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Special Section:

Carbon degassing through volcanoes and active tectonic regions

Key Points:

- Depth-dependent (volcanics to deep crust) and lateral (forearc to backarc) magma volume addition rates are calculated from exposed continental crustal sections
- Volume addition increases with depth and is lower in the forearc and backarc compared to the main arc, while crustal-wide, long-term rates are similar between arcs
- Addition rates are used to calculate global CO₂ fluxes from continental arcs; calculated values are similar to global CO₂ fluxes estimated by other methods

Supporting Information:

- Supporting Information S1

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Spatial and Depth-Dependent Variations in Magma Volume Addition and Addition Rates to Continental Arcs: Application to Global CO₂ Fluxes since 750 Ma

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Abstract Magma transfer from the mantle to the crust in arcs is an important step in the global cycling of elements and volatiles from Earth's interior to the atmosphere. Arc intrusive rocks dominate the total magma mass budget over extrusive rocks. However, their total volume and rate of addition is still poorly constrained, especially in continental arcs. We present lateral (forearc to backarc) and depth-dependent (volcanics to deep crust) magma volume additions and arc-wide magma addition rates (MARs) calculated from three continental arc crustal sections preserving magma flare-up periods. We observe an increase in volume addition with depth and less magma added in the forearc (~15%) and backarc (~10% to 30%) compared to the main arc. Crustal-wide MARs for each section are remarkably similar and around 0.7–0.9 km³/km²/Ma. MARs can be used to estimate CO₂ fluxes from continental arcs. With initial magma CO₂ contents of 1.5 wt.%, global continental arc lengths, and MARs, we calculate changes in C (Mt/year) released from continental arcs since 750 Ma. Calculated present-day global C fluxes are similar to values constrained by other methods. Throughout the Phanerozoic, assuming equal durations of flare-up and lull magmatism, calculated continental CO₂ flux rates vary between 4 and 18 Mt C/year with highest values in the Mesozoic. These fluxes are considered minima since the intake of mantle and/or crustal carbon is not considered. Magmatic episodicity in continental arcs and changes in arc thickness and width are critical to consider when calculating MARs through time.

Plain Language Summary The transfer of magma from Earth's interior to the crust and surface via volcanic eruptions transports elements and volatiles, which can ultimately form economically important ore deposits and release gases to the atmosphere. However, the amount and timescales of magma addition to the crust, especially in continental settings, is poorly understood. In this study, we use exposed igneous rocks solidified at different depths in the crust and deposited during volcanic eruptions to determine the amount and timescales of magma addition. We use these newly constrained rates to calculate the total amount of CO₂ gas released to the atmosphere by emplacement and crystallization of magma in the crust. Our calculations agree well with present-day published estimates of CO₂ degassing from continental arcs and allow us to extrapolate CO₂ fluxes throughout Earth History to track relative changes in CO₂ degassing to the atmosphere.

1. Introduction

Magmatic activity in arcs involves the transfer of mass, heat, elemental, and volatile species from the mantle to the crust and ultimately to the atmosphere. Thus, knowing magma volumes and addition rates in arcs is crucial to understanding the budgets of global heat transfer, volatile cycling, ore formation, and the mass balance and isostatic behavior of the arc crustal column, which variably influences mountain building, erosion rates, and climate (e.g., Cao et al., 2016; Lee et al., 2015).

Despite their critical importance, estimates of regional magmatic (volcanic and plutonic) volume additions (VAs) are nonexistent for most continental arcs. Continental arcs have two major complications, which makes VA calculations challenging. First, they are built into continental material consisting of igneous rocks associated with earlier magmatic periods and/or metasedimentary units and basement rocks, and thus, it is necessary to estimate the proportions of new added igneous material versus old (recycled) crust. And second,

continental arcs show episodic behavior resulting in magmatic flare-up periods during which large amounts of magma are added to the crust. These alternate on 10^6 - to 10^7 -year periods with lulls, during which magmatism is sparse (Paterson & Ducea, 2015). This episodic behavior must be accounted for when calculating magma addition to the crust over longer timescales.

Numerous studies have attempted to constrain rates of VA to the crust in arc settings (Crisp, 1984; Dimalanta et al., 2002; Fujii, 1975; Gehrels et al., 2009; Jicha & Jagoutz, 2015; Nakamura, 1974; Paterson et al., 2011; Reymer & Schubert, 1984; White et al., 2006). Some of these studies consider the loss and gain of material (e.g., surface erosion) throughout the lifespan of individual arcs and take these volume changes in account when calculating VA rates (e.g., Jicha & Jagoutz, 2015; Reymer & Schubert, 1984). The techniques used to calculate magma addition rates (MARs) differ greatly. In particular, using seismic profiles to determine magma volumes in continental arcs (e.g., Reymer & Schubert, 1984) is problematic because it is not straightforward to distinguish host rock from intrusive material in active arcs and no information is available about rock age. Finally, many studies (e.g., Crisp, 1984) only consider present-day thicknesses of individual plutonic bodies or crust segments, which are used to calculate rates, thus underestimating these.

In this study, we propose a new protocol to determine magma VA and crustal-wide MARs including forearc, main arc, and backarc in continental arcs over the duration of individual flare-up periods constrained from continental crustal sections exposing different depth slices and/or tilted sections. After introducing this new protocol, we provide examples from three extensively studied continental arc sections, (1) the Cretaceous Sierra Nevada arc, California, (2) the Ordovician Famatinian arc, Argentina, and the (3) Cretaceous Cascades Crystalline Core, Washington State, that allow us to estimate depth-dependent VA and MARs from volcanics to the deep crust. The crustal sections discussed are all high magma volume “Cordillera-type” continental arcs in flare-up state where ~60% to 90% of the original host rock is replaced by plutonic material. Low-volume continental arcs in which only 10%–30% host rock is replaced (e.g., Appalachians; Paterson & Schmidt, 1999) are similar to Cordilleran-type arcs in lull states.

Magma VA and MARs have many important implications: They control the construction durations of magma reservoirs and melt residence timescales (e.g., Karakas et al., 2017; Ratschbacher et al., 2018), thus ultimately controlling crustal differentiation. Furthermore, in magma-rich arcs, the volume of magma added to the crust influences its rheology and mass balance causing crustal thickening and mountain building (e.g., Cao & Paterson, 2016). In this study, we focus on the use of MARs to estimate the contribution of CO_2 outgassing from magmas emplaced in the crust to the global CO_2 budget. The release of CO_2 to the atmosphere through arc volcanoes plays a major role in the global carbon cycle (e.g., Kelemen & Manning, 2015), and its influence on modulating climate variability throughout Earth’s history has been documented (e.g., McKenzie et al., 2016). Less well studied is the contribution of CO_2 from magmas stalled and crystallized in the crust, which exsolve a volatile phase lost to the surface (i.e., diffusive outgassing). Plutonic footprints of arc systems are volumetrically enormous in comparison to volcanic caps, with plutonic to volcanic ratios ranging from 10:1 to 30:1 (Lipman & Bachmann, 2015; Paterson & Ducea, 2015; Tierney et al., 2016; Ward et al., 2017; Zandt et al., 2003). MARs calculated in this study include plutonic and volcanic rocks and thus allow the estimate of potential diffusive CO_2 outgassing and outgassing at volcanic centers associated with eruption. This provides a unique opportunity to compare CO_2 outgassing constrained by MARs to CO_2 outgassing constrained by analyses of active volcanic systems and compare it to the amount of CO_2 stored in subducted sediments and subducted lithosphere (e.g., Hilton et al., 2002; Kelemen & Manning, 2015). We further calculate global estimates of CO_2 outgassing through time by upscaling individual MARs from the investigated arcs to global values based on the record of changing global continental arc lengths since 750 Ma from Cao et al. (2017).

2. Methods: A Protocol for Magma Addition Calculations in Continental Arcs

The net addition of magma from the mantle to arc crust has to be estimated when considering mass transfer between mantle, crust, and ultimately the atmosphere. However, this estimate is complicated by several tectonic, erosional, and igneous processes operating in arcs. In the following, we present a protocol to estimate mantle-derived magma addition to continental arcs. This protocol is based on VAs constrained from different depths and lateral positions of exposed arc crustal sections. It also takes into account processes that remove material from the arc crustal column (see Jicha & Jagoutz, 2015, for a similar protocol established for intraoceanic arcs).

Figure 1. Schematic cross section of a continental arc subduction system showing the various mechanisms removing igneous material from the arc (black arrows) and major processes involved in the CO_2 cycle in subduction zones (blue arrows; modified after Kelemen & Manning, 2015). Shown is also the division into fore-arc, main arc, and back-arc areas and the depth of exposure of studied arc sections relative to the total crustal thickness.

The amount of mantle-derived magma added to the continental arc crustal column is here defined as MMA (mantle-derived magma addition) and is calculated as the sum of mantle produced crust preserved in the arc section (mantle-derived crust preserved; MC_P) and mantle produced crust removed from the arc section (mantle-derived crust removed; MC_R). Note that crustal production rates as defined by Jicha and Jagoutz (2015) are the amount of material preserved in the crust ignoring mantle-derived material potentially lost over time (e.g., through lower crustal foundering) and thus are not strictly MMA rates.

1. $\text{MMA} = \text{mantle-derived crust preserved (MC}_P) + \text{mantle-derived crust removed (MC}_R)$

MC_P is the volume of igneous material added to the crustal column (VA) minus the amount of recycled crustal-derived material generated via processes such as assimilation and partial melting (recycled crust, RC):

2. $\text{MC}_P = \text{volume addition to arc crust (VA)} - \text{recycled crust (RC)}$

MC_R is refined from Jicha and Jagoutz (2015) as the sum of igneous material removed from the arc crust by arc rifting, surface erosion, subduction erosion, and volcanic air fall outside of the arc (Figure 1). Note that lower crustal delamination is also a process removing material from the crustal column; however, VA calculations are performed assuming no loss of lower crust, thus already account for potential delamination processes.

3. $\text{MC}_R = \text{rifted igneous arc crust} + \text{igneous material eroded from surface} + \text{igneous material eroded by subduction erosion} + \text{volcanic air fall outside the arc}$

Estimating the extent of material lost by all of these processes in extinct continental arc systems is not straightforward but is a necessary step to evaluate the amount of MMA. Knowledge of MC_P and MC_R allows estimation of MMA and a MMA rate following equation (1).

2.1. Volume of Igneous Material Added to the Arc Crustal Column (VA)

VA in continental arcs can be estimated from continental arc crustal sections. It is important, however, to recognize that the spatial distribution of magmatism across an arc segment is not uniform and can be divided into magma-poor fore-arc and back-arc regions and a magma-rich main arc section. The width of these individual regions as well as the overall arc width can change throughout its lifespan (e.g., de Bremond d'Arcs

et al., 1995). Moreover, the amount of magma added at different crustal levels (volcanics to deep crust) can vary dramatically, typically showing an increase in magmatism toward deeper levels of the crust (e.g., DeBari & Greene, 2011). And lastly, the magnitude of deformation of the crust can vary during the lifespan of individual arc segments and with crustal depth (e.g., Cao et al., 2015) contributing to variable arc widths and thicknesses, which affect magma addition calculations. This complex behavior of continental arc magmatism must be accounted for when calculating magma VAs to the arc crust.

In order to do this, each studied arc section is divided based on exposure into a fore-arc, main arc, and back-arc crustal columns, with each column divided into a surface (i.e., volcanic), upper, middle, and deep crustal box resulting in 12 boxes if exposure permits it. For each box, VAs are determined. If only limited crustal depths are exposed, then assumptions about VAs for other depths are made.

VA estimates for each box are determined as follows: (1) Geochronologic data sets (bedrock and detrital U-Pb zircon ages) must be linked to geologic maps to establish areal distributions of igneous units falling into the timespan of the flare-up considered (see supporting information for data sources); (2) these igneous units are retro-deformed to remove tectonic effects using tectonic studies and strain analyses to determine predeformation 2-D surface areas of igneous units. This step does not significantly alter total plutonic areas but will have a dramatic effect on volcanic areas (see supporting information). Where volcanic units are exposed in isolated pendants, local stratigraphic correlations between pendants are used to infer predeformation lateral extents. Based on recent publications (e.g., Ward et al., 2017), volcanic additions are thought to be less than 10% of the plutonic additions. Thus, we are generous with our volcanic estimates in an attempt to avoid underestimating the volcanic additions. However, moderate errors in our volcanic estimates will only have a small effect on the total MAR calculations because of the large plutonic/volcanic ratios; (3) then estimate the vertical thicknesses of volcanic layers and plutonic sections and calculate volumes of both volcanic and plutonic units. Thicknesses for volcanic units are based on stratigraphic thicknesses after removal of strain. Plutonic thicknesses are calculated by estimating the total areal percentage of plutons (versus total surface area of individual depth exposures) falling in the timespan of the flare-up for each box. These percentages are used to establish a vertical gradient of plutonic to host rock ratio by assuming that the determined ratio is true for the entire volume of the box the 2-D section(s) is representative of.

Each of the studied arc sections exposes crustal depths to ~30 km; thus, in order to compare calculated MARs for different crustal depths between arc sections, we decided on the following box thicknesses: Volcanic box thickness depends on exposure, 10 km each for the upper, middle, and deep crust respectively, resulting in ~30 km of total exposed crust. These box thicknesses agree well with exposed crustal depths in each of the sections as constrained by geobarometry (see detailed description of areas and constraints on crustal depth in the supporting information). An additional box is added below the deep crustal box in each arc segment (fore-arc, main arc, and back-arc columns) to account for the unexposed part of the crust since none of the arc sections expose crustal depths down to the crust-mantle boundary. The thickness of this box at any time during the flare-up is unknown, but we attempt to estimate the total, cumulative, and time-integrated crustal thickness after the flare-up for each arc section assuming no delamination (loss of lower crust to the mantle) has taken place. The vertical thickness of this box (and thus the overall crustal thickness) can be estimated by (a) examining geophysical data for recent comparable arc systems, (b) using geochemical proxies indicative of crustal thickness (e.g., Sr/Y ratios; Profeta et al., 2015), (c) simple geochemically constrained mass balance calculations (e.g., Jicha & Jagoutz, 2015), and/or (d) using isostatic mass balance modeling predicting crustal thicknesses (e.g., Cao & Paterson, 2016). VA for these lowermost boxes is estimated with the assumption that the plutonic areal % is the same as in the lowermost exposed box in each arc section. Real values of the amount of igneous material in these unexposed parts of the crust are likely higher (up to 90% in accordance with observations from exposed intraoceanic crustal sections; Jagoutz & Kelemen, 2015); thus, VAs for this “unexposed box” are regarded as minima. Additionally, we do not have any age constraints on magmatism in the unexposed parts of the crust but assume that the magmatism spans the same flare-up timescales as observed in the shallower, exposed parts of the crust as the crustal column represents a genetically connected magma plumbing system.

Finally, (4) all VA are reported in units of volume/area (km^3/km^2) for each box and for each entire crustal column (forearc, main arc, and backarc). We prefer normalization to area (km^2) rather than arc length (km)

as commonly used because the width of arc footprints can vary significantly during active magmatism and between individual arc segments.

2.2. Recycled Crust in Arc Magmas (RC)

Isotopic studies have been used to gain insights into the role of assimilation-fractional crystallization-mixing processes in generating continental crust and thus the bulk contribution of mantle and crust in arc magma compositions (e.g., Chapman et al., 2017). Orogen-wide compilations of Cordilleran-type subducting margins show that isotopic trends are spatially and temporally variable (e.g., Ardill et al., 2018) on long time-scales (10 to 100 Ma), encompassing a wide range of geochemically diverse arc magmas. This implies that processes such as arc migration, age, and thickness of the overriding plate do play an important role in modulating isotopic compositions and so do the inputs of various end-members, which can vary significantly.

Because of the complex temporally and spatially variable contributions of mantle versus crust to arc magmas, we consider here two end-member scenarios of (a) 80:20 and (b) 50:50 of mantle versus crustal input into arc magmatism. This is in accordance with estimates from the Central Andes suggesting an equal contribution of mantle and crust (e.g., Freymuth et al., 2015) and studies on gabbros in the southern Sierra Nevada recording ~18% crustal input (Lackey et al., 2005).

2.3. Igneous Material Removed From the Arc Crust (MC_R)

2.3.1. Delamination of Igneous Arc Crust

The removal of lower crust and mantle lithosphere via lower crustal delamination (e.g., Ducea, 2002; Kay et al., 1994) into the underlying mantle can explain the apparent lack of large volumes of mafic to ultramafic cumulates in exposed arc sections required by mass balance. Evidence for root foundering comes from geophysical investigations (e.g., Zandt et al., 2004) and petrological studies (e.g., Bloch et al., 2017) and is implied by surface uplift due to isostatic rebound (e.g., Garzione et al., 2006). However, the spatial and temporal extent of lithospheric removal is controversial.

Dependent on the bulk composition of arc magmas in intraoceanic arcs, Jicha and Jagoutz (2015) stated that the volume lost to delamination is approximately twice that of the present-day arc crust. In continental arcs, Ducea (2002) calculated that mass balance requires a residue of 1 to 4 times the mass of the tonalitic batholith crust depending on the parental mantle magma composition emplaced in the crust. For the continental crustal sections studied here, which expose ~30-km-thick dominantly tonalitic to granodioritic compositions, we calculated required total crustal thicknesses between 63 and 90 km (see section 3). These crustal thicknesses are at the higher end of present-day active arcs (e.g., ~70 km for the Andes; e.g., Assumpção et al., 2013); however, the crust in the studied sections could have lost material during multiple delamination events throughout the flare-up period and rarely acquired these total thicknesses. In order to calculate the total VA to the crust, we need to estimate the time-integrated, additive crustal thickness at the end of the flare-up period, for which it is not important whether delamination occurred in a single event, multiple small events, or did not occur at all.

2.3.2. Subduction Erosion

Subducting margins can be accretionary or erosive, thus adding or removing material to or from the overriding plate (e.g., Clift et al., 2009; Stern, 2011). While these processes are crucial for total crustal growth and destruction calculations over geological timescales, in this study, only the removal of igneous arc material during the time the arc was active is of interest. Both frontal subduction erosion (erosion and collapse of the fore-arc wedge) and basal subduction erosion (abrasion above the subduction channel) potentially remove material from the overriding plate, which in some cases can be reincorporated into arc magmas and underplated beneath the fore-arc wedge (Stern, 2011). We argue here that both basal subduction erosion and frontal erosion are insignificant for VA calculations during the active time of the arc because these processes primarily erode away fore-arc sedimentary material.

2.3.3. Surface Erosion

Both physical and chemical weathering processes can take place during the active time of the arc; however, these processes only become important from a mass balance standpoint if material is transported outside of the arc. In general, we consider the presence of volcanic and shallow intrusive rocks in the studied arc sections as evidence that erosion was limited and thus assume an erosion rate of 0.2 km³/km²/Ma. This agrees with erosion rates estimated by Jicha et al. (2006) based on the emplacement depth of intrusive rocks and the time needed to exhume plutonic material to the surface (assuming that erosion is the primary exhumation

mechanism) in the active Aleutian arc. Material removed from the surface is not all igneous; we thus instead take the percentages of igneous material in the upper crust as constrained from each crustal section to calculate the amount of igneous material eroded away.

2.3.4. Volcanic Ash Fall Outside the Arc

Elder (1988) traced Upper Cretaceous bentonite beds ascribed to Cretaceous magmatism in the Cordillera across much of the western interior of the United States. This provides evidence that volcanic ash fall outside of the arc can cover large areas; however, the volume of these beds is difficult to constrain but generally regarded as negligible compared to the large amounts of intrusive material.

2.3.5. Modification of Arc Crust by Deformation

Changes in arc crustal thickness by extension (thinning of the crustal column) and shortening (thickening of arc crust) during magmatism can affect VA calculation as they can influence assumptions about total crustal thickness. Arc-perpendicular shortening and thickening can decrease the width of the arc and thus increase the apparent VA estimates for the main arc versus forearc/backarc but is not believed to influence the crustal-wide VA calculations in a significant manner.

During active magmatism, transpressional and transtensional movements can additionally occur, which can laterally transport material. Strike-slip motion of 3 cm/year (strike slip in arcs range from 0 to 16 cm/year with approximately 3 cm/year = average; e.g., Paterson & Tobisch, 1988) during, for example, 60 Myr of flare-up magmatism would result in ~1,800-km displacement. Although strike slip movement can be significant, it does not change VA calculations unless displacement varies across the arc (i.e., perpendicular to the strike). Large magnitude rifting during active arc magmatism is typically recognized in the rock record and available to examine (e.g., Stern, 2002). Neither rifting nor extensive strike-slip motion affected the studied arc crustal sections during active magmatism; thus, modification of the arc crust by these processes is not considered.

3. Results: Application of the Protocol to Three Well-Studied Continental Arc Sections

Calculation of magma VA, long-term (over multiple million of years of a flare-up period) MARs and ultimately MMA as outlined above requires (1) detailed geochronology of intrusive and extrusive units, (2) maps showing the extent of individual compositionally distinct plutonic bodies and volcanic stratigraphy, (3) structural features to reconstruct syn- and post-arc deformation, (4) exposure of different crustal levels, and (5) knowledge about the input of mantle and crust into arc magmatism. These data sets are always incomplete. Nevertheless, here we make an attempt to quantify VA for three well-studied continental arc sections: the Cretaceous Sierra Nevada arc in California (~140 to 80 Ma), the Ordovician Famatinian arc in Argentina (~485 to 445 Ma), and the Cretaceous Cascades arc in Washington State (~96 to 84 Ma). Additionally, we use published values on areal extent of igneous material and duration of the Cretaceous flare-up (~120 to 78 Ma) in the Coast Mountains batholith in British Columbia from Gehrels et al. (2009) to calculate VA and MARs from this arc section and compare it to the others presented here. Detailed literature on these arc sections have been published elsewhere, and only a brief summary of the characteristics of each arc section is presented here. Results of VA, long-term MAR calculations, and mantle-derived MMA are then presented in Table 1 and Figures 2 and 3. Supporting information provides a detailed description of the data used to constrain the depth of exposure, duration of flare-up magmatism, ratio of igneous to host rocks, and total crustal thickness in each of the studied arc section.

3.1. Sierra Nevada Arc, California, USA

The Mesozoic Sierra Nevada magmatic arc segment with a length of ~450 km is built through an amalgamated basement of oceanic and continental margin rocks (Bateman, 1992; Chapman et al., 2012; Kistler, 1993; Saleeby et al., 1989). U-Pb bedrock and detrital zircon ages of both Mesozoic volcanic and plutonic units in the Sierra Nevada clearly show that Mesozoic magmatism was highly episodic forming three flare-ups, peaking at ~225, 165, and 100 Ma, bounded by four magmatic lulls (Kirsch et al., 2016; Paterson et al., 2011; Paterson & Ducea, 2015). Magma addition estimates indicate that 100–1,000 times more magma is added to the crust during flare-ups in comparison to intervening lulls, resulting in plutonic/volcanic ratios of >20:1 (Paterson & Ducea, 2015). We will focus on the Cretaceous flare-up that is 2 to 5 times volumetrically larger than the earlier two. This Cretaceous arc became active circa 140 Ma in what is now considered

Arc section	Sierra Nevada, California				Famatinian arc, Argentina					
Duration of flare-up period (Ma)	60				40					
	Forearc		Main arc		Backarc		Forearc		Main arc	
	VA (km ³ /km ²)	MAR (km ³ /km ² /Ma)	VA (km ³ /km ²)	MAR (km ³ /km ² /Ma)	VA (km ³ /km ²)	MAR (km ³ /km ² /Ma)	VA (km ³ /km ²)	MAR (km ³ /km ² /Ma)	VA (km ³ /km ²)	MAR (km ³ /km ² /Ma)
Volcanic (specific for each section)			3	0.05					3.73	0.09
Upper crust (0–10 km)			7.00	0.12					4.61	0.12
Mid crust (10–20 km)			8.00	0.13					9.32	0.23
Deep crust (20–30 km)			9.00	0.15					8.30	0.21
Unexposed crust (specific for each section)			54.00	0.90					24.89	0.62
Entire crustal column for forearc, main arc and backarc	11.50	0.19	81.00	1.35	27.00	0.45	9.00	0.22	50.85	1.27
Volcanic to plutonic ratio				1:35						
Percentage igneous rocks	38.33		90.00	90.00		38.60	20		1:20	80.71
Percentage igneous rocks entire crust				62.25					47.02	
Entire arc volume addition (km ³ /km ²)				50.90					33.93	
Entire arc magma addition rate (km ³ /km ² /Ma)				0.85					0.84	
Mantle-derived magma addition (MMA) assuming 80% mantle/20% crust										
Mantle-derived crust emplaced (MCP; km ³ /km ²)			40.72						27.14	
Mantle-derived crust removed (MCR; km ³ /km ²)			8.4						3.68	
MMA (km ³ /km ²)			49.12						30.82	
MMA rate (km ³ /km ² /Ma)			0.82						0.77	
Mantle-derived magma addition (MMA) assuming 50% mantle/50% crust										
Mantle-derived crust emplaced (MCP; km ³ /km ²)			25.45						16.96	
Mantle-derived crust removed (MCR; km ³ /km ²)			8.4						3.68	
MMA (km ³ /km ²)			33.85						20.64	
MMA rate (km ³ /km ² /Ma)			0.56						0.52	
<i>Note.</i> MAR = magma addition rate; MCP = mantle-derived magma volume emplaced in the crustal column; MCR = mantle-derived crust removed from arc; MMA = mantle-derived magma addition; VA = magma volume addition. References to data used to do these calculations can be found for each area in the supporting information.										

Table 1 (continued)

Arc section	Famatinian arc, Argentina		Casades Crystalline Core, WA		Coast Mountains batholith, BC			
Duration of flare-up period (Ma)	40		12		42			
	Backarc		Unconstrained		Forearc		Main arc	
	VA (km ³ /km ²)	MAR (km ³ /km ² /Ma)	VA (km ³ /km ²)	MAR (km ³ /km ² /Ma)	VA (km ³ /km ²)	MAR (km ³ /km ² /Ma)	VA (km ³ /km ²)	MAR (km ³ /km ² /Ma)
Volcanic (specific for each section)	not exposed		not exposed		not exposed		not exposed	
Upper crust (0–10 km)		5.36		0.45				
Mid crust (10–20 km)		3.89		0.32				
Deep crust (20–30 km)		2.63		0.22				
Unexposed crust (specific for each section)		11.15		0.93				
Entire crust column for forearc, main arc and backarc	6.93	0.17	23.02	1.92	8.18	0.19	40.89	0.97
Volcanic to plutonic ratio								
Percentage igneous rocks		15.40		not exposed		26.56	unknown	22.00
Percentage igneous rocks entire crust		47.02		30.69			51.11	39.44
Entire arc volume addition (km ³ /km ²)		33.93		23.02			29.69	
Entire arc magma addition rate (km ³ /km ² /Ma)		0.84		1.92			0.71	
Mantle-derived magma addition (MMA) assuming 80% mantle/20% crust								
Mantle-derived crust emplaced (MCP; km ³ /km ²)		27.14		18.42			23.75	
Mantle-derived crust removed (MCR; km ³ /km ²)		3.68		1.27			4	
MMA (km ³ /km ²)		30.82		19.69			27.75	
MMA rate (km ³ /km ² /Ma)		0.77		1.64			0.66	
Mantle-derived magma addition (MMA) assuming 50% mantle/50% crust								
Mantle-derived crust emplaced (MCP; km ³ /km ²)		16.96		11.51			14.84	
Mantle-derived crust removed (MCR; km ³ /km ²)		3.68		1.27			4	
MMA (km ³ /km ²)		20.64		12.78			18.84	
MMA rate (km ³ /km ² /Ma)		0.52		1.06			0.45

Figure 2. (a) Histogram showing depth-dependent volume addition (km^3/km^2) from the main arc sections of the Sierra Nevada and the Famatinian arc and the Cascades Core crustal section. Box diagram to the left illustrates the “box model” setup to constrain depth-dependent volume addition. (b) Histogram plot showing lateral differences in the long-term (flare-up duration), crustal-wide magma addition rate ($\text{km}^3/\text{km}^2/\text{Ma}$) between main arc, fore-arc, and back-arc sections. Values for the CMB are taken from Gehrels et al. (2009). The question mark indicates that the value for the forearc of the CMB is unknown but here taken to be 20% of the value calculated for the main arc section in accordance with observations from the other arcs. CMB = Coast Mountain batholith.

the fore-arc region (Saleeby, 2004) and migrated eastward around 2.7 mm/year into the location of the main arc and eventually back-arc regions (Ardill et al., 2018). Arc magmatism lasted circa 60 Myr during which the main flare-up began circa 125 Ma and began to decrease after circa 85 Ma. During this flare-up relative Farallon-North American plate motions resulted in dextral transpression of the arc (e.g., Cao et al., 2015; Tikoff & Saint Blanquat, 1997).

The Cretaceous Sierran arc exposes crustal depths from volcanics to ~35-km depth across a present-day width of ~240 km with the forearc comprising ~65 km (25%), the main arc section ~125 m (52%), and the back-arc section ~50 km (21%) of the total width. The magmatic flare-up period lasted for ~60 Ma from ~140 to 80 Ma as the arc migrated eastward and was accompanied by syn-magmatic crustal deformation resulting in greater than ~60% shortening in the main arc. Total thickness of the arc crust has been estimated to be ~80 km, based on calculations by Cao et al. (2016) and Cao and Paterson (2016) and ~90 km by Chin et al. (2015). We thus use a crustal thickness of 90 m to calculate VA and MARs.

Figure 3. Histogram showing magma MARs ($\text{km}^3/\text{km}^2/\text{Ma}$) from arc sections studied here for both flare-up (orange) and lull magmatism (red). MMA rates for flare-up states of each of the studied sections assuming a mantle to crust contribution to arc magmatism of 80:20 and 50:50. Additionally shown are published MMA rates from Jicha and Jagoutz (2015) for intraoceanic arcs. MAR = magma addition rate; MMA = mantle-derived magma addition; CMB = Coast Mountain batholith.

We have made VA estimates in the central Sierra Nevada using published maps of an ~ 110 km, east-west corridor across a portion of the main arc and VA reconnaissance estimates for the fore-arc (western edge of Western Metamorphic belt) and back-arc (White-Inyo Mountains) sections. Main arc and back-arc estimates are made from published maps and U-Pb zircon ages (see supporting information). Fore-arc magmatism is largely not exposed due to burial beneath the Great Valley Group sediments, but some scattered plutons of this age occur in the Western Metamorphic belt and supporting inferences can be made from drill core data that tapped 140- to 120-Ma mafic cumulates, diorites, and tonalites beneath the Great Valley (May & Hewitt, 1948; Saleeby, 2004). Depth estimates approximately 2–3 kbar in the main arc section in the Central Sierra Nevada locally increase in the southern Sierra Nevada where emplacement pressures increase to >9 kbar (Chapman et al., 2012).

In the main arc section, an increase in VA with depth can be observed from $3 \text{ km}^3/\text{km}^2$ in the volcanic section to $9 \text{ km}^3/\text{km}^2$ in the lower crust (Figure 2a). Crustal column-wide VA and long-term MARs using a flare-up duration of 60 Myr are significantly lower in the fore-arc ($11.5 \text{ km}^3/\text{km}^2$; $0.19 \text{ km}^3/\text{km}^2/\text{Ma}$) and back-arc regions ($27 \text{ km}^3/\text{km}^2$; $0.45 \text{ km}^3/\text{km}^2/\text{Ma}$) compared to the main arc region ($81 \text{ km}^3/\text{km}^2$; $1.35 \text{ km}^3/\text{km}^2/\text{Ma}$). For the entire duration of the Cretaceous magmatic flare-up period in the Sierra Nevada, we calculated a total VA of $50.90 \text{ km}^3/\text{km}^2$ and a long-term MAR of $0.85 \text{ km}^3/\text{km}^2/\text{Ma}$ using the proportions of fore-arc, main arc, and back-arc sections listed above (Figure 2b). In the

main arc section, 90% of the entire crustal column consists of igneous rocks after the flare-up period ended with only 10% host rock remaining. Considering the entire arc crustal column (including fore-arc and back-arc sections), $\sim 62\%$ of the total volume consists of igneous material.

MMA to the crust in the Sierra Nevada arc section was calculated at $49 \text{ km}^3/\text{km}^2$ in case 1 (mantle to crust ratio in magmas of 80/20) and $34 \text{ km}^3/\text{km}^2$ in case 2 (mantle to crust ratio in magmas of 50/50). MMA rates vary from $0.82 \text{ km}^3/\text{km}^2/\text{Ma}$ (case 1) to $0.56 \text{ km}^3/\text{km}^2/\text{Ma}$ (case 2—see Figure 3).

3.2. Famatinian Arc, Argentina

Igneous rocks associated with the Paleozoic Famatinian arc span $\sim 2,500$ km from Colombia to Patagonia. Here we focus on a segment exposed in the Sierras Pampeanas of Argentina (28 to 33°S). The Ordovician Famatinian arc preserves a flare-up period along the Gondwana margin (e.g., Rapela et al., 2018). The Famatinian arc was built into a Cambrian to early Ordovician shallow marine sedimentary succession deposited outboard of the Pampean arc along the Gondwana margin (Alasino et al., 2016; Dahlquist et al., 2008; Pankhurst et al., 1998; Pankhurst et al., 2000). The presence and potential thickness of Mesoproterozoic basement beneath the Sierras Pampeanas is controversial. Based on bedrock and detrital U-Pb zircon geochronology, the Ordovician magmatic flare-up period is constrained to ~ 40 Myr from 485 to 445 Ma and was accompanied by syn-magmatic crustal shortening at all crustal levels (Ratschbacher, 2017). The spatially limited bedrock ages do not allow us to distinguish temporal heterogeneity in the spatial extent of magmatism. The present-day exposure of north-south elongated mountain ranges divided by sediment-filled basins is the consequence of Cenozoic Andean tectonics related to flat-slab subduction of the Nazca plate, which exhumed older rocks exposed along multiple, N-S trending reverse faults (Jordán & Allmendinger, 1986; Ramos et al., 2002). Total thickness of the Ordovician arc crust has been estimated to be ~ 63 km based on isostatic mass balance modeling (updated modeling from Ratschbacher, 2017 by Ratschbacher et al., 2017).

The segment in the Sierras Pampeanas exposes crustal levels from volcanics to ~ 30 -km depth across a present-day width of ~ 280 km with the main arc section comprising ~ 171 km (61%), the back-arc section ~ 81 km (29%), and the fore-arc section ~ 28 km (10%). In the main arc section, an increase in VA with depth can be observed from 3.73 in the volcanic section to $8.30 \text{ km}^3/\text{km}^2$ in the deep crust (Figure 2a). The

Famatinian arc comprises a peak in VA in the middle crust of $9.32 \text{ km}^3/\text{km}^2$. Due to the lack of multiple exposure depths in the back-arc region, exposure from the middle to deep crust (~ 4 to 6 kbar) has been used to calculate crustal-wide VA and MARs ($6.93 \text{ km}^3/\text{km}^2$; $0.17 \text{ km}^3/\text{km}^2/\text{Ma}$). The fore-arc region in the Famatinian arc exposes the deepest sections of the arc (e.g., Sierra de Pie de Palo, up to 13 kbar, Garber et al., 2014) and results in $9 \text{ km}^3/\text{km}^2$; $0.22 \text{ km}^3/\text{km}^2/\text{Ma}$ (Figure 2b). VA and long-term MARs are significantly lower in the fore-arc and back-arc regions compared to the main arc region. A total volume of $33.93 \text{ km}^3/\text{km}^2$ magma is added to the crustal column during the flare up period assuming the proportions of main arc, back-arc, and the fore-arc sections as listed above. The main arc section of the Famatinian arc consists of 81% igneous rocks after the flare-up with only 19% host rock remaining. The entire crustal column (including fore-arc and back-arc sections) consists of 47% igneous material after the flare-up.

MMA to the crust in the Famatinian arc section was calculated at $31 \text{ km}^3/\text{km}^2$ in case 1 (mantle to crust 80/20) and $21 \text{ km}^3/\text{km}^2$ in case 2 (mantle to crust 50/50; Figure 3). MMA rates vary from $0.77 \text{ km}^3/\text{km}^2/\text{Ma}$ (case 1) to $0.52 \text{ km}^3/\text{km}^2/\text{Ma}$ (case 2).

3.3. Cascades Crystalline Core, Washington State, USA

The Cascades Crystalline Core in Washington State preserves multiple magmatic flare-up events emplaced into accreted metasedimentary units and oceanic terranes (e.g., Miller et al., 2009); however, in this study we focus on the volumetrically most significant mid-Cretaceous magmatic flare-up period comprising a duration of ~ 12 Myr from ~ 96 to 85 Ma (Paterson et al., 2011). Its location relative to other segments of the Cretaceous arc in North America is debated. It has been proposed that it comprises a back-arc segment of the Coast Mountains batholith; however, a recent study by Sauer et al. (2019) indicates that the Cascades Core (or at least sedimentary units of it) comprises a fore-arc segment of the Sierra Nevada arc translated northward by margin-parallel displacement (Baja-BC hypothesis). Present-day exposure of the Cascades Core comprises a corridor of ~ 90 -km width and exposes intrusive rocks emplaced from ~ 5 - to 35-km depth. Mid-Cretaceous magmatism in the Cascades Crystalline Core was accompanied by syn-magmatic shortening and crustal thickening at all crustal levels leading to maximum estimates of crustal thickness at the end of the flare-up of ~ 75 km (see supporting information for data sources). This value is used to calculate VA and MARs.

The mid-Cretaceous Cascades Core crustal section is shorter lived and magma-poorer compared to the other studied sections. VA and long-term MARs are highest in the upper crust ($5.36 \text{ km}^3/\text{km}^2$; $0.45 \text{ km}^3/\text{km}^2/\text{Ma}$); however, this value is considered too high due to the limited exposure of shallow crust in the section (see supporting information), considerably lower in the middle crust ($3.89 \text{ km}^3/\text{km}^2$; $0.32 \text{ km}^3/\text{km}^2/\text{Ma}$; Figure 2a) and slightly lower in the deep crust ($2.62 \text{ km}^3/\text{km}^2$; $0.22 \text{ km}^3/\text{km}^2/\text{Ma}$; Figure 2a). The entire Cascades Core crustal section has VA per area of $23.02 \text{ km}^3/\text{km}^2$ and a long-term MAR of $1.92 \text{ km}^3/\text{km}^2/\text{Ma}$ (Figure 3). After the flare-up, magmatism ended the Cascades Core crustal column consisted of 31% igneous and 69% host rock material.

MMA to the crust in the Cascades Crystalline Core arc section was calculated to $20 \text{ km}^3/\text{km}^2$ in case 1 (mantle to crust 80/20) and $13 \text{ km}^3/\text{km}^2$ in case 2 (mantle to crust 50/50). MMA rates vary from $1.64 \text{ km}^3/\text{km}^2/\text{Ma}$ (case 1) to $1.06 \text{ km}^3/\text{km}^2/\text{Ma}$ (case 2; Figure 3).

3.4. Coast Mountains Batholith, British Columbia, Canada

The Coast Mountain batholith (CMB) exposes ~ 175 Ma of arc magmatism along the North American margin in multiple magmatic flare-up periods emplaced in accreted terranes experiencing normal faulting, thrusting and strike-slip motion (e.g., Heyden, 1992). Recognized flare-up events are at 160–140, 120–78, and 55–48 Ma, which alternate with magmatic lulls at 140–120 and 78–55 Ma (Gehrels et al., 2009). Gehrels et al. (2009) studied a ~ 350 -km-long segment of the CMB in British Columbia preserving arc magmatism from 225 to 55 Ma. We focus here on the Cretaceous flare-up from 120 to 78 Ma. Metamorphism and magmatism of this age were synchronous with large-scale (>100 km of displacement), SW vergent thrusting at structurally higher levels in the Coast Belt thrust system (e.g., Journeay & Friedman, 1993; McGroder, 1991; Rubin et al., 1990). Magmatism migrated eastward during the Cretaceous flare-up similarly to the Sierra Nevada arc (Gehrels et al., 2009); thus, we integrate here over the entire area of flare-up magmatism. Gehrels et al. (2009) provide areal estimates of igneous material spanning a wide range of crustal levels from subvolcanic to >25 km, which are used to calculate VA and MARs assuming a total crustal thickness of 80

km after the flare-up magmatism. Whereas the main arc section in the CMB is well defined, the present-day back-arc section is interpreted to be sector H in Figure 8 of Gehrels et al. (2009), which is reasonable given its location and low amount of magmatism. The fore-arc region is less well defined and regarded here as comprising 20% of the magmatism of the main arc section based on results from the Sierra Nevada and Famatinian arc crustal sections.

In the main arc section of the CMB, $41 \text{ km}^3/\text{km}^2$ ($0.97 \text{ km}^3/\text{km}^2/\text{Ma}$; Figure 2b) is added to the crustal column, which consists of 51% igneous material after the flare-up. Estimates for the back-arc section are $17.6 \text{ km}^3/\text{km}^2$ ($0.42 \text{ km}^3/\text{km}^2/\text{Ma}$) and for the fore-arc section $8.2 \text{ km}^3/\text{km}^2$ ($0.19 \text{ km}^3/\text{km}^2/\text{Ma}$). The entire arc section, assuming that the main arc section comprises 60%, the back-arc and fore-arc sections each 20% of the entire arc width, shows VA of $29.7 \text{ km}^3/\text{km}^2$ and a long-term, crustal-wide MAR of $0.71 \text{ km}^3/\text{km}^2/\text{Ma}$ (Figure 3). At the end of the flare-up, the entire crustal column consists of $\sim 39\%$ igneous material.

MMA to the crust in the Coast Mountains arc section was calculated to $28 \text{ km}^3/\text{km}^2$ in case 1 (mantle to crust 80/20) and $19 \text{ km}^3/\text{km}^2$ in case 2 (mantle to crust 50/50). MMA rates vary from $0.66 \text{ km}^3/\text{km}^2/\text{Ma}$ (case 1) to $0.45 \text{ km}^3/\text{km}^2/\text{Ma}$ (case 2).

3.5. Comparing Continental and Oceanic MARs

We compare MARs and MMA rate calculated in this study with MMA rate results of oceanic arcs from Jicha and Jagoutz (2015), who developed a similar calculation protocol calculating MMA. In order to compare results, we convert values from reported $\text{km}^3/\text{km}/\text{Ma}$ in Jicha and Jagoutz (2015) to $\text{km}^3/\text{km}^2/\text{Ma}$ by calculating the arc width (and thus area) of oceanic arcs from their reported volume, thickness, and length. The results in Figure 3 indicate that the majority of MARs in oceanic arcs are similar to MARs during continental arc flare-up periods, while continental lull periods showing much lower MARs. MMA rates during flare-up periods strongly depend on the assumption of mantle versus crust involvement in magmatism but are in the same range as oceanic MMA rates as calculated by Jicha and Jagoutz (2015). The Cascades Core, however, shows unusual high MARs and MMA, reasons for this are discussed in section 6.

4. Global Arc Magma VA Estimates Throughout the Phanerozoic

Cao et al. (2017) compiled continental arc lengths since 750 Ma (see detailed description in paper). We use this data set to upscale calculated long-term (over the duration of the flare-up) and crustal-wide MARs from the studied continental arc crustal sections to global values and monitor changes in MARs since 750 Ma.

It has been well documented that the active arc widths during individual flare-up periods as well as the finite arc width after the flare-up period can vary between different arc segments. Thus, when doing these calculations, the variability of arc widths and the episodic behavior of continental arc magmatism needs to be considered. De Bremond d'Ars et al. (1995) provides a compilation of present-day active arc widths ranging from 23 to 290 km with a mean width of 97 km. We use these width estimates in combination with the continental arc lengths of Cao et al. (2017) to calculate areas of continental arcs since 750 Ma. The global change in volume of magma addition to continental arcs through time is then calculated by taking these continental arc areas and multiply them with the average MARs ($\text{km}^3/\text{km}^2/\text{Ma}$) from the crustal-wide (forearc to back-arc) MAR of the Sierra Nevada and Famatinian arcs ($0.848 \text{ km}^3/\text{km}^2/\text{Ma}$), which we have studied in detail. These agree well with MARs from the CMB published by Gehrels et al. (2009) as shown in Figure 3. Since these arcs record flare-up states, our global values are regarded as maxima. Moreover, global MARs comprise VA addition to the crust over a certain timescale and not true MMA, which would be lower but difficult to estimate given the uncertainty and variability in mantle versus crustal input in arc magmas. We thus attempt to calculate total global VA instead of MMA. The results (see supporting information Figure S4) comprise magma addition (km^3/Ma) for continental arcs in flare-up state since 750 Ma and vary according to the choice of arc width to calculate arc areas and the choice of maximum, average or minimum arc lengths reported by Cao et al. (2017). The difference between the latter increases with geologic age as the rock record becomes sparser. VA during lull periods is calculated by assuming that they comprise 1/10 of the VA during flare-up periods (Paterson & Ducea, 2015). Present-day magma addition is calculated from continental arc lengths reported for the last one million years (present-day lengths of Cao et al., 2017).

And lastly, the switch between flare-up and lull magmatism in individual segments of continental arcs needs to be considered when calculating global magma VA through time. The episodic nature of continental arc

magmatism has been well documented (e.g., Armstrong & Clark, 1988; DeCelles et al., 2009; Ducea & Barton, 2007; Kirsch et al., 2016; Paterson et al., 2011; Paterson & Ducea, 2015). To determine the relative durations of flare-up versus lull states in arcs, we examined both bedrock and detrital U/Pb zircon age histogram and probability plots presented in Kirsch et al. (2016), which show age distributions from circa 80 to 400 Ma in Cordilleran arcs. Two approaches were used, which gave similar results: (1) measuring and summing the durations between inflection points from the probability curves and (2) summing the durations of age bins when either the number of ages was decreasing or at low numbers relative to the amount of ages dating the flare-up period and comparing to the summed durations of when the number of ages were increasing or at high values relative to the ages dating the flare-up period. The percentage of flare-up mode for the southern, central and northern Andes, PRB, Sierras, and Cascades/CMB are 54%, 38%, 50%, 50%, and 52%, respectively. Thus, an average of 50% flare-up and 50% lull state is regarded as representative and was used in the following.

5. Amounts of Global Arc CO₂ Outgassing Based on VA

One approach to estimate present-day arc CO₂ emissions is to use a well constrained emission rate for a gas (usually ³He) at mid-ocean ridges (MORs), scale the flux and the associated MAR at MOR to arcs, estimate the ³He flux from arcs and then use an appropriate average CO₂/³He ratio of arc gases to estimate a CO₂ flux (e.g., Sano & Williams, 1996). This results in a global arc CO₂ flux of ~100 Mt/year (2,200 Gmol/year; Kagoshima et al., 2015). The issue with this approach is that the arc magma flux is not measured but is based on an assumed arc/MOR magma addition ratio (Crisp, 1984). An alternative approach is to use estimated MARs and assume an initial magmatic CO₂ content of magmas and complete degassing of CO₂ upon emplacement, eruption, and crystallization. Initial arc magma CO₂ contents remain poorly constrained because it has been recognized that CO₂ entrapped in melt inclusions of minerals in arc magmas are degassed (e.g., Wallace, 2005). Attempts to obtain undegassed initial magma CO₂ contents have resorted to using arc CO₂ fluxes and estimate initial magma CO₂ contents to be on the order of >3,000 (Wallace, 2005) to 7,600 ppm for arcs not built on massive continental crust (e.g., the Andes, for which estimates are higher and around ~23,000 ppm; Fischer & Marty, 2005). Blundy et al. (2010) used arc melt inclusion CO₂ contents and degassing and crystallization modeling to obtain initial magma CO₂ contents of ≥1.5 wt.%. While more studies are needed to better constrain initial arc magma CO₂ contents and how these contents vary depending on the arc system, for this contribution we assume a global initial CO₂ content of 1.5 wt.% and complete degassing upon ascent and crystallization. Using these broad assumptions, we can estimate global arc CO₂ fluxes since 750 Ma using MARs, published estimates of global continental arc lengths and a range of arc widths (Figure 4). We also note that mantle CO₂ degasses not solely through volcanic craters but also diffusely through extensional fault systems (Lee et al., 2016), through large hydrothermal areas (Werner & Brantley, 2003) and on the flanks and hydrothermal areas of volcanic systems (e.g., Chiodini et al., 2015; Salazar et al., 2004). Overall, diffuse degassing through faults has long been recognized as efficient and significant contribution to the global mantle-derived CO₂ budget (Mörner & Etiope, 2002). Based on investigations of individual arc segments, we choose a flare-up to lull ratio of 50/50 and an average arc width of 97 km to calculate global CO₂ fluxes in Figure 4. Supporting information Figure S5 illustrates how CO₂ fluxes change using other flare-up to lull ratios.

6. Discussion

In summary, the Sierra Nevada and Famatinian arc sections, as well as estimates from the CMB in flare-up mode, show similar long-term, crustal-wide MARs of ~0.70 to 0.84 km³/km²/Ma (Figure 3). The Cascades Core crustal section shows exceptionally high MARs (1.92 km³/km²/Ma). Note that the flare-up magmatism preserved in the Cascades Core is much shorter lived (~12 Myr) compared to the flare-ups recorded in the other crustal sections (40 to 60 Myr) and comprises the smallest exposed area. Thus, we interpret the Cascades Core as a high magma flux but short-lived flare-up event. Volumetrically, the Cascades Core (23 km³/km²) is comparable to the back-arc section of the Sierra Nevada (27 km³/km²), which comprises a much larger and longer-lived system. The percentage of igneous material in the crustal column after the flare-up period is largest in the Sierra Nevada (~62.25%) and lower in the Famatinian arc (~47.02%), CMB (~39.44%), and the Cascades Core (~30.69%). The main arc sections in the Sierra Nevada and Famatinian

Figure 4. Plot showing calculated CO₂ degassing fluxes (Mt C/year) since 750 Ma (assuming 1.5 wt.% CO₂ in the melt; Blundy et al., 2010), a ratio of flare-up to lulls of 50:50 and an arc width of 97 km. Shown is also the relative importance of arc magmatism throughout the Phanerozoic (red curve) from zircon data and global greenhouse and icehouse climates after McKenzie et al. (2016). Ranges of global continental arc CO₂ fluxes determined by other methods are shown in green. These values are calculated from the cited publications assuming that continental arcs comprise 30% of the total arc length today (Lee et al., 2013).

arcs comprise the largest amount of added igneous material, whereas the forearc comprises ~15% and the backarc 10%–30% of the main arc section magmatism (Figure 2). Mantle-derived magma addition and addition rates strongly depend on the assumption of mantle versus crustal contributions in the emplaced magmas. Assuming that the emplaced magmas comprise a mantle to crustal input ratio of 50:50, the rate of MMA is in average ~38% lower than the MAR calculated from the exposed emplaced igneous rocks, around ~0.51 km³/km²/Ma (and higher at ~1.06 km³/km²/Ma for the Cascades Core).

6.1. Uncertainties of VA and MAR Calculations

VA and long-term MARs calculated in this study rely on the assumption that exposed arc crust slices are representative for the entire arc at the observed depth. As the rock record is always incomplete, this can never be known with absolute certainty. However, the continental arc crustal sections investigated here are among the best studied and expose both shallow and deep arc continental crust; we thus regard them as ideal sites to perform these calculations.

Areas used to constrain the extent of flare-up-related igneous rocks span >2,500 km² and up to 6,000 km² from individual crustal depths and are thus considered as robust. One exception is the upper crust in the Cascades Core. The exposure from this crustal level is exceptionally small (825 km²); we regard this as biased toward higher amounts of intrusive rocks (supporting information Figure S1), which contributes to the unusually high MARs. Volcanics in the studied arc sections are subject to deformation and erosion and thus their reconstruction of original thickness and spatial extent is challenging. However, detailed compositional and structural mapping for both the Sierra Nevada and Famatinian volcanic slices (see supporting information) provide us with confidence that these estimates are reasonable. Furthermore, the similarity of long-term MARs between the Sierra Nevada, Famatinian, and CMB arc sections provides assurance that the calculations are reasonable and in the correct range for high magma volume arcs. However, future work acquiring more geochronologic data will improve our understanding of the duration of flare-up periods and will influence calculations.

Uncertainties in arc-wide VA can also result from inaccurate assumptions about the total thickness (i.e., petrologic crust-mantle boundary) of the arc crust at the end of the flare-up. Moho depths in active arcs constrained by seismic velocities range from ~35 to 40 km in the Cascades arc (Kiser et al., 2016) to ~60 km beneath the Central Andes (Ryan et al., 2016). Identification of the Moho depth by seismic velocities in active arcs is challenging, as sharply defined discontinuities are rare or absent (e.g., Jagoutz & Kelemen, 2015). Moreover, seismic Moho depths do not necessarily coincide with and commonly underestimate the depth of the petrological crust-mantle boundary as this boundary is complex transition between lower crustal rocks and mantle peridotites involving mantle-like cumulates. Although estimated crustal thicknesses of ~63 to 90 km appear large compared to present-day continental arc thicknesses, we estimated time-integrated crustal thicknesses acquired throughout the entire flare-up period, which does not imply whether these thicknesses were realized at any point in time or kept low by multiple delamination events during the flare-up. Moreover, our values are conservative from a mass balance crustal fractionation point, which predicts thicknesses of up to 140 km (Ducea, 2002). In active arcs, some of this material likely was lost via delamination, reducing their present-day crustal thickness. Using the total crustal thicknesses presented here, the ratio of exposed crustal depth to total crustal thickness is 50:50, meaning that the lower half of continental arc crust is not exposed. Estimates about the volume of igneous rocks in this part of the crust are based on the observations that even in the deepest exposed arc crust, compositions are tonalitic to gabbroitic and thus the unexposed part of the crust has to be dominated by mafic to ultramafic igneous compositions according to mass balance if fractionation is the dominant continental crust differentiation mechanism (e.g., Jagoutz & Klein, 2018).

The impact of using different arc widths on global magma VA estimated can be constrained by using a minimum value of 23 km, average of 97 km, and a maximum value of 290 km of arc widths of de Bremond d'Ars (supporting information Figure S4). The effect is that calculations using the mean width of 97 km are ~4 times higher than calculations using the minimum of 23 km and ~3 times lower than calculations using the maximum of 290 km. As it is difficult to reconstruct the changes in arc widths through time, we regard the true values to lie between these end-members. Since continental arcs are long-lived systems, magmatism during individual flare-up periods can migrate (Ardill et al., 2018) and change its width dramatically along strike (Ducea, Paterson, et al., 2015; Ducea, Saleeby, et al., 2015). This behavior is strongly scale dependent and makes it difficult to estimate one arc width for an individual continental arc, let alone through time.

Furthermore, uncertainties in the total lengths of continental arcs throughout the Phanerozoic are an unavoidable consequence of the rock record and plate reconstructions (Cao et al., 2017). As shown in supporting information Figure S4, the difference between estimates of maximum, average, and minimum arc lengths become especially large before 500 Ma resulting in a decrease in VA of 1.25 and 1.65 times using the average and minimum length, respectively, compared to the maximum length. Since it is difficult to infer the correct arc lengths through time, we consider the true values to lie between the maximum and minimum end-members.

In general, extrapolation to global MARs using only a few well-studied arc sections from which we constrained MARs is controversial but given the presently published literature the best we can do. Future work needs to investigate more arc sections for comparison and better evaluate the role of other arc styles in the global magma mass budget.

6.2. Magma Addition in Continental Versus Oceanic Arcs

Figure 3 illustrates the similarity between MMA rates during continental flare-up magmatism and oceanic arc magmatism. This supports the idea previously stated by Jicha and Jagoutz (2015) that flare-up magmatism in continental arc reflects the “normal” MMA rate (comparable to oceanic MMA rate), whereas lull magmatism represents unusual low addition rates, which are intrinsic to continental arcs. The driving mechanism causing episodic magmatic behavior in continental arcs is a matter of ongoing debate indicating that both external factors (e.g., subducting plate kinematics) and internal factors (e.g., processes in the upper plate) contribute to modulating magmatic episodicity in continental arcs (e.g., Kirsch et al., 2016).

In addition to the two end-member (Cordilleran-type continental and oceanic) arcs discussed here, low-volume continental arcs such as the Alps, the Lachlan fold and thrust belts in Australia, and the Appalachians-Caledonian arcs are more similar to Cordilleran-type lull magmatism.

6.3. Global CO₂ Budget of Continental Arcs

We focus on one application of MARs calculations: to determine CO₂ fluxes from continental arcs constrained from observed igneous material emplaced in the crustal column. In general, estimates of CO₂ fluxes from arc volcanoes based on direct measurements of gas concentrations and flux calculations are higher (e.g., 18–43 Mt C/year) compared to estimates of diffusive outgassing in arcs (e.g., 4–12 Mt C/year; Kelemen & Manning, 2015). Although the latter is difficult to constrain, these estimates are surprising given the large plutonic to volcanic ratio observed (e.g., Ward et al., 2017; Table 1). However, assuming that these estimates are reasonable, one explanation could be that arc volcanoes source the underlying magma plumbing systems at several crustal levels and thus channelize CO₂ from magma chambers to the surface. Then, measurements at volcanic centers comprise a combination of CO₂ degassing during crystallization at depth and associated with the eruption of material. MARs calculations presented in this study provide an estimate of total CO₂ fluxes based on total amount of magma added to the crustal column and are not dependent on the understanding of volcanic-plutonic connections.

As a first step, we can estimate present-day global CO₂ fluxes using present-day lengths of continental arcs (Cao et al., 2017) and MARs from this study and compare these to published estimates of CO₂ fluxes. Calculated present-day global continental arc flare-up state CO₂ fluxes vary between ~3 and 36 Mt C/year using the average arc length and minimum (23 km) and maximum (290 km) arc widths. Published estimates for global arc volcanic CO₂ fluxes range between 23 Mt C/year (Fischer, 2008) and 26 Mt C/year (Kagoshima et al., 2015) and between 18 and 43 Mt C/year (recent compilation of arc fluxes by Kelemen & Manning, 2015). These published estimates, however, represent the total of global CO₂ fluxes from arc volcanoes, not distinguishing between oceanic and continental arcs. In order to compare global continental CO₂ fluxes calculated in this study to published CO₂ flux values, we assume that 30% of the global present-day CO₂ flux is emitted from continental arcs (following Lee et al., 2013, which report present-day continental arc lengths as comprising 30% of the total length of all subduction zones). This results in estimates of global continental arc volcanic CO₂ fluxes of 6.9 Mt C/year (Fischer, 2008), 7.8 Mt C/year (Kagoshima et al., 2015), and 5.4 to 12.9 Mt C/year (Kelemen & Manning, 2015). However, not all present-day continental arcs are in flare-up state (e.g., flat slab subduction in the southern Central Andes) and during lull periods, CO₂ fluxes are much lower, varying between ~0.3 and 3.6 Mt C/year dependent on the choice of arc width. The true values lie between these end-members and in Figure 4, we assume that 50% of the global continental arcs are in flare-up state and 50% are in lulls state at any point in time in agreement with Kirsch et al. (2016). This results in calculated present-day global continental CO₂ fluxes of ~7.8 Mt C/year, which is in good agreement with CO₂ flux estimates using other methods (Figure 4).

Our calculations of CO₂ fluxes depend solely on the MARs calculated from exposed arc sections and the assumption of 1.5 wt.% CO₂ in the magma. We do not consider processes such as mobilization of carbon stored in the crust (Lee et al., 2013) or mantle (Kelemen & Manning, 2015). Kelemen and Manning (2015) propose that significant amounts of C are transferred and continuously accumulate in the overlying plate above subduction zones. Some of this C may eventually contribute to C accumulation in the lithospheric mantle below continental rifts (Foley & Fischer, 2017) while some of it may also be incorporated into the deep sections of arcs and could result in higher initial arc magma CO₂ contents. Until initial arc melt CO₂ contents are better constrained, we cannot improve our estimates. We, however, point out that the good agreement between CO₂ fluxes constrained in this study using MARs and published global CO₂ fluxes indicates that a value of 1.5 wt.% CO₂ in the magma calculated by Blundy et al. (2010) is reasonable.

The approach presented here to infer CO₂ degassing from continental arcs via MARs enables us to estimate arc CO₂ emissions through time at least on a relative scale. Figure 4 illustrates the differences in CO₂ fluxes in Mt C/year since 750 Ma. During the Late Neoproterozoic-Cambrian and Mesozoic, CO₂ fluxes were elevated compared to present-day values. These correlate with major global greenhouse climates and increased continental arc activity as constrained by zircon ages (McKenzie et al., 2016; red dashed line in Figure 4). Additionally, the Late Ordovician-Silurian and Carboniferous also record an increase in CO₂ fluxes, the latter of which also coincides with increased arc activity recorded by McKenzie et al. (2016). Absolute values of CO₂ fluxes are difficult to constrain because they depend strongly on (a) arc lengths, (b) arc widths, (c) flare-up or lull state, and (d) assumption of CO₂ in the magma. However, a minimum of a 2.5-fold increase in CO₂ fluxes during the Late Mesozoic compared to present-day CO₂ flux estimates is well constrained. Combined

with the effect of enhanced magmatism through continental arcs, this could have further augmented the global volcanic CO₂ emissions and the atmospheric CO₂ content. In summary, this implies that continental arc magmatism through the combined effect of magmatic CO₂ emissions and crustal carbon uptake through weathering processes contributed to long-term climate modulation throughout the Phanerozoic.

7. Conclusions

The volume and rate of magma addition to the crustal column influences a large variety of processes: heat budget, elemental exchange between mantle, crust and ultimately atmosphere, crustal deformation and thickening, the size and longevity of magma chambers, igneous differentiation, volcanic-plutonic connection, isostatic responds, and mass balance of the crust. Exposed continental arc crustal sections provide a great opportunity to better constrain these values.

The rate of magma addition to the crustal column governs its isostatic behavior, especially in magma-rich arcs. With a better understanding of MARs, isostatic mass balance calculations can be used to constrain the change in elevation and thus mountain building rate in these systems, which influences surface erosion rates and ultimately CO₂ uptake through weathering processes (e.g., Lee et al., 2013). Future studies need to evaluate the timing between magma addition, volcanic CO₂ degassing, elevation increase, changing erosion, and weathering rates to fully capture the influence of continental arc magmatism on global long-term climate variability.

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