Tracking changes in crustal thickness during orogenic evolution with Sr/Y: An example from the North American Cordillera

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ABSTRACT

Global compilations indicate that the geochemistry of arc magmatism is sensitive to Moho depth. Magmatic products are prevalent throughout the history of Cordilleran orogenesis and can be employed to constrain the timing of changes in crustal thickness as well as the magnitude of those changes. We investigate temporal variations in crustal thickness in the United States Cordillera using Sr/Y from intermediate continental arc magmas. Our results suggest that crustal thickening began during the Late Jurassic to Early Cretaceous and culminated with 55–65-km-thick crust at 85–95 Ma. Crustal thicknesses remained elevated until the mid-Eocene to Oligocene, after which time crustal thicknesses decreased to 30–40 km in the Miocene. The results are consistent with independent geologic constraints and suggest that Sr/Y is a viable method for reconstructing crustal thickness through time in convergent orogenic systems.

INTRODUCTION

Several geochemical indices have been proposed as proxies for crustal thickness in magmatic arcs (Dickinson, 1975; Leeman, 1983; Hildreth and Moorbath, 1988; Plank and Langmuir, 1993; Mantle and Collins, 2008; Chiaradia, 2015). These proxies are all calibrated on a regional to global scale by comparing the compositions of recently emplaced magmatic rocks to geophysically determined crustal thicknesses. In principle, if correlations exist between geochemical parameters and crustal thickness in modern arc regions, geochemical indices could then be used to determine crustal thicknesses in the geologic past. For example, Mantle and Collins (2008) used maximum Ce/Y in basalts to infer changes in crustal thickness of the New Zealand orogen since 400 Ma. However, in continental arcs dominated by intermediate to felsic compositions, geochemical signatures can be generated by multiple petrogenetic processes, which introduces interpretive uncertainty (Ducea et al., 2015). This uncertainty is overcome in global correlations by using very large data sets (e.g., Chiaradia [2015] for Sr/Y), but becomes problematic when attempting to apply these techniques to specific orogens through time with more limited data. As a result, geochemical indices have most often been employed as qualitative indicators of crustal thickness in continental arcs (e.g., Kay and Mpodozis, 2001; Best et al., 2009; Paterson and Ducea, 2015).

To explore how to bridge the gap between global compilations and studies focused on single orogens, we chose to examine the United States (U.S.) Cordillera interior using Sr/Y. Sr/Y in magmatic arcs has recently been correlated to crustal thickness globally (Chiaradia, 2015), and the petrologic controls on Sr/Y have received considerable attention because of its use in classifying adakites (Castillo, 2012). The U.S. Cordillera is an ideal area to test correlations between Sr/Y and crustal thickness because of the prevalence of calc-alkaline, arc-like magmatism that was active during orogenic growth and collapse. Crustal thickening in the U.S. Cordillera commenced in the Mesozoic and culminated in the formation of an orogenic plateau, the Nevadaplano (western U.S.), which was eventually dismembered by extension and crustal thinning to create the Great Basin (DeCelles, 2004; McQuarrie and Wernicke, 2005).

Sr/Y AND CRUSTAL THICKNESS

During partial melting of lower-crustal gabbros or magmatic fractionation of mantle-derived mafic magmas, Sr is compatible at low pressures (<~10 kbar) where it strongly partitions into plagioclase (e.g., Kay and Mpodozis, 2001). However, at high pressures (>12 kbar), where plagioclase is unstable, Sr is incompatible and preferentially enters the liquid phase. Conversely, Y is incompatible at low pressures, but readily partitions into garnet and amphibole at high pressure (e.g., Lee et al., 2007). As a result, Sr/Y is a common qualitative indicator of the average crustal pressure, or depth, at which magmatic differentiation occurred (Paterson and Ducea, 2015). A larger Sr/Y ratio signifies a greater pressure or depth. Observations in many magmatic arcs have shown repeatedly that the bulk of compositional diversification processes take place in the deeper parts of arc crust (MASH [melting, assimilation, storage, homogenization] zone), where it is thermally more efficient (e.g., DePaolo, 1981; Hildreth and Moorbath, 1988), regardless of whether the arc had a thin or thick crust. Therefore, the expectation that these geochemical parameters can map out crustal thickness is not unrealistic. This inference is supported by the variability in Sr/Y for intermediate compositions when averaged over multiple arcs and by global correlations between Sr/Y and Moho depth (Chiaradia, 2015).

Melting of subducted oceanic crust can also generate intermediate magmas with high Sr/Y (Defant and Drummond, 1990), but recent studies demonstrate that the majority of Phanerozoic arc magmatic products owe their Sr/Y values to partial melting or crystal fractionation in the crust (Richards and Kerrich, 2007; Castillo, 2012; Chiaradia, 2015). We find little evidence for oceanic slab melts in the U.S. Cordillera during the Mesozoic to Cenozoic. Isotopic data (e.g., $^{18}O/^{16}O$, $^{143}Nd/^{144}Nd$, $^{87}Sr/^{86}Sr$) from igneous rocks indicate a component of continental crust (King et al., 2004; Kistler, 1990; Farmer and DePaolo, 1983), and relatively few analyses have produced Sr/Y > 100, which is greater than expected for differentiation within even the thickest crust based on global compilations.

Limiting analyses to intermediate compositions removes mafic rocks potentially originating from the mantle and more felsic rocks, including leucogranites (rhyolites), that originated by partial melting of local metasedimentary rocks within the middle to upper crust. Although measures of differentiation are commonly linearly related, there is still considerable scatter within natural data sets. As a result, we use multiple measures of differentiation including MgO (cf. Chiaradia, 2015), SiO_2 (cf. Profeta and Ducea, 2015), and Rb/Sr.

Sr and Rb concentrations both rise during magma differentiation, but in highly fractionated magmas Sr declines as crystallization of feldspar removes Sr from the remaining melt, causing Sr/Y to decrease (Gelman et al., 2014; Lee and Morton, 2015). Crustal melts and fractionation within the middle to upper crust are common in areas of very thick crust, including orogenic plateaus like the Altiplano (South America; DeSilva et al., 2015), and we would expect a similar prevalence in the Nevadaplano. Because Rb does not decline with Sr in highly differentiated magmas, we use elevated Rb/Sr as an indicator of highly fractionated magmas. There is significant scatter in the correlation between Rb/Sr and SiO_2, and it is likely that some analyses of intermediate rocks could be affected by Sr loss, even after high-Rb/Sr samples are discarded (Fig. DR1 in the GSA Data Repository[1]). For

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[1] GSA Data Repository item 2015308, Figure DR1 (unfiltered Great Basin rock analyses with proposed data filters); Table DR1 (Great Basin geochemical data); Table DR2 (accepted Great Basin data subsets by area); Table DR3 (discarded Great Basin data subsets by area); Table DR4 (global geochemical data for Quaternary rock analyses); and Table DR5 (compiled global geochemical data by arc), is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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example, extrusive rocks produced from the Altiplano-Puna magmatic body, located at ~18 km depth, are depleted in Sr but have a broad range of Rb/Sr at intermediate compositions (Muir et al., 2014). For this reason, we suggest that Sr/Y in magmatic rocks from the U.S. Cordillera may provide minimum estimates of crustal thickness, particularly for analyses from rocks with ages <45 Ma, which are dominated by ignimbrites.

METHODS AND RESULTS

We used major and trace element data on magmatic (intrusive and extrusive) rocks in the Great Basin region from Nevada and Utah between 119°W and 112°W. We chose this region as it is the best-studied area of the U.S. Cordilleran interior and the Nevadaplano (DeCelles, 2004). We included rock analyses with ages between 200 Ma and 20 Ma, which was intended to capture the orogenic lifespan of the Cordilleran interior, excluding magmatism associated with Basin and Range extension (McQuarrie and Wernicke, 2005). The primary sources for these data are the Western North American Volcanic and Intrusive Rock Database (NAVDAT, www.navdat.org) and a compilation by Best et al. (2009). We filtered data by MgO (1–6 wt%) and SiO_2 (55–70 wt%) and created data subsets by grouping individual analyses with similar ages and geographic location (Fig. 1). We removed Sr/Y outliers from these data subsets using the modified Thompson tau statistical method and calculated median Sr/Y. Data subsets with Sr/Y standard deviations >10 or with average Rb/Sr > 0.2 or Rb/Sr < 0.05 were discarded. Because of unevenly reported or absent age uncertainties in our compiled data, we report mean ages from the data subsets and 5% age uncertainties. Individual analyses, discarded data subsets, and retained data subsets are located in the Data Repository (Tables DR1–DR3).

To ensure that our treatment of the U.S. Cordillera data did not skew existing global correlations (Chiaradia, 2015), we reconstructed the global correlation between Sr/Y and crustal thickness using the same filters and processing steps that we applied to the U.S. Cordillera data set (Fig. 2). We compiled data from the Geochemistry of Rocks of the Oceans and Continents (GEOROC, georoc.mpch-mainz.gwdg.de/georoc/) database and filtered for SiO_2, MgO, and Rb/Sr using the values described above and removed outliers with the Thompson tau method. We included additional arcs and arc segments with thick crust in our correlation (e.g., Andean arc) that were not included in the correlation of Chiaradia (2015) to help investigate periods of time when the crust was thick. When available, we used the same source for crustal thickness estimates as Chiaradia (2015). Otherwise, we used recently published estimates of Moho depth from geophysical studies (see Tables DR4–DR5). All of the compiled arc data form a linear trend, except for the central portion (20°–26°S latitude) of the Central Volcanic Zone (CCVZ) in the Andes, which hosts the Altiplano-Puna magmatic body. Excluding the CCVZ, we performed a simple least-squares regression through the global data set to convert Sr/Y to crustal thickness in the U.S. Cordillera (Fig. 2). We propagated uncertainty from the regression into our estimates of crustal thickness. The greatest variability in Sr/Y occurs for arc thicknesses of 25–30 km, similar to the result of Mantle and Collins (2008) who found the largest variability in Ce/Y to occur for arc thicknesses of ~30 km. This is a common crustal thickness range for arcs, and it is possible that arcs in this range are near steady state and may rapidly change their crustal thickness, depending on subtle dynamics of the subduction system.

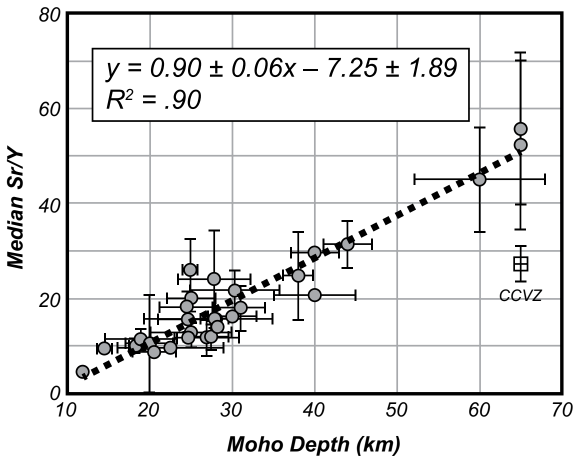

Figure 2. Global correlation between geophysically determined Moho depth and median Sr/Y from Pliocene and younger magmatic arcs, compiled from GEOROC database (georoc.mpch-mainz.gwdg.de/georoc/). Median Sr/Y was calculated using same filters and processing steps as applied to Great Basin data. Data regression includes all data except central segment of Central Volcanic Zone (CCVZ) in the Andes; see text for discussion. Compiled data are included in Tables DR4 and DR5 (see footnote 1).

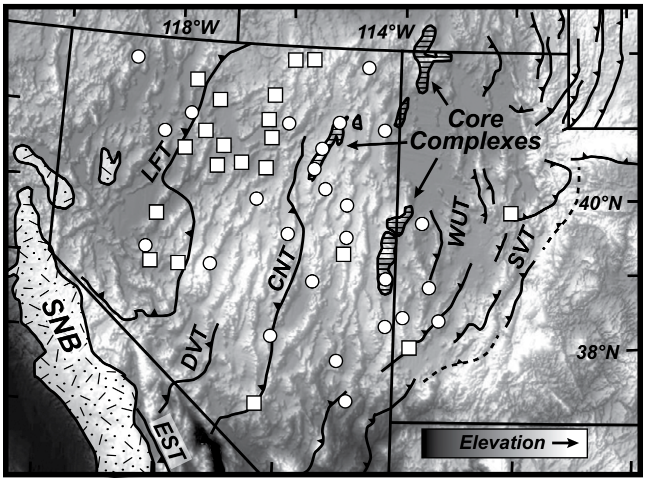

Figure 1. Map of Great Basin region showing all data subsets analyzed (circles) and data subsets used in reconstruction of crustal thickness after data filters were applied (squares). Information on each subset is included in Tables DR1–DR3 (see footnote 1). SNB—Sierra Nevada batholith; EST—Eastern Sierra thrust belt; DVT—Death Valley thrust system; LFT—Luning-Fencemaker thrust belt; CNT—Central Nevada thrust belt; WUT—Western Utah thrust belt; SVT—Sevier thrust belt. Thrust faults are shown with barbs on hanging wall, dashed where approximate.

Median Sr/Y and calculated crustal thickness for the U.S. Cordillera are plotted against age in Figure 3. From the Middle to Late Jurassic, Sr/Y remained relatively constant, corresponding to an average crustal thickness of 30–45 km. Starting in the latest Jurassic to Early Cretaceous, Sr/Y increased, reaching a maximum at 85–95 Ma, corresponding to a crustal thickness of 55–65 km. From the middle Cretaceous to at least the middle Eocene, Sr/Y remained high but relatively constant, corresponding to an average crustal thickness of 55–65 km. Sr/Y began to decrease in the middle Eocene to Oligocene and continued to decrease into the early Miocene, when arc magmatism ceased. Sr/Y in the earliest Miocene correlates to a crustal thickness of 30–40 km. The data coverage reflects a magmatic gap from 130 to 110 Ma, a lull in magmatism from 80 to 45 Ma as the dip of the Farallon slab decreased, and an abundance (flare-up) of magmatism related to roll-back, or foundering, of the slab from 45 to 20 Ma during which time magmatism swept southward through the Great Basin (Dickinson, 2006).

INDEPENDENT CONSTRAINTS ON CRUSTAL THICKNESS

The modern Great Basin once formed the core of the Nevadaplano, a Cordilleran interior orogenic plateau similar to the modern Altiplano-Puna plateau in South America. It was located behind the frontal magmatic arc (Sierra Nevada) and in the hinterland of the retroarc (Sevier) thrust belt (Fig. 1). The Sr/Y data compiled here suggest that crustal thickness began to increase in the Late Jurassic to Early Cretaceous (Fig. 3),

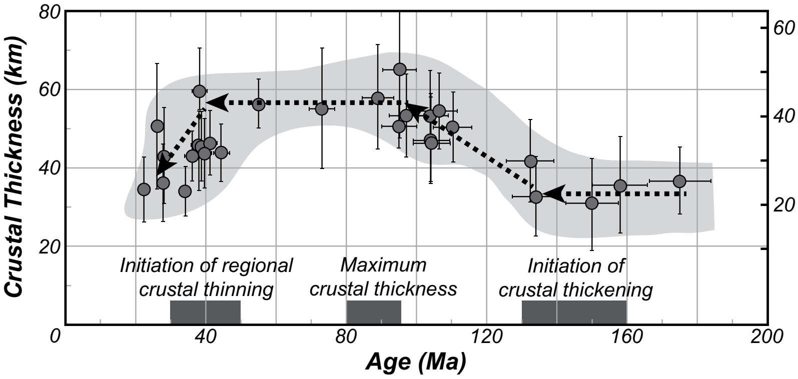

Figure 3. Plot of changes in median Sr/Y in magmatic rocks and calculated crustal thickness through time for Great Basin region. Shaded region and dashed arrows show interpreted trends in data. Timing for events listed at bottom of plot is constrained by independent geologic studies; see text for discussion. Compiled and plotted data are included in Tables DR1–DR3 (see footnote 1).

consistent with estimates for the initiation of shortening in the Cordilleran retroarc thrust belt in Utah and Nevada (Allmendinger and Jordan, 1981), the formation of a regional foreland basin system (DeCelles, 2004), and thermobarometry from the Sevier hinterland (Cruz-Uribe et al., 2015).

The timing of maximum crustal thickening in the Nevadaplano is constrained by peak Barrovian metamorphism where deep crustal levels are exposed in metamorphic core complexes. In the study area, peak metamorphism occurred at 80–90 Ma in the Ruby, East Humbolt, and Snake Range core complexes (Miller and Gans, 1989; McGrew et al., 2000; Sullivan and Snoke, 2007; Wells et al., 2012). These estimates are in broad agreement with the Sr/Y data that suggest maximum crustal thicknesses at 85–95 Ma (Fig. 3). The magnitude of Late Cretaceous crustal thickness calculated from the Sr/Y data also closely aligns with independent constraints. Structural reconstructions for the U.S. Cordillera indicate that crustal thicknesses were 50–60 km in the Late Cretaceous (DeCelles and Coogan, 2006). Similarly, stable isotope, paleo-geomorphic, and low-temperature thermochronology studies suggest that the elevation of the Nevadaplano in the Late Cretaceous was >3 km (House et al., 2001; Cassel et al., 2014; Snell et al., 2014), which implies a crustal thickness of >50 km assuming Airy isostatic compensation.

The timing for extension and crustal thinning in the Great Basin region is debated and likely diachronous. Localized extension may have begun as early as ca. 80 Ma (Wells et al., 1990; Druschke et al., 2009; Long et al., 2015), although most authors have suggested that regional extension began in the Eocene (Sonder and Jones, 1999). Contraction ended in the Sevier thrust belt by ca. 50 Ma (Constenius, 1996). Syn-extensional deposition began by the mid-Eocene (Vandervoort and Schmitt, 1990; Axen et al., 1993), and structural relationships suggest that extensional faulting was widespread by the late Eocene (Mueller et al., 1999; Gans et al., 2001; Druschke et al., 2009). Extension and exhumation in the Nevadaplano metamorphic core complexes also initiated at 45–50 Ma (Lee, 1995; McGrew et al., 2000; Wells et al., 2000), although the bulk of exhumation in the Nevadaplano core complexes may have occurred during the Oligocene or later (Sullivan and Snoke, 2007). Many authors also have suggested that initial Eocene extension may have been minor and that significant extension did not occur until the Miocene, associated with Basin and Range extension (McQuarrie and Wernicke, 2005; Colgan et al., 2006, 2010; Henry, 2008; Best et al., 2009; Cassel et al., 2014). Sr/Y began to decrease at 40–50 Ma, in good agreement with estimates for a mid-Eocene initiation of extension, although there is considerable scatter in the Sr/Y data. Possible explanations for the scatter in the Cenozoic Sr/Y data include diachronous extension in the Great Basin and Sr loss during fractionation within the crust. By the Miocene, Sr/Y had decreased, and corresponding crustal thicknesses had returned to values similar to modern-day estimates of 30–35 km (Gilbert, 2012).

CONCLUSIONS

Understanding how crustal thickness changes through time is essential to deciphering how orogens evolve and which processes influence that evolution. We have demonstrated that Sr/Y from intermediate continental calc-alkaline magmatic rocks in a convergent orogenic setting can be used to track temporal variations in crustal thickness. In the case of the interior U.S. Cordillera, we can resolve when crustal thickening initiated, when maximum crustal thickness was achieved, and, with less precision, when crustal extension began (Fig. 3). These periods represent fundamental shifts in the geodynamics of the orogen and are exemplary of the type of data often targeted by tectonic studies in ancient Cordilleran systems (e.g., Kapp et al., 2005). In addition, we have presented magnitudes for crustal thickness through time for the U.S. Cordillera using a customized global correlation between Sr/Y and Moho depth (Fig. 2). Whereas the uncertainties in these magnitudes remain large (average uncertainty in Fig. 3 is ~±10 km), they nonetheless appear to be reasonable estimates and provide valuable, quantitative constraints on crustal thickness.

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