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The role of arc migration in Cordilleran orogenic cyclicity

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ABSTRACT

Continental arc rocks located further away from the trench are typically characterized by more evolved radiogenic isotopic compositions. Episodic arc migration away from the trench would produce a temporal record distinguished by episodic shifts to more evolved compositions. In most continental arcs, temporal shifts to evolved isotopic compositions correlate with magmatic high-flux events, which are the basis for cyclicity models in Cordilleran orogenic systems. Landward arc migration into more melt-fertile regions of the continental lithosphere can explain both episodic shifts in isotopic composition and high-flux events without requiring underthrusting of retroarc lithosphere. If arc migration is predominantly autocyclic, controlled by intra-arc processes, then arc migration itself may drive orogenic cyclicity. Conversely, periodic arc migration may be controlled by allocyclic processes like slab anchoring or folding in the mantle transition zone. In either case, arc migration may be the key to understanding what drives high-flux events and cyclicity in Cordilleran orogens.

INTRODUCTION

Models for orogenic cyclicity in Cordilleran systems espouse teleconnections between forearc, intra-arc, and retroarc deformation; magmatic arc tempos and composition; crustal thickening; uplift, erosion, and sedimentation; and subcrustal mass transfer like arc root growth, arc root foundering, lithospheric delamination, and tectonic underplating (Ducea, 2001; Ducea and Barton, 2007; DeCelles et al., 2009; Cao et al., 2015; DeCelles and Graham, 2015; Ducea and Chapman, 2018). The foundation of orogenic cyclicity models is the episodic nature of continental arc magmatism, manifest as arc flare-ups or high-flux events (generally occurring every 30–70 m.y.) separated by magmatic lulls (Armstrong and Ward, 1993; DeCelles et al., 2009; Paterson and Ducea, 2015; Ducea et al., 2015; Kirsch et al., 2016). A breakthrough in deciphering the underlying cause of orogenic cyclicity came from the recognition that the radiogenic isotopic composition of continental arc rocks commonly become more evolved during high-flux events (Ducea, 2001; Ducea and Barton, 2007). These temporal shifts to evolved compositions have been called isotopic pull-downs because initial ε_{Nd} values become more negative (DeCelles et al., 2009). There is no consensus on what drives high-flux events and isotopic pull-downs, but a prominent hypothesis is that shortening in the retroarc (retrowedge) thrust belt underthrusts continental lower crust and mantle into the melt source region beneath the arc (Ducea, 2001; Ducea and Barton, 2007; DeCelles et al., 2009; DeCelles and Graham, 2015; Lee and Lackey, 2015). The logic behind the hypothesis is that the influx of melt-fertile lower crust produces the high-flux event, and the antiquity of the crust produces the isotopic pull-down.

However, not all Cordilleran batholiths that exhibit high-flux events show isotopic pull-downs (e.g., the Coast Mountains batholith in British Columbia [Canada] and Alaska [United States]; Girardi et al., 2012; Cecil et al., 2018). This suggests that other factors may play a role or that in these instances there is not enough isotopic contrast to produce a pull-down. Another complexity is that some Cordilleran arcs record high-flux events despite limited amounts of retroarc underthrusting (e.g., the southern Andean arc; Kirsch et al., 2016; Horton, 2018). Existing models for producing isotopic pull-downs have generally treated the position of the arc as static, but if the locus of magmatism shifts across lithosphere of variable age and isotopic composition, then isotopic pull-downs could be related to arc migration and need not be caused by retroarc underthrusting.

A common feature of igneous rocks in Cordilleran orogens is a spatial isotopic trend in which arc rocks located further from the trench (up to a few hundred kilometers) are more radiogenically evolved (Kistler and Peterman, 1973; Farmer and DePaolo, 1983; Chapman et al., 2017). Controls on this trend include (1) crustal assimilation (DePaolo, 1981), and (2) the nature of the mantle in the melt source region: asthenospheric (juvenile) near the trench, and lithospheric (evolved) away from the trench (Chapman et al., 2017). As a result of this spatial isotopic trend, landward arc migration may produce an isotopic pull-down, which would be reflected in any temporal records of magmatism (e.g., detrital zircon ε_{Hf} data sets). By inference, arc-migration processes may also be linked to periodic high-flux events in Cordilleran orogenic systems.

DATA AND METHODS

To explore this idea, arc magmatism is examined in the Sierra Nevada (western United States), the continental arc originally used to develop Cordilleran orogenic cyclicity concepts (Ducea, 2001; Ducea and Barton, 2007; DeCelles et al., 2009). We compiled a variety of data sets relevant to the evolution of the batholith, which are summarized in Figure 1 and presented in the GSA Data Repository[1]. Although not examined here, associations between arc migration and isotopic pull-downs (e.g., central Andean arc; Haschke et al., 2002; Kay et al., 2005) and arc migration and high-flux events (e.g., Gangdese batholith [Tibet]: Chapman and Kapp, 2017; Coast Mountains batholith: Cecil et al., 2018) can also be observed in other modern and ancient Cordilleran systems.

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[1] GSA Data Repository item 2019223, tables of compiled data with data sources, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

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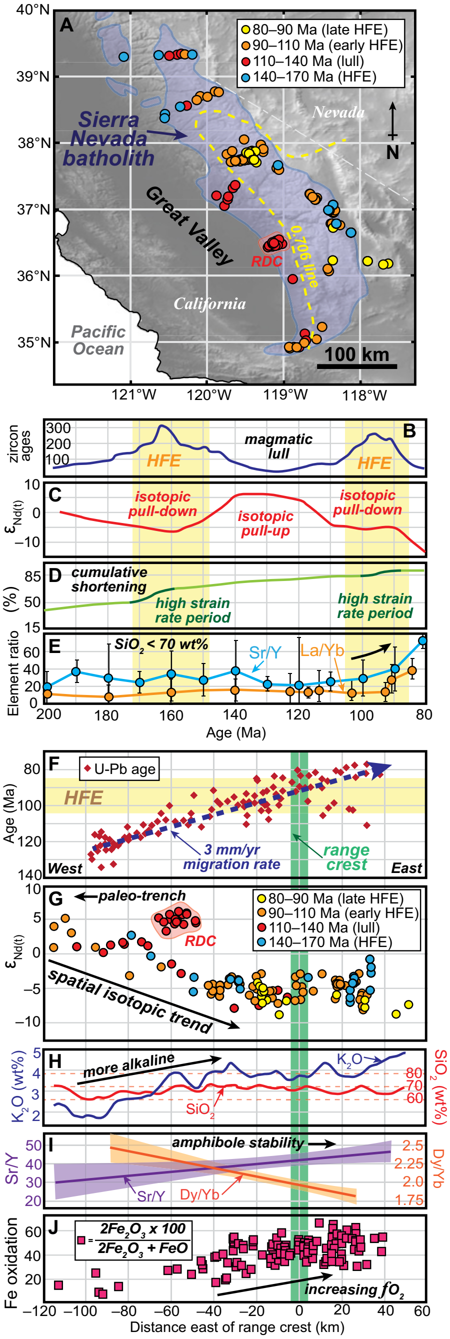

Figure 1. A: Map of Sierra Nevada batholith (western United States) showing age and position of Mesozoic continental arc rocks plotted in panel G. During Jurassic and mid-Cretaceous high-flux events (HFE), arc magmatism was concentrated in the eastern Sierra Nevada, farthest from the trench. "0.706 line" is Sr^{87}/Sr^{86} = 0.706 isopleth. RDC—mafic-ultramafic ring dike complex. B,C: Compilations of zircon U-Pb ages and whole-rock initial ε_{Nd} values for the Sierra Nevada (from Kirsch et al., 2016). High-flux events (yellow bars) correlate with isotopic pull-downs. D: Cumulative shortening through time showing periods of high-strain rate that correlate with high-flux events (from Cao et al., 2015). E: Sr/Y and La/Yb values through time showing increase during the Late Cretaceous high-flux event (black arrow) (from Karlstrom et al., 2014; Profeta et al., 2015; Kirsch et al., 2016). Median values are plotted with ±1σ uncertainty. Only rocks with <70 SiO_2 wt % are plotted, to exclude highly fractionated melts. F: U-Pb rock ages from Sierra Nevada showing eastward (landward) migration of magmatism during the mid-Cretaceous (from Cecil et al., 2012). Mid-Cretaceous high-flux event occurred when magmatism migrated into the eastern Sierra Nevada. G: Spatial isotopic trend in the Sierra Nevada, showing more-evolved initial ε_{Nd} values located farther from the trench. Map location of data is shown in panel A. Data are projected onto a vertical plane with strike oriented perpendicular to the trend of the Sierra Nevada batholith. H–J: West-to-east spatial geochemical gradients in the Sierra Nevada show increase in weight percent K_2O (from Bateman, 1992) (H), increase in Sr/Y and decrease in Dy/Yb (from Ardill et al., 2018) (I), and increase in ferrous-ferric (oxidation) ratio (from Dodge, 1972) (J). Methods, data, and data sources for panels A and G are presented in the Data Repository (see footnote 1).

Sierra Nevada Batholith

The Sierra Nevada displays prominent spatial isotopic trends in which radiogenic isotopes become more evolved landward of the trench (Fig. 1). The Sr^{87}/Sr^{86} spatial isotopic trend is the most well known because the Sr^{87}/Sr^{86} = 0.706 isopleth ("0.706 line") has been used as a proxy for the western edge of North American basement (Kistler and Peterman, 1973, 1978), outboard of which are a series of isotopically juvenile accreted oceanic and ophiolitic terranes (Snow and Scherer, 2006). The spatial distribution of ε_{Nd} mimics that of Sr^{87}/Sr^{86} (negative correlation) and shows increasingly evolved values to the east (Fig. 1). Similar isotopic trends are known from within the underlying continental mantle lithosphere (Ormerod et al., 1988; Wenner and Coleman, 2004). The radiogenic isotopic composition of magmatism throughout the history of the batholith has followed the spatial isotopic trend. The Sierra Nevada experienced three high-flux events during the Mesozoic, centered on ca. 225 Ma, ca. 160 Ma, and ca. 95 Ma (Ducea, 2001; Cecil et al., 2012; Paterson and Ducea, 2015). All three high-flux events are associated with isotopic pull-downs, and all three occurred when magmatism was concentrated furthest from the trench (Ducea and Barton, 2007; Kirsch et al., 2016) (Fig. 1). As a result, the Triassic, Jurassic, and Cretaceous arcs are largely spatially coincident and form a composite batholith.

The final high-flux event is diachronous from north to south, but it occurred during the Late Cretaceous in the southern and central Sierra Nevada where it is the most well documented (Paterson and Ducea, 2015). During the magmatic lull preceding the Late Cretaceous high-flux event, magmatism was located closer to the trench (modern-day western Sierra Nevada and Great Valley) and produced rocks with more juvenile isotopic compositions (Fig. 1). From 130 to 80 Ma, magmatism migrated away from the trench at 2–5 mm/yr and produced rocks with increasingly evolved isotopic compositions (Chen and Moore, 1982; Cecil et al., 2012; Ardill et al., 2018) (Fig. 1). Arc migration started during a magmatic lull, ca. 130 Ma. The Late Cretaceous high-flux event occurred when the arc was located in what is today the eastern Sierra Nevada, 30–40 m.y. after arc migration had started (Fig. 1). The data suggest not only that the Nd isotopic pull-downs and high-flux events in the Sierra Nevada were produced by delivery of more isotopically evolved and melt-fertile material into a fixed melt source region beneath the arc, but that the melt source region and arc itself had migrated landward into a different part of the lithosphere.

Higher Sr/Y and La/Yb suggest an increase in crustal thickness during this time (Karlstrom et al., 2014; Profeta et al., 2015; Kirsch et al., 2016), and an east-west spatial gradient in Sr/Y (Ardill et al., 2018) indicates that this thickening was concurrent with arc migration (Fig. 1). Other spatial geochemical gradients that were produced during eastward arc migration include increasing alkalinity (at approximately constant weight percent SiO_2; Bateman, 1992), increasing oxygen fugacity (Dodge, 1972), and decreasing Dy/Yb (Ardill et al., 2018). Xenolith data indicate that the mantle lithosphere was also thickened during this time, at least in part by melt entrapment (Chin et al., 2012). In the central to northern Sierra Nevada, melt depletion and/or a thickened lithosphere that impinged on the subducting slab may have terminated the high-flux event and all subduction magmatism at ca. 80 Ma (Ducea, 2001; Chin et al., 2012; Karlstrom et al., 2014).

Melt Fertility

Generating a high-flux event requires increased melt fertility, which is primarily dependent on rock composition, pressure, temperature, and water content. Any mechanism to explain the high-flux events in the Sierra Nevada should also produce more isotopically evolved compositions, occur on an episodic basis, and be associated with landward arc migration. One possibility is that landward arc migration simply hastens the delivery of lower-crustal material to the arc and adds to the rate of retroarc underthrusting. Shallowing of the subduction angle (causing landward arc migration) is commonly associated with increased plate coupling and crustal shortening, which may explain the correlation between high-flux events in the Sierra Nevada and kinematic jumps (new frontal thrust sheets) in the Sevier retroarc thrust belt (DeCelles et al., 2009; DeCelles and Graham, 2015).

A second possibility is that high-flux events are produced when an arc migrates into a more melt-fertile crustal province, regardless of retroarc dynamics. The accreted oceanic and ophiolitic terranes that compose basement in the western Sierra Nevada are relatively more mafic (Snow and Scherer, 2006) and presumably less melt fertile (cf. Clemens and Viezeuf, 1987) than the intermediate igneous and quartzofeldspathic rocks that compose (cratonic) North American crust in the eastern Sierra Nevada (Kistler and Peterman, 1978). However, the degree of crustal assimilation in the Sierra Nevada remains contested (see review by Nelson et al. [2013]), and some researchers have suggested that the mantle exerts a first-order control on isotopic compositions, particularly in the eastern Sierra Nevada—the locus of the Late Cretaceous high-flux event (Wenner and Coleman, 2004; Lackey et al., 2008; Jagoutz and Klein, 2018).

If the mantle is an important contributor to Sierra Nevada arc rocks, then a third possibility to consider is whether processes that increase melt fertility in the mantle, specifically hydration ± (re)fertilization, could be responsible for producing high-flux events. There is some evidence to suggest that this may be the case. Chin et al. (2012, 2014) documented refertilized mantle (peridotite and garnet pyroxenite) xenoliths from the Sierra Nevada and suggested that refertilization occurred contemporaneously with the Late Cretaceous high-flux event and that refertilization increased with depth in the mantle lithosphere. Compared to the convecting asthenospheric (depleted) mantle wedge, a thick and cool mantle lithosphere allows for efficient melt entrapment, incompatible element chromatography, and long-term storage of water in hydrous phases and hydrated nominally anhydrous minerals (O'Reilly and Griffin, 2013). Many of the temporal and spatial geochemical gradients in the Sierra Nevada that correlate with landward arc migration—increased Sr/Y, La/Yb, and oxygen fugacity, and decreasing Dy/Yb (Fig. 1)—are consistent with exceptionally hydrous melt conditions and the stabilization of amphibole ± garnet (Müntener et al., 2001; Davidson et al., 2007). A landward increase in weight percent K_2O in the Sierra Nevada (Fig. 1), and other arc systems globally, has been called the K-*h* (where *h* is depth) relationship (Dickinson, 1975). One of the many plausible explanations for the K-*h* relationship is partial melting of fluid- and/or melt-metasomatized mantle lithosphere (e.g., phlogopite-peridotite), which is a common explanation for alkaline magmas in general (Menzies and Murthy, 1980). High-K magmas from the Sierra Nevada, erupted during the Pliocene, have been related to melting of (delaminated) fluid-metasomatized mantle lithosphere (Farmer et al., 2002).

We envision a scenario in which melt-fertile, subduction-related, metasomatic products accumulate over time in the mantle lithosphere, landward of the arc axis (Fig. 2). Landward migration of the arc and mantle wedge into hydrated and fertile parts of the lithosphere may trigger a high-flux event. This mechanism allows for a slow buildup (perhaps during magmatic lulls) but rapid delivery of melt-fertile material to a melt source region. The mid-Cenozoic ignimbrite flareup in the North American Cordillera (Lipman, 1992) may be partially analogous to the high-flux mechanism proposed above. Low-angle subduction of the Farallon plate resulted in widespread refrigeration and hydration of the North American lithosphere (Humphreys et al., 2003). After the Farallon slab foundered (or rolled back), hydrated North American mantle lithosphere was heated by upwelling asthenosphere and produced the mid-Cenozoic flareup (Farmer et al., 2008). Metasomatic accumulation and storage in the deep lithosphere followed by rapid heating may be a relatively common way to generate arc flareups and high-flux events.

Arc Migration

Cyclical arc migration has been observed in long-lived Cordilleran orogenic systems (e.g., central Andes; Haschke et al., 2002), but what drives this behavior is debated. Periodicity rules out many noncyclical factors like subducting plate age, plate thickness, and rates of motion, which could control slab dip. Explanations for periodic arc migration generally fall into two categories: autocyclic processes (occurring within the arc system) or allocyclic processes (externally driven). Examples of autocyclic processes include magmatic and tectonic thickening of the arc root and arc lithosphere, which could deflect the mantle wedge or locus of pluton emplacement landward (Karlstrom et al., 2014) or decrease slab dip by increasing mantle wedge suction (O'Driscoll et al., 2009). Examples of allocyclic processes include mechanisms like alternating periods of slab anchoring and slab break-off (Faccenna et al., 2013) or periodic slab folding in the mantle transition zone (Gibert et al., 2012), which affect slab dip and plate coupling. Regardless of the exact processes (autocyclic or allocyclic) involved, we suggest that episodic arc migration through a spatial isotopic trend may be a contributing factor to producing isotopic pull-downs in the Sierra Nevada.

CONCLUSIONS

In many continental arcs, relatively subtle changes in the spatial distribution of magmatism influence radiogenic isotopic compositions. In the Sierra Nevada, initial ε_{Nd} compositions

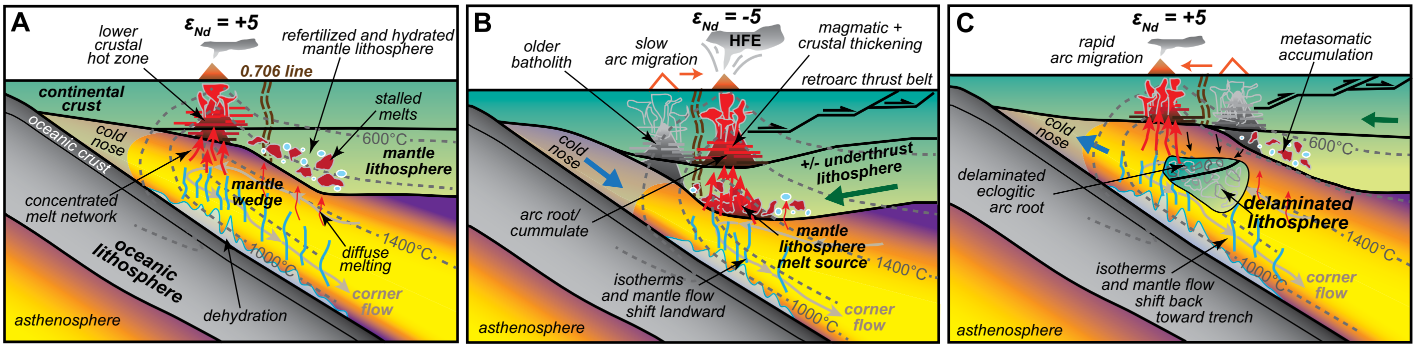

Figure 2. Schematic cross sections for continental arc, illustrating the potential role of arc migration in Cordilleran orogenic cyclicity. A: Arc magmatism during magmatic lull. Asthenosphere is the main upper-mantle melt source region. Metasomatic products accumulate in the deep lithosphere landward of the main arc axis, increasing melt fertility. B: During landward arc migration, the upper-mantle melt source region incorporates more enriched continental mantle lithosphere and encounters a hydrated and (re)fertilized region of lithosphere, producing a high-flux event (HFE) and isotopic pull-down. C: Delamination of arc root and thickened mantle lithosphere may cause the arc to migrate back toward the trench, restarting the cycle. Green arrow represents the possibility of underthrust lithosphere. Although the model presented is generalized, the projected position of the 0.706 line (Sr^{87}/Sr^{86} = 0.706 isopleth, dashed brown double line) in the Sierra Nevada batholith is shown for reference.

range from +5 to –5 (west-to-east gradient) in <100 km across strike of the arc. Nd isotopic pull-downs and high-flux events in the Sierra Nevada correlate to periods when the locus of magmatism shifted landward, away from the trench, and into more evolved lithospheric provinces and enriched upper-mantle melt source regions. Subduction-related metasomatism (refertilization and hydration) prior to high-flux events may gradually increase melt-fertility of the deep lithosphere in subduction zones. Arc migration into these cumulatively metasomatized regions could spark a high-flux event. High-flux events may be generated by multiple processes, but the role and contribution of arc migration should be considered in models of Cordilleran orogenic cyclicity.

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