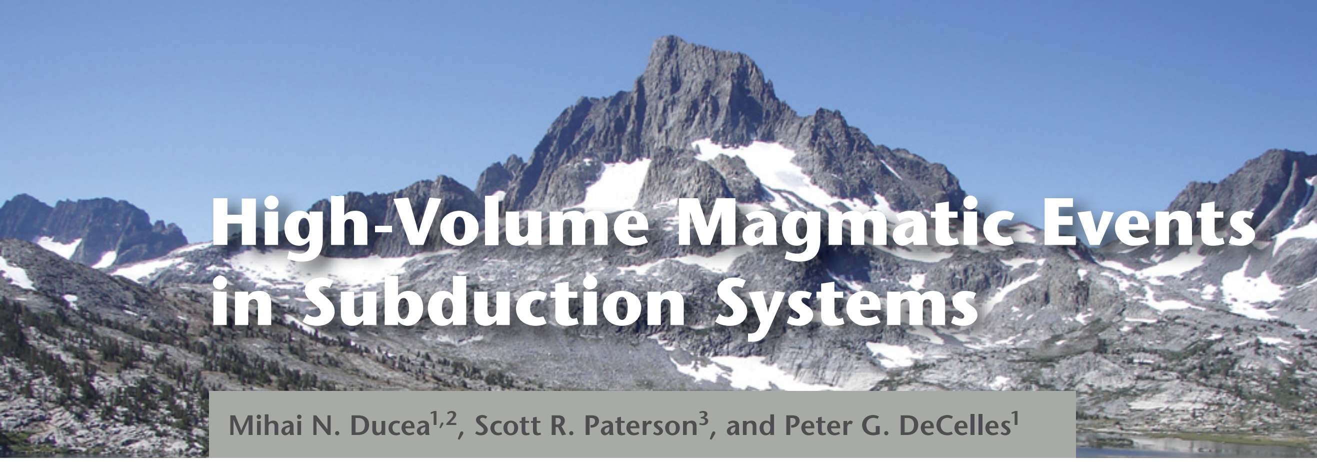

High-Volume Magmatic Events in Subduction Systems

Mihai N. Ducea[1,2], Scott R. Paterson[3], and Peter G. DeCelles[1]

1811-5209/15/0011-099$2.50 DOI: 10.2113/gselements.11.2.99

The world's biggest Phanerozoic magmatic arcs formed above subduction zones and comprise the products of continuous magma emplacement into the crust over periods of up to 500 My. However, the intensity of magmatic activity can vary significantly. Punctuated magmatic events lasting from 5 to 20 My can dwarf the volume of magmas generated through the remainder of an arc's history: these high-volume events are called "flare-ups" and can completely rebuild an arc's crust. In arcs formed on continental lithosphere, flare-ups typically correlate with regional structural events that shorten and/or thicken the crust. Geochemical and isotopic signatures show that these high magmatic addition rate events involve ~50% recycled upper-plate crust and mantle lithosphere; the remaining ~50% comes from the mantle wedge.

Keywords: subduction, arc magmatism, batholiths, magmatic addition rates, Phanerozoic

INTRODUCTION

Subduction-related magmatic arcs represent immense accumulations of intermediate, calc-alkaline igneous rocks and are considered the main factories of continental crust on Earth. Estimating the pace at which these giant volumes of magmatic rock were added to the crust and the mechanisms responsible for magmatic addition are fundamental issues for the disciplines of igneous petrology and continental tectonics. For decades, geologists have recognized that the evolution of arcs, and in particular those formed onto continental lithosphere, is not steady state but is punctuated by high-volume magmatic, pulses termed "flare-ups," occurring against a background of lower-volume activity (Armstrong 1988). These magmatic flare-ups do not appear to simply represent a bias in sampling: they dominate the magmatic input for arcs and must reflect some fundamental cyclical behavior of subduction systems. However, quantifying true magmatic volumes is difficult unless one has a large number of reliable ages and a good understanding of how such ages are distributed among the volcanic rocks, the deep crustal plutons, and the cumulates. A further complicating factor is that arcs laterally migrate over time. Therefore, the task of quantifying a given magmatic addition rate (MAR) at a convergent margin is as difficult as it is important for understanding arc magmatism and convergent margins tectonics in general.

The purpose of this paper is twofold. First, to inform the general geoscience reader how the fluctuations in magmatic volume over time can be quantified through gathering easy-to-understand yet difficult-to-obtain volumetric and temporal geologic data. Second, to provide the more expert reader with a summary of recent developments in quantifying changes of magmatic addition rates (MARs) through time and possible triggers for high-flux magmatic events at several better-known locations. We also review four questions to be answered when quantifying magmatic volumes in subduction environments that include continental lithosphere. These questions are as follows: (1) How much surficial versus intrusive igneous materials exist in arcs? (2) What is the spatial footprint of long-lived arcs in subduction settings? (3) What is the vertical crustal column of arcs and what are the changes in composition with depth? (4) How can ages of a magmatic arc be tracked? We then summarize the temporal evolution of a few major Phanerozoic arcs, pointing out their high-MAR events and discuss their possible driving mechanisms. No consensus exists in the literature as to which mechanism, if any, is the main driver of high-MAR events at convergent margins. Finally, we briefly address the possibility that certain arc flare-up events may be of global significance. We focus primarily on frontal Andean arcs (see below), which complements the articles in this issue that discuss MAR events in island arcs (Jicha et al. 2015 this issue) and continental interiors of compressive margins, such as the Altiplano–Puna plateau of the modern Andes (de Silva et al. 2015 this issue).

PLUTONIC VERSUS VOLCANIC PRODUCTS

The biased view of a modern (active) arc is one dominated by volcanic products. Large stratovolcanoes can reach 4 km above average regional elevation and can form over several million years. Yet, unless the edifices are collapsed or subject to unusually high erosion rates, the only exposed parts are those small fractions represented by the most recent products of the eruptive record. In contrast, old (inactive) arcs tend to be eroded down to subvolcanic or plutonic levels, with the volcanic cover preserved only as eroded remnants or as detritus in the sedimentary basins surrounding the former arc. Arcs sometimes preserve a window into both the volcanic top and its shallow plutonic root (e.g. Busby 2004; Economos et al. 2012). The volcanic-to-plutonic ratio, by mass, in arc magmatism is highly variable from region to region and generally difficult to constrain; it can range from 1:2 to 1:30 (Paterson et al.

1 University of Arizona, Department of Geosciences
Tucson, AZ 85721, USA
E-mail: ducea@email.arizona.edu, decelles@email.arizona.edu

2 University of Bucharest, Department of Geology and Geophysics
Bucharest, Romania

3 University of Southern California, Department of Earth Sciences
Los Angeles, CA 90089, USA
E-mail: paterson@usc.edu

2011), but on average is probably closer to 1:10. This latter ratio suggests that, to a first order, the greatest volume of igneous rocks freezes at depth in subduction zones and only a small volume escapes to the surface. In this paper, we provide examples of both active and ancient arcs in order to understand magmatism and its changes in volume over time in subduction systems.

MAGMATIC ARC FOOTPRINTS

The present-day exposure area, or footprint, of an eroded long-lived arc can be extraordinary large. The Sierra Nevada Batholith and the related terrains in California (USA) are exposed as more than 100,000 km^2 of granitoid and volcanic rocks. Figure 1 is a photograph showing a small fraction (<3%) of the well-exposed central part of the Sierra Nevada arc in the Yosemite area and illustrates the large surface area occupied by plutonic rocks. The Sierra Nevada and other equivalent gigantic concentrations of magmatic bodies, which were emplaced in small increments (as small plutons, most commonly stock-like) over millions of years, are known as composite batholiths. They are the roots of eroded stratovolcanoes and of other arc-related edifices and are the exposed "views" into defunct magmatic arcs stripped of their cover (de Silva et al. 2015). Older arcs that formed after the Neoproterozoic breakup of the Rodinia supercontinent do exist (see Supplementary Table 1[4]), but their preservation in the geologic record suffers from subsequent geologic processes such as fragmentation, due to recycling into newer plate margin settings, and extensive metamorphism. The geologic archive of the last 700 My provides a wide range of end-member products of magmatism at convergent margins. All of these arcs exhibit non–steady state patterns in terms of composition and magmatic production.

Arcs can be of oceanic (e.g. Talkeetna, USA; Kohistan, Pakistan), continental (e.g. the coastal batholiths of western North America; the Famatinian arc in Argentina), or of mixed origin (e.g. the Peninsular Ranges Batholith of Baja, Mexico, and southernmost California, USA) (see Supplementary Table 1). The term "mixed" refers to long-lived, continental arcs that incorporate coeval island arcs that collided and accreted to a continental upper plate. Oceanic arcs, and some continental ones, form in low relief, commonly submarine, environments outboard of main continental masses and are ultimately accreted to a continental mass. Arc–continent collisional events may take place with or without associated metamorphism, but these collisions will certainly lead to significant deformation of the accreting arcs. For that reason, continental arcs tend to be better preserved in the geologic record. The main products that are derived from a magmatic arc tend to form parallel to trenches, at approximately 100–125 km above the subducting slab (Stern 2002). The clearly identifiable line of volcanoes that correspond to the main arc is sometimes referred to as the frontal arc, and this is located above where the slab releases the largest amount of water via serpentinite and other dehydration reactions. The freed water ascends through the mantle wedge and promotes melting of the wedge peridotite (e.g. Stern 2002). The width of an arc is 30–40 km at any given time, depending on how focused the magmatism is. Therefore, the typical footprint of an arc can be simplified as a 35-km-wide band parallel to the trench. Additionally, back-arc regions, which also generate magmas via dehydration melting reactions in the mantle, extend the footprint of magmatism beyond the main (frontal) arc.

Arcs also migrate over time. The 30–40 km wide "ribbon" of frontal arc magmatism can sweep inboard or outboard relative to a fixed location within the interior of the upper plate. Most commonly, arcs migrate continuously at rates of 1–5 mm/y. For example, the Sierra Nevada Batholith experienced steady-state migration during the Cretaceous at a well-constrained rate of 2–3 mm/y. A similar trend has also been documented for other arcs, such as the Coast Mountains Batholith in southeastern Alaska and British Columbia (Gehrels et al. 2009). In both examples, migration was inboard; but outboard migrations are common, too. The net result is a wide belt of magmatic arc products that obliterate previous geologic features and that add to the mass budget of the arc. Segments of various ages align themselves near vertically next to each other parallel to the trench, giving most arcs a distinctive structural (geometric) style of parallel bands in map view (Fig. 2; Gehrels et al. 2009). When exposed at paleodepths of >25 km (the deep crust for thinner arcs, and the mid-crust for thick Andean ones), this alignment is also evident (Saleeby et al. 2003).

The classic explanation for steady-state subtle arc migration is a change in slab dip, although a certain component can be simply related to local structural processes that involve making room for incoming magmas. In contrast to the steady-state migration patterns, the location of arc magmatism can suddenly migrate by tens to hundreds of kilometers, as was the case with the well-studied inboard migration of magmatism in the western United States during the Laramide orogeny during the Cretaceous (e.g. Saleeby et al. 2003). While changes in slab dip due to subduction of seamounts and plateaus are plausible for such sudden episodes of magmatic migration, an equally likely explanation is that trenches themselves migrate during catastrophic episodes of (inboard) subduction erosion or (outboard) accretion of terranes, such as island arcs.

4 Supplementary tables mentioned in this article can be found online at elementsmagazine.org/supplements

Figure 1 Aerial view of a central portion of the Sierra Nevada Batholith (Late Cretaceous) showing its voluminous nature (image encompasses ~30 km at the horizon line). Photo credit: Scott Paterson

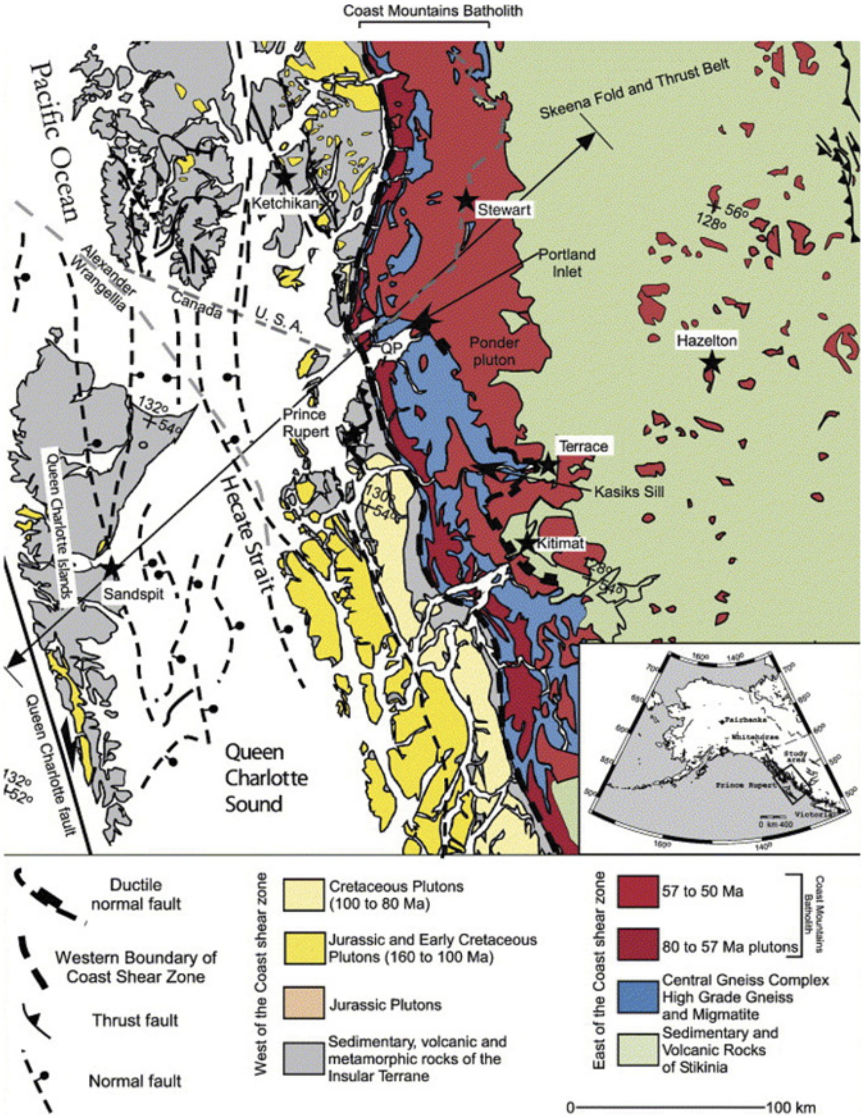

Figure 2 Geological map of the Coast Mountains region in northern British Columbia showing the distribution of Mesozoic and Cenozoic igneous belts. These belts are aligned parallel to the former trench. The line (arrows at both ends) drawn across the strike of the orogen shows the approximate width of the composite magmatic arc (Early Jurassic to Eocene). Modified from Hollister and Andronicos (2006)

Regardless of whether the migration is slow and continuous or is marked by a dramatic and sudden jump relative to the trench, the net result is that long-lived magmatic arcs can leave a footprint several hundred kilometers wide from the trench toward the interior of the upper plate. For example, the Coast Mountains Batholith was active from 210 Ma to 50 Ma and averages in width between 350 km and 400 km (Fig. 2); in the central Andes, post-Jurassic arc-related volcanic and plutonic rocks have a width of 300–650 km. The overall structural width of the arc can, in certain cases, be subsequently widened by extensional collapse of the upper plate. When this happens, the collapsed part needs to be ignored for the purpose of calculating the true exposed surface area of the arc.

INTO THE DEEP CRUST AND MANTLE

In cross-sectional view, the total “thickness” of magmatic and restitic rocks in long-lived arcs can span tens of kilometers. A crustal column (a one-dimensional vertical lithologic log) of an arc shows it to be made almost entirely of igneous rocks and their cumulates, ranging from 30 km thick in some ancient tilted island arcs (Talkeetna; Hacker et al. 2011a) to >100 km thick in long-lived continental arcs (Sierra Nevada; Saleeby et al. 2003). These are examples of arcs that were tilted and eroded as relatively coherent blocks such that they provide a continuous view into the depth of the arc; as such, they provide the best physical evidence for changes in arc chemistry and petrography with depth. Most commonly, exposed crustal sections represent only partial windows into these vertically extensive arcs.

Surficial products range in shape from major high-standing stratovolcanoes in Andean settings, to giant silicic calderas in Cordilleran interiors, to submarine volcanoes and associated thick accumulations of lavas and pyroclastic flows in oceanic arcs (Busby 2004). Shallow intrusive rocks (assembled as composite batholiths) are the most common occurrence of arc products. Emplacement depth for plutons is routinely determined using geobarometry on metamorphic country rocks or directly on the intrusive rocks. For North American subduction-related batholiths, more than 75% of intrusive rocks related to subduction are exposed to paleodepths of 2–10 km, with an average exposure level of 7.5 km below the surface (e.g. Ducea and Barton 2007).

Deeper tectonic windows into magmatic arc processes are less common. There are a few notable tilted exposures known, and their paleodepths range from 0 to 55 km (see Supplementary Table 2). Although uncommon, xenoliths in volcanic rocks offer a glimpse into what lies below these tilted sections: rocks from both sides of the Moho. The Sierra de Valle Fértil is one example of the rare deeper tectonic windows, this one into the Ordovician Famatinian arc of South America (Otamendi et al. 2012). Figure 3 is a schematic crustal column of the Sierra de Valle Fértil; this arc is essentially tilted on its side (90° rotation from the horizontal), such that the geologic map view represents a cross section from ~15 to 30 km paleodepths, thus providing a continuous vertical view.

There are three important lessons to be learned from studying crustal exposures from top to bottom. First, overall arc compositions become more mafic and richer in cumulate/restite assemblages (collectively referred to as residues) with depth. Second, magmatic products of the arc dominate everywhere in the crust. Third, the intrusive and/or volcanic ages and their relative distribution typical of the upper crust are identical with those in the lower crust.

The estimated compositional variation with depth for most arcs (Paterson et al. 2011; Jagoutz and Schmidt 2013) clearly indicates that there is a transition towards less silicic assemblages at depth. The deepest crustal levels are dominated by ultramafic assemblages, which are composed mostly of clinopyroxene and amphibole, with or without garnet, and with lesser amounts of orthopyroxene (Lee et al. 2006). Petrographically they are clinopyroxenites. With the disappearance of plagioclase at depth and the gradual replacement by garnet, these residual assemblages, which belong to the magmatic budget of arcs, undergo a change from sub-arc crust to mantle. Arguably, the Moho beneath an arc is a complex transition from granulite to eclogite facies rocks that span depths of 35–50 km, as opposed to the sharper compositional change from plagioclase-bearing rocks to peridotite, as is the case in most other regions on Earth.

Geochronological data show that the age ranges found in the upper crust are mirrored by age ranges from deeper crustal levels. For example, U–Pb zircon ages from the Famatinian arc's deep crustal exposure (20–30 km paleodepths) from the Sierra de Valle Fértil, (Argentina; 470–495 Ma) match U–Pb ages of the shallower exposures from nearby ranges. This and several other examples suggest that the magmatic products of a certain age range in arcs do not concentrate at a given depth in the crust (horizontal distribution), but are similarly abundant at all crustal levels (vertical distribution). Despite the obvious exposure complexity, we argue that the vertical "wall" of rocks that show the same age range from the surface to the deep crustal levels is a characteristic of most arcs. This observation attests to the verticality of magma transport, petrogenetic processes, and the emplacement in arc rocks.

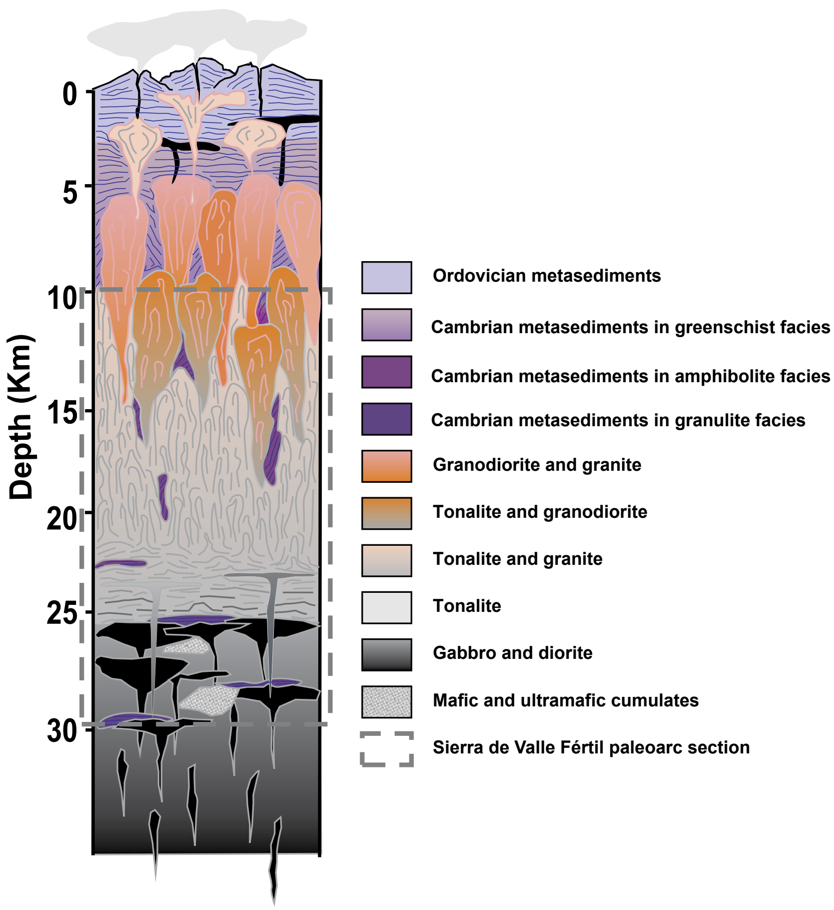

FIGURE 3 A schematic crustal column though the Ordovician Famatinian arc (Argentina) illustrating the rock assemblages that dominate at different depths. The critical depths exposed in the paleo-arc (Sierra de) Valle Fértil segment are shown within a dashed rectangle. MODIFIED FROM TIBALDI ET AL. (2013)

Sills, laccoliths and other horizontal or near-horizontal intrusions are common in nature. But they are not the norm under the main parts of an arc. Instead, horizontal igneous intrusions are more commonly found toward the interior of the upper plate in the back-arc (such as the interior Cordillera of North America, now the collapsed Basin and Range province). They become volumetrically significant in arcs that formed while the upper plate was compressional (e.g. the modern central Andes; de Silva et al. 2015), where they can produce some of the largest individual eruptions of intermediate to silicic magmas on Earth. However, quantifying their relative contribution to the magmatism above a subduction system is difficult. Nevertheless, we suggest that, based on a rough estimate for the interior Cordillera of North America, these "back-arc" magmas could add as much as 50% to the mass of an arc. However, the average contribution would probably be only 10–20%.

MAGMATIC AGES

Ages of magmatism are easily determined using modern geochonological techniques. The highest precision tool available is zircon U–Pb geochronology (Mattinson 2013), but several alternatives exist that depend on the composition and the depth of emplacement of the rock (Supplementary Table 3). Detailed studies of age distributions in intrusive and extrusive suites indicate that individual stratovolcanoes and their intrusive equivalents can be active for as long as 5–10 My. In other words, at any given location within an arc, the assembly of an intrusive suite (and its surface equivalents) takes place incrementally in variably sized batches of magma over several million years. The Tuolumne Intrusive Complex and equivalent suites in the eastern Sierra Nevada all formed over an ~10 My period during the Late Cretaceous; their footprint on geologic maps is approximately 1000 km^2. They probably represent the shallow roots of eroded stratovolcanoes. Each intrusive suite consists of several to potentially hundreds of mappable individual bodies with distinctive U–Pb zircon ages.

A complementary record for determining the life and temporal pulsing of a magmatic arc is provided by the sedimentary archive in forearcs and back-arcs. Detrital zircons in siliciclastic rocks provide powerful complementary information for arc duration, and possible high magma addition rate events (see Paterson and Ducea 2015 this issue), because they can act as a proxy to find the averaged erosion rates of two types of crust: (1) upper-crustal arc segments, which are often difficult to study directly; (2) the ancient and eroded sediments of arc domains. In addition, routine petrographic investigations of the sedimentary archive can distinguish between sediments derived from volcanic versus intrusive sequences. As a consequence, the detrital zircon age record is an extraordinarily valuable complement to any arc tempo study performed on the magmatic rocks themselves. The limitation of detrital datasets is that they do not provide quantitative information about the volume of igneous material. Growing datasets now exist that allow a comparison between detrital ages and the ages of nearby igneous units in arcs; typically, these comparisons show excellent matches between both volcanic and plutonic flare-ups and lulls (see also Paterson and Ducea 2015).

MAGMATIC PULSES AND FLARE-UPS

Major long-lived Phanerozoic arcs, for which thousands of age data are available, all have a non–steady state evolution that shows brief 5–20 My high-MAR episodes, alternating with longer, 30–50 My, periods of low-MAR episodes. Periods of almost no magmatism are associated with times when subduction is temporarily replaced by transform boundaries. This is the case today with the segments dominated by the San Andreas and Queen Charlotte faults in western North America. Apparent magmatic output can fluctuate over one to three orders of magnitude (Paterson and Ducea 2015) as is found with the magmatic arcs in the western North American Cordillera (Fig. 4). The evolution of arcs through flare-up events, with conservatively estimated apparent intrusive rates up to 1500 km^2/My and separated by lulls of 0 to 100 km^2/My, is remarkable. High-MAR events are of equally important magnitude elsewhere: about 85% of the Sierra Nevada arc was formed within 20 My (Chapman et al. 2012), 90% of the Gobi–Tianshan arc in Mongolia formed over 10 My (Economos et al. 2012), and 90% of the Famatinian arc crust (~30 km thickness preserved) was formed over a period of less than 5 My, with about 50% new additions from the mantle and 50% pre-existing crust (Otamendi et al. 2012).

ORIGIN OF HIGH-MAR EVENTS

On average, a magmatic arc enters a flare-up mode every 30–70 My (DeCelles et al. 2009). Oceanic island arcs are, therefore, unlikely to display more than one high-MAR event because their average lifetime is <40 My; but continental arcs could experience repeated episodes of high-MARs. Contrary to common assumptions about arc magmatism, high-MAR events do not appear to be related to convergence rates or to the obliquity of subduction (Ducea and Barton 2007). Instead, there may be a connection to regional upper-plate tectonics, specifically, with deformation patterns in the upper plate. Two processes, both requiring lithospheric thickening, have been put forward: retro-arc (back-arc) thickening and trench-side thickening. An alternative lower-plate-driven mechanism, which had previously been proposed to explain higher magmatic fluxes, is that of slab roll-back, i.e. the process of steepening of the subduction angle (e.g. Ferrari et al. 2007). Another proposed trigger for MAR events is repeated magmatic underplating: the intrusion of new melts generated in the mantle below and stalled in the lower crust by basalts from above the subduction zone.

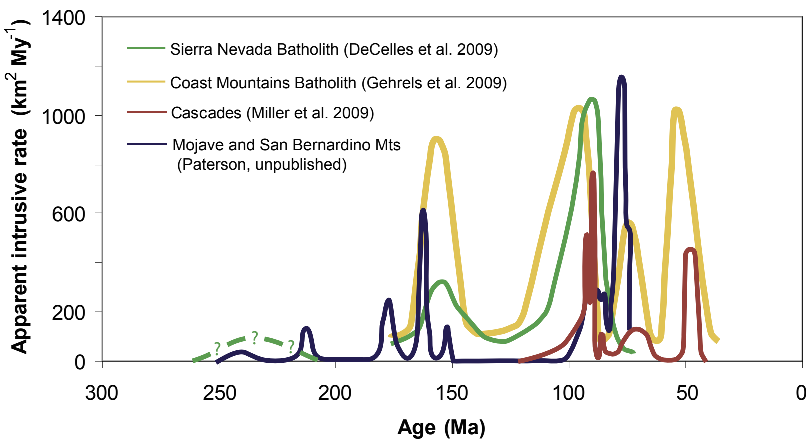

Figure 4 Graph of apparent intrusive rates versus age for various segments of the Mesozoic to early Cenozoic magmatic arcs in the western North American Cordillera. Derived from the surface area of the plutonic rocks (based on available mapping) of various ages (based on geochronology) for the four arc segments. Modified from Paterson et al. (2011)

The Cordilleran arcs of North America and the central Andes have an increased input of upper-plate materials during high-MAR magmatism. DeCelles et al. (2009) proposed that high-MAR events in Cordilleran arcs represent the large-scale cyclical behavior of arcs in which crustal thickening, primarily from foreland-driven fold-and-thrust belts, leads to magmatic flare-ups, in turn followed by the generation of large residual roots (Kay and Mahlburg-Kay 1991). After a flare-up, these root materials are prone to being recycled into the mantle by delamination or convective removal.

Most documented flare-up events (all the North American arcs, the central Andes, the Gangdese arc of southern Tibet) are geochemically characterized by high Sr/Y in rocks of intermediate composition (55–70% SiO_2). This geochemistry indicates that these rocks form in areas of thick crust and that their melts were extracted from depths in excess of 35–40 km (e.g. Annen et al. 2006). Lithospheric materials with significant crustal input (high $^{87}Sr/^{86}Sr$, low ε_{Nd}, and high $\delta^{18}O$) also dominate by mass during high-MAR events. This suggests that not only do these episodes generate large volumes of magmatic rocks, but they also contain a significant proportion (~50% by mass or more) of recycled crust and lithospheric mantle (Ducea and Barton 2007; Lackey et al. 2008).

Half of the current subduction margins are eroding (Clift and Vannucchi 2004). Therefore, the vast amounts of sedimentary materials that are "missing" from the trenches may not only be transported downward and be recycled into the mantle but they can partially make their way back into the upper crust via partial melting. Two mechanisms have been put forward to incorporate trench-derived rocks into arc magmas: tectonic underplating and relamination. Tectonic underplating is a structural process in which trench sediments (Clift and Vanucchi 2004) and/or accreted arcs (Busby 2004) are transported downward below a thrust sheet before being reattached to the bottom of the upper plate at the base of the crust in a process analogous to duplexing in a thrust belt. Relamination involves the diapiric rise of subducted sediment through the mantle wedge (Hacker et al. 2011b). Both processes can lead to partial melting; however, it is unclear what would be the salient signal that would identify trench contributions in arcs. These materials would be a mix of eroded arc and pelagic (ocean floor) sediments. If anything, their contributions would be less typical of the upper plate (e.g. higher ε_{Nd}), which is not what arc flare-ups produce. The role of massive amounts of missing trench sediments in magmatism at eroding margins remains to be quantified, with current estimates plausibly favoring a large proportion of eroded trenches and fore-arcs contributing to arc magmatism (Clift and Vannucchi 2004).

A non-tectonic cause for arcs entering a high-MAR mode is a thermal runaway effect from long-term emplacement of mafic material into the lower crust (Dufek and Bergantz 2005). The Dufek–Bergantz mechanism predicts that a thickened crust above a subduction zone continuously replenished by mafic magmas will eventually lead to the partial melting of the newly underplated crust and preexisting crustal materials. This process could be short-lived (<5 My), triggered by reaching a threshold in lower-crustal temperature. This model requires constant additions of mafic material from the mantle; most exposed tilted crustal sections show that mafic magmatism also increases significantly during flare-up events. The thermal-runaway end-member model may operate in conjunction with a tectonically evolving upper plate and may be a major driver of oceanic arc flare-ups.

GLOBAL FLARE-UPS OF ARCS?

Arc magmatism is arguably the most important mechanism responsible for crustal growth. There are several proposed periods of accelerated crustal growth in the history of the Earth (Condie et al. 2012), and they represent periods of extensive intermediate-composition magmatism and zircon growth. Do periods of accelerated crustal growth correspond to high-MAR events in arcs, and, if so, can we identify global high-MAR events in the Phanerozoic record? What is the ultimate tectonic driver of such periods?

Preserved in the Phanerozoic geologic record are four periods of arc magmatism that appear to show a more-or-less synchronous magmatic flare-up mode (>1000 km^2/My) in several unrelated regions: Middle–Late Ordovician (470–450 Ma), Middle Mississippian of the Carboniferous (330–300 Ma), Middle–Late Jurassic (170–150 Ma) and Late Cretaceous–Early Eocene (90–55 Ma). During these periods, island arcs and continental arcs produced higher volumes of magma than normal. These Phanerozoic peaks in arc MARs do not coincide with supercontinent formation. But the MAR peaks are prominent in the rock record and they coincide with times of major zircon growth. Because about 50% by mass of magmatic addition is derived from preexisting upper-plate lithospheric and crustal melting, the MARs are not necessarily events of new crustal growth.

There are two different possible global triggers for these four Phanerozoic flare-ups in arc magmatic activity. For the Carboniferous and Cretaceous events, there may have been periods of accelerated production of oceanic crust and overcrowding of older lithospheric material. For the Ordovician and Jurassic events, unusually slow periods of oceanic production might have lead to an increase in the presence of island arcs globally. This is an exciting new area of geological research and much remains to be done.

ACKNOWLEDGMENTS

We acknowledge funding from the National Science Foundation (NSF EAR-1019525 and NSF EAR-0907880 to MND and NSF EAR-0537892 and EAR-0073943 and 5 years of financial support through the USGS EDMAP program to SRP) and the Romanian state-funding agency UEFISCDI (project PN-II-ID-PCE-2011-3-0217 to MND). The manuscript benefited greatly from constructive reviews by Joshua Schwartz, Cathy Busby, and principal editor John Valley.

REFERENCES

Annen G, Blundy JD, Sparks RSJ (2006) The genesis of intermediate and silicic magmas in deep crustal hot zones. Journal of Petrology 47: 505-539

Armstrong RL (1988) Mesozoic and early Cenozoic magmatic evolution of the Canadian Cordillera. Geological Society of America Special Paper 218: 55-91

Busby C (2004) Continental growth at convergent margins facing large oceanic basins: a case study from Mesozoic convergent-margin basins of Baja California, Mexico. Tectonophysics 392: 241-277

Chapman AD and 6 coauthors (2012) Late Cretaceous gravitational collapse of the southern Sierra Nevada batholith, California. Geosphere 8: 314-341

Clift P, Vannucchi P (2004) Controls on tectonic accretion versus erosion in subduction zones: implications for the origin and recycling of the continental crust. Reviews of Geophysics 42: RG2001, doi: 10.1029/2003RG000127

Condie KC, Bickford ME, Aster RC, Belousova E, Scholl DW (2012) Episodic zircon ages, Hf isotopic composition, and the preservation rate of continental crust. Geological Society of America Bulletin 123: 951-957

DeCelles PG, Ducea MN, Kapp P, Zandt G (2009) Cyclicity in Cordilleran orogenic systems. Nature Geoscience 2: 251-257

de Silva SL, Riggs NR, Barth AP (2015) Quickening the pulse: fractal tempos in continental arc magmatism. Elements 11: 113-118

Ducea MN, Barton MD (2007) Igniting flare-up events in Cordilleran arcs. Geology 35: 1047-1050

Dufek J, Bergantz GW (2005) Lower crustal magma genesis and preservation: a stochastic framework for the evaluation of basalt-crust interaction. Journal of Petrology 46: 2167-2195

Economos RC, Paterson SR, Said LO, Ducea MN, Anderson JL, Padilla AJ (2012) Gobi-Tianshan connections: field observations and isotopes from an early Permian arc complex in southern Mongolia. Geological Society of America Bulletin 124: 1688-1701

Ferrari L, Valencia-Moreno M, Bryan S (2007) Magmatism and tectonics of the Sierra Madre Occidental and its relation with the evolution of the western margin of North America. Geological Society of America Special Paper 422: 1-39

Gehrels GE and 16 coauthors (2009) U-Th-Pb geochronology of the Coast Mountains batholith in north-coastal British Columbia: constraints on age and tectonic evolution. Geological Society of America Bulletin 121: 1341–1361

Hacker BR and 8 coauthors (2011a) Thermochronology of the Talkeetna intraoceanic arc of Alaska: Ar/Ar, U-Th/He, Sm-Nd and Lu-Hf dating. Tectonics 30: TOC1011, doi: 10.1029/2010TC002798

Hacker BR, Kelemen PB, Behn MD (2011b) Differentiation of the continental crust by relamination. Earth and Planetary Sciences Letters 307: 501-516

Hollister L, Andronicos CL (2006) Formation of new continental crust in Western British Columbia during transpression and transtension. Earth and Planetary Sciences Letters 241: 29-38

Jagoutz O, Schmidt MW (2013) The composition of the foundered complement to the continental crust and a re-evaluation of fluxes in arcs. Earth and Planetary Sciences Letters 371-372: 177-190

Jicha BR, Jagoutz O (2015) Magma production rates for intraoceanic arcs. Elements 11: 105-111

Kay RW, Mahlburg-Kay S (1991) Creation and destruction of the lower continental crust. Geologische Rundschau 80: 259-278

Lackey JS, Valley JW, Chen JH, Stockli DF (2008) Dynamic magma systems, crustal recycling, and alteration in the central Sierra Nevada batholith: the oxygen isotopic record. Journal of Petrology 49: 1397-1426

Lee C-TA, Cheng X, Horodyskyi U (2006) The development and refinement of continental arcs by primary basaltic magmatism, garnet pyroxenite accumulation, basaltic recharge and delamination: insights from the Sierra Nevada, California. Contributions to Mineralogy and Petrology 151: 222-242

Mattinson JM (2013) Revolution and evolution: 100 years of U–Pb geochronology. Elements 9: 53-57

Otamendi JE, Ducea MN, Bergantz GW (2012) Geological, petrological and geochemical evidence for progressive construction of an arc crustal section, Sierra de Valle Fértil, Famatinian Arc, Argentina. Journal of Petrology 53: 761-800

Paterson SR, Ducea MN (2015) Introduction to magmatic arc tempos. Elements 11: 91-98

Paterson SR, Okaya D, Memeti V, Economos R, Miller RB (2011) Magma addition and flux calculations of incrementally constructed magma chambers in continental margin arcs: combined field, geochronologic, and thermal modeling studies. Geosphere 7: 1439-1468

Saleeby J, Ducea M, Clemens-Knott D (2003) Production and loss of high-density batholithic root, southern Sierra Nevada, California. Tectonics 22: 1064, doi: 10.1029/2002TC001374

Stern RJ (2002) Subduction zones. Reviews of Geophysics 40: 1012, doi: 10.1029/2001RG000108

Tibaldi AM, Otamendi JE, Cristofolini EA, Baliani I, Walker BA Jr, Bergantz GW (2013) Reconstruction of the Early Ordovician Famatinian arc through thermobarometry in lower and middle crustal exposures, Sierra de Valle Fértil, Argentina. Tectonophysics 589: 151-166