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GR Focus Review

Spatial and temporal radiogenic isotopic trends of magmatism in Cordilleran orogens

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ABSTRACT

An intrinsic feature of Cordillera-style orogenic systems is a spatial trend in the radiogenic isotopic composition of subduction-related magmatism. Magmatism is most isotopically juvenile near the trench and becomes increasingly evolved landward. A compilation of radiogenic isotopic data from the central Andes, U.S. Cordillera, and Tibet (the most well-studied examples of modern and ancient Cordilleran systems) demonstrate such spatial trends are long-lived and persist throughout the life of these continental subduction margins. The consistency of the isotopic trend through time in magmatic products is surprising considering the plethora of orogenic processes that might be expected to alter them. In addition to longevity, spatial isotopic trends encompass a broad spectrum of geochemical compositions that represent diverse petrogenetic and geodynamic processes. The two end-members of the spatial isotopic trends are represented by melts sourced within isotopically juvenile asthenospheric mantle and melts sourced from isotopically evolved continental lithospheric mantle and/or lower crust. Mantle lithosphere generally thins toward the magmatic arc and trench in Cordilleran orogens because sub-lithospheric processes such as delamination, subduction erosion, and subduction ablation, operate to thin or remove the continental mantle lithosphere. With time, magmatic additions may impart the isotopic composition of the mantle source on the lower crust, giving rise to an isotopically homogenous deep lithosphere. The results of this analysis have significant implications for interpreting temporal and spatial shifts in isotopic composition within Cordilleran orogens and suggest that the continental mantle lithosphere may be a significant source of magmatism in orogenic interiors.

Contents

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1. Introduction

Analysis of spatial and temporal changes in the radiogenic isotopic composition of magmatism is one of the primary tools available for studying the evolution of the deep continental lithosphere in convergent orogens (Ducea and Barton, 2007). Isotopic changes through time have played a key role in interpreting diverse tectonic phenomena including continental subduction (Chu et al., 2011; Bouilhol et al., 2013), subduction erosion (Kay et al., 2005), delamination (Kay et al., 1994), arc root foundering (Ducea, 2002), lithospheric extension (DePaolo and Daley, 2000), changes in crustal thickness (Haschke et al., 2002), and retroarc thrusting (DeCelles et al., 2009, 2015; DeCelles and Graham, 2015). If systematic variations in the isotopic composition of igneous rocks are related to their location in an orogenic system, then these temporal isotopic shifts should be evaluated against concurrent spatial changes in magmatism.

Subduction related (island arc and continental arc) orogenic systems may be divided into retreating and advancing end-members (Uyeda, 1982). Retreating orogens are characterized by long-term subduction rollback and upper plate extension resulting in the formation of intra-arc and back-arc basins (Cawood et al., 2009). These orogens characterize much of the western Pacific today and include numerous island-arc systems (Schellart et al., 2006). This contribution focuses solely on Cordilleran-style orogens that are dominated by continental arc magmatism and large-scale horizontal crustal shortening. The Cordilleran orogens examined here are: 1) the central Andes, an active Cordilleran margin, 2) the western United States (U.S.) Cordillera, an ancient Cordilleran system that has experienced collapse, extension, and marginal transform faulting, and 3) Tibet, a previous Cordilleran margin that has transitioned into a continental collisional orogen following India-Asia collision (Yin and Harrison, 2000). The conclusions and inferences concerning isotopic trends in this paper may not be applicable to retreating accretionary margins (e.g., the Tasmanides of eastern Australia, and the Apennines).

Lu-Hf, Sm-Nd, Rb-Sr, and Pb isotopic data were compiled on magmatic rocks from the Andes, the U.S. Cordillera, and Tibet. These three orogens have long-lived geologic histories and have experienced numerous tectonic processes that may influence the isotopic composition of magmatism. Despite their differences, each of these orogens exhibits similar systematic spatial changes in the isotopic signature of upper-plate magmatism (Fig. 1). Isotopic values become increasingly evolved landward of the (paleo) trench. Magmatism closest to the trench is comparable to the depleted mantle in isotopic composition, and magmatism at the most landward portion of this trend is more isotopically evolved.

The spatial isotopic trends in these orogens share some characteristic traits. First, the isotopic value of magmatism at any given location in the orogenic system varies within a limited isotopic range throughout the life of the continental arc (Fig. 2). A corollary to this observation is that contemporaneous magmatism will have different isotopic compositions when emplaced at different distances from the trench. Another shared trait is that at a given location in the orogen there is limited variation of isotopic values in rocks that have experienced considerably different degrees of magmatic differentiation (Fig. 3). Based on the observations that the isotopic trend is common to multiple orogens, is long-lived, and occurs across a range of geochemical compositions, we propose that the spatial isotopic trend is an inherent feature of Cordilleran orogenic systems.

The commonality in the spatial isotopic trends between the different orogens suggests that there may be a dominant petrogenetic or tectonic process controlling the trend. Previous researchers have observed similar isotopic trends in individual orogens (Kistler and Peterman, 1973, 1978; Zartman, 1974; Farmer and DePaolo, 1983, 1984; Rogers and Hawkesworth, 1989; Glazner and O'Neil, 1989; Stern, 1991; Ghosh, 1995; Kay et al., 2005; Mamani et al., 2010; Zhu et al., 2011; Boekhout et al., 2015; Jones et al., 2015). Whereas these studies generally agree that the depleted asthenospheric mantle is the isotopically juvenile end-member in the isotopic trend, no consensus on the origin of the more isotopically evolved end-member has emerged. By comparing the isotopic trend across multiple orogens, through geologic time, and from a range of compositions, the potential source region for the isotopically evolved end-member can be constrained. We argue that the deep lithosphere, composed of an isotopically homogenized continental lithospheric mantle and lower crust, is the ultimate source region for the isotopically evolved end-member and that the spatial isotopic trend can provide information on the architecture and tectonic history of the mantle lithosphere in Cordilleran orogens.

2. Terminology and data

The term "isotoptically evolved" is used throughout this paper to refer to unradiogenic or depleted $^{176}Hf/^{177}Hf$ and $^{143}Nd/^{144}Nd$ ratios (relatively low values) and radiogenic or enriched $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ ratios (relatively high values). Likewise, "isotopically juvenile" refers to radiogenic $^{176}Hf/^{177}Hf$ and $^{143}Nd/^{144}Nd$ or unradiogenic $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$. In this context, "isotopically evolved" or "isotopically juvenile" loosely reflects the amount of time elapsed since the melt or melt source has been isolated from the convecting mantle, which is (continually) depleted in Hf/Lu, Nd/Sm, and Rb/Sr (Faure and Mensing, 2005). Melts recently derived from the convecting, "depleted" mantle have more isotopically juvenile compositions than melts generated from the depleted mantle in the past. For example, in an isotopically closed system, magmatic products generated by melting older continental crust will be more isotopically evolved than magmatic products generated by melting younger continental crust. The use of the terms "isotopically evolved" or "isotopically juvenile" do not necessarily reflect magmatic differentiation (i.e., the change from mafic to felsic bulk compositions) or how depleted versus enriched is the source region in their trace elements other than those whose isotopes are referred to. Magmatic differentiation may be largely decoupled from isotopic evolution (e.g., pure fractional crystallization) or closely tied to isotopic evolution in the case of crustal or host rock assimilation (Faure, 2001).

The radiogenic isotopic systems most commonly employed to study orogenic magmatism are Hf, Nd, Pb, and Sr. For historical reasons, different continents tend to be characterized by and associated with different isotopic systems. South America, with metallic ore deposits exposed along the length of the Cordillera, has a preponderance of Pb isotopic data that have been used to map distinct basement isotopic domains (Macfarlane et al., 1990; Wörner et al., 1992; Aitcheson et al., 1995). In North America, Sr isotopic data became widespread in the 1960s and 1970s in conjunction with the advent of Rb-Sr geochronology. The iconic $^{87}Sr/^{86}Sr = 0.706$ isopleth (isotopic contour) is the most widely recognized isotopic feature of the U.S. Cordillera and is thought to approximately demark the western edge of cratonic basement (Kistler and Peterman, 1973, 1978) (Fig. 4). In Tibet and throughout East Asia, abundant and rapidly increasing in-situ Hf isotopic data from zircon have been used to understand the structure of the lithosphere (e.g., Zhu et al., 2011).

Despite geographic idiosyncrasies in data abundance, the Lu/Hf, Sm/Nd, and Rb/Sr systems behave in a coherent manner with respect to fractionation between the crust and mantle. Global compilations of isotopic data from sedimentary systems show that εNd and εHf are positively correlated and that εNd and $^{87}Sr/^{86}Sr$ (which is more commonly used than εSr) are negatively correlated (Ben Othman et al., 1989; Vervoort et al., 1999) (Fig. 5). Radiogenic $^{208}Pb/^{206}Pb$ (daughter products of ^{232}Th and ^{238}U) shows moderate correlation with εNd; however $^{206}Pb/^{204}Pb$ (with non-radiogenic ^{204}Pb in the denominator) does not, which has been explained by an open Pb system in the mantle (Galer and O'Nions, 1985; White, 1993). In general the mantle has a wide range of Pb isotopic compositions (White, 1985; Hart, 1988) and can be heterogeneous in Cordilleran orogenic systems (e.g., Chiaradia and

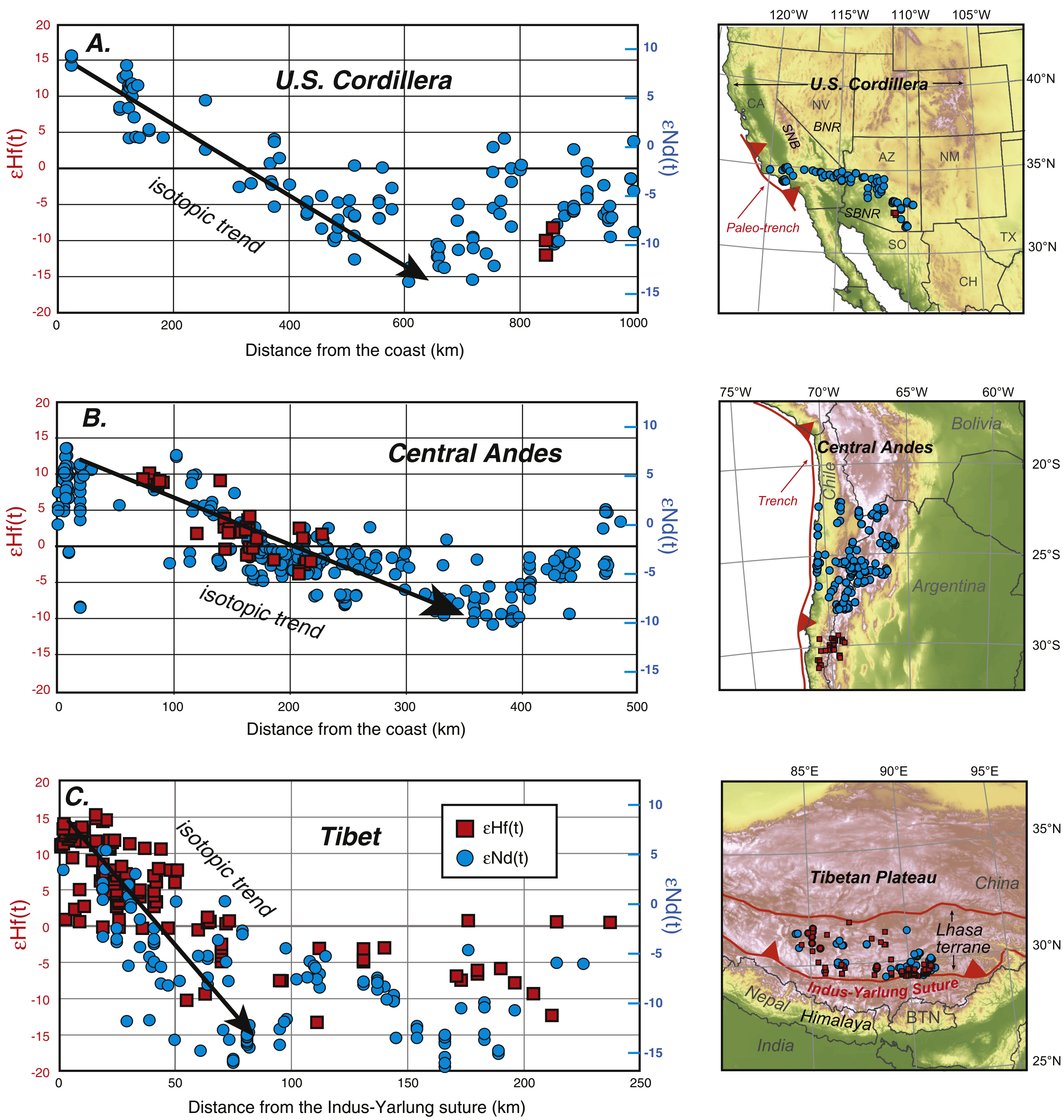

Fig. 1. Compiled Hf and Nd isotopic data for Mesozoic to recent magmatism in: A) the U.S. Cordillera, B) the central Andes, and C) Tibet. There is a spatial trend (black arrows) in which the composition of magmatism becomes more isotopically evolved landward of the trench or suture zone. The isotopic trend may ultimately be related to mixing between the depleted asthenospheric mantle and isotopically evolved continental mantle lithosphere. BTN = Bhutan, SNB = Sierra Nevada Batholith, BNR = Basin and Range Province, SBNR = Southern Basin and Range Province, CA = California, NV = Nevada, AZ = Arizona, NM = New Mexico, TX = Texas, SO = Sonora, CH = Chihuahua.
Data sources are discussed in the text.

Fontbote, 2002). Early Pb isotope studies suggested that the lower crust may be less radiogenic than the mantle (Doe and Zartman, 1979; Zartman and Doe, 1981), but subsequent studies have shown that the Pb isotopic composition of the lower crust is variable and that unradiogenic Pb (e.g., low $^{206}Pb/^{204}Pb$) is limited to cratonic areas that have not experienced recent orogenic activity (Rudnick and Goldstein, 1990). Fluid circulation during orogenesis may be particularly important for regulating Pb isotope ratios in the crust (McCulloch and Woodhead, 1993).

This contribution focuses primarily on the Hf and Nd isotopic systems, but also includes $^{87}Sr/^{86}Sr$ data for the U.S. Cordillera (Fig. 4) and the Andes (Fig.6). Hf and Nd isotope ratios are approximately linearly related, allowing for a direct comparison of data sets (Fig. 5) (Vervoort et al., 1999) and together, Hf and Nd comprise the largest shared isotopic dataset among the Cordilleran orogens examined in this study. All εNd and $^{87}Sr/^{86}Sr$ values come from whole rock analyses, and εHf values come from both whole rock and in-situ zircon analyses. There is little fractionation of Hf isotopes between zircon and associated whole rocks

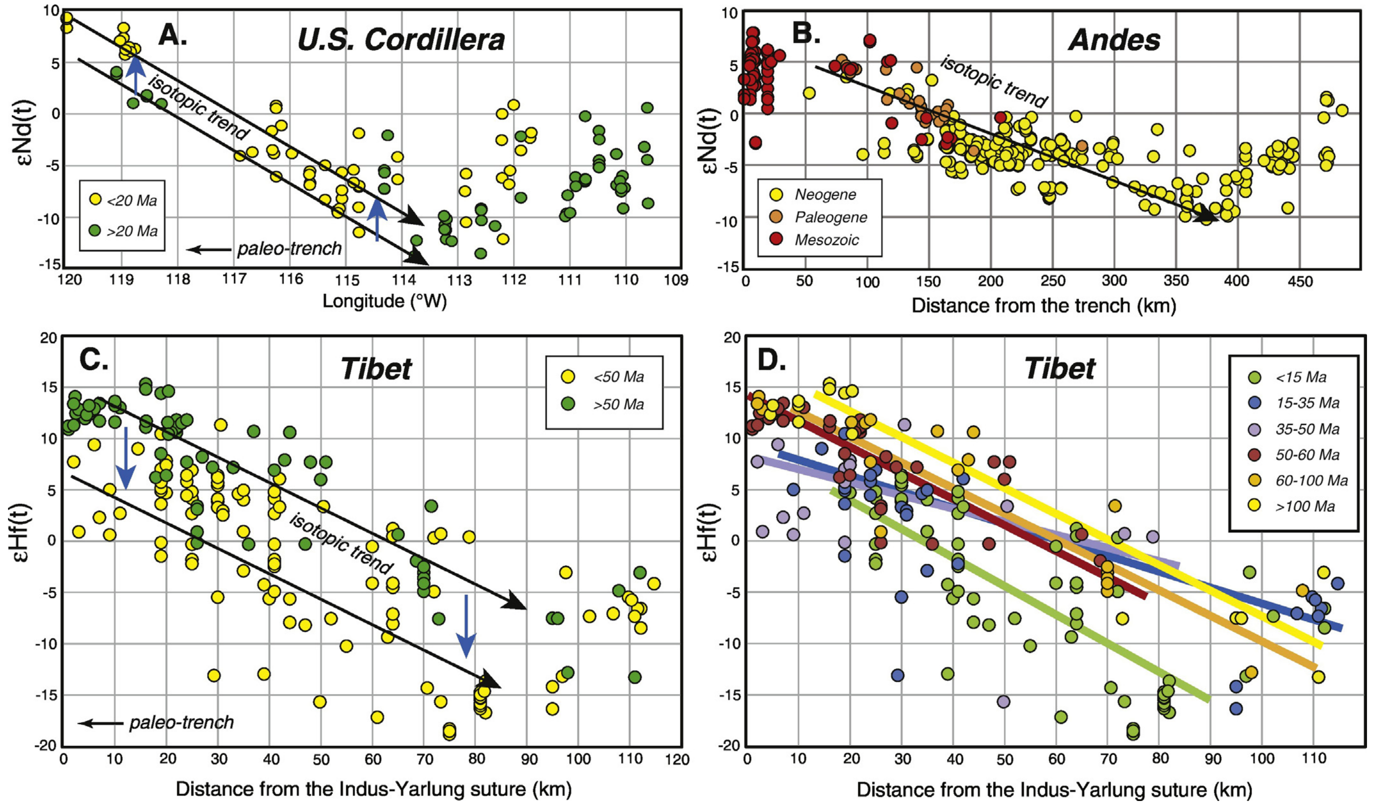

Fig. 2. Radiogenic isotopic data from Cordilleran orogens with magmatic rocks distinguished by age. A) In the U.S. Cordillera, magmatism <20 Ma is shifted to more juvenile isotopic compositions (blue arrows), potentially related to infiltration of asthenosphere into the continental lithospheric mantle during Miocene extension. Although these periods represent different tectonic scenarios (compression vs. extension) they display a similar spatial isotopic trend. B) In the Andes the spatial isotopic trend appears to have been relatively similar since the Mesozoic. Note that widespread magmatism during the Neogene is not isotopically constant when observed across the width of the orogen. C) In Tibet, magmatism <50 Ma is shifted to more evolved isotopic compositions (blue arrows), that may be related to crustal thickening and increased crustal assimilation following India-Asia collision. D) The exact isotopic value of the spatial isotopic trend in Tibet has varied during the last 100+ Ma, however, the overall shape and magnitude has remained relatively similar. Colored lines are interpreted spatial isotopic trends that correspond to the data points of the same color. εHf and εNd data are plotted together in A-D and are converted using the terrestrial array of Vervoort et al. (1999).
Data sources are discussed in the text.

(Kinny and Maas, 2003). In-situ εHf values reported are averages of multiple single grain εHf analyses for a given sample. On plots showing both εHf and εNd data, the axes or data points are related by the terrestrial array of Vervoort et al. (1999) (Fig. 5). In all instances in the text, $^{87}Sr/^{86}Sr$ refers to initial $^{87}Sr/^{86}Sr$ and εHf and εNd refer to $^{176}Hf/^{177}Hf$ and $^{143}Nd/^{144}Nd$ relative to CHUR at the time of crystallization.

Nd and Sr isotopic data for the Andes come from the Central Andes Geochemical GPS Database (http://andes.gzg.geo.uni-goettingen.de) and the Geochemistry of Rocks of the Oceans and Continents database (GEOROC, http://georoc.mpch-mainz.gwdg.de). Nd data for the Andes were analyzed between 27°S and 21°S latitude and between 71°W and 66°W longitude (Fig. 1). Sr data for the Andes were analyzed between 28°S and 22°S latitude and between 70.5°W and 63°W longitude (Fig. 6). Hf data for the Andes come from Jones et al. (2015). Andean magmatism examined in this study ranges in age from Pleistocene to Jurassic. The Jurassic to early Cretaceous Andean Cordilleran margin was characterized by subduction rollback and upper plate extension (Ramos, 2009), which raises the possibility that the magmatic products produced at this time are not equivalent to magmatism during later constructional phases. However, Mesozoic radiogenic isotopic data show similar spatial isotopic trends to data from Paleogene and Neogene magmatic rocks (Fig. 2B).

Hf and Nd isotopic data from Tibet are compiled from numerous literature sources (Supplementary Material File 1) and were analyzed between 84°E and 91.5°E longitude and between 29°N and 32°N latitude (Fig. 1). Magmatism in our Tibetan dataset ranges in age from Late Miocene to Jurassic (Fig. 2D). Nd and Sr isotopic data for the U.S. Cordillera comes from the western North American Volcanic and Intrusive Rock Database (NAVDAT, www.navdat.org). Nd data for the U.S. Cordillera were analyzed between 31°N and 35°N latitude and from 120°W to 105°W longitude (Fig. 1). Sr data for the U.S. Cordillera were analyzed between 38°N and 42.2°N latitude and from 123.4°W to 112.5°W longitude (Fig. 4). Limited Hf isotopic data come from Fornash et al. (2013). U.S. Cordilleran data considered in this study range in age from late Miocene (~5 Ma) to Jurassic (Fig. 2A). Most, but not all, magmatism <5 Ma in the U.S. Cordillera is exceptionally isotopically juvenile (≥+5 εNd) and is associated with advanced crustal extension that took place long after the Cordillera had transitioned away from its constructional phase (Farmer et al., 1995). Data include both intrusive and extrusive magmatic products. All data presented are compiled in Supplementary Material File 1.

3. Results

The central Andes, U.S. Cordillera, and Tibet all exhibit a spatial trend in which magmatism becomes increasingly isotopically evolved landward of the trench or suture zone (Figs. 1, 4, 6). This trend is consistent through time and includes a broad range of geochemical compositions. In the following section, we report on this common isotopic trend and the shared characteristics from each orogenic system.

3.1. Isotopic variation in relation to the distance from the trench

In the transect of the U.S. Cordillera in Fig. 1 there is a trend from isotopically depleted values (+5 to +10 εNd) near the Coast Ranges and Southern Sierra Nevada (~119°W) to more evolved isotopic compositions (−10 to −15 εNd) in southern Arizona (~113°W) (Fig. 1). Similar

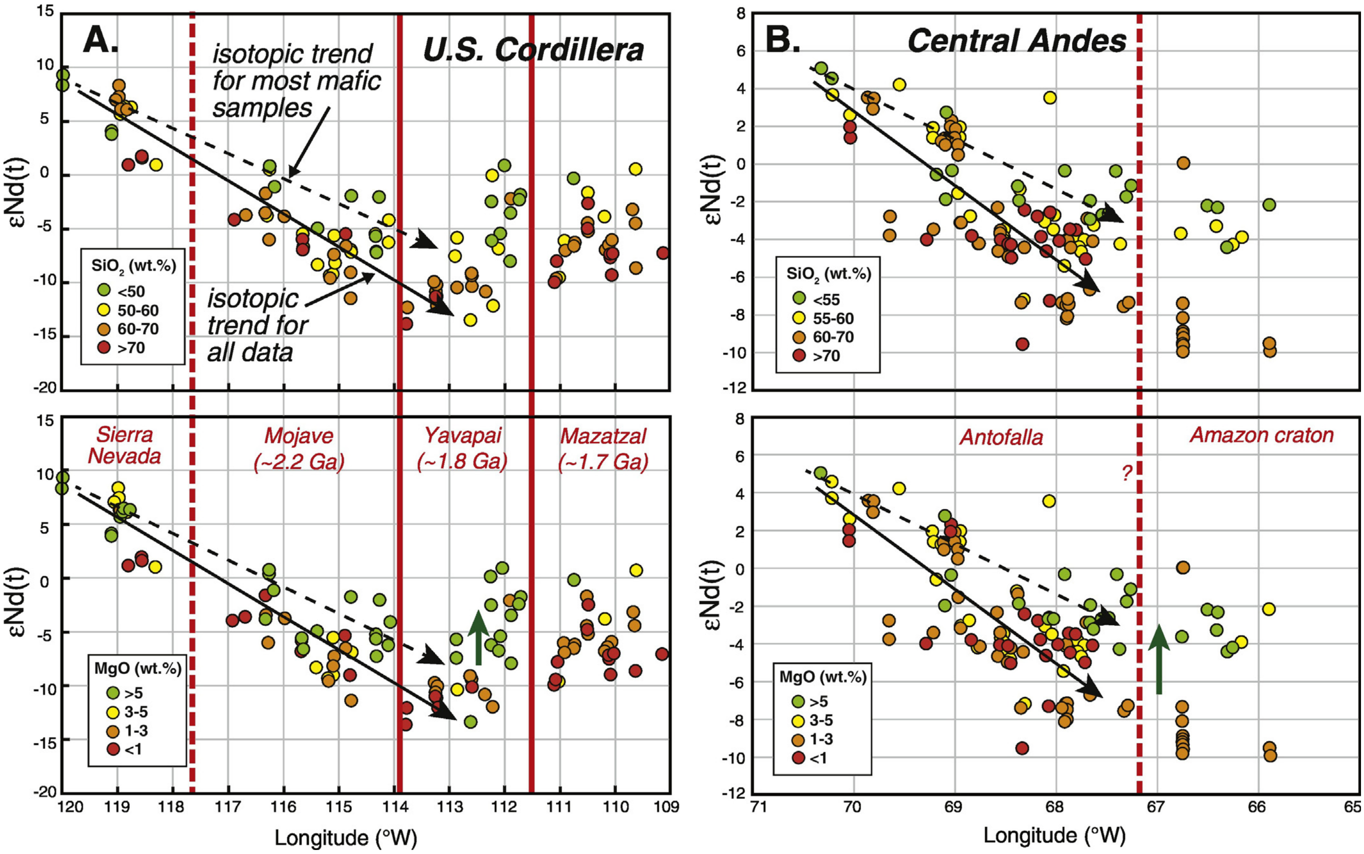

Fig. 3. A) Nd isotopic data from the U.S. Cordillera and B) the central Andes, as shown in Fig. 1, plotted by SiO_2 weight % (top panels) and MgO weight % (bottom panels) as a proxy for the degree of magmatic differentiation. At any given location in the spatial isotopic trends, there is ≤10 εNd unit variation that can be attributed to magmatic differentiation (vertical green arrows). The spatial isotopic trend is present even when considering the most mafic analyses, suggesting that crustal contamination of an asthenospheric (depleted mantle) source cannot account for the full range of the isotopic data. Dashed arrows are interpreted spatial isotopic trends for only the most mafic samples. Basement terrane or province boundaries are shown with vertical red bars and average crustal model ages (in parentheses) are from Wooden et al. (2013), Whitmeyer and Karlstrom (2007), and Ramos (2009).
Data sources are discussed in the text.

spatial trends in radiogenic isotopic data are present at other latitudes throughout the western U.S. (Kistler and Peterman, 1973, 1978; Farmer and DePaolo, 1983, 1984; Glazner and O'Neil, 1989; Miller et al., 2000). Examples of $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ isotopic trends for the northern Basin and Range are shown for comparison in Fig. 4. The length of the trends in Figs. 1 and 4 are ~600 km, but because the transect area has experienced up to ~100% extension during the Miocene (McQuarrie and Wernicke, 2005) the length of the isotopic trend prior to extension was likely significantly shorter, perhaps <300 km.

A comparable spatial isotopic trend is present in the Andes (Fig. 1). Magmatism in the central Andes is most isotopically juvenile (~+5 εNd) closest to the trench and becomes increasingly isotopically evolved toward the craton, reaching εNd values of −10 in the Eastern Cordillera (Fig. 1). An example of the $^{87}Sr/^{86}Sr$ spatial isotopic trend for the central Andes is presented in Fig. 6. This isotopic trend is present at other latitudes in the Andes as well (Rogers and Hawkesworth, 1989; Stern, 1991; Kay et al., 2005; Boekhout et al., 2015; Jones et al., 2015). The length of the isotopic trend in Fig. 1 is ~350 km, although up to ~250 km of subduction erosion since the Jurassic may have truncated this trend (Ziegler et al., 1981; Stern, 1991; Scheuber and Reutter, 1992). Much of the material proposed to have been removed by subduction erosion in central Andes would be accretionary wedge and forearc crust (Kay et al., 2005; Clift and Hartley, 2007). Forearc crust and forearc magmatism are isotopically juvenile (Stern et al., 2012) and it is possible that the spatial isotopic trend in the central Andes had a longer isotopically juvenile "tail" that extended toward the trench. Fig. 4 from the U.S. Cordillera provides an example of what this isotopically juvenile tail may have looked like in the Andes prior to subduction erosion.

Like the U.S. Cordillera and the Andes, Tibet displays an isotopic trend that becomes increasingly evolved north of the Indus-Yarlung suture (Fig. 1), along which oceanic lithosphere was subducting northward beneath Asia prior to the subduction of the Indian plate (Yin and Harrison, 2000). Isotopic ratios are most juvenile closest to the suture zone (+10 to +15 εHf) and decrease to more isotopically evolved values (−10 to −15 εHf) in as little as 75 km north of the suture in the Lhasa terrane. Opposite to the western U.S., this isotopic trend may have been compressed by crustal shortening before and during the India-Asia collision (Burg and Chen, 1984; Yin and Harrison, 2000; Kapp et al., 2007). We speculate that the original length of the Tibetan spatial isotopic trend was ≥100 km. Landward of the spatial isotopic trend, the isotopic composition of magmatism appears to remain relatively constant (Tibet) or trend toward more isotopically juvenile compositions (U.S. Cordillera, Andes) (Fig. 1).

3.2. The spatial isotopic trend through time

The isotopic data for the central Andes, western U.S., and Tibet span the Mesozoic to the present. Data for the central Andes include analyses from periods of low-angle subduction and steeper subduction as the magmatic arc swept back and forth across certain sectors of the orogen (Mamani et al., 2010). The spatial isotopic trend is present in both Neogene (e.g., Kay et al., 2005) and Paleogene (Jones et al., 2015) magmatic rocks in the long-lived South American Cordillera (Fig. 2B). Data for the U.S. Cordillera span a time period that includes Farallon slab flattening (Laramide orogeny), low-angle subduction, foundering, and ultimately

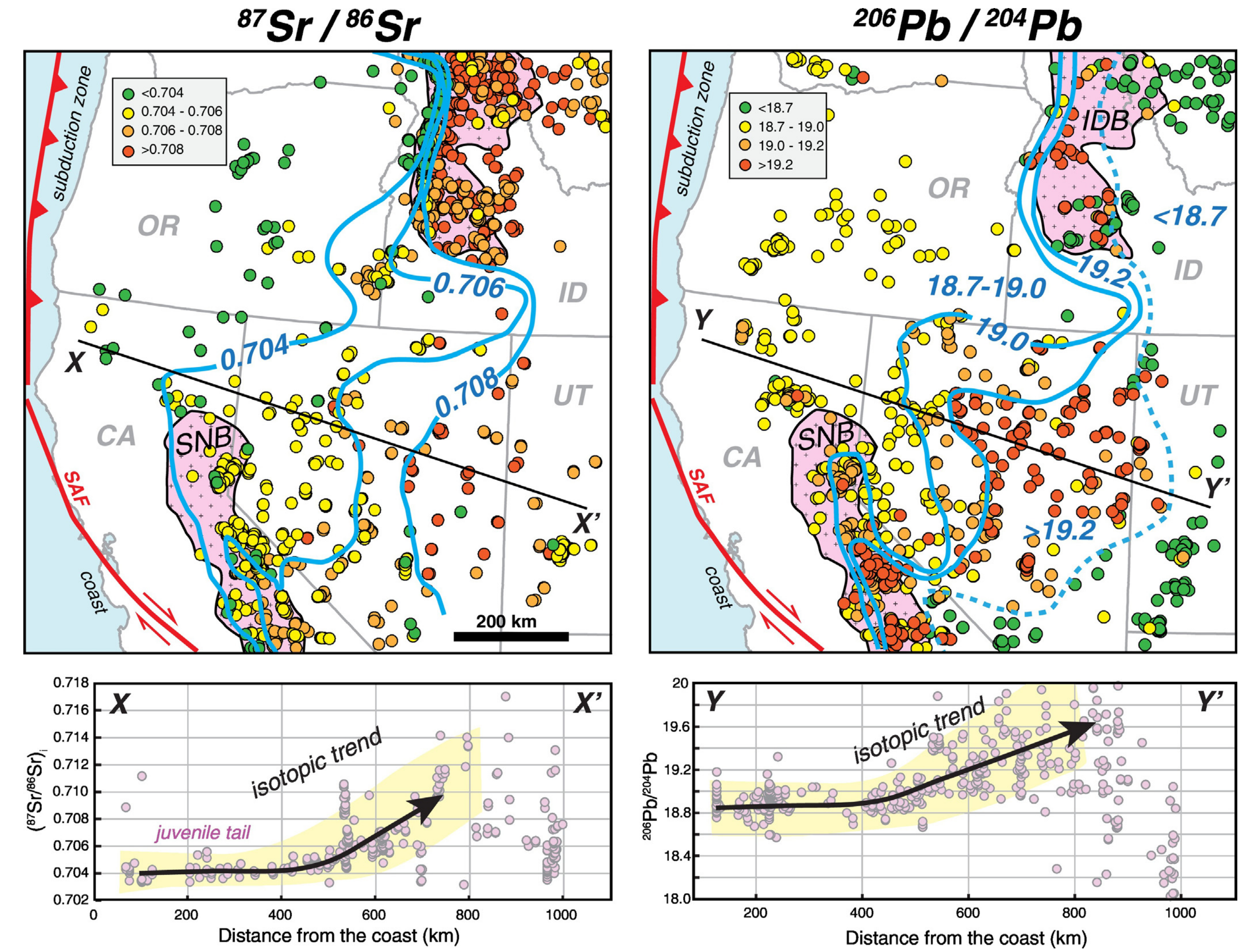

Fig. 4. Top) Maps of ^{87}Sr/^{86}Sr and ^{206}Pb/^{204}Pb isotopic data from Jurassic to Pliocene magmatism in the Northern Basin and Range Province in the U.S. Cordillera. Blue lines are isotopic contours (isopleths) except for the dashed blue line that is a sharp isotopic boundary. Bottom) Plots of isotopic data vs. distance across the U.S. Cordillera. Data plotted is from within ~100 km on either side of the cross-section line. Both Sr and Pb data display spatial trends (black arrows) to more evolved isotopic compositions in a landward direction. OR = Orgeon, ID = Idaho, CA = California, UT = Utah, SAF = San Andreas Fault, IDB = Idaho Batholith, SNB = Sierra Nevada Batholith.
Data sources are discussed in the text.

crustal extension (Miller et al., 2000). The timing for the start of Cenozoic continental extension in the U.S. Cordillera is diachronous, but widely distributed "Basin and Range" extension appears to have initiated at ~20 Ma (McQuarrie and Wernicke, 2005). Magmatism younger than 20 Ma **s**hows a 5 to 10 unit shift of εNd to more isotopically juvenile values, although the broad shape of the isotopic trend is still reasonably preserved (Fig. 2A). The data compiled from the U.S. Cordillera do not include magmatic rocks <5 Ma, which display the strongest temporal shift to more juvenile isotopic compositions (e.g., Farmer et al., 1989), although there are many locations where Pliocene and younger basalts associated with extension do have isotopically evolved compositions (Ormerod et al., 1991; DePaolo and Daley, 2000). Isotopic data from Tibet show a 5 to 10 unit shift of εHf to more isotopically evolved values for analyses of rocks younger than ~50 Ma (Fig. 2C), following the India-Asia collision (Yin and Harrison, 2000). Fig. 2D shows interpretive trend lines drawn through subsets of the Tibetan magmatic data for several time periods, which are intended to represent the spatial isotopic trend at that time. The exact isotopic values and slope of the spatial isotopic trend varies through time in Tibet, although it consistently shows more isotopically evolved values north of the suture zone (negative slope in Fig. 2D) and the range of isotopic values encompassed by the trend is generally on the order of 20 to 30 εHf units.

Together, these results suggest that the spatial isotopic trend remains relatively constant (trend slope, isotopic range) throughout the life of a Cordilleran orogen. During this time, numerous processes such as slab flattening, roll-back, and subduction erosion may shift the locus of magmatism; however, the spatial isotopic trend persists. Remarkably, it appears that the gross shape of the spatial isotopic trend may be preserved during a transition to a different tectonic environment. In Tibet the spatial trend was shifted to more isotopically evolved values following continental collision (Fig. 2C) and in the U.S. Cordillera, the spatial trend was shifted to more isotopically juvenile values following orogenic collapse and continental extension starting in the Miocene (Fig. 2A). Continued extension in the U.S. Cordillera since the Pliocene has resulted in widespread eruption of isotopically juvenile basalt (e.g., Farmer et al., 1989) that marks the end or disruption of the spatial isotopic trend. Thus, for retreating collisional or retreating accretionary orogens that have experienced significant arc or back-arc extension, the spatial isotopic trend may be disrupted.

3.3. Magmatic differentiation and the spatial isotopic trend

Another shared characteristic of the three Cordilleran orogenic belts examined is that the spatial trend toward more evolved isotopic

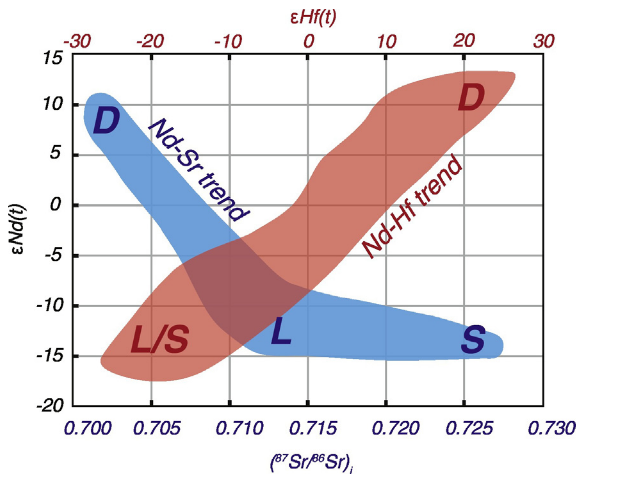

Fig. 5. Compilations of isotopic data of all ages from global sedimentary systems that is representative of the continental crust. The εNd and $^{87}Sr/^{86}Sr$ isotopic data is encompassed by the blue shaded area and the εNd and εHf isotopic systems is encompassed by the red shaded area. Potential melt components in Cordilleran magmatism includes the depleted mantle (D), the deep lithosphere (L) including the mantle lithosphere and lower crust, and upper crust or sediments (S).
Data is from Ben Othman et al. (1989) and Vervoort et al. (1999).

compositions occurs despite large variations in bulk composition. Fig. 3 presents data from the U.S. Cordillera and the central Andes and distinguishes individual analyses by weight % SiO_2 and weight % MgO as an indicator of magmatic differentiation. Tibet is not considered here as most of the data come from in-situ Hf analyses of zircon and less whole rock major element data are available. Magmatic differentiation appears to have an important, but second-order, effect on the isotopic trend. Isotopic data from the U.S. Cordillera show a 5 to 10 unit shift of εNd to more isotopically juvenile compositions for the most mafic samples (Fig. 3A). This isotopic shift mirrors the shift in analyses <20 Ma in the U.S. Cordillera that may be affected by lithospheric extension and crustal thinning (Fig. 2A). In the central Andes, the relationship between magmatic differentiation and isotopic composition is less clear, but there appears to be a similar shift (≤5 εNd units) to more isotopically juvenile compositions for the most mafic analyses (Fig. 3B).

A key observation is that the spatial isotopic trend is present when considering only the most felsic or most mafic (e.g., <55 wt% SiO_2) analyses (Fig. 3). The range of isotopic values that can be attributed to magmatic differentiation (≤10 εNd units) is large, but the salient observation is that it is generally smaller than the overall range in isotopic values (15 to 25 εNd units) across the entire spatial isotopic trend. In some locations, however, the isotopic difference between the most mafic and most felsic samples can account for up to half of the spatial isotopic trend. One way to constrain the deep lithospheric isotopic signature is to define mantle limit lines (e.g., Miller et al., 2000) or to examine the spatial isotopic trend for only the most mafic samples (dashed arrows, Fig. 3). This approach suggests that; 1) the role of magmatic differentiation (distance between the dashed and solid arrows in Fig. 3) increases away from the (paleo) trench and 2) that the magnitude for the spatial isotopic trend may be smaller than observed when considering only the deep lithospheric components. This magnitude is on the order of 10 εNd units for the U.S. Cordillera and the Andes (Fig. 3), which is similar to the maximum range in isotopic compositions for a given location. As a result, if bulk rock compositions can be determined, they are important to help interpret possible isotopic trends.

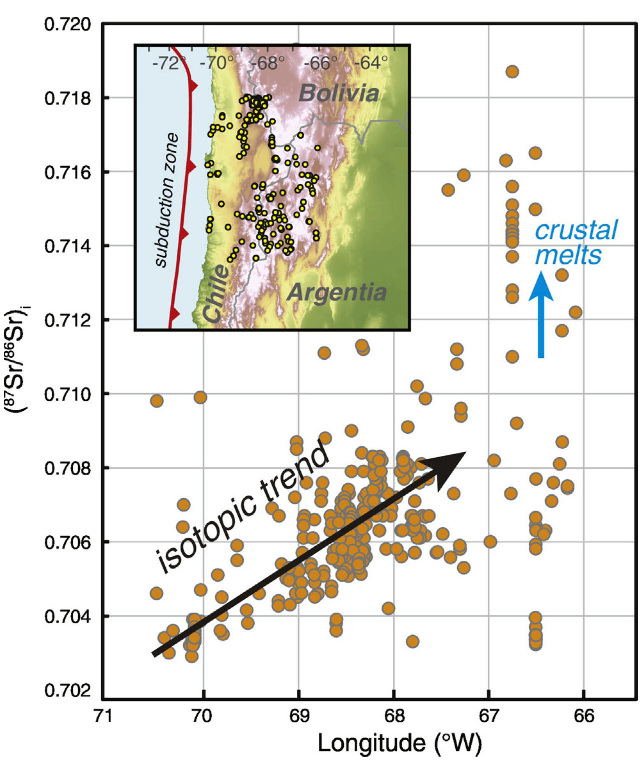

Fig. 6. $^{87}Sr/^{86}Sr$ isotopic data from Mesozoic to modern magmatism the Central Andes showing a spatial isotopic trend with more isotopically evolved values located further from the trench (black arrow). High $^{87}Sr/^{86}Sr$ (>0.712) are interpreted to reflect crustal melting in the Altiplano region (blue arrow).
Data sources are discussed in the text.

4. Discussion

The presence of a spatial trend in the radiogenic isotopic composition of magmatism in three distinct Cordilleran orogens with comparable dimensions (width of trend) and magnitudes (range of isotopic values) leads us to propose that this spatial trend is an inherent feature of Cordilleran orogens. Reinforcing this view is the observation that the spatial trend has persisted throughout geologic time and is present regardless of the degree of magmatic differentiation in each of the examined orogens. This observation is perhaps surprising considering the numerous and diverse tectonic, petrologic, and geodynamic processes that have occurred in these orogenic systems throughout their existence. Below, possible origins for the spatial isotopic trend are considered and some of the implications of the observations are discussed.

4.1. Constraints on the origin of spatial isotopic trends

Although spatial isotopic trends have been recognized in many individual Cordilleran orogens no consensus exists concerning the mechanisms or processes that generate this trend (Kistler and Peterman, 1973, 1978; Farmer and DePaolo, 1983, 1984; Harris et al., 1988; Rogers and Hawkesworth, 1989; Glazner and O'Neil, 1989; Stern, 1991; Ghosh, 1995; Kay et al., 2005; Mamani et al., 2010; Zhu et al., 2011; Boekhout et al., 2015; Jones et al., 2015). In general, three major end-member isotopic source regions exist for Cordilleran magmatism (Ducea, 2001): the depleted asthenospheric mantle (D), the deep lithosphere (L) including the mantle lithosphere and lower crust, and a sedimentary component (S) (Fig. 5). The sedimentary component may be assimilated during magmatic differentiation and emplacement, could originate from subducted sediments or sedimentary rocks, or may be transported to the lower crust during shortening. Most petrogenetic models for Cordilleran magmatism agree that the asthenospheric mantle is the source region for the most isotopically juvenile magmatism (Grove et al., 2012). Discerning the nature of the isotopically evolved end-member(s) in the spatial isotopic trend is more challenging.

The isotopic composition of mantle lithosphere can be heterogeneous, but many studies of upper-mantle xenoliths and mafic volcanism in Cordilleran orogens have shown that the mantle lithosphere can be as isotopically evolved as the overlying crust (Menzies et al., 1983; Carlson and Irving, 1994; Lee et al., 2001; Ducea, 2002). For example, mantle lithosphere xenocrysts erupted during the Miocene in the central Lhasa terrane in Tibet have isotopic values similar to those of their host rocks (≤− 10 εNd) (Miller et al., 1999). Isotopically evolved signatures in mantle peridotites are generally linked to metasomatic events that enrich the mantle lithosphere in incompatible trace elements (e.g., Hf, Nd) (Hawkesworth et al., 1990; Carlson et al., 2005). Presuming that most continental lithosphere was created at magmatic arcs, the elevated concentrations of incompatible elements in the mantle lithosphere likely originate from the subducting slab (Pearce, 1983; McCulloch and Gamble, 1991). Incompatible element enrichment may be contemporaneous with original melt depletion (e.g., Pearson et al., 1995) or may reflect subsequent tectonomagmatic (and fluid enrichment) events (e.g., Gao et al., 2002). In either case, there appears to be long-term mechanical and isotopic coupling between the crust and the mantle lithosphere (Carlson et al., 2005). Partial melts of either the continental mantle lithosphere or the mafic lower crust may have similar isotopic values that predominantly reflect the age of the lithosphere. For lithosphere of sufficient age, the deep lithosphere (L) could potentially be the source region for the isotopically evolved end-member in the spatial isotopic trend (Fig. 5).

In addition to crust-mantle fractionation, the Rb/Sr system is sensitive to intracrustal fractionation. Rb/Sr, and hence $^{87}Sr/^{86}Sr$, increases exponentially for felsic melts >~65 wt% SiO_2 (Faure, 2001). Values of $^{87}Sr/^{86}Sr$ >~0.712 have been linked to upper-crustal processes including crustal anatexis, advanced fractional crystallization in plagioclase-bearing systems, and weathering-erosion-sedimentation cycles (McCulloch and Chappell, 1982; McDermott and Hawkesworth, 1990). The effect of intracrustal fractionation can be visualized by the change in slope for global data trends above $^{87}Sr/^{86}Sr = 0.712$ in plots of εNd versus $^{87}Sr/^{86}Sr$ (Fig. 5). Because of these characteristics, $^{87}Sr/^{86}Sr$ data are a powerful tool to recognize sedimentary or upper crustal (S) components. High values of $^{87}Sr/^{86}Sr$ are rare in spatial isotopic trends, with relatively few data points >0.712 (Figs. 4, 6). In some cases, like the central Andes, these high $^{87}Sr/^{86}Sr$ values are too large to be a credible end-member of the spatial isotopic trend (Fig. 6). Instead, these high values likely represent a separate, intracrustal fractionation trend associated with crustal melting in the Altiplano (de Silva, 1989; Rogers and Hawkesworth, 1989). In other cases, like the U.S. Cordillera, this relationship is less clear and high $^{87}Sr/^{86}Sr$ values could be an end-member in a mixing trend with a depleted mantle end-member (Fig. 4). Distinguishing between a deep lithosphere (L) source region or mixing between upper crustal/sedimentary (S) and depleted mantle (D) components presents a fundamental dilemma in interpreting isotopic data in Cordilleran magmatism, as these two options are often isotopically non-unique (Fig. 5).

4.2. Evaluating crustal components in Cordilleran magmatism

Two potential mechanisms can mix upper crustal or sedimentary components with depleted mantle components in Cordilleran magmatism: contamination of the melt region and assimilation during emplacement. Contamination of a mantle source to generate more isotopically evolved magmatism can occur by melting sediment or crust that was subducted. For example, in the central Andes, a shift to more evolved isotopic compositions during the Neogene is coincident with an eastward (landward) geographic shift in magmatism (Haschke et al., 2006; Mamani et al., 2010). Some researchers have suggested that sediment subduction and subduction erosion could explain both the more isotopically evolved magmatism and the landward geographic shift (Stern, 1991; Kay et al., 2005). Sediment subduction and subduction erosion may be important processes throughout the history of the Andes or other Cordilleran orogens, but the persistence of the spatial isotopic trend through geologic time suggests that subduction of sediment/crust is not the dominant mechanism generating the isotopic trend. A very specific set of subduction parameters would need to be met to always emplace magmatism with similar isotopic compositions in the same geographic location throughout geologic time (Rogers and Hawkesworth, 1989, 1990; Stern, 1990). Sediment subduction and subduction erosion are episodic and volumetrically variable (von Huene and Scholl, 1991) and it is unlikely that mixing between the depleted mantle wedge and subducted continental material would consistently produce the same isotopic composition at the same position. Moreover, much of the sediment delivered to the trench in Cordilleran systems is derived from relatively isotopically juvenile magmatic arcs with more limited volumes of sediment originating from the more isotopically evolved continental interior (Linn et al., 1992; Ghatak et al., 2013; Dumitru et al., 2015; Ducea et al., 2015b).

A similar set of arguments suggests that subducted continental lithosphere may not be responsible for the spatial isotopic trend. Of the Cordilleran systems examined here, only Tibet is considered to have experienced widespread subduction of continental lithosphere. Although a shift to more evolved isotopic compositions in magmatism follows the collision of India (Ji et al., 2009; Xu et al., 2010; Jiang et al., 2014; Chen et al., 2015), the spatial isotopic trend in Tibet existed throughout the Mesozoic, prior to the collision of India, and its shape and range of values have remained relatively constant (Fig. 2B). As in the case of the Andes, we find it improbable that the various petrologic processes have aligned in such a way as to consistently produce magmatism of similar isotopic values the same distance from the Indus-Yarlung suture throughout geologic history (Fig. 2C). It is also unclear why melting of subducted continental crust (i.e., India) or continentally-derived sediment would produce an isotopic trend that becomes more isotopically evolved away from the trench rather than toward the trench or consistently across the orogen (Fig. 1). Subduction of continental lithosphere in the down-going plate is distinct from underthrusting in a retroarc thrust belt, which is a viable mechanism to introduce isotopically evolved deep lithospheric (lower crust and mantle lithosphere) components into a melt source region (Ducea, 2001).

Crustal assimilation is the other mechanism that could introduce sedimentary or crustal components into Cordilleran magmatism and produce the spatial isotopic trend (Farmer and DePaolo, 1983, 1984; Mamani et al., 2010; Jones et al., 2015). The majority of magmatic products in Cordilleran orogens are of intermediate composition and require at least a two-stage melt process that involves melting in the mafic lower crust (Ducea et al., 2015b). Melting, assimilation, storage, and homogenization (MASH) processes in the lower crust and assimilation and fractional crystallization (AFC) processes all conspire to contaminate magmas with crustal material that may be more isotopically evolved than the original mantle source (DePaolo, 1981; Hildreth and Moorbath, 1988; Annen et al., 2006). This suggests that the age of the crust could play an important role in determining the isotopic composition of intermediate magmatism.

Crustal contamination may produce the spatial isotopic trend by assimilating older, more isotopically evolved, continental crust farther away from the trench (Fig. 7A). This model has been most successfully applied to the central U.S. Cordillera where changes in isotopic values spatially coincide with the transition between cratonic basement and younger accreted terranes (Farmer and DePaolo, 1983), commonly delimited by the $^{87}Sr/^{86}Sr = 0.706$ line (Kistler and Peterman, 1973, 1978) (Fig. 4). In contrast with the central U.S. Cordillera, the ages of basement terranes generally decrease and become more isotopically juvenile landward of the paleo-trench in the southern U.S. Cordillera (Bowring and Karlstrom, 1990; Wooden et al., 2013) (Fig. 3). The oldest basement terrane in the southern U.S. Cordillera is the Mojave terrane with ~2.2 Ga Nd model ages (Wooden et al., 2013). The western limit to the Mojave terrane is unknown, but Miller et al. (2000) suggests that Proterozoic crust extends at least to ~117°W and some studies suggest it may extend all the way to the San Andreas Fault (Martin and Walker, 1992). If assimilation of variably aged continental crust was the primary control on the spatial isotopic trend, compositions would

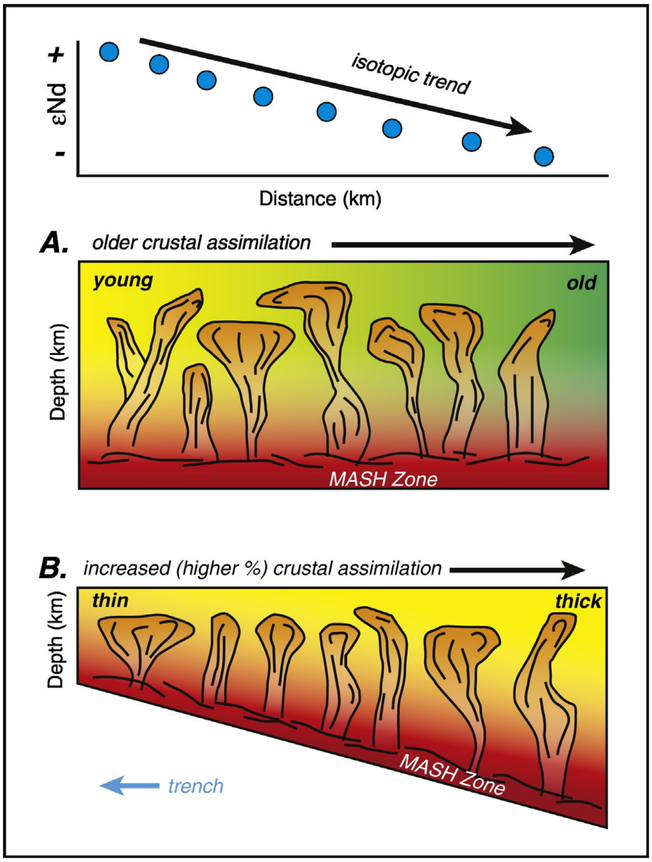

Fig. 7. A diagram showing two ways that crustal assimilation could produce the spatial isotopic trend. In both cases, the depleted asthenospheric mantle is the source for magmatism. A) Assimilation of older (i.e. more isotopically evolved) crustal material located further from the trench. B) Larger degree of assimilation as a result of thicker or hotter crust of uniform age and isotopic composition. Both explanations (A and B) are unsatisfactory because of the limited variation of isotopic values associated with differences in magmatic differentiation and the existence of the spatial isotopic trend when considering only the most mafic magmatic products (Fig. 3). Crustal assimilation processes may be superimposed on the spatial isotopic trend. MASH = mixing, assimilation, storage, homogenization.

be expected to become more isotopically evolved as they were emplaced into older terranes. For example, this pattern is observed when considering magmatism between the Mazatzal terrane (~1.7 Ga crust) and Yavapai terrane (~1.8 Ga crust) (Fig. 3). However, the isotopic compositions of magmatism in the older Mojave terrane are on average more isotopically juvenile than the adjacent Yavapai terrane (Fig. 3). Furthermore, in the other Cordilleran orogens examined, there is no obvious correlation between the spatial isotopic trend and crustal basement provinces. In Tibet, the spatial isotopic trend occurs entirely within the Lhasa terrane (Yin and Harrison, 2000) and in the central Andes, the isotopic trend occurs within the para-autochthonous Antofalla terrane (Ramos, 2009; Casquet et al., 2014) (Fig. 3). These Cordilleran orogens would require heretofore unrecognized crustal sub-provinces to account for the spatial isotopic trend. For example, Zhu et al. (2011) have proposed southern, central, and northern Lhasa terrane sub-provinces to explain the existence of the spatial isotopic trend in Tibet.

Another way that crustal assimilation could account for the spatial isotopic trend is if the degree of contamination increases landward (Fig. 7B). An increase in crustal thickness away from the trench could lead to more efficient assimilation (hotter lower crust) or prolonged crustal assimilation during magma ascent that may lead to more evolved isotopic compositions (Farmer and DePaolo, 1983; Hildreth and Moorbath, 1988). This concept has been proposed as a way to estimate crustal thicknesses by assuming that melts originate with depleted mantle isotopic compositions and become progressively enriched in thicker crust (DePaolo et al., 2013; Harison et al., 2013). Although crustal assimilation is an important process in determining the isotopic composition of magmatism, we suggest that the effect of assimilation is subordinate to and superimposed upon the Cordilleran spatial isotopic trend. The spatial isotopic trends from the U.S. Cordillera and central Andes both show limited isotopic variation (<10 εNd units) with changes in wt% SiO_2 and MgO (Fig. 3) that can be attributed to crustal assimilation. The post ~50 Ma shift (≤10 εHf units) to more evolved isotopic compositions at a given distance from the Indus-Yarlung suture in Tibet may also reflect increased crustal contamination, perhaps associated with the thickening of Tibetan crust (Liu et al., 2014) (Fig. 2). The magnitude of the isotopic shift (≤10 εHf units) ascribed to crustal assimilation is relatively constant along the length of the isotopic trends (Fig. 3), which suggests that the distance from the trench may not significantly affect the degree of assimilation.

A hybrid mechanism to incorporate upper crust or sedimentary components into the melt region, involving both subduction and assimilation, is relamination (Hacker et al., 2011). Like other subduction related processes discussed above, relamination is a sporadic process and is expected to generate temporally variable isotopic magmatism that reflects the amount of subducted sedimentary component (Vogt et al., 2013) and cannot explain the persistence of the spatial isotopic trend through time. Like crustal assimilation processes discussed above, there is no explanation for why relamination would occur in a spatially consistent pattern through time or why the amount of relaminated material in the lower crust would regularly increase landward of the trench and magmatic arc.

Magmatic suites that show a correlation between magmatic differentiation and radiogenic isotopic composition are commonly interpreted to have obtained their isotopically evolved character through crustal contamination (DePaolo, 1981). A common method to work around or "see through" the potential influences of crustal contamination is to examine only the most mafic end-members in a magmatic suite (e.g., Coleman and Glazner, 1997). It is difficult to contaminate a mafic melt with enough felsic crustal material to generate significantly evolved isotopic signatures (>~5 εNd unit shift) without changing the major and trace element composition of the melt (Rudnick, 1990; Reiners et al., 1995; Bohrson and Spera, 2001). If the spatial isotopic trend represents a mixing line between isotopically juvenile basalt extracted from the mantle wedge and isotopically evolved crustal material, then the most mafic end-members in a magmatic suite should preserve relatively juvenile isotopic compositions that are independent of the composition of the overlying crust. The results reveal that the isotopic composition of the most mafic magmatism in Cordilleran orogens mirrors the overall spatial isotopic trend and becomes increasingly isotopically evolved landward of the trench (Fig. 3), suggesting that the isotopically evolved mafic end-members were derived from a more isotopically evolved mantle lithosphere source. This observation is supported by studies examining vertical changes in isotopic composition in Cordilleran batholiths. Lower crustal xenoliths commonly show similar isotopic compositions to the upper crust (Domenick et al., 1983; Ducea and Saleeby, 1998; Vervoort et al., 2000) and vertical sections through extinct, exhumed Cordilleran arcs show limited changes in isotopic composition (<10 εNd units) with changes in depth as well as weight % SiO_2 (Otamendi et al., 2009; Walker et al., 2015) (Fig. 8). The lower crust in Cordilleran arcs is dominated by mafic plutonic complexes that are transitional with and sourced by the mantle (Saleeby, 2003; Ducea et al., 2015b), supporting the isotopic association between the upper mantle and lower crust in Cordilleran arcs (Fig. 8).

4.3. The role of continental mantle lithosphere

Seismic data from active Cordilleran margins, including the Andes and the northwest U.S. Cordillera (Cascades), show that the distribution

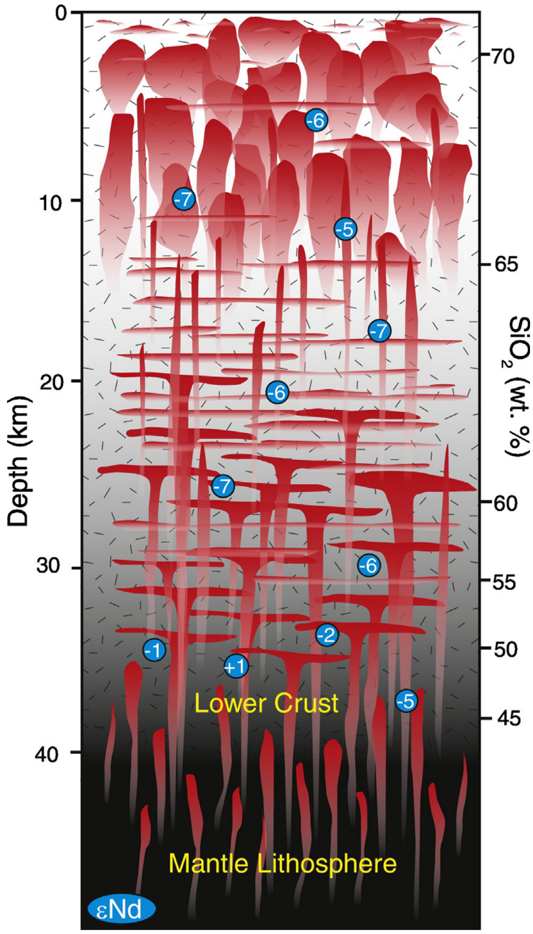

Fig. 8. A schematic vertical section through the Ordovician Famatinian continental arc in Argentina (modified from Otamendi et al., 2012). Plotted in blue circles, according to SiO_2 weight %, are εNd data from samples collected along an exhumed portion of the Famatinian arc (Walker et al., 2015). The section and the depth of the SiO_2 contents are illustrative only and are one possible representation of the magmatic and crustal architecture in a Cordilleran arc batholith. The mantle lithosphere and mafic lower crust are compositionally and isotopically transitional. Limited changes in εNd occur from top to bottom in the vertical section.

of mantle lithosphere is highly irregular and that in many places mantle lithosphere has been removed or is in the process of being removed (Beck and Zandt, 2002; Levander and Miller, 2012). The removal of mantle lithosphere beneath continental arcs is thought to be neither steady nor uniform in time (Beck et al., 2015). Numerous tectonic processes serve to remove mantle lithosphere beneath Cordilleran orogens. Cumulates in the root of continental magmatic arcs periodically founder into the asthenospheric mantle, removing lithospheric mantle in the upper plate (Ducea and Saleeby, 1998; Ducea, 2002). Crustal thickening can result in delamination of lower crust and mantle lithosphere (Molnar et al., 1993; Kay et al., 1994; Sobolev et al., 2006). Tectonic ablation by the subducting plate may erode upper plate mantle lithosphere (Pope and Willett, 1998; Levander et al., 2014). Convective removal may also intermittently destroy mantle lithosphere (Houseman et al., 1981; Molnar et al., 1993; Platt and England, 1994). Besides removal, conductive cooling (McKenzie et al., 2005) and compositional changes associated with melt extraction are possible mechanisms to build or add mantle lithosphere (Lee et al., 2011), but these processes occur on time scales often exceeding the life of the orogen. Another possible mechanism to add mantle lithosphere beneath a Cordilleran orogen is by underthrusting (upper plate) lower crust and mantle lithosphere in a retroarc thrust belt (Ducea, 2001). If upper plate shortening in the retro-arc thrust belt and sub-lithospheric processes that remove or thin mantle lithosphere are linked in an orogenic cycle (DeCelles et al., 2009, 2015; DeCelles and Graham, 2015), then feedbacks could potentially converge on a steady-state or stable mantle lithosphere geometry on time scales equivalent with the periodicity of the cyclic processes (10s of Myr). In contrast to the dynamic upper mantle beneath Cordilleran orogens, the mantle lithosphere in continental interiors is thought to be stable and thick (Yuan and Romanowicz, 2010). Thus, a first-order feature of Cordilleran orogenic architecture is a transition from thick, stable mantle lithosphere far from the active margin to variably thinned or modified mantle lithosphere beneath the frontal arc. Tectonically undisturbed mantle lithosphere accounts for much of the strength of continental lithosphere (Burov and Watts, 2006) and the loss or modification of the mantle lithosphere in tectonically active regions is likely a critical factor in the reduction of lithospheric strength (Thatcher and Pollitz, 2008) and ultimately may explain the diffuse nature of deformation in continental convergent margins (Molnar, 1988).

Partial melting in the mantle is primarily controlled by temperature, pressure, and water content and occurs over a broad region (≥100 km horizontal distance) (Tatsumi, 1989). Inclusion of (potentially melt-fertile) mantle lithosphere in the melt region could result in the amalgamation of melt that includes both lithospheric and asthenospheric mantle. Far from the magmatic arc, where mantle lithosphere is thick, the influence of asthenospheric melts may be small, producing more isotopically evolved magmatism (Fig. 9). The influence of the depleted mantle grows as the volume or thickness of the mantle lithosphere decreases trenchward (Fig. 9). As magmatism sweeps back and forth across a Cordilleran orogen, melts originating in the mantle could impart an isotopic signature to the lower crust that reflects the variable mixing of lithospheric and asthenospheric mantle at depth. Small-scale foundering of mafic lower crustal cumulates may also result in isotopic mixing in the upper mantle (Ducea and Saleeby, 1998).

For example, consider the Gangdese magmatic arc in Tibet. This arc records ~150 Myr of Cordilleran-style subduction and magmatism prior to the collision with India (Fig. 2C, D). During this time, there may never have been an isotopically evolved mantle lithosphere source beneath the southern margin of the Lhasa terrane, insofar as Lhasa terrane lower crust has been dominated by isotopically juvenile additions throughout the lifetime of the arc (Zhu et al., 2011). This scenario is similar to the western Sierra Nevada batholith (Wenner and Coleman, 2004). In the central to northern Lhasa terrane, however, intact or mildly thinned mantle lithosphere likely existed prior to the collision of India (DeCelles et al., 2007, 2011) and could have influenced the isotopic composition of the lower crust. Post-collisional magmatism in Tibet involving secondary melting in the lower crust or crustal anatexis may retain this isotopic signature, even if the original mantle lithosphere beneath the Lhasa terrane has been replaced by subducted Indian lithosphere (Owens and Zandt, 1997). It is also possible that a thin Tibetan mantle wedge, preserved beneath the Lhasa terrane after subduction of India, continued to be the source region for orogenic magmatism into the Cenozoic (Lu et al., 2015).

An extension of the argument presented above, that the deep lithosphere (isotopically homogenized mantle lithosphere and lower crust) forms the isotopically evolved end-member farthest from the trench in the spatial isotopic trend, is that magmatism located landward of the spatial isotopic trend should also reflect the isotopic composition (and age) of the deep lithosphere and the depleted asthenospheric mantle component may be less significant (Fig. 9). If the age of the lithosphere is laterally consistent, then the isotopic value of magmatism may remain constant landward of the isotopic trend (e.g., Tibet, Fig. 1). If the age of the lithosphere changes, for example across basement terrane boundaries, then the isotopic signature of magmatism may reflect that change. Fig. 3A shows that in the southern U.S. Cordillera, basement terranes become younger (more juvenile) eastward, consistent with the increase in εNd beyond the spatial isotopic trend (east of ~113°W longitude). Magmatism also becomes increasingly isotopically juvenile east of the spatial isotopic trend in the Andes (Fig. 3B). This may reflect a younger part of the Antofalla crustal domain (Mamani et al.,

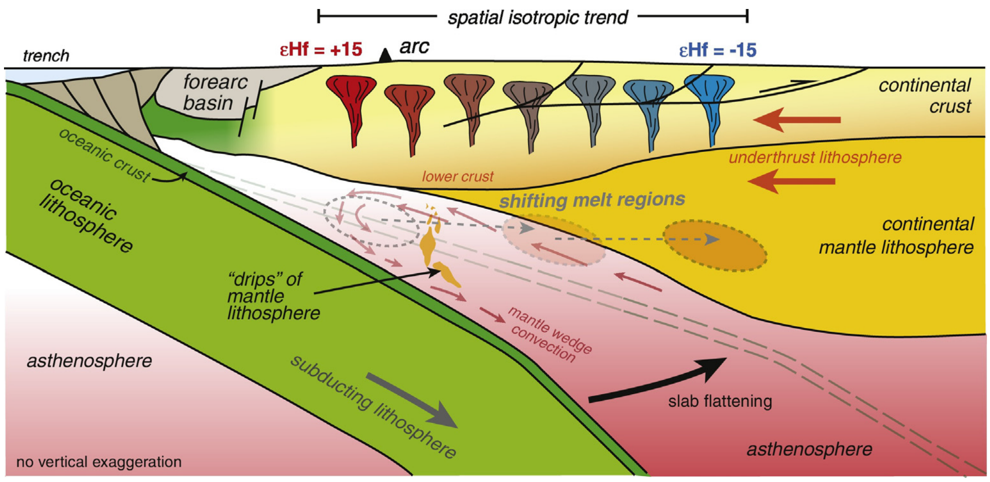

Fig. 9. A generic cross-section across a Cordilleran orogen illustrating a possible scenario that explains the origin of the spatial isotopic trend. Relatively thicker continental lithospheric mantle underlies continental crust landward of the trench, toward the craton. Closest to the trench no mantle lithosphere is preserved. Beneath the orogen, sub-lithospheric processes like dripping, delamination, subduction erosion, and tectonic ablation have thinned or removed the mantle lithosphere. This is a single snapshot in time, in reality the distribution of mantle lithosphere beneath an active continental arc is dynamic and includes periods of net removal, addition, and chemical modification. In this example, the age and isotopic composition of the continental lithosphere is constant and does not change laterally (from left to right in the figure). In orogens with older (more isotopically evolved) lithosphere thrust beneath the arc, the spatial isotopic trend may be amplified. Melts originating in the upper mantle closest to the trench are isotopically juvenile and derived from the asthenosphere. Partial melting of the mantle that occurs farther away from the trench (e.g., in response to slab flattening) may incorporate increasing amounts of isotopically evolved continental lithospheric mantle in the melt region. Through time, melts from the upper mantle may impart their isotopic composition on the lower crust. The spatial isotopic trend, which may be up to a few hundred kilometers in width, is a result of the locus of magmatism shifting back and forth across a modified mantle lithosphere (and isotopically similar lower crust) that may have a general tapered shape when considered over long (10^7 yr) time scales.

2010) or perhaps be related to the Mesozoic Salta rift system (Ramos, 2009). Collectively, the results suggest that much of the magmatism in orogenic interiors may have a deep lithospheric source. In all of the cases considered, magmatism that extends up to several hundred kilometers inboard of the subduction zone likely reflects changes in subduction zone dynamics like low-angle or flat subduction. In these situations, the magmatic products and eruptive volumes may not be reflective of the type of arc magmatism that produces large coastal batholiths (e.g., Sierra Nevada, Gangdese) and experiences periodic high flux events (Ducea and Barton, 2007).

4.4. Implications for tectonic studies

The characteristics of the spatial isotopic trend can be employed to explore the role of the continental lithospheric mantle in the evolution of Cordilleran orogenic systems. This is a boon to studies of the deep lithosphere as the mantle lithosphere is one of the most difficult parts of the lithosphere to study. However, it also requires vigilance in interpretations of tectonic processes, particularly those involving the crust, and highlights the non-uniqueness of such interpretations.

One possible application of the spatial isotopic trend may be to provide information about subduction polarity in continental arcs. Tectonic settings of many ancient continental arcs are obscured by subsequent deformation and accretion processes, such as the Mesozoic Carpathian arc (Gallhofer et al., 2015) or Paleozoic arcs within the Central Asian Orogenic Belt (Windley et al., 2007). The persistence of the spatial isotopic trend throughout the life of a Cordilleran orogen suggests that this isotopic pattern may be preserved in the geologic record. Ideal candidates for this type of application would include magmatic belts with a large range of isotopic compositions (≥15 εNd units) that are emplaced within a single lithospheric domain (similar age and composition).

If the spatial isotopic trend is reflective of a ratio between asthenospheric depleted mantle components and deep lithospheric melt components, as proposed, then it is a possible that isotopic values within this trend can be used to gauge the volume or thickness of the mantle lithosphere in modern and ancient Cordilleran orogens, assuming long-term coupling of the lithosphere and no significant lateral changes in age or composition of the mantle lithosphere. This potential application is complicated in Cordilleran orogens with large amounts of shortening (e.g., Central Andes) where hundreds of kilometers of lower crust and mantle lithosphere were underthrust beneath the magmatic arc (McQuarrie et al., 2008). In the right circumstances and with enough temporal resolution, changes in the spatial isotopic trend could be used to explore modifications to the mantle lithosphere. Consider the Death Valley region (~117°W longitude) in the western U.S. Cordillera, which is part of the Mojave crustal province, a Paleoproterozoic basement terrane (Wooden et al., 2013). In the Death Valley area, Mesozoic arc rocks are isotopically evolved (εNd = −15 to −5) (Rämö et al., 2002), late Paleogene to early Miocene magmatic rocks are more moderately isotopically evolved (εNd = −5 to +5) (Miller et al., 2000) and Pliocene and younger volcanic rocks are isotopically juvenile (εNd = +5 to +10) (Farmer et al., 1995). Although the Pliocene and younger volcanic rocks are all basaltic (~50 wt% SiO_2), the Mesozoic to early Miocene rocks have a large range of SiO_2 contents (50–75 wt%), but have a limited range of isotopic values within a single time period, supporting the role of the mantle lithosphere. In this region, flat-slab subduction of the Farallon plate is thought to have thinned or removed part of the mantle lithosphere (Livaccari and Perry, 1993; Miller et al., 2000; Wells and Hoisch, 2008), potentially leading to the late Paleogene increase in εNd. Lithospheric extension in the Pliocene is believed to have further dismembered the mantle lithosphere and replaced it with asthenospheric mantle, resulting in the second increase in εNd (DePaolo and Daley, 2000). Contrast this example with the Catalina Mountains of southern Arizona (~110°W longitude), which did not experience thinning or removal of the mantle lithosphere prior to Miocene extension. Here, intermittent, intermediate to felsic igneous rocks of Cretaceous through early Miocene age have similar isotopic compositions (εNd = −11 to −5), including a two-mica granite (S-type) associated with the development of a metamorphic core complex (Fornash et al., 2013). Besides the two-mica granite, all of these magmatic rocks were likely produced by secondary melting processes (mantle melt + lower crustal melt) that involved an isotopically homogeneous mantle lithosphere and lower crust. The consistency of the isotopic values indicates a stable and isotopically coupled deep lithosphere (mantle lithosphere and lower crust) throughout this period.

As the locus of magmatism moves or simply broadens across orogenic systems, the resulting magmatic records could be used to interpret periods of arc advance and retreat as magmatism passes through melt regions with variable amounts of mantle lithosphere (i.e., passes across the spatial isotopic trend). For example, in Tibet a shift to more juvenile isotopic values from the middle Eocene to the Miocene (Chung et al., 2005; Liu et al., 2014) was accompanied by a geographic shift in magmatism toward the paleo-trench (south in present-day coordinates). This geographic shift has been interpreted to be related to an increase in the dip of subducted Indian lithosphere (Nomade et al., 2004; Ji et al., 2009; DeCelles et al., 2011). Based on similar correlations between magmatic isotopic compositions and tectonic phenomena, some authors have suggested that isotopic changes may record crustal deformation processes (Kemp et al., 2009; Boekhout et al., 2015). In these models, extension in the upper plate may generate or allow emplacement of more isotopically juvenile magmas and crustal shortening and thickening may result in more isotopically evolved magmas. Although processes like slab roll-back, crustal extension, and arc migration may be intimately linked, the resultant temporal shifts in magma isotopic compositions could simply reflect the composition of the deep lithosphere, rather than crustal deformation processes. Distinguishing between these processes is particularly difficult for detrital studies where the spatial record of magmatism is not well constrained.

In another example from Tibet, a shift to more isotopically evolved arc isotopic values between 90 and 30 Ma has been attributed to subduction and melting of Indian continental crust or derivative sediments (Ji et al., 2009, 2012; Xu et al., 2010; Chu et al., 2011; Jiang et al., 2014; Chen et al., 2015). These studies potentially put constraints on the timing of India-Asia collision. However, the same isotopic data can be explained by a contemporaneous spatial shift in magmatism northward from the Indus-Yarlung paleo-trench/suture (Chung et al., 2005). Because the spatial isotopic trend existed prior to the collision of India (Fig. 2C), an alternative mechanism besides the incorporation of Indian continental material is needed to explain landward decreases in εHf values during the Mesozoic. Considering all the data in Tibet, the spatial isotopic trend occurs over a remarkably short distance with a change of ~30 εHf over ~75 km, or ~0.4 εHf/km across the Gangdese Batholith (Fig. 1); this underscores how important even small geographic shifts in the location of magmatism may be to isotopic composition. In the U.S. Cordillera, parts of the Mesozoic coastal batholith that have not experienced significant lithospheric extension also show relatively narrow spatial trends including the Idaho batholith (Fig. 4) and the northern Peninsular Ranges batholith (Kistler et al., 2003).

4.5. Orogenic cyclicity and the isotopic record

Cordilleran magmatic arcs experience periodic, high-flux magmatic episodes (Armstrong, 1988; Barton, 1990; Ducea and Barton, 2007; Ducea et al., 2015a). In some Cordilleran magmatic arcs, these high-flux episodes are associated with temporal shifts to more isotopically evolved magmatic compositions (Ducea, 2001; Haschke et al., 2002; Ducea and Barton, 2007; Kirsch et al., 2016), sometimes called "isotopic pull-downs" as a result of more negative εNd or εHf values (DeCelles et al., 2009). There are two leading explanations for this association. First, Haschke et al. (2002, 2006) suggested that the isotopic pull-downs are reflective of greater crustal assimilation due to periods of crustal thickening. This observation was expanded upon in an orogenic cyclicity model where crustal thickening leads to delamination of lower crust and mantle lithosphere to generate the high-flux events (Ramos, 2009; Ramos et al., 2014). The second, alternative model for orogenic cyclicity suggests that retroarc underthrusting of more isotopically evolved and melt-fertile lower crust into the melt source region may drive isotopic pull-downs and high-flux events (Ducea, 2001; Ducea and Barton, 2007; DeCelles et al., 2009, 2015). The latter process is required to reconcile known large-scale retroarc shortening in thrust belts that do not include lower continental crust and lithospheric mantle (Allmendinger et al., 1990; McQuarrie, 2002; DeCelles and Coogan, 2006) with observed complexity in upper mantle tomographic images beneath the active central Andean cordillera (Beck et al., 2015). A third possibility is that high-flux episodes may be associated with a spatial shift in magmatism away from the trench that produces an isotopic excursion toward more evolved values. Slab migration, potentially associated with a change in slab-dip, may encounter more melt-fertile regions of the lithosphere. Or, high-flux events themselves may magmatically thicken the arc root and drive arc migration by shifting the melt region or melt pathway (Karlstrom et al., 2014). In Cordilleran orogens formed on continents cored by older cratonic lithosphere, cratonward migration of magmatism and retroarc underthrusting of older continental lithosphere into the melt source region would both produce a temporal isotopic shift to more evolved magmatic compositions. It is likely that all of these processes may play a role in isotopic pull-downs associated with high-flux magmatic events to different degrees in different continental arcs, but in any discussion of temporal shifts in isotopic composition, the distance from the trench should be considered. Temporal isotopic shifts are best evaluated when data are analyzed from a single location within an orogen. Generating spatial isotopic trends of the type described in this paper requires long-distance (100s of km) migration of magmatism.

5. Conclusions

Cordilleran orogenic systems share a common spatial trend in which the radiogenic isotopic composition of magmatism becomes increasing evolved landward of the trench, exemplified by the εHf, εNd, and $^{87}Sr/^{86}Sr$ isotopic systems (Figs. 1, 4, 6). This trend occurs within a few hundred kilometers of the trench and persists throughout the life the orogen, which may extend for >100 Myr (Fig. 2). The longevity of the spatial isotopic trend rules out many temporally variable petrogenetic/tectonic processes that could explain the origin of the spatial trend (e.g., materials originating from subducted sediment via either solid-state dehydration reactions or partial melting). The spatial isotopic trend encompasses geochemically diverse magmatic rocks that display a wide range of magmatic differentiation, including low SiO_2/high MgO wt% mafic end-members that were derived from a mantle melt region (Fig. 3). The trend may result from mixing between depleted asthenospheric mantle and isotopically evolved continental lithospheric mantle. Mantle lithosphere can thin toward the trench in Cordilleran systems and its volumetric significance in the mantle wedge is modulated by various processes including delamination, dripping, and subduction ablation that maintain this geometry over time. Thick mantle lithosphere is associated with relatively isotopically evolved magmatic compositions that reflect the age of the lithosphere, and thin to absent mantle lithosphere results in magmatism with juvenile isotopic compositions (Fig. 9). The lower crust in Cordilleran arcs is dominated by mafic magmatic accumulations derived from the underlying mantle that reflect the isotopic composition of the mantle source (Fig. 8). Far from the subduction interface, mantle lithosphere may have remained mechanically and isotopically coupled to the overlying crust since the formation of the lithosphere. Long-term magmatic additions to the crust result in isotopic homogenization of the mantle lithosphere and lower crust, the two components of the deep lithosphere. The results of this study indicate that the asthenospheric mantle wedge may not be a significant source of Cordilleran magmatism away from the plate margin in orogenic interiors and that the deep lithosphere (mantle lithosphere + lower crust) is a more important magmatic component than commonly appreciated. Most models of mantle melting at subduction zones hypothesize that melting takes place almost entirely in the asthenospheric mantle wedge (e.g., Grove et al., 2012).

Many processes affect the isotopic composition of Cordilleran magmatism and they can be superimposed on the spatial isotopic trend. In the examples surveyed in this study the spatial isotopic trend ranges from approximately +10 εNd to −15 εNd (+15 εHf to −20 εHf) (Fig. 1). Deviations of up to ~10 εNd units are common in the spatial isotopic trend and appear to frequently reflect crustal assimilation, in some cases associated with changes in crustal thickness (Figs. 2, 3). Several other processes can affect the isotopic signature of Cordilleran magmatism, including cyclical orogenic processes that are manifest by variations of up to 10 εNd units (Ducea and Barton, 2007; DeCelles et al., 2009, 2015). Because the spatial isotopic trend is imprinted in the deep lithosphere, it may continue to influence the isotopic composition of magmatism even after Cordilleran orogenesis has ceased. For example, Cenozoic collisional magmatism in Tibet continued to reflect the Cordilleran spatial isotopic trend (Fig. 2). Conversely, large magnitude lithospheric extension in the U.S. Cordillera has partially replaced mantle lithosphere and brought asthenospheric mantle close to the base of the crust, resulting in widespread decompression melting and basaltic volcanism in the Pliocene that does not reflect the prior spatial isotopic trend (Menzies et al., 1983). Locally, in places where the U.S. Cordilleran lithosphere has avoided significant extension, these basalts reflect deep lithosphere isotopic components (Farmer et al., 1989). Resolving spatial isotopic trends and exploring deviations from the trend can provide insight into the evolution and architecture of the mantle lithosphere in orogenic systems.

Recognition of the spatial isotopic trend also has important implications for interpreting the causes of temporal changes in the isotopic composition of Cordilleran magmatism. Some temporal isotopic shifts can be explained by the advance, retreat, or broadening of magmatic centers, which could change the proportion of continental mantle lithosphere present in the primary mantle melt region. Detrital isotopic studies in particular (e.g., U-Pb-εHf in zircon) should include arc migration, irrespective of the tectonic processes associated with that migration, as one of the possible interpretations of temporal isotopic shifts. Temporal isotopic trends recorded in a single location should not be affected by the spatial isotopic trend. Removing, or correcting for, spatially controlled isotopic variations may help resolve or highlight the significance of isotopic changes related to other orogenic processes.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gr.2017.04.019.

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