying Earth's crustal processes along active plate margins (Kemp et al., 2009; Chapman et al., 2017). There is a well-established framework for understanding links between subduction, magmatism, and shortening in advancing Cordilleran-style accretionary orogens using isotopic signatures in igneous and detrital zircon (e.g., Cawood et al., 2009; DeCelles et al., 2009; Pepper et al., 2016). However, less attention has been given to retreating accretionary orogens, where subducting slab retreat results in upper-plate extension, intra-arc and backarc basin formation, and in some cases the creation of oceanic lithosphere (Collins, 2002; Kemp et al., 2009; Nelson and Cottle, 2018; Chapman et al., 2021).

The current generalized framework for interpreting εHf and εNd of zircon and bulk rock in convergent margins is that crustal thickening due to collision and shortening produces a trend toward isotopically evolved arc magmatism, whereas crustal extension due to slab rollback and trenchward arc migration produces a trend toward isotopically juvenile arc magmatism (Fig. 1; Kemp et al., 2009; Chapman and Ducea, 2019). The largest-magnitude changes in isotopic signatures in convergent margins are thought to be associated with arc migration across isotopically distinct lithospheric provinces (Chapman et al., 2017). However, arcs built on juvenile lithosphere, like young accreted terranes, have shown a lack of the expected evolved isotopic shift because there is no isotopically evolved reservoir to generate an evolved signal during crustal thickening (Chapman et al., 2021). Thus, an effective framework incorporates the mechanisms driving the isotopic response and identifies the available isotopic reservoirs (Chapman et al., 2021; Chapman and Ducea, 2019). This is especially applicable for retreating orogens, which inherently produce compositionally heterogeneous upper-plate rocks due to backarc rifting and ocean spreading (Dalziel et al., 1974; Vasey et al., 2021). We hypothesize that upper-plate variations in retreating margins associated with the development of oceanic backarc basins would result in a protracted juvenile isotopic signature during the backarc's closure phase (Fig. 1). The main isotopic melt source would come from attenuated or oceanic lithosphere formed during the extensional phase and subsequently underthrusted during closure and retroarc shortening.

We test this hypothesis by evaluating the detrital zircon εHf(t) and εNd(t) igneous whole rock evolution in the Patagonian Andes (Fig. 2). The study area hosts a convergent margin with a well-characterized history of retreating and advancing margin dynamics, represented by backarc extension with ocean spreading followed by basin closure and crustal shortening (Dalziel et al., 1974; Fosdick et al., 2011). We compare previously published age and isotopic signatures from the magmatic arc with new detrital zircon results from the backarc rift and

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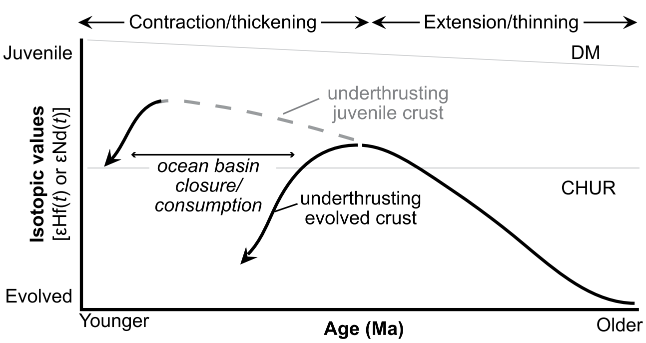

Figure 1. Generalized and proposed models for isotopic evolution of accretionary margins, which link tectonic switching with isotopic values [εHf(*t*) and εNd(*t*)] in arc magmatism (modified from DeCelles et al., 2009; Kemp et al., 2009; Nelson and Cottle, 2018). Our proposed response (dashed lines) accounts for underthrusting of juvenile crust during contracting and closure of an ocean basin. See text for description. Abbreviations: DM—depleted mantle; CHUR—chondritic uniform reservoir (Vervoort and Blichert-Toft, 1999; Bouvier et al., 2008).

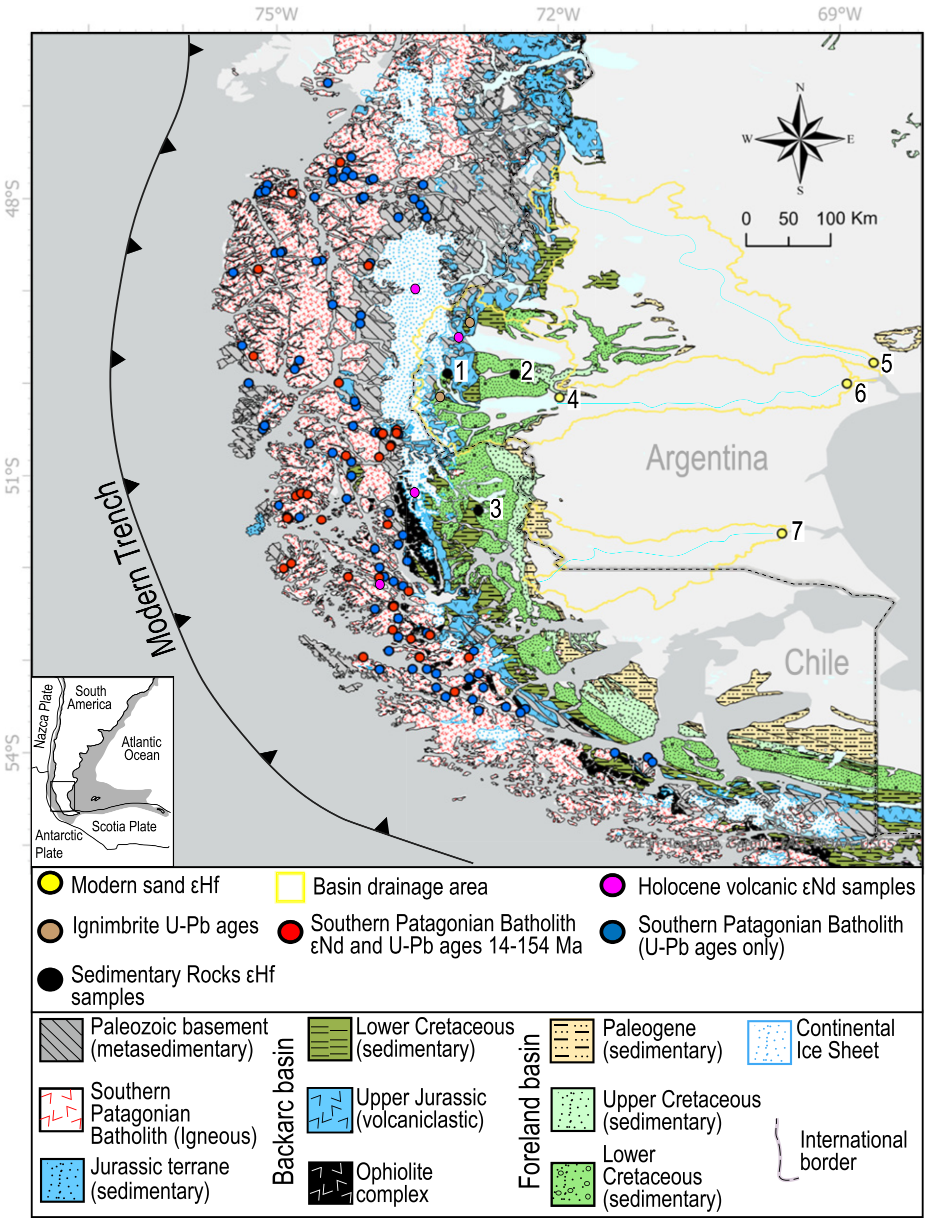

Figure 2. General geology of the Southern Patagonian region (modified from Malkowski et al., 2017) showing new (1: EC141 and EC75, 2: RG47, 3:TN25, 4: RSC) and compiled (Halpern, 1973; Weaver et al., 1990; Bruce et al., 1991; Stern and Kilian, 1996; Martin et al., 2001; Hervé et al., 2007; 5, 6, and 7: Pepper et al., 2016) sample locations included in this study. The basin drainage area from the modern river sands is shown surrounded by yellow polygons. Ignimbrite U-Pb ages (brown circles) are from Pankhurst et al. (2000) and Malkowski et al. (2016).

retroarc foreland phases of the adjacent basin. Our results provide a case study for magmatic and detrital isotopic records from retreating orogens.

GEOLOGICAL BACKGROUND

Eastward subduction along the Southern Patagonian margin began by ca. 175 Ma in a retreating stage, resulting in backarc extension and crustal thinning (Rapela et al., 2005) to form the Rocas Verdes Basin (Dalziel et al., 1974; Rapela et al., 2005). Continued extension of the Rocas Verdes Basin from 155 to 140 Ma resulted in widespread silicic volcanism and diachronous sea-floor spreading (Pankhurst et al., 2000; Calderón et al., 2007; Malkowski et al., 2016), extending 100–300 km in width (Eagles, 2016). At ca. 120 Ma, the increasing rate of spreading of the southern Atlantic Ocean and accelerated subduction rates along the Pacific margin (Vérard et al., 2012) are interpreted to have driven the closure of the Rocas Verdes Basin and the incipient rise of the Patagonian Andes (Fosdick et al., 2011). Rift basin inversion and subsequent fold-and-thrust belt and foreland basin development began in the north and propagated southward from ca. 120 to 100 Ma resulting in an arc-continent collision from ca. 100 to 80 Ma (Fosdick et al., 2011; Calderón et al., 2012; Malkowski et al., 2017). Closure of the Rocas Verdes Basin involved underthrusting and west-dipping subduction of quasi-oceanic lithosphere beneath the magmatic arc (Klepeis et al., 2010). Arc-continent collision triggered slab break-off of the west-dipping subducting slab (Cunningham, 1995) and development of an east-vergent fold-and-thrust ophiolitic suture belt in the orogenic wedge (Calderón et al., 2012).

Subduction persisted along the Andean margin with varying tectonic regimes during the Cenozoic (Ghiglione et al., 2016). Mostly neutral conditions dominated from ca. 80 to 30 Ma with a minor shortening episode between 40 and 50 Ma, whereas a period of more rapid convergence and shortening ensued between 30 and 15 Ma, possibly preceding subduction of the Chile Ridge spreading center (Ghiglione et al., 2016). Arc magmatism remained mostly active between 155 and 15 Ma, with a lull from ca. 66 to 40 Ma, evident through both igneous and detrital zircon U-Pb ages (Figs. 2 and 3; Hervé et al., 2007).

METHODS

Detrital zircon U-Pb ages and Lu-Hf isotopic analyses were obtained from Lower and Upper Cretaceous sandstone (samples EC141, EC75, RG47, and TN25) and modern river sands from the upper Santa Cruz River (sample RSC), which drains the modern orogenic belt (Fig. 2). Lu-Hf isotopic analyses were acquired from selected grains with U-Pb ages of 200 Ma

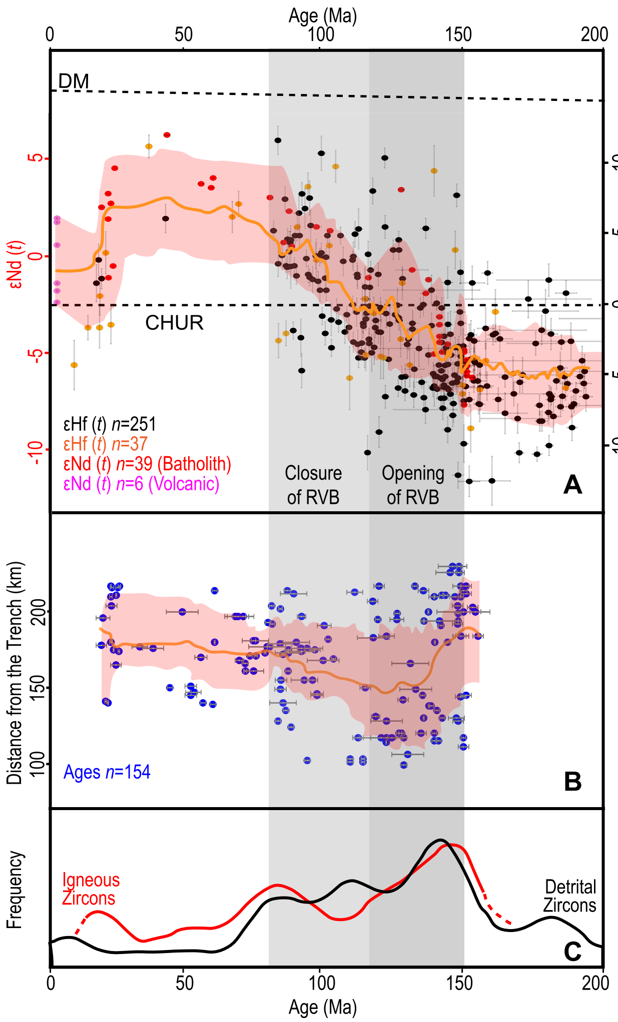

Figure 3. Summary of geochronological and isotopic data from the Patagonian Andes. (A) Detrital zircon εHf(*t*) from samples from this study (black) and a previous study (orange; Pepper et al., 2016) and igneous whole rock εNd(*t*) from samples from the Southern Patagonian Batholith (red; Martin et al., 2001; Hervé et al., 2007; Dobbs et al., 2022) and the modern volcanic arc (purple; Stern and Kilian, 1996) versus age. Abbreviations: DM—depleted mantle; CHUR—chondritic uniform reservoir (Vervoort and Blichert-Toft, 1999; Bouvier et al., 2008); RVB—Rocas Verdes Basin. (B) Distance of arc samples from modern trench versus age (Halpern, 1973; Weaver et al., 1990; Bruce et al., 1991; Martin et al., 2001; Hervé et al., 2007). Plots A and B show moving averages (window size = 20; orange line), two standard deviations (red shaded area), and error bars (2σ). (C) Comparison of detrital and igneous zircon age distributions shown as a kernel density estimate plot (bandwidth = 5 m.y.).

or younger (Fig. 3A; see Supplemental Material[1]). Previously collected εHf(*t*) values from river sands near the Atlantic coast are also included in the data set (Pepper et al., 2016). Zircon Hf isotopic data are reported in epsilon units (ε), using the standardized measurement for the chondritic uniform reservoir and the depleted mantle (Vervoort and Blichert-Toft, 1999; Bouvier et al., 2008). We compiled previously published age and isotopic values from igneous whole rock samples (Halpern, 1973; Weaver et al., 1990; Bruce et al., 1991; Stern and Kilian, 1996; Martin et al., 2001; Hervé et al., 2007). Compiled whole rock εNd(*t*) data were converted to equivalent εHf values using the terrestrial array ($\varepsilon Hf = 1.36; \varepsilon Nd + 2.95$) of Vervoort et al. (1999; Fig. 3A). The ages of arc samples were plotted against the orthogonal distance from the modern trench to infer the movement of arc volcanism over time (Fig. 3B).

RESULTS

Detrital zircon εHf(*t*) trends mimic those of εNd(*t*) magmatic arc values and are consistent with the density of ages during modal peaks (150 Ma and 80 Ma) and lulls (after 75 Ma) (Fig. 3). Detrital zircon εHf(*t*) values show more variability compared to the relatively consistent pattern observed in the εNd(*t*) magmatic arc values (Fig. 3A). Both detrital and magmatic isotopic values steadily became more juvenile at the onset of Rocas Verdes Basin opening (ca. 154 Ma; Malkowski et al., 2016). Evolved isotopic values dominate until ca. 150 Ma (Fig. 3A), concurrent with initial rift-related ignimbrite eruptions at 154.5 ± 1.4 Ma and 152.0 ± 2.0 Ma in the region (Pankhurst et al., 2000; Fig. 2). The marked progressive evolution to more juvenile isotopic compositions started at 150 Ma, continuing until at least 80 Ma. This protracted phase of juvenile mantle signatures flattened between 80 and 30 Ma and transitioned to a more evolved trend after 30 Ma (Fig. 3A).

The onset of the juvenile trend coincided with trenchward migration (~30 km) of the magmatic arc between 150 and 130 Ma, later shifting ~20 km cratonward until ca. 80 Ma, when it became stationary (Fig. 3B). Between 150 and 80 Ma, the arc width was ~80 km, narrowing to 60 km after 80 Ma (Fig. 3B).

DISCUSSION

Similarities between the age and isotopic composition of detrital and igneous samples in the Patagonian Andes support the utility of retroarc sediments as a reliable time-integrated archive of arc-generated zircon in accretionary orogens (Fig. 3; Nelson and Cottle, 2018; Capaldi et al., 2021). In this study, we attribute scatter in the detrital record to disparities in data abundance or derivation from a broad swath of the arc or recycled sediment (Malkowski et al., 2017).

The juvenile signal in εHf(*t*) and εNd(*t*) values between 150 and 120 Ma coincides with syn-rift volcanism and is synchronous with the initiation of backarc extension (Figs. 1, 3A, and 4A). We interpret this juvenile isotopic trend as a response to trenchward migration of the magmatic arc away from thicker continental lithosphere (Kemp et al., 2009), which is consistent with the arc migration record (Fig. 3B) and with models proposing trench retreat of the western Gondwanan margin (Rapela et al., 2005).

Although the backarc rifting phase of the orogen tracks closely with igneous and detrital isotopic compositions, the contractional phase deviates from what previously proposed isotopic frameworks (Kemp et al., 2009; Nelson and Cottle, 2018) predict (Fig. 3A). Specifically, an isotopically evolved trend is expected during contraction of the orogen with a later return to isotopic values similar to what was observed before the backarc extension. Detrital and igneous isotopic trends remained juvenile during closure and arc-continent collision (120–80 Ma), instead of displaying the expected negative shift in response to contraction and lithospheric thickening (Fig. 3A). Furthermore, coinciding with Rocas Verdes Basin closure (Fig. 4B), the magmatic arc gradually migrated cratonward (Fig. 3B), which could suggest a reduction in the subducting slab dip angle.

We propose that the continuous positive isotopic trend during backarc basin closure and collision (120–80 Ma) was the result of protracted retroarc underthrusting of oceanic and attenuated continental crust, generated during the backarc extensional phase (Fig. 4B). In this model, the underthrusted rocks were partially melted by the ascending magma below the arc, maintaining the already juvenile isotopic composition of the melt (Fig. 4B). Thus, the juvenile isotopic trend continued, even during a period of crustal thickening and shortening.

The anticipated isotopic inflection toward more evolved magmatism associated with clo-

[1]Supplemental Material. (1) Locations of the unpublished detrital zircon U-Pb zircon samples, (2) detrital zircon U-Pb geochronological data from the unpublished samples, and (3) detrital zircon Lu-Hf isotopic data from the unpublished samples. Please visit https://doi.org/10.1130/GEOL.S.25236694 to access the supplemental material; contact editing@geosociety.org with any questions.

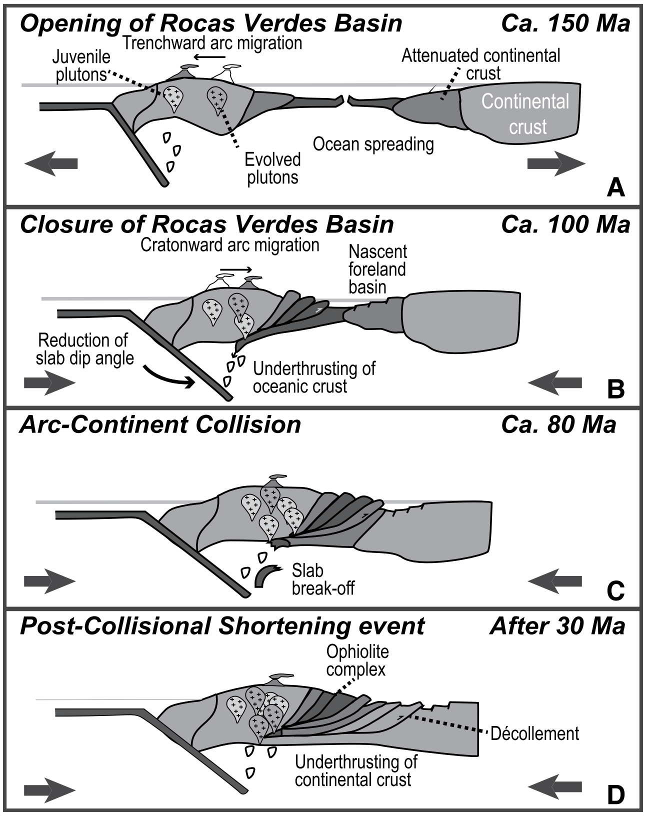

Figure 4. Tectonic evolution of the Patagonian region with proposed geochemical changes in arc magmatism. (A) Opening of the Rocas Verdes Basin (ca. 150 Ma) with backarc ocean spreading and trenchward migration of arc magmatism, which generated the onset of the juvenile isotopic trend. (B) Closure of the Rocas Verdes Basin (ca. 100 Ma) and underthrusting of oceanic crust below the magmatic arc (Calderón et al., 2012) and incipient west-dipping subduction (Klepeis et al., 2010), which generated a fold-and-thrust belt and a foreland basin and maintained the isotopic positive trend during crustal shortening, despite the cratonward migration of the arc. (C) Arc-continent collision (ca. 80 Ma), slab break-off in the west-dipping subduction zone, and removal of juvenile material from beneath the arc (Cunningham, 1995). (D) Post-collisional shortening event (after 30 Ma), which includes reactivation of the fold-and-thrust belt and underthrusting of continental crust through a décollement fault under the arc to produce more-evolved magmatism. The obducted ophiolite complex remains a relict of backarc basin closure.

sure (Fig. 1) did not begin until 30 Ma. We speculate that by this time, the oceanic and strongly attenuated continental crust generated during the opening of the Rocas Verdes Basin had subducted below the arc during the closure stage (Klepeis et al., 2010; Calderón et al., 2012) and then detached during arc-continent collision (Fig. 4; Cunningham, 1995), leaving only thinned and average continental crust to be underthrusted westward below the arc during subsequent growth of the fold-and-thrust belt after 30 Ma (Fig. 4D). Thus, the type of underthrusted material beneath the magmatic arc changed the isotopic composition of the melt, transitioning to more evolved values (Fig. 4D).

The retreating and advancing margin characteristics of the Patagonian Andes offer a valuable analog for studying other retreating and transitional orogens where both oceanic and continental crust were consumed (e.g., western Klamath terrane, western U.S.: LaMaskin et al., 2021; Caucasus: Vasey et al., 2021). Additional work is needed to test these models in other modern and ancient retreating orogens to establish a well-characterized isotopic framework of magmatism, tectonism, and backarc basin evolution.

CONCLUSIONS

Detrital zircon isotopic signatures of retroarc sediments in the Patagonian Andes closely resemble those of igneous samples, highlighting the retroarc basin's utility as a record of arc-magmatism and tectonic environment in retreating and transitional orogens. A trend toward isotopically positive values accompanies the initiation of backarc extension in southern Patagonia; however, the transition to closure and arc-continent collision does not exhibit the expected trend toward isotopically negative values typically observed in advancing orogens. Instead, a protracted juvenile signature is observed for tens of millions of years after the backarc basin closure. We propose that partial melting of underthrusted attenuated and oceanic crust prolonged the isotopically juvenile signatures in arc magmatism during backarc basin closure and arc-continental collision. Our interpretation of detrital and igneous records along a retreating orogen reveals that tectonic regime alone does not fully explain the magmatic isotopic composition. Factors like assimilation and melting of lower-crustal material help to better understand the results, offering deeper insights into the isotopic response and tectonic evolution of retreating orogens.

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