Geochemistry, Geophysics, Geosystems

Supporting Information for

Spatial and depth-dependent variations in magma volume addition and addition rates to continental arcs: Application to global CO_2 fluxes since 750 Ma

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Introduction

The Supporting information describes the areas and types of datasets (maps, geochronology and barometry) used to calculate volume addition and magma addition rates in the Sierra Nevada arc (California, USA; Text S1), the Famatinian arc (Argentina; Text S2) and the Cascades Crystalline Core (Washington, USA; Text S3) crustal sections. Each text section begins with a general geologic overview of the area of consideration, followed by summary of the types of datasets used to constrain the age, depth and spatial extent of exposed igneous rocks and their host rocks. A section evaluating evidence for the crustal thickness at the end of the flare-up period of each individual studied arc crustal section and constraints on fore-arc and rear-arc sections if exposed are also included. Note that although not explicitly mentioned in the text, all areal extent of igneous and host rocks from geological maps are determined by either ArcGIS tools or the Adobe Illustrator area tool.

Text S1 – The Sierra Nevada arc crustal section

The Mesozoic in California is dominated by three superposed continental margin arcs, which alternatively can be viewed as three magmatic flare-ups peaking in the Triassic (225 +/- 12 Ma), the Jurassic (161 +/- 14 Ma) and Cretaceous (98 +/- 8 Ma) (Ducea et al., 2015). Here we focus just on the Cretaceous arc or flare-up. Preserved Cretaceous rocks in California define an accretionary wedge (Franciscan complex), a fore-arc basin (Great Valley Group), a main arc (plutons and volcanics forming much of the bedrock in the Sierra Nevada Mountains), and a back arc region (scattered plutons and volcanics) extending eastward into the state of Nevada. This Cretaceous arc became active ca. 140 Ma in what is now considered the fore-arc region (Saleeby, 2004) and migrated eastward around 2.7 mm/yr into the main arc and eventually back-arc regions (Ardill et al., 2018). The main magmatic flare-up began ca. 125 Ma and began to decrease after ca. 95 Ma, and lasted ca. 60 Myr, with flare-up magmatism centered in the main arc and was accompanied by syn-magmatic crustal deformation resulting in up to ~60 % shortening in the main arc (Cao et al., 2016; Kirsch et al., 2016).

The Cretaceous Sierran arc exposes crustal depths from volcanics to ~35 km across a present-day arc width of ~240 km with the fore-arc comprising ~65 km (25 %), the main arc section ~125 km (52 %) and the rear-arc section ~50 km (21 %) of the total width (Supplementary Figure 1). Total thickness of the main arc crust has been estimated to be ~ 70-90 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 km to calculate VA and MARs. Below we describe how estimates of Cretaceous magma additions were established for the fore-arc, main arc, and back-arc.

Excellent exposure throughout the main Sierran range allow good estimates of preserved volcanic material in scattered pendants in the Central Sierra Nevada (CSN) and upper crustal (CSN) to deep crustal (southern Sierra Nevada) plutonic material. We focused our calculations in the CSN using published maps (Bateman, 1992; Wagner et al., 1991) and published ages and barometry (Chapman et al., 2012) enhanced by our ongoing geochronology. Depths in the CSN range from metavolcanic and metasedimentary sections and shallow porphyry intrusions to 2.5 to 3.5 kbars in the CSN. These shallow to mid-crustal levels increase to deep crustal levels (8-12 kbars) at the very southern end of the exposed Sierra batholith (Ague & Brimhall, 1988; Chapman et al., 2012). Bedrock and detrital U/Pb zircon ages indicate that the Cretaceous flare-up dominates at all crustal levels (Paterson & Ducea, 2015). We made reconnaissance estimates of deeper crustal levels from published maps (maps in Chapman et al., 2012). Total thickness of the Cretaceous 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 use a crustal thickness of 90 km to calculate VA and MARs in the main arc section.

Volcanics: Preserved volcanic rocks in the CSN only occur as moderately to steeply dipping sections in small to large (e.g. Ritter Range) pendants. Strain in volcanic units range from 0% to ca. 70 % shortening with an arc wide average of ca. 50 % (Cao et al., 2016). To estimate volcanic volumes we completed the following steps: (1) established ages of stratigraphic packages in all CSN pendants; (2) unstrain units using average shortening estimates from each pendant; (3) un-rotated beds and determined vertical thicknesses of units; (4) used ages, stratigraphic information and approximate thicknesses to correlate units from one pendant to another. Our goal was to not underestimate potential volcanic material: so we assumed correlated packages extended throughout the regions and maintained thicknesses between pendants; (5) estimated 2D surface areas of volcanic units broken into 5 Myr age bins and used thicknesses plus areas to estimate volcanic volumes through time. On average these steps indicated a ca. 3 km average thickness of Cretaceous volcanics along the central axis to eastern edge of the main arc section. We assume in our calculations that any part of the main arc dominated by Cretaceous magmatism had a comparable blanket of volcanic rocks.

Plutonic estimates: The CSN provides a well-exposed upper to mid-crustal arc section. We used published maps, leveraged by many published 15 minute geologic quandrangles (National Geologic Map Database at ngmdb.usgs.gov) and our own mapping, combined with published and new U/Pb zircon ages from plutons to establish the areal extent of plutons grouped into 5

Myr age bins. Our estimates indicate that ca. 70 % of exposed rock consists of Cretaceous plutons with ages falling between 125 – 85 Ma. Examination of published maps in deeper parts of the Sierra (Chapman et al., 2012) indicate that this percent of Cretaceous plutons falling in this same age range increase to 70 % and 80 % in the middle and deep crust. That is very little metamorphic host rock or older plutons are preserved in these middle and lower crustal sections. Thus in the main arc section, an increase in VA with depth can be observed from 3 km^3/km^2 in the volcanic section to 9 km^3/km^2 in the lower crust (Figure 2 in main text). Crustal column-wide VA and long-term MARs using a flare-up duration of 60 Myr main arc region (81 km^3/km^2; 1.35 $km^3/km^2/Ma$).

Fore-arc: It is now well established that Cretaceous magmatism is preserved as plutons in bedrock beneath the Great Valley Group (Saleeby, 2004). 140-130 Ma plutons have been intersected by drill holes into bedrock beneath the GVG (Saleeby, 2004). Scattered plutons of these same ages also occur along the western edge of the exposed Western Metamorphic belt (WMB) and we interpret these to be part of this fore-arc (in present reference frame) magmatism. Cretaceous regional metamorphism in this part of the WMB is greenschist facies and nearby Cretaceous plutons have Al-in hornblende pressures of 2.5-3.5 kbars (Ague and Brimhall, 1988). Thus exposed plutons reflect upper crustal magmatism. No Cretaceous volcanic rocks are preserved in the WMB and no middle or lower crustal depths exposed.

We used published maps and U/Pb zircon ages from plutons measure the area of Cretaceous plutons versus total examined area in the WMB and obtained estimates of 15 % to 25 %. We use the higher value since plutons of this age potentially increase in areal percent to the south and because of the inferred wider distribution from drill hole data. Thus we use 25 % to represent the area consisting of ca. 140-130 Ma plutons at upper crustal levels in the fore-arc. This is about 1/3 of the value determined for these levels in the main arc. Since no Cretaceous volcanics are exposed in the WMB, we use this ratio obtained from the plutonic comparison and assume that the amount of eroded forearc volcanics is 1/3 of the main arc. And as is seen in the main arc, we assume magmatism increases in middle and lower crustal fore-arc sections to 35 % and 45 %, respectively. We are not aware of any evidence of a large crustal root in the forearc at this time, a time when a large marine basin was forming. By totaling all crustal levels, these estimates provide a total fore-arc value of Cretaceous magmatism of 11.5 km^3/km^2; 0.19 $km^3/km^2/Ma$.

Back-arc: There is some debate about where the back-arc region of the Cretaceous arc begins (Van Buer et al., 2009). But immediately east of the CSN in the White-Inyo Range, the areal percent of Cretaceous plutons decreases dramatically: we thus interpret this range to reflect volumes of back arc magmatism. This implies that even though the arc was continuing to migrate eastwards, the volume of magmatism decreased drastically around 85 Ma (Paterson and Ducea, 2015). In this backarc section we face some of the same issues as the forearc, although exposure is excellent in the White-Inyo Range. However only upper-crustal levels are exposed and Cretaceous volcanics are not preserved. Thus we used an identical approach to that in the forearc: we used published maps and U/Pb zircon ages from plutons to measure areas of all known Cretaceous plutons and obtained an areal estimate of ca 30%. We used the ratio of backarc to main-arc plutons to infer a similar ca 1/3 ratio of former Cretaceous volcanic rocks. No middle and lower crust are exposed in White-Inyos, therefore we infer the same depth increase to 35% and 40% for middle and lower crust, respectively. One difference with the fore-arc is that this backarc region is now considered to be part of high plateau in the Cretaceous (Van Buer et al., 2009) extending from the Sierras well inboard across the Basin and Range area. This plateau is inferred to have a crustal root of ca. 40 km and we thus use this thickness in our calculations. Totaling magmatism at all crustal levels results in a rear-arc magma volume additions of ca. 27 km^3/km^2; 0.45 km^3/km^2/Ma.

Text S2 – The Famatinian arc crustal section

Rocks associated with the Late Cambrian to Late Ordovician Famatinian arc are exposed for ~2500 km from Colombia to Patagonia (e.g. Pankhurst et al., 1998; Rapela et al., 1998). The Famatinian arc segment considered in this study is exposed in the Sierras Pampeanas of Northwest Argentina (28° to 33° S; Supplementary Figure 2) and comprise a composite arc crustal section from volcanics to ~ 30 km depth (e.g. Tibaldi et al., 2013) with generally increasing exposure depths from east to west and north to south. The arc was emplaced into metasedimentary successions deposited in the Middle - Late Cambrian to Early Ordovician (e.g. Achavil and Negro Peinado formations in the Sierra de Famatinia) comprising shallow marine siliciclastic deposits, slate and sandstones. These have been interpreted as deposited in a fore-arc basin adjacent to Gondwana (Mángano & Buatois, 1996; Mángano & Buatois, 1997; Collo et al., 2009). The Famatinian arc succeeded the early Cambrian Pampean magmatic flare-up event and is associated with eastward subduction beneath the Gondwana margin, which caused extensive emplacement of arc-related Lower to Middle Ordovician extrusive and intrusive rocks and amphibolite to granulite facies metamorphism (Alasino et al., 2016; Dahlquist et al., 2008; Pankhurst et al., 1998; Pankhurst et al., 2000). The Famatinian flare-up period is exposed to the west of the Cambrian Pampean arc such as reintrusion of the older flare-up period by the younger is limited. The present-day width of the Famatinian arc comprise ~ 280 km and can be divided into in a main arc region (~ 171 km; 61 %), dominated by igneous rocks and a rear-arc (~ 81 km; 29 %) and fore-arc (~ 28 km; 10 %) region with sparse arc-related plutonic bodies (Supplementary Figure 2). The Famatinian rear-arc region experienced high-temperature, low-pressure metamorphism, anatexis and spatial heterogenous deformation (Büttner, 2009; Larrovere et al., 2011; Finch et al., 2017). In the Western Sierras Pampeanas, a ~60 km wide zone of Mesoproterozoic crystalline basement with a Neoproterozoic to Early Paleozoic sedimentary cover (Rapela et al., 2016 and references therein) shows sparse Famatinian related magmatism, we here call this area the Famatinian fore-arc. We, however, note that this term is not associated with Famatinian-age fore-arc basin formation and sedimentary deposits.

Pankhurst et al (2000) distinguished three contemporaneous intrusive rock types in the Famatinian arc: I-type granitoids exposed as an elongated belt at the western edge of the Eastern Sierra Pampeanas (Supplementary Figure 2), S-type granitoids characterized by two mica, cordierite-bearing granites and small scattered exposures of TTGs in the Eastern Sierra Pampeanas. Duration of Famatinian arc magmatism is constrained to 40 Ma based on a compilation of bedrock and detrital zircon ages across the Sierras Pampeans (Supplementary Figure 2B and C). Geochronology is not detailed enough to evaluate migration of arc magmatism during the Famatinian flare-up period and constrain potential changes in active arc widths during the 40 Ma period of flare-up magmatism. Multiple, approximately north-south striking ductile shear zones in parts crosscut Famatinian arc rocks and appear to be synchronous with arc magmatism in the Sierras Pampeanas provide evidence of syn-orogenic and arc-parallel crustal shortening and thickening (e.g. Whitmeyer and Simpson, 2003). The timing of shear zone development and its relationships to Famatinian arc magmatism are controversial (e.g. Cristofolini et al., 2014; Höckenreiner et al., 2003).

Upper Devonian-Carboniferous A-type magmatism intrudes and crosscuts both the Famatinian intrusive rocks and the north-south striking shear zones putting a younger age limit to solid-state deformation in the region. Middle Carboniferous to Upper Tertiary continental sedimentary successions unconformably overlie the Famatinian arc crust and both experienced Andean deformation and uplift as the youngest tectonic phase in the area (Jordan et al., 1983). The present-day exposure as north-south elongated mountain ranges divided by sediment-filled basins is the consequence of Cenozoic Andean tectonics related to flat-slap subduction of the Nazca plate, which caused deformation and exhumation of older basement rocks along multiple, N-S trending reverse faults (Jordan & Allmendinger, 1986; Ramos et al., 2002). Exhumation is spatial heterogeneous but is interpreted to not exceeded ~ 7-4 km (Safipour et al., 2015).

To constrain the aerial extent of igneous and host rocks, we used the map of the Sierras Pampeanas by Rapela et al., (2016) and Larrovere et al., (2011) as the base map for our calculations (Supplementary Figure 2) and published geologic maps of Argentinian provinces of the Servicio Geologico (Ragona et al., 1995; Gonzalez et al., 1994) as well as more detailed maps from individual publications (see below) to constrain the igneous versus host rock ratios in different parts of the Famatinian arc. Areas covered by Quaternary sediments are not considered in the calculations. Areas of younger, Devonian-Carboniferous magmatism intruding the Famatinian arc are not considered in the calculations. The depth of exposed crustal slices is constrained by a combination of textural observations (volcanic and shallow intrusive rocks versus deeper intrusive rocks), Al-in-hornblende barometry and syn-magmatic metamorphic pressure estimates (Supplementary Figure 2D). We note here, however that the Famatinian arc section is the least-well studied section considered in this study and thus subject to the largest uncertainties in depth and age estimates.

Volcanic section: The Chaschuil section (CH in Supplementary Figure 2) exposes shallow crustal intrusive and dominantly marine sedimentary, volcanic and volcanoclastic rocks associated with the Famatinian arc. This area was mapped and studied in detail to characterize the uppermost part of the Famatinian arc in terms of depositional, deformational and temporal evolution during arc activity (Ratschbacher, 2017 and most recent, updated publication by Lusk et al., 2017). This area was used to constrain the thickness and percentage of volcanic, volcanoclastic and sedimentary rocks deposited during ~20 Ma of arc magmatism. Three main magmatic phases can be observed: early andesitic, dacitic and rhyolitic sheets and lavas are interlayered with volcanoclastic debris flow deposits, as well as turbidite deposits, siltstones and massive, laminated mudstone, the latter of which comprises Tremadocian fossil ages in the Los Angosturas area and Arenigian to Llanvirn fossil ages in the Las Planchadas area (Cisterna & Coira, 2014; Mángano & Buatois, 1997). This early Ordovician phase is intruded by the Los Angosturas granite (485 ± 7 Ma, Rubiolo et al., 2002; 484.6 ± 5.3 Ma, Safipour et al., 2015), which is hypabyssal indicating shallow emplacement depths. Recent mapping showed that rhyolite sheets intrude parallel to bedding as well as discordantly into already folded volcano-sedimentary strata in the northern part of the Las Planchadas area. Locally, rhyolite contacts with host rock show magmatic mullions with the mullion axes parallel to regional fold axes and thus comprise evidence for syn-emplacement shortening. This indicates that folding of the earliest Ordovician volcano-sedimentary units took place in the Mid-to Late Ordovician. The Los Angosturas and the Las Planchadas areas form separate blocks divided by a younger fault running approximately north-south through the Chaschuil river valley exposing deeper units (shallower upper crustal intrusive rocks) in the east and a volcanic section in the west. We use the volcanic section preserved in the Chaschuil area to infer volcanic volume additions for the entire Famatinian arc – this is an obvious simplification and we note that volcanic output and deformation at the top of the arc where likely spatial and temporally heterogeneous. However, we do believe that the Chaschuil area is best-preserved upper crustal section of the Famatinian arc and thus the bets area to perform these calculations.

Upper crustal section: The uppermost crust in the Famatinian arc is exposed in the Chaschuil area in the form of hypabyssal granite intrusions into slightly older volcanic-sedimentary sequences (e.g. Cisterna & Coira, 2014). Slightly deeper parts of the upper crust are also exposed in the Sierra de Chepes to the south, here Dahlquist et al. (2005) record emplacement pressures of 2 to 3 kbar. We consider both areas as part of the upper crustal box recording emplacement depths from ~ 2.7 to 8 km (using 2.7 g/cm^3 as rock density). The map of Dahlquist et al. (2005) is used to constrain the igneous to host rock ratio in the Sierra de Chepes. In the Chaschuil area, results from our own mapping were used to constrain areal extent of igneous versus host rocks.

Mid-crustal section: The mid crust in the Famatinian arc is exposed in the Sierra de Velasco (Supplementary Figure 2) in the form of I- and S-type granite, granodiorite and tonalite intrusions and metasedimentary host rock slices. Thermobarometric data of hornfels from the southwest side of the Sierra de Velaso indicate pressures of ~ 5 kbar (13.5 km using a rock density of 2.7 g/cm^3; Rossi & Toselli, 2004). This is in agreement with De los Hoyos et al. (2011), who showed that migmatization of host rocks at 14 to 18 km depth is coeval with emplacement of mid-crustal plutons in the eastern part of the Sierra de Velasco. Thus the Sierra de Velasco record emplacement depths from ~ 13 to 18 km. The map of Grosse et al. (2011) is used to constrain the aerial extents of igneous and host rocks.

Deep crustal section: The deepest exposed part of the Famatinian arc is represented by the Sierra de Valle Fertil section (e.g. Cristolfini et al. 2014; Ducea et al. 2017; Otamendi et al., 2009; Tibaldi et al. 2013; Walker et al., 2015). The Sierra de Valle Fertil is truncated at its western edge by the steeply dipping, post-magmatic Valle Fertil lineament (or shear zone; Cristolfini et al., 2014). The section exposes eastward tilted arc intrusive and sedimentary units (metapelites, marbles and graywackes; Otamendi et al., 2009) from 12 to 32 km depth (Tibaldi et al. 2013), we thus interpret this section and the areal exposure of intrusive and host rocks as representative for the deepest exposed crust. A stratification of the crust can be observed, from shallowest exposed parts comprising tonalite to granodiorite plutonic bodies to heterogeneous but dominantly gabbro to tonalite rocks in the deepest exposed parts (Walker et al., 2015). Peak metamorphism recorded in the host rocks appears to be coeval with the emplacement of plutonic units (Otamendi et al., 2008). A recent study using high-precision U-Pb TIMS zircon ages from the Sierra de Valle Fertil concluded that the entire exposed crust was build in ~ 4 Myr during he early stages of Famatinian arc magmatism (Ducea et al., 2017). Our compilation of U-Pb zircon ages from different parts of the arc (Fig. Supplementary Figure 2A) shows that arc magmatism is active for ~ 40 Myr throughout the Sierras Pampeanas at more shallower crustal levels. We thus regard the short construction timescale for the Sierra de Valle Fertil as an arc segment, which shut off relative early in the flare-up period but which is not been the case for the entire deep crust of the Famatinian arc as supported by prolonged felsic magmatism in other parts of the arc. As such the Sierra de Valle Fertil can be compared to the short-lived Cascades Crystalline Core, which was constructed in ~ 12 Myr, much shorter compared to other arc section studied here.

Late Ordovician crustal thickness constraints in the main arc section: Pre-arc crustal thickness has been estimated to ~30 km by Otamendi et al. (2012) but as Alasino et al. (2016) noted, these value is a minimum estimate since Mesoproterozoic basement, which forms the base of the crust is not exposed in the Eastern Sierras Pampeanas. If we assume that the pre-arc crustal thickness is 30 km, then a crustal thickness of ~60 km at the end of the flare-up period seems reasonable given that > 50 % of the exposed rock type in the mid and deep crust is igneous (Fig. 1A). Ratschbacher et al (2017) calculated a crustal thickness of 63 km at the end of the flare-up period based on isostatic mass balance modeling following Cao and Paterson (2016). We adopt this value for the calculations. The volcanic record of the Famatinian arc is dominantly submarine indicating that the crust at least during the duration represented by volcanic deposits is likely not overthickened, which would lead to an increase in elevation due to isostasy.

Fore-arc and back-arc sections: The fore-arc section in the Famatinian arc is constrained as the area between the Sierra de Valle Fertil and Sierra de Famatina, which are dominated by arc magmatism in the rock record and the areas further to the west, which are ascribed to be part of the Precordillera exotic terrane or rocks younger then mid Paleozoic. This includes the Sierra de Maz, Sierra de Umango and Sierra della Toro Negro (Geologic map of La Rioja province; Guerreo et al., 1993) as well as the Sierra de Pie de Palo (Geologic map of San Juan province; Ragona et al., 1995). The fore-arc area exposed the deepest pars of the arc with pressures recorded in metasedimentary rocks and gneiss up to 12 kbar (Mulcahy et al., 2014). However in this area it is not entirely clear if metamorphism is coeval with arc magmatism. In some cases (e.g. Lucassen & Becchio, 2003) metamorphic age constraints are overlapping but also younger ranging from ~466 to 428 Ma. Because further constraints regarding the depth of emplacement of arc rocks are not present, we assume that the areal extent determined in these areas is representative for the entire arc crustal section in the fore-arc region. The back-arc area of the Famatinian arc is spatial constrained by the significant decrease of arc-related magmatism and encompassed the Sierra de Ambato, Sierra de Ancasti, Sierra de Aconquija and the Sierra de Quilmes. We used the Geologic map of Catamarca and Tucuman province (Martinez, 1995; Gonzales, 1994) to constrain the exposed areas of igneous and host rocks. Few barometric data on metasedimentary host rocks is available from these areas, but published values vary from 4 to 8 kbar (Supplementary Figure 2D). We thus assume that the determined igneous to host rock ratios are representative for the entire rear-arc crustal column. The crustal thicknesses of both the fore-arc and back-arc sections of the Famatinian arc are unknown. We thus assume a crustal thickness of 45 km for both areas. Due to the significant decrease in magmatism and the exposed crustal depths, we regard this assumption as reasonable.

Text S3 – The Cascades Crystalline Core arc crustal section

The composite Cascades Crystalline Core (CCC) arc crustal section in Washington State is bound to the west by the Straight Creek Fault, an Eocene right-lateral strike-slip fault system (Supplementary Figure 3; e.g. Vance, 1957; Monger & Brown, 2016). Restoration of this right-lateral motion places the CCC ~80 to 190 km (dependent on interpretation; see Monger and Brown, 2016 for discussion) to the north in a rear-arc position of the Coast Mountain batholith in British Columbia. Recent work by Sauer et al (2019), however, implies that sedimentary units in the CCC have been transported ~1600 km of northward during margin-parallel displacement at 85–55 Ma. To the northeast, the northern segment of the Ross Lake Fault zone marks the border of the CCC (Miller & Bowring, 1990; Miller et al., 2016). In the south, the exposure of the CCC is restricted by the Miocene Columbia River Basalts and its boundary to the north is the US-Canadian border, which we used to restrict the study area. The CCC preserved multiple arc magmatic flare-up events beginning at ~ 240 Ma; this event was followed by a flare-up at ~ 140, then the volumetrically most significant mid-Cretaceous flare-up from ~ 97-86 Ma, a late-Cretaceous flare-up from ~ 78-65 Ma and the youngest flare-up with ages of ~ 48-45 Ma (Miller et al., 2009; Kirsch et al., 2016) followed by more recent Oligocene to present-day arc volcanism. Our study focuses on the volumetrically most significant mid-Cretaceous magmatic flare-up from ~ 96 to 84 Ma, which is preserved in numerous fault-bounded slices of different crustal depths. In the following, we outline in detail data used to constrain the depth of exposure, maps used to calculate the ratio of igneous to host rocks at each exposed depth and age data used to constrain the temporal duration of the mid-Cretaceous magmatic flare-up in the CCC. We both used Al-in-hornblende crystallization pressure estimates from mid-Cretaceous intrusive rocks as well as peak metamorphic pressure estimates from host rocks. Numerous studies indicate that the peak of metamorphism recorded in host rocks coincides with the emplacement of magmatism throughout the mid-Cretaceous crustal column (e.g. Miller and Paterson, 2001;Plummer, 1980; Paterson et al. 1994; Whitney et al. 1999), we are thus confident that the barometric data are compatible with inferred crustal depths.

We use the Geologic Map of the North Cascades Range, Washington (Haugerud & Tabor, 2009) as the base map for our calculations. Smaller scale maps are additionally used to distinguish compositionally different units, which have been ascribed different ages in more recent literature and to investigate the mineralogy of intrusive units, which can further constrain exposure depths (e.g. the presence of magmatic epidote). These maps and accompanying map descriptions are: Bunning, 1990; Carter & Crowder, 1967; Crowder et al., 1966; Dragovich et al., 1997; Tabor et al., 1993; and Tabor et al., 2002; Tabor et al., 1987.

In the following, we describe in detail the map areas assigned to different crustal depths and from which the ratio of igneous to host rocks have been calculated. In general, older then mid-Cretaceous intrusive units are regarded as host rocks. Areas covered by Quaternary sediments, water and glaciation are not considered in the calculations. Younger then mid-Cretaceous intrusive units are also not considered in the calculations since it is difficult to estimate what they replaced. The following literature references to published U-Pb zircon ages have been used to constrain the duration of 12 Ma for the flare-up magmatism: Chan et al. 2017; Haugerud et al. 1991; Matzel et al. 2006; Mattinson, 1972; Shea et al. 2016; Shea, 2014; Walker and Brown, 1991. We refer to the cited publications for detailed method description and discussion of data interpretation, as this is not the scope of this study.

Upper crustal section: The upper crustal section in the CCC is represented by area A in Supplementary Figure 3. This area is constrained in the southwest by the Gabriel Peak tectonic zone and in the northeast by the Ross Lake fault zone (Foggy Dew fault) and its contact to the Methow basin. This is the smallest (aerial extent) crustal slice in the CCC. The Black Peak intrusive complex comprises Al-in hornblende crystallization pressures of 1 to 3 kbar at its eastern margin (Shea et al., 2016) in accordance with low-grade metamorphism in the Midnight Peak Formation and Pasayten Group forming the host rocks in this area (Shea et al., 2016). No evidence for magmatic epidote in the Black Peak intrusive complex has been found supporting a rather low-pressure emplacement. Towards the south, higher pressures of up to 5 kbar have been reported from the Napeequa host rock unit (Miller et al., 1993). Using a rock density of 2.7 g/cm^3, area A exposes crustal depths from ~ 2.5 km to 13 km. The upper crustal section of the CCC shows unusual high MARs in comparison to the other studied upper crustal sections from the Sierra Nevada and Famatinian arc. Since this area is the smallest and dominated by the Black Peak intrusive complex and two younger plutons (the Oval Peak and Golden Horn plutons), from which we do not know what they replaced (host rocks or mid-

Cretaceous intrusive units), we conclude that this area might not be representative of the entire upper crust and thus calculated MARs should be handled with care.

Mid-crustal section: The mid crust of the CCC is represented by the area B in Supplementary Figure 3. This area includes host rock units of the Chiwaukum schist, the Ingalls ophiolite and the Nason Ridge Gneiss. Various pressure estimates from metamorphic host rocks (Whitney et al. 1999; Supplementary Figure 3) and Al-in hornblende barometry of plutonic rocks (Anderson et al. 2012) constrain this crustal slice to exposed pressures ranging from 3 to 8 kbar, which by using a density of 2.7 g/cm^3 translates into crustal depths of 8 to 21 km. Furthermore, magmatic epidote has been described from the Wentachee Ridge Gneiss (Zaggle, 2015) and the Chaval pluton (Brown & Talbot, 1989). Although controversial (see discussion in Schmidt & Poli, 2004), the presence of magmatic epidote has been ascribed to crystallization pressures of > 5 kbar (Zen and Hammerstrom, 1984) and provides further indication of a deep mid-crustal emplacement depth of this intrusive unit. Miller and Paterson et al. (2001) document based on field observations widespread unfocused magmatism in the host rock units, which they estimate to 19 % of the total plutonic (focused) magmatism. We adopt this value here and add 19 % of the determined areal extent of intrusive units to the total of arc magmatism in this slice.

Deep crustal section: Two deep crustal sections are exposed in the CCC: west (area B in Supplementary Figure 3) and east (area C in Supplementary Figure 3) of the post-metamorphic Entiat fault, respectively. Area B is bordered in the southwest by the post-metamorphic Entiat fault, excluding the Swakane gneiss, which comprise younger ages and lacks any arc-related plutonism (Miller & Paterson, 2001; Supplementary Figure 3). In the northeast, the southern part of the Ross Lake fault zone marks the extension of this area. Both metamorphic pressure estimates and intrusive crystallization pressures of mid-Cretaceous intrusive units indicate a range between 6 and 10 kbar (16 to 27 km depth; Whitney et al. 1991; Miller & Paterson, 2001; Supplementary Figure 3). Furthermore, magmatic epidote has been reported from the Seven Fingered Jack intrusive complex indicating deep emplacement levels (Elkins, 2015). The Skagit Gneiss Complex records a large age span with youngest ages of migmatization into the Cenozoic (Haugerud et al., 1991; Miller et al., 2016). Mid-Cretaceous protoliths to orthogneisses in the Skagit Gneiss complex have also been recorded (e.g. Haugerud et al., 1991; Mattinson, 1972; Miller et al., 1989; Miller and Bowring, 1990) however it is difficult to determine the exact amount for magma addition calculations, thus we assume here 30 %. Furthermore, area B shows widespread post mid-Cretaceous magmatism indicating that these plutons likely replaced mid-Cretaceous intrusive units, however how much is not easy to establish, thus our calculations are regarded as minimum MARs. Area C is bordered on the southwest at the contact to area B by the post-peak metamorphic, NE-dipping, reverse White River shear zone (Van Diver, 1967) and in the northeast by the Entiat fault and a thrust just north of the Late-Cretaceous Jordan Lakes pluton (Supplementary Figure 3). The largest mid-Cretaceous intrusive complex in this area is the Tenpak pluton, which has been constrained to emplacement depths from 7 to 10 kbar (Miller & Paterson, 2001). This intrusive complex and the further north emplaced Sulphur Mountain pluton both contain magmatic epidote indicating emplacement depths > 5 kbar (Brown & Talbot, 1989; Zen & Hammerstrom, 1984;). Host rock peak metamorphic pressures range from 9 kbar in the south to 3 kbar in the north (Miller & Paterson, 2001; Whitney et al., 1999). However the one analyses from the northern part appears too low for peak pressures when compared other metamorphic pressures and Al-in-hornblende barometry of intrusive rocks, we thus consider the entire area representing depths between 19 and 27 km.

Mid-Cretaceous crustal thickness constraints: Miller and Paterson (2009) argued for a crustal thickness of > 55 km after the mid-Cretaceous flare-up period largely based on exposure and tectonic observations. During the buildup of the magma plumbing systems, the crustal column underwent tectonic thickening expressed as southwest-directed thrusting at shallower crustal levels and ductile deformation at deeper crustal levels (e.g. Brandon, 1988; Miller & Paterson, 2001, 2009; Misch, 1966). Using MARs and tectonic shortening calculations during the mid-Cretaceous flare-up, Ratschbacher (2017) calculated a crustal thickness of ~ 75 km at the end of flare-up event, which is used in this study. Further indication of a thick crust and the presence of cumulate material below the exposure level come from the rather evolved composition (dominated by tonalite) at even the deepest exposed parts of the system (e.g. Tenpeak pluton). Shea et al. (2018) has recently shown that at the end of the flare-up period, one of the youngest mid-Cretaceous intrusive units, the Black Peak intrusive complex records strong evidence for a garnet signature, which increases during its ~ 5 Ma lifespan indicating that the crust becomes exceptionally thick prior to shut down of arc magmatism.

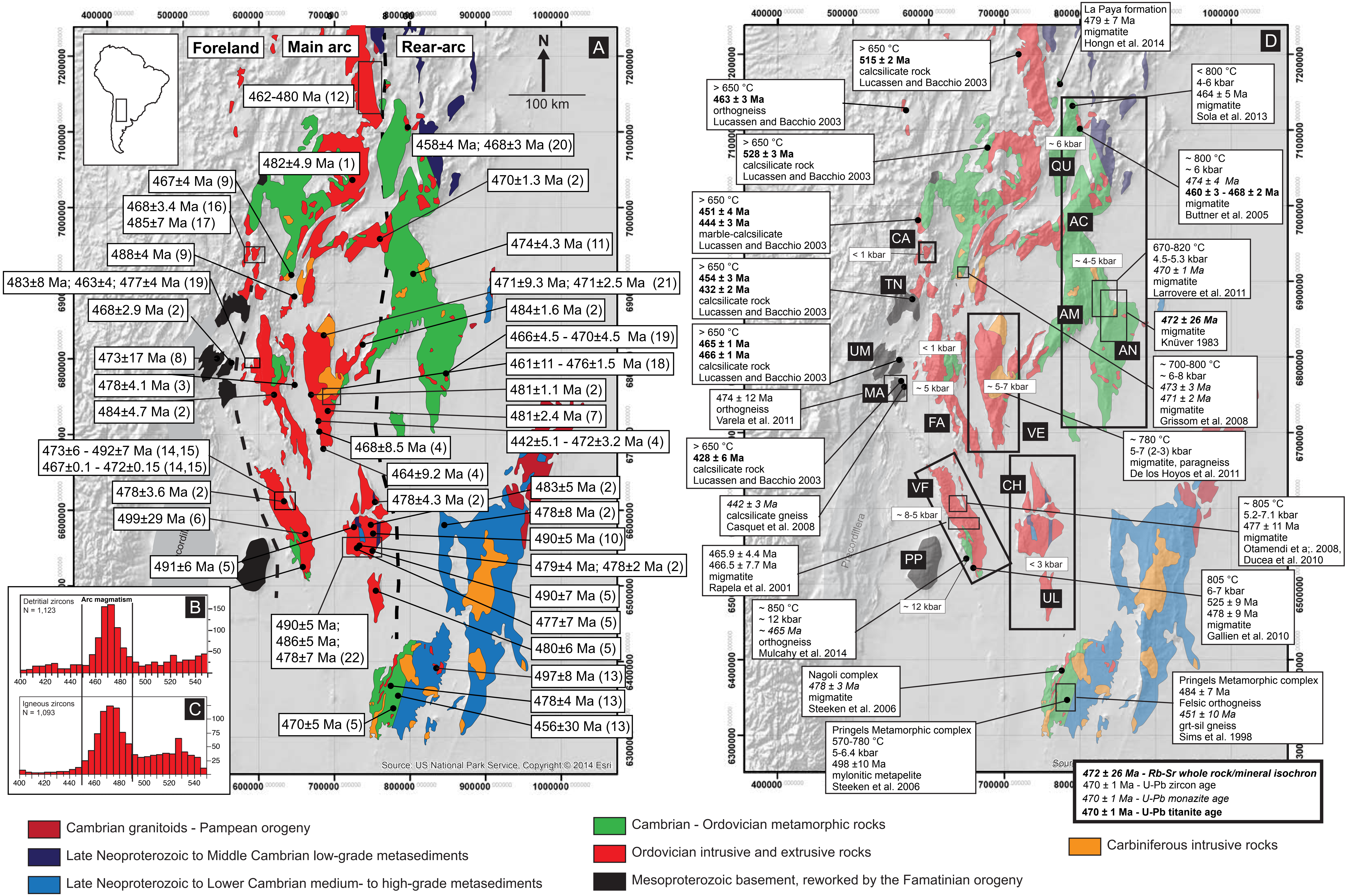

Fore-arc
Main Arc
Back Arc
Mono Lake
STANISLAUS NATIONAL FOREST
INYO NATIONAL FOREST
VOLCANIC TABLELAND
Turlock
Merced
Los Banos
MERCED NATIONAL WILDLIFE REFUGE
38°00'
37°00'
120°00'
119°00'

Supplementary Figure 1: This figure shows the main areas in the central Sierra Nevada where we made estimates of Cretaceous magmatism in the fore-arc, main arc, and back arc. This is a partially redrafted composite map from two 1/250,000 (or 1 by 2 degree) geologic quadrangles. We used the entirely of the U.S.G.S. 1992 Mariposa quadrangle compiled by Paul C. Bateman and the ca eastern 1/3 of the 1991 San Jose-San Francisco California State quadrangle compiled by D.L Wagner, E. J. Bortugno and R.D. McJunkin. Contour intervals are 200 ft. Up on map = geographic north. Please see original map keys for full details of color and symbols and be aware that colors are not consistent from the State to U.S.G.S. quadrangles.

Along the western (left) edge of the map, the light greens, oranges, and yellows designate sedimentary units in the Great Valley, a Cretaceous fore-arc basin, although Cretaceous plutons encountered in drill cores are known to form basement under these unit. Just east of the Great Valley, light and dark greens represent Mesozoic metavolcanics and metasedimentary units in the Western Metamorphic belt. We used the area west of the Melones fault to estimate fore-arc magmatism in the Cretaceous arc since small, scattered plutons (pinks, reds) exist with overlapping ages to those beneath the Great Valley. Light blue units in the Western Metamorphic belt, east of the Melones fault are Paleozoic to Mesozoic metasedimentary units.

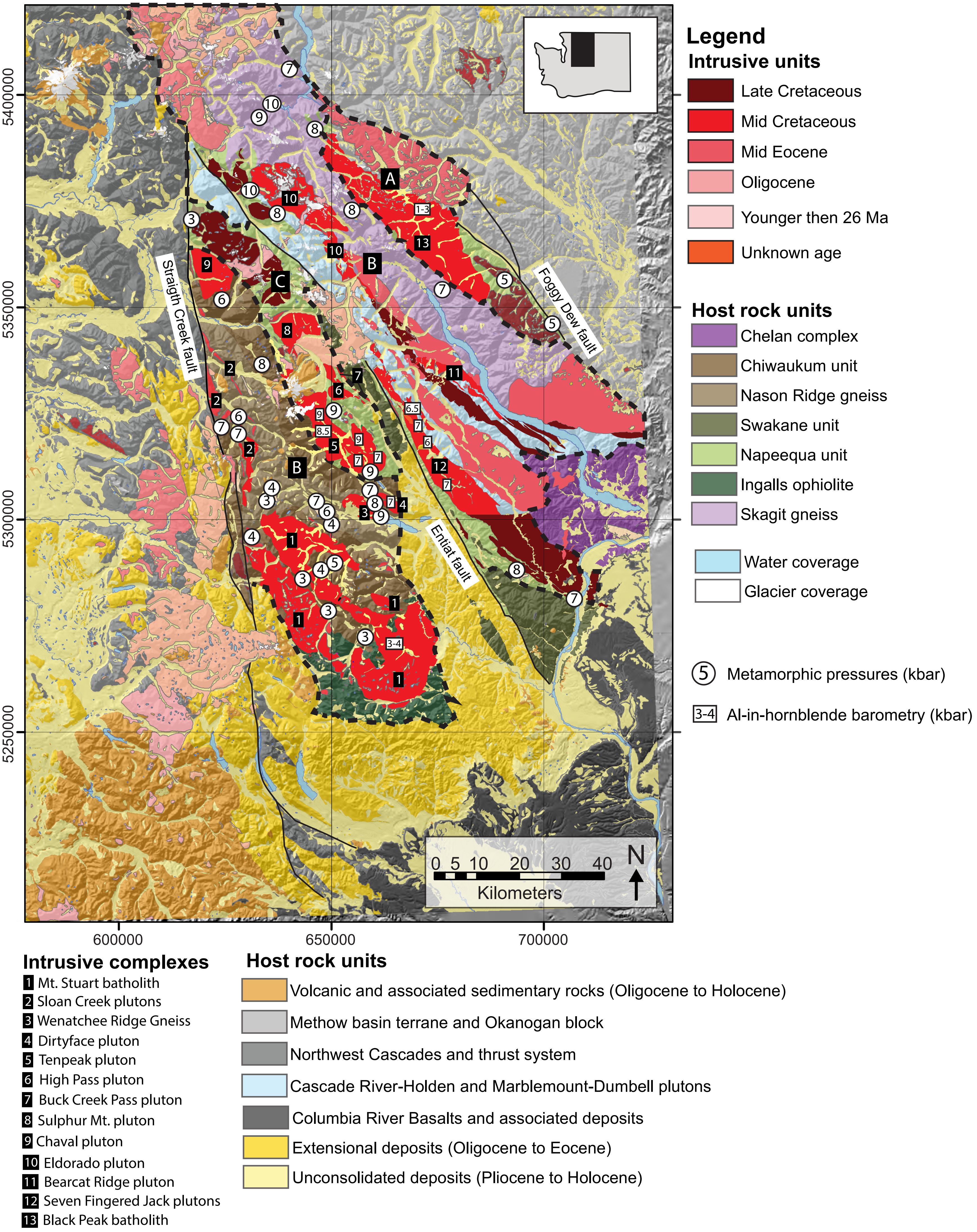
The main batholith is clearly defined in the central part of the map where greater than 80 % of the rocks are Cretaceous plutons (pinks, reds, oranges, purples, marshmallow browns, one yellow). Much less common Jurassic and Triassic plutons (particularly on eastern edge of main range) also occur in this region. Small metamorphic pendants are show with blue (Paleozoic units) and greens (Mesozoic volcanic and sedimentary units).

The eastern 1/3 of the map shows the effects of Tertiary Basin and Range extension resulting in basement horsts (e.g. the White-Inyo Range) separated by grabens (filled with sediments marked in yellows). We used the entire White-Inyo Range horst (only northern ½ shown) to estimate back-arc Cretaceous magmatism. This range shows a greater amount of Jurassic plutons (reds) and associated volcanics (green) the former intruding Paleozoic metasedimentary units (blues, orange). The volumetrically smaller Cretaceous plutons are show in reds. Details of ages and pressures for units are discussed in text and displayed in other published figures.



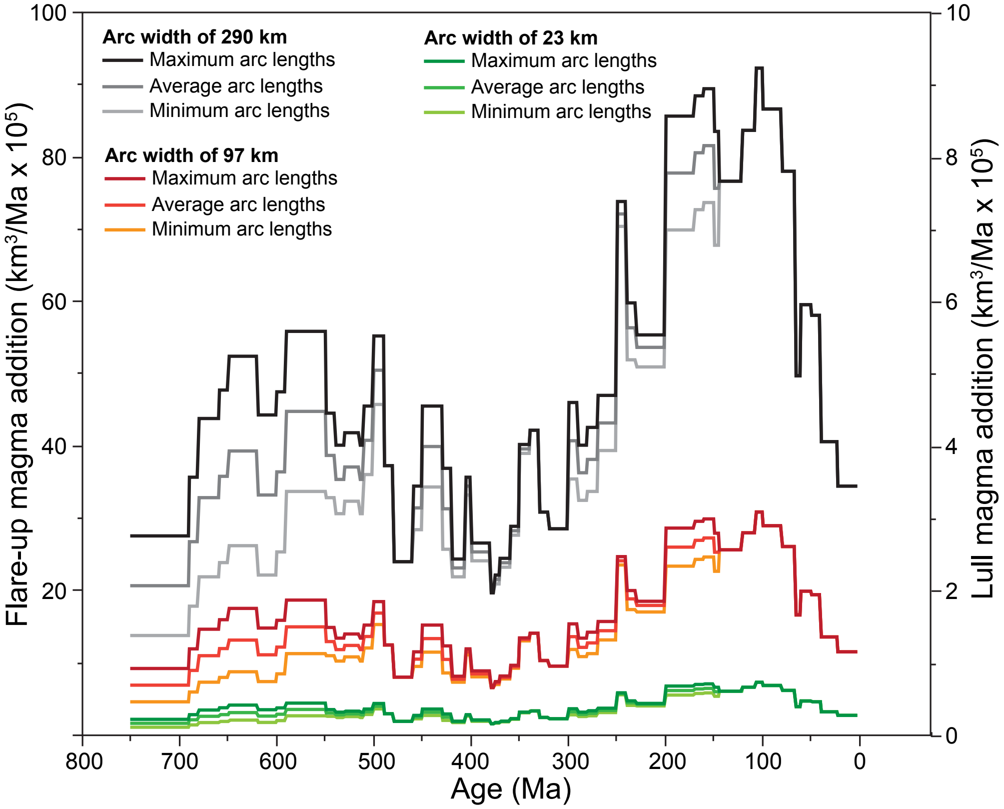
Foreland
Main arc
Rear-arc
A
N
100 km
462-480 Ma (12)
458±4 Ma; 468±3 Ma (20)
482±4.9 Ma (1)
467±4 Ma (9)
470±1.3 Ma (2)
468±3.4 Ma (16)
485±7 Ma (17)
474±4.3 Ma (11)
488±4 Ma (9)
483±8 Ma; 463±4; 477±4 Ma (19)
471±9.3 Ma; 471±2.5 Ma (21)
468±2.9 Ma (2)
484±1.6 Ma (2)
466±4.5 - 470±4.5 Ma (19)
473±17 Ma (8)
461±11 - 476±1.5 Ma (18)
478±4.1 Ma (3)
481±1.1 Ma (2)
484±4.7 Ma (2)
481±2.4 Ma (7)
468±8.5 Ma (4)
442±5.1 - 472±3.2 Ma (4)
473±6 - 492±7 Ma (14,15)
467±0.1 - 472±0.15 (14,15)
464±9.2 Ma (4)
478±3.6 Ma (2)
478±4.3 Ma (2)
483±5 Ma (2)
499±29 Ma (6)
478±8 Ma (2)
490±5 Ma (10)
491±6 Ma (5)
479±4 Ma; 478±2 Ma (2)
490±7 Ma (5)
490±5 Ma;
486±5 Ma;
478±7 Ma (22)
477±7 Ma (5)
480±6 Ma (5)
497±8 Ma (13)
478±4 Ma (13)
470±5 Ma (5)
456±30 Ma (13)
Precordillera
Source: US National Park Service, Copyright:© 2014 Esri
400000
500000
600000
700000
800000
900000
1000000
7200000
7100000
7000000
6900000
6800000
6700000
6600000
6500000
6400000
6300000
B
Detritial zircons
N = 1,123
Arc magmatism
150
100
50
400
420
440
460
480
500
520
540
C
Igneous zircons
N = 1,093
100
75
50
25
400
420
440
460
480
500
520
540
D
La Paya formation
479 ± 7 Ma
migmatite
Hongn et al. 2014
> 650 °C
515 ± 2 Ma
calcsilicate rock
Lucassen and Bacchio 2003
> 650 °C
463 ± 3 Ma
orthogneiss
Lucassen and Bacchio 2003
< 800 °C
4-6 kbar
464 ± 5 Ma
migmatite
Sola et al. 2013
> 650 °C
528 ± 3 Ma
calcsilicate rock
Lucassen and Bacchio 2003
~ 6 kbar
QU
~ 800 °C
~ 6 kbar
474 ± 4 Ma
460 ± 3 - 468 ± 2 Ma
migmatite
Buttner et al. 2005
> 650 °C
451 ± 4 Ma
444 ± 3 Ma
marble-calcsilicate
Lucassen and Bacchio 2003
AC
CA
< 1 kbar
~ 4-5 kbar
670-820 °C
4.5-5.3 kbar
470 ± 1 Ma
migmatite
Larrovere et al. 2011
> 650 °C
454 ± 3 Ma
432 ± 2 Ma
calcsilicate rock
Lucassen and Bacchio 2003
TN
AM
472 ± 26 Ma
migmatite
Knüver 1983
AN
> 650 °C
465 ± 1 Ma
466 ± 1 Ma
calcsilicate rock
Lucassen and Bacchio 2003
UM
< 1 kbar
~ 700-800 °C
~ 6-8 kbar
473 ± 3 Ma
471 ± 2 Ma
migmatite
Grissom et al. 2008
474 ± 12 Ma
orthogneiss
Varela et al. 2011
MA
~ 5 kbar
~ 5-7 kbar
FA
VE
> 650 °C
428 ± 6 Ma
calcsilicate rock
Lucassen and Bacchio 2003
~ 780 °C
5-7 (2-3) kbar
migmatite, paragneiss
De los Hoyos et al. 2011
VF
CH
442 ± 3 Ma
calcsilicate gneiss
Casquet et al. 2008
~ 8-5 kbar
~ 805 °C
5.2-7.1 kbar
477 ± 11 Ma
migmatite
Otamendi et a;. 2008,
Ducea et al. 2010
465.9 ± 4.4 Ma
466.5 ± 7.7 Ma
migmatite
Rapela et al. 2001
PP
< 3 kbar
805 °C
6-7 kbar
525 ± 9 Ma
478 ± 9 Ma
migmatite
Gallien et al. 2010
UL
~ 850 °C
~ 12 kbar
~ 465 Ma
orthogneiss
Mulcahy et al. 2014
~ 12 kbar
Nagoli complex
478 ± 3 Ma
migmatite
Steeken et al. 2006
Pringels Metamorphic complex
484 ± 7 Ma
Felsic orthogneiss
451 ± 10 Ma
grt-sil gneiss
Sims et al. 1998
Pringels Metamorphic complex
570-780 °C
5-6.4 kbar
498 ±10 Ma
mylonitic metapelite
Steeken et al. 2006
472 ± 26 Ma - Rb-Sr whole rock/mineral isochron
470 ± 1 Ma - U-Pb zircon age
470 ± 1 Ma - U-Pb monazite age
470 ± 1 Ma - U-Pb titanite age
🟥 Cambrian granitoids - Pampean orogeny
🟦 Late Neoproterozoic to Middle Cambrian low-grade metasediments
🟦 Late Neoproterozoic to Lower Cambrian medium- to high-grade metasediments
🟩 Cambrian - Ordovician metamorphic rocks
🟥 Ordovician intrusive and extrusive rocks
⬛ Mesoproterozoic basement, reworked by the Famatinian orogeny
🟧 Carbiniferous intrusive rocks

Supplementary Figure 2: a: Generalized geologic map (modified after Larrovere et al. 2011 and Rapela et al. 2016) of the Sierras Pampeanas showing the main exposed rock types and division into fore-arc, main arc and back-arc areas. Bedrock zircon U-Pb ages are taken from: (1) this study; (2) Pankhurst et al., 2000; (3) Varela et al., 2008; (4) Bellos et al., 2015; (5) Stuart-Smith et al., 1999; (6) Gallien et al., 2010; (7) Rapela et al., 2001; (8) Varela et al., 2003; (9) Höckenreiner et al., 2003; (10) Pankurst et al., 1998; (11) Larrovere et al., 2011; (12) Lork & Bahlburg 1993; (13) Steenken et al., 2006; (14) Ducea et al. 2010; (15) Ducea et al., 2017; (16) Fanning et al., 2004; (17) Rubiolo et al., 2002; (18) De Los Hoyos et al., 2011; (19) Dahlquist et al., 2008 and Dahlquist et al., 2012; (20) Büttner et al. 2005; (21) Báez et al., 2004; (22) Sims et al., 1998. AC - Sierra de Aconquija; AN - Sierra de Ancasti; AM -Sierra de Ambato; CA – Chaschuil; CH - Sierra de Chepes; FA - Sierra de Famatina; FI - Sierra de Fiambala; PP - Sierra de Pie de Palo; MA - Sierra de Maz; QU - Sierra de Quilmes; TN - Sierra de Toro Negro Ul - Sierra de Ulapes; UM- Sierra de Umango; VE - Sierra de Velasco; VF- Sierra de Valle Fertil. B and c: Histogram pattern of (A) detrital zircon ages and (B) Igneous zircon age compilation from Ratschbacher (2017) showing the distribution of ages from 550 to 400 Ma and constraining the Famatinian arc activity to ~ 490 to 450 Ma. D: Pressure estimates are from intrusive rocks and metamorphic rocks (peak metamorphic estimates; bold boxes). References for pressures: Alasino et al., 2014; Büttner et al., 2005; Garber et al., 2014; Larrovere et al., 2011; Mulcahy et al., 2011; Mulcahy et al., 2014; Pankhurst et al., 1998; Rossi et al., 2005; Tibali et al., 2013; Toselli et al., 2007. Hypabyssal rocks are assumed to have formed < 1 kbar.


Legend
Intrusive units
Late Cretaceous
Mid Cretaceous
Mid Eocene
Oligocene
Younger then 26 Ma
Unknown age
Host rock units
Chelan complex
Chiwaukum unit
Nason Ridge gneiss
Swakane unit
Napeequa unit
Ingalls ophiolite
Skagit gneiss
Water coverage
Glacier coverage
⑤ Metamorphic pressures (kbar)
3-4 Al-in-hornblende barometry (kbar)
Straigth Creek fault
Foggy Dew fault
Entiat fault
A
B
C
5400000
5350000
5300000
5250000
600000
650000
700000
0 5 10 20 30 40
Kilometers
N
Intrusive complexes
1 Mt. Stuart batholith
2 Sloan Creek plutons
3 Wenatchee Ridge Gneiss
4 Dirtyface pluton
5 Tenpeak pluton
6 High Pass pluton
7 Buck Creek Pass pluton
8 Sulphur Mt. pluton
9 Chaval pluton
10 Eldorado pluton
11 Bearcat Ridge pluton
12 Seven Fingered Jack plutons
13 Black Peak batholith
Host rock units
Volcanic and associated sedimentary rocks (Oligocene to Holocene)
Methow basin terrane and Okanogan block
Northwest Cascades and thrust system
Cascade River-Holden and Marblemount-Dumbell plutons
Columbia River Basalts and associated deposits
Extensional deposits (Oligocene to Eocene)
Unconsolidated deposits (Pliocene to Holocene)

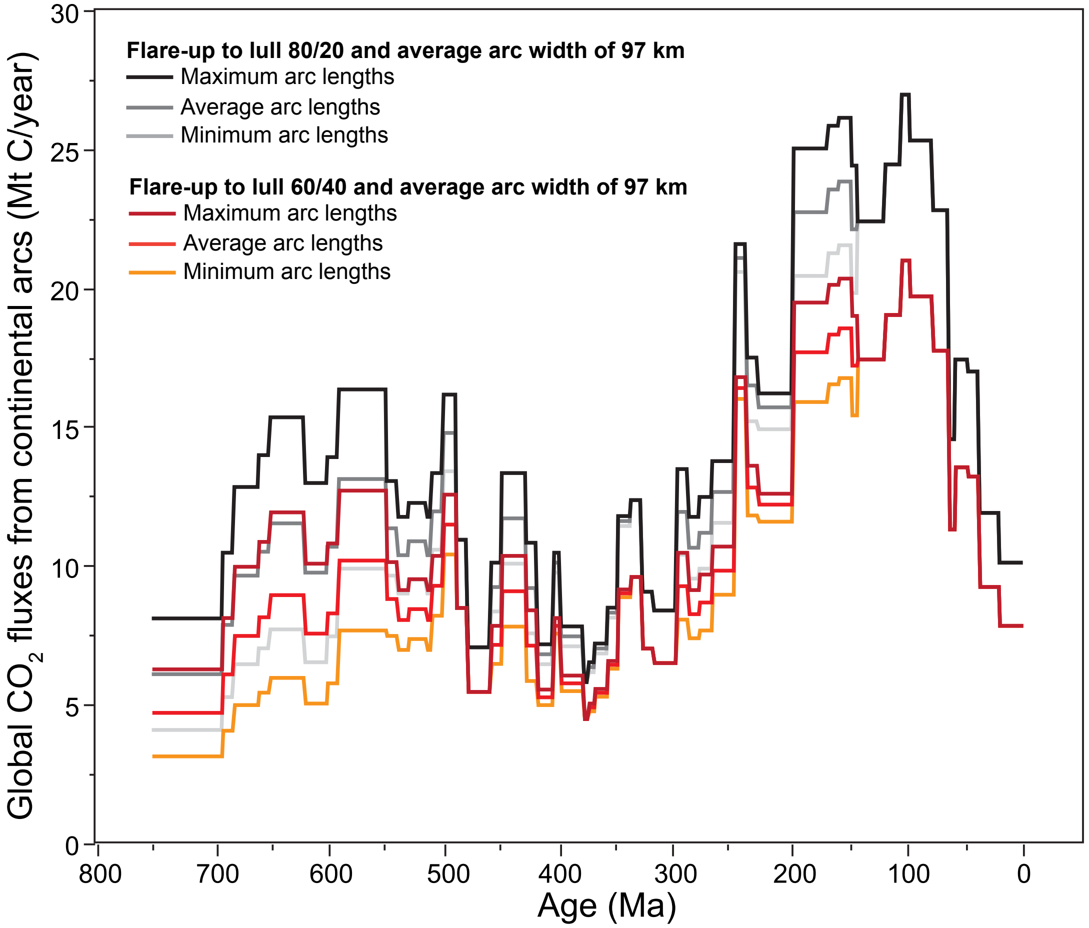
Supplementary Figure 3: Geologic map of the Cascades Crystalline Core modified after Haugerud and Tabor (2009) and Miller et al (2009). Area representing upper crust (A), mid-crust (B) and deep crust (C) are outlined with a dashed line. Metamorphic and Al-in hornblende barometry are from Anderson et al (2012), Shea (2014), Whitney et al (1999) Miller and Paterson (2001).

Supplementary Figure 4



Supplementary Figure 4: Calculated global flare-up (scale of the left side of the diagram; km^3/Ma) and lull magma addition rates (scale on the right side of the diagram; km^3/Ma) versus age for continental arc since 750 Ma using arc widths of 23 km, 97 km and 290 km (from De Bremond d'Ars et al., 1995) and estimates of minimum, average and maximum arc lengths (for 1 Ma steps from Cao et al., 2017). Lulls magma addition rates are calculated assuming they comprise 1/10 of the volume emplaced during magmatic flare-up periods. Differences between minimum and maximum arc lengths degrease towards younger ages due to the better preservation in the rock record.

Supplementary Figure 5



Supplementary File 5: Calculated global CO_2 fluxes from continental arcs (Mt C/year) versus age. Calculations are performed using the average arc width from De Bremond' Ars (1995) and a flare-up to lull ratio of 80/20 black/grey) and 60/40 (red/orange).