Arc Magmatic Tempos: Gathering the Evidence

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In this issue of *Elements* we explore the characteristics, potential causes, and implications of episodic magmatism in arcs. A comparison of U–Pb bedrock and detrital zircon ages in arcs with independent calculations of volumetric magma addition rates (MARs) indicates that the former nicely track the episodic temporal histories of arc magmatism but not MARs. MAR estimates indicate that 100–1000 times more magmatism is added to continental arcs during flare-ups than during lulls and result in plutonic/volcanic ratios of >30/1. Episodic arc magmatism may result from external forcing on arc systems caused by events outside the arc and/or from internal cyclic processes driven by feedback between linked tectonic and magmatic processes within the arc. Along and across arc strike, changes and asymmetries in magmatic, tectonic, and geochemical histories provide important constraints for evaluating these poorly understood driving mechanisms.

Keywords: arc magmatism, batholiths, magmatic addition rates, magmatic tempos

INTRODUCTION

A fascinating aspect of Earth's evolution is that deep, hot rocks rise upward, by convection, to near-surface environments. This process helps cool the planet and is the main driver behind plate tectonics, as well as being the underlying cause of a wide range of associated magmatic processes. These magmatic processes have, in turn, played a key role in the overall differentiation of the planet, including the growth of oceanic and continental crust and the formation of an atmosphere. Along with the production of oceanic crust at mid-ocean ridges, one of the main results of such magmatism is the formation of long arcuate belts of volcanoes that overlie huge subsurface magmatic systems formed above subduction zones. These are called *oceanic arcs*[3], when built into and on oceanic floor, or *continental arcs*, when built into the edge of continents. These magmatic arcs are associated with linear zones of highly deformed crust called *orogenic belts*, which are particularly impressive in continental-margin settings. The broad characteristics of these volcanic chains, their underlying magmatic footprints, and the associated orogenic belts are discussed by Ducea et al. (2015 this issue).

One puzzling aspect of the evolution of magmatic arcs is that, despite continued ocean-plate subduction beneath them, the production of melts, the growth of the magmatic systems, and the associated volcanic eruptions are all highly *episodic*. Armstrong (1988) was among the first to document the episodic behavior of continental arcs (initially for the Coast Mountains region in British Columbia and Alaska and subsequently throughout the western US Cordillera) using an extensive regional geochronologic database. Now, through a combination of a rapidly growing number of U–Pb zircon crystallization ages from both volcanic and plutonic rocks, plus the expansion of U–Pb detrital zircon dating (Figs. 1 and 2), there is considerable evidence that magmatism in arcs is episodic in space and time at scales ranging from entire arcs to single volcanoes (Ducea 2001; Gehrels et al. 2009; Paterson et al. 2011; Memeti et al. 2014). Long segments of continental arcs can simultaneously *flare-up* with magmatic activity within a ~30 My window (Fig. 2), and be followed by *lulls* in which volumetrically little magma is added to the arc. Magmatic episodicity at typically shorter durations is also well established at the scale of single magmatic plutonic or volcanic systems (e.g. Jicha et al. 2006; Matzel et al. 2006; de Silva and Gosnold 2007; Lipman 2007; Memeti et al. 2014).

Episodic arc behavior is also recognized at regional scales in Phanerozoic arcs worldwide. This is based on the relative abundance of arc plutonic and volcanic rocks of known ages in the geologic record (Condie et al. 2012; Ducea et al. 2015). Futhermore, there is growing appreciation that the global length, and thus potentially the total volume, of continental arcs varies with time (Lee and Lackey 2015 this issue). Global fluctuations in arc magmatism have been suggested based on detailed analysis of detrital zircon data in continental regions (McKenzie et al. 2014). Although the preserved record of arcs during the first few billion years of Earth history is severely limited, as are windows into the deeper portions of both ancient and modern arcs, it is becoming clear that the temporal behavior (*tempo*) of arc magmatism throughout Earth history is episodic. Potential causes and consequences of this episodic behavior are examined in this issue.

This episodic magmatic activity, best established in continental arcs, draws attention to whether similar episodic magmatic activity occurs in oceanic arcs. Four factors make answering this question challenging. (1) Because

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[3] Key definitions of terminology commonly used in the study of arc magmatism are presented in the glossary.

oceanic arcs form on subducting oceanic plates, island arcs typically have a shorter magmatic history than continental arcs. (2) The demise of oceanic arcs coincides either with the arc being subducted (resulting in the loss of the historical record) or undergoing a collisional event (resulting in severe modification during amalgamation to continents). (3) In contrast to the number of tilted continental arc sections available (Fountain and Salisbury 1981; Miller and Snoke 2009) only a few tilted oceanic arc sections have been recognized (e.g. the Kohistan and Talkeetna arcs), making study of the deeper oceanic arc sections problematic. (4) The age record of oceanic arcs is difficult to obtain because zircon is less common in mafic igneous rocks. Consequently, the age distribution of some oceanic arcs is based on volcanic rock Ar–Ar subsolidus cooling ages (e.g. Jicha and Jagoutz 2015 this issue). Thus, large U–Pb zircon geochronologic data sets (>400 U–Pb ages) are still lacking for oceanic arcs, particularly for their volumetrically large, deep plutonic systems. These factors limit the size, number, and spatial distribution of episodic events that may be recorded.

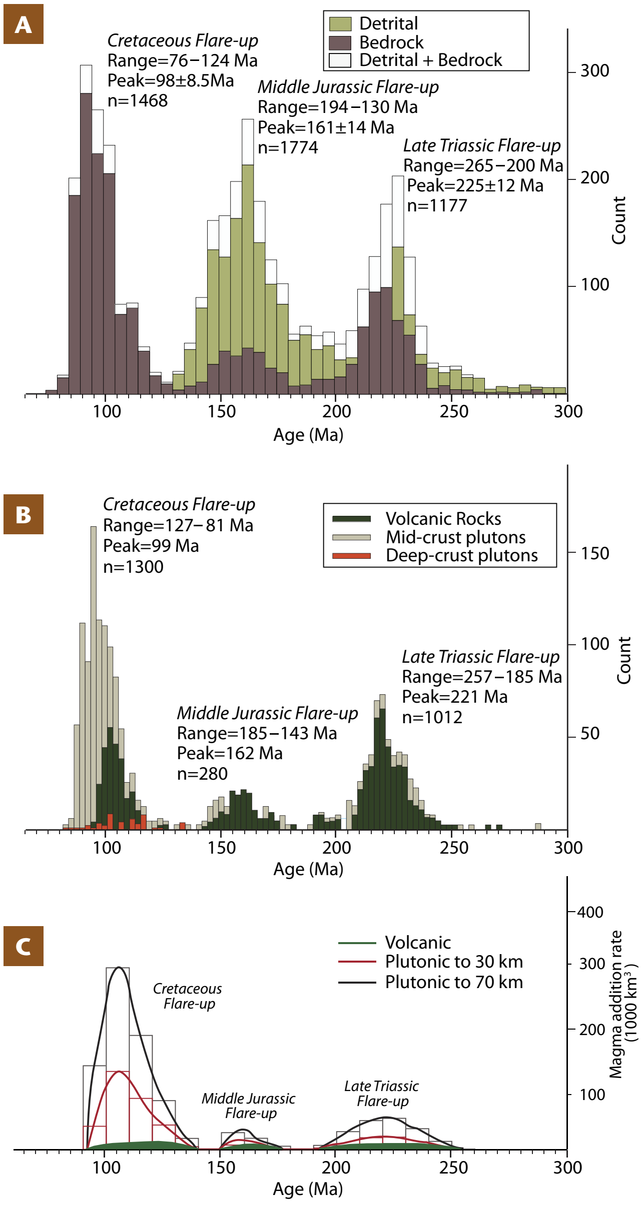

FIGURE 1 (**A**) Comparison of exposed bedrock U–Pb zircon ages with displaced detrital zircon U–Pb LA-ICPMS ages from the Sierra Nevada Batholith (California, USA). Both data sets temporally define the beginning (~250 Ma) and cessation (~85 Ma) of Mesozoic magmatism plus timing of three magmatic flare-ups and four lulls. (**B**) Depth comparison of bedrock Sierran U–Pb igneous ages, with ages separated into surface volcanic, shallow plutons (emplaced above 6 kbar), and deep plutons (>6 kbar emplacement). Timing of flare-ups and lulls appears depth independent, although volcanism may peak slightly earlier than plutonism in the Jurassic and Cretaceous flare-ups. (**C**) Calculated magma addition rates, measured in km^3 for 10 My age bins for both plutonic and volcanic materials in a 110 km wide corridor across the central Sierra Nevada. Plutonic curves show volume estimates for the top 30 km and 70 km of crustal sections. These curves show huge (100 to 1000) increases of magma added during flare-ups versus lulls resulting in plutonic/volcanic ratios of ~30/1 in this arc.

A few small U–Pb zircon data sets suggest that the typical lifespan of an oceanic arc is ~60–70 My or less and that episodic magmatism of shorter duration and involving smaller volumes may occur in oceanic arcs (Fig. 3). But until much larger geochronologic data sets that sample the entire arc section become available, these observations remain uncertain. Jicha and Jagoutz (2015) examine a number of related issues associated with estimating crustal growth rates during the evolution of oceanic arcs.

CHARACTERIZING EPISODIC MAGMATISM

Episodic magmatism in arcs is a relatively recent topic in the Earth sciences: the terminology and data sets used to examine episodic magmatism are in a rapid state of flux. We must keep in mind that episodic magmatism may result from *external forcing* of arc systems caused by events outside the arc (e.g. change in mantle flow, plate reconfigurations, collisions), and/or result from internal *cyclic processes* driven by feedback between linked tectonic and magmatic processes. Both mantle and *upper plate* (i.e. all rock above a subducting plate) and *lower plate* processes/events need to be considered when evaluating the potential role of forcing events or cyclicity (van Hunen and Miller 2015 this issue). Particular attention should be paid to the role played by upper plates that are made of thin oceanic crust (Jicha and Jagoutz 2015) versus thick continental crust (de Silva et al. 2015 this issue).

Periods when there is a high magma addition rate (MAR) to arcs are termed *flare-ups*; these are separated by periods of low MAR, termed *lulls*. Interestingly, flare-ups and lulls display apparent wave-like patterns of waxing and waning magmatism (Fig. 1C). This pattern has inspired scientists to examine the temporal spacing (i.e. *wavelength*) of these patterns and the changes in inferred volumes of magmatism (i.e. *amplitudes*) at various spatial scales (from single plutonic or volcanic centers to entire arc lengths). Questions have subsequently arisen about whether similar temporal patterns exist in other processes such as mantle convection, melting, deformation, magma ascent, erosion, sedimentation, and mountain building. Together, the episodic temporal patterns of these potentially linked processes are increasingly called *arc tempos*. Distinct external forcing events may not be directly linked to one another; thus, in this case, the concept of tempos may be less appropriate. Nevertheless, the temporal spacing of these events and response of the arc to the events are still of great interest.

To explore the temporal histories of arcs, large geochronologic data sets (>400 crystallization ages) are needed. Issues of (1) combining data obtained from different U–Pb dating techniques, such as TIMS, SIMS, LA-ICPMS, and bulk versus single zircon ages; (2) plotting techniques and statistical methods; and (3) sampling biases and preservation are significant, but will not be discussed in this paper. A complementary record for determining the life and temporal pulsing of a magmatic arc is provided by the sedimentary record in fore-, intra-, and back-arc basins. Detrital zircons in siliciclastic sediments derived from the

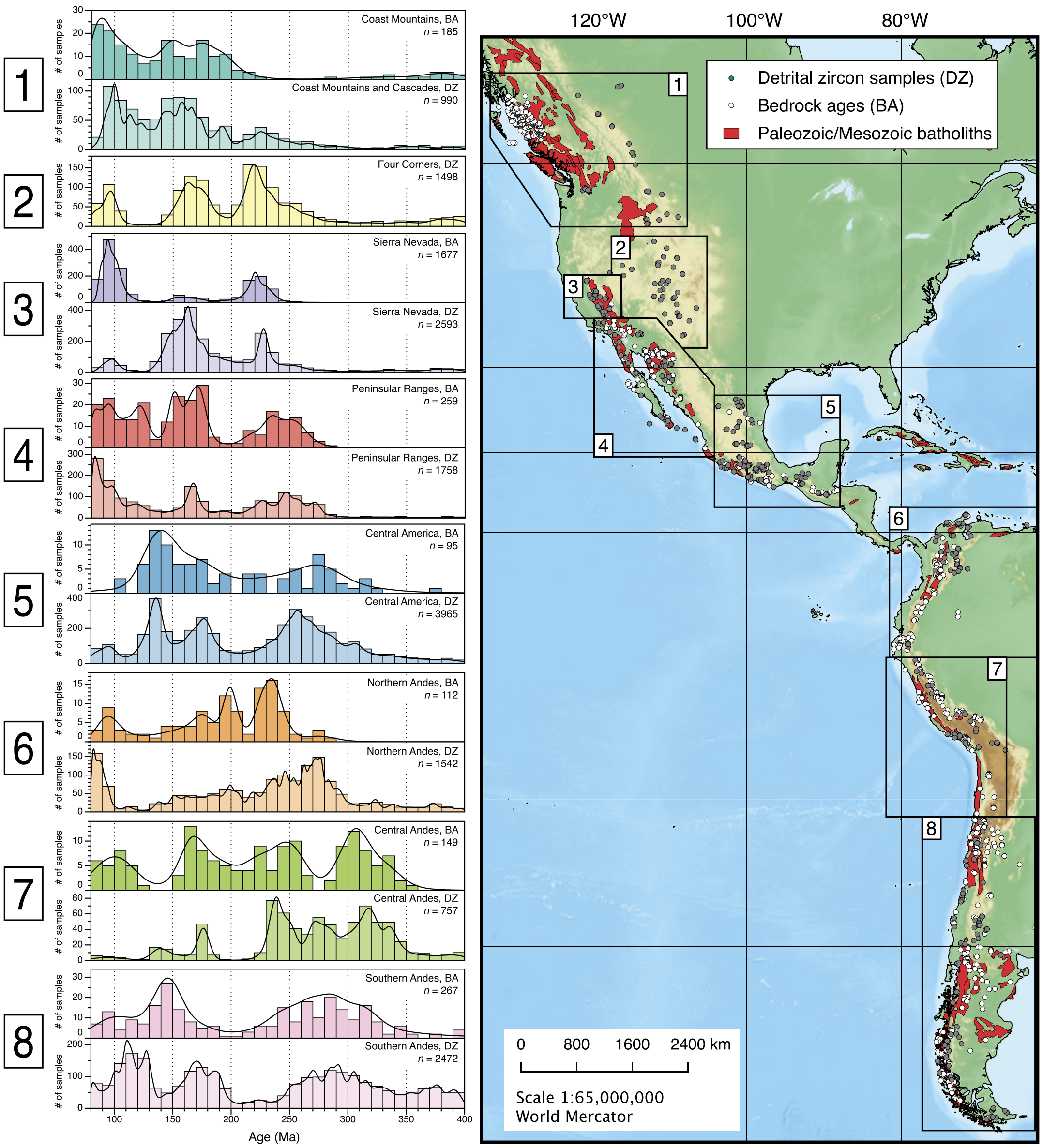

Figure 2 Comparison of bedrock (BA) versus detrital (DZ) U–Pb zircon ages along ~15,000 km of Mesozoic arcs in North, Central, and South America. Locations of age sets shown on map to right. White circles are bedrock ages; grey circles are detrital zircon ages. Age histograms for different domains are shown to the left. References of data sources are available online at elementsmagazine.org/supplements.

erosion of arcs provide important information about the timing and duration (but not necessarily the volumes) of high and low MAR events (Fig. 1). Siliciclastic sediments reflect the eroded volumes of upper crustal arc segments that are often difficult to study directly and/or reflect the arc domains that were eroded in the past (Gehrels 2014). In addition, petrographic investigations of the sedimentary record can distinguish between sediments derived from volcanic versus intrusive sequences. As a consequence, the record of detrital zircon ages is an important complement to arc-tempo studies that have already been established by bedrock dating of igneous rocks. One must also remember that bedrock sampling is essentially a 2-D investigation through a surface of an arc, despite the fact that the abundance of zircon of any given age can only be qualitatively equated to higher magmatic volumes (Fig. 1).

Continental arcs have an average composition of 57–64% SiO_2. It is intriguing to speculate on whether all rock types fundamentally produce similar amounts of zircon. Growing data sets now exist that allow detrital ages to be compared to bedrock igneous ages in arcs (Figs. 1 and 2); such comparisons show excellent matches between both volcanic and plutonic flare-ups and lulls as long as both data sets are large (>400 zircon ages). The ability to rapidly generate large detrital zircon data sets often results in more detailed information about the temporal history of nearby arc magmatism than provided by the typically smaller data sets obtained from bedrock igneous ages. The potential dangers in the interpretation of detrital zircon data sets include the following: (1) less precise and less accurate U–Pb ages (Pb-loss and inheritance problems are not rigorously addressed); (2) data sets may include ages from zircon grains that have been transported from outside the arc; (3) the total number of zircon grains of certain ages can be biased by local sources and the protolith ages of the sampled sedimentary rocks that contain the zircon grains.

Table 1 lists terminology often used in recent literature to quantify the change of magmatic additions to arcs, although often with rather inconsistent usage (Paterson et al. 2011). We particularly caution against use of the term *flux* because this implies knowledge about the areal dimension of the magma feeder system(s), which is rarely known. Instead we encourage use of the term *magma addition rates*, MARs, (a volcanic subcategory of "magma eruption rate," or MER, is used by de Silva et al. 2015). The MAR can potentially be normalized to an along-strike length of the arc over which measurements are made or to the size of individual magma systems. This makes MAR a better comparative measure of magmatic activities in arcs.

Geochronologic data sets, such as those shown in Figures 1A, 1B, 2, and 3, provide only indirect information about the volumetric magnitudes of high and low MAR events.

To determine MARs, temporal data sets must be linked to five other data sets: (1) geologic maps showing areal distributions of igneous units; (2) retrodeformation (e.g. the removing of tectonic effects) of the igneous units; (3) determination of predeformation 2-D surface areas of igneous units; (4) estimates of the vertical thicknesses and volumes both of the volcanic and the plutonic units; (5) calculation of the volume of magma added per time increment. One example of the temporal history of MARs, calculated using the above steps for the central Sierra Nevada arc, California, is shown in Figure 1. This plot dramatically emphasizes the waxing and waning patterns of magmatism. Huge volumes of magma were added to the arc during flare-ups (particularly the Cretaceous flare-up), this added magma being volumetrically anywhere from 100 to 1000 times greater than magma added during lulls. The plot also emphasizes that the plutonic footprints of these systems are volumetrically enormous in comparison to volcanic caps, with plutonic/volcanic ratios typically 30/1 or greater. These large plutonic/volcanic ratios are in excellent agreement with other recent calculations derived from very different approaches (Ward et al. 2014; Lipman and Bachmann 2015) and are much larger than previous estimates. Comparisons between the MAR plots and plots of bedrock and detrital U–Pb zircon geochronology shows that the latter correctly identify the temporal characteristics of the MAR histories but can be very misleading with respect to volume additions.

A MAR calculation should not be equated with the volume of mantle magma added to the crust without first determining three things: (1) estimates of mantle versus recycled crust in these magmatic systems, (2) the amounts of oceanic arcs now amalgamated to continental arcs, (3) the amounts of igneous material removed either from the roots of these arcs and transported back into the mantle or by topographic erosion into nearby basins (e.g. Paterson et al. 2011; Jicha and Jagoutz 2015).

MAR calculations also have been estimated for single plutons (e.g. Matzel et al. 2006; Memeti et al. 2014) and for volcanoes (de Silva and Gosnold 2007; de Silva et al. 2015). In these systems, there is clear evidence that younger magma pulses are magmatically eroding and recycling older plutonic material (e.g. Paterson et al. 2008) leading to extensive mixing of melts and crystals (e.g. Memeti et al. 2014). This mixing of crystals has also been widely recognized for 3 decades in volcanic rocks (e.g. Davidson et al. 2007). Thus, modern MAR calculations will systematically underestimate the volumes of older magmatic materials. MER calculations (for volcanoes) may approximate erupted materials but one must estimate two other factors: (1) the amount of magmatically eroded and recycled volcanic materials; (2) the magnitudes of erupted airfall deposits that lie outside the volcanic centers. The clear evidence of magmatic recycling and mixing further supports the conclusion that arc-scale MAR estimates face these same factors, although the magnitudes at the arc scale are not well known.

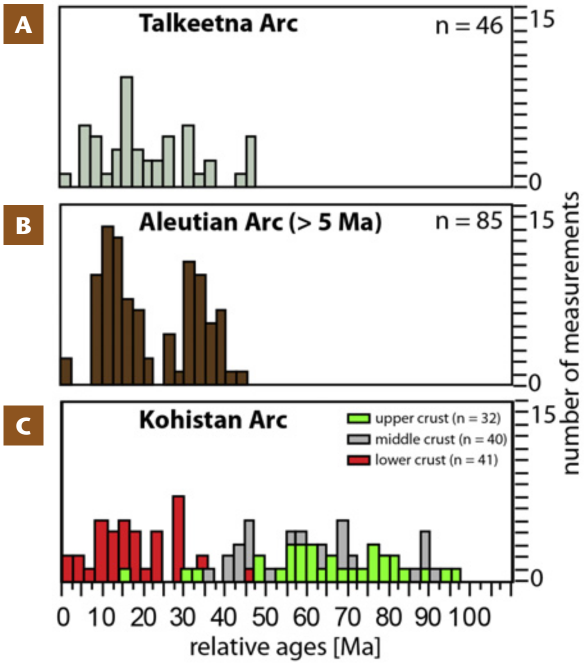

Figure 3 Bedrock age histograms for one modern (Aleutians) and two older (Talkeetna, Kohistan) oceanic arcs with ages normalized to when arc magmatism started. Numerous ages of currently active magmatism in Aleutians (<5 Ma) were excluded so as to not swamp details of older peaks. Ages in the Kohistan arc are color-coded by depth of emplacement into upper, middle, and lower crust. References of data sources are available online at elementsmagazine.org/supplements.

Table 1 COMMONLY USED QUANTITIES IN DISCUSSIONS OF MAGMA ADDITIONS TO ARCS. The quantity "volumetric flux" depends on knowledge of the areal dimensions of magmatic feeders and is rarely known. Thus, volume (or magma) addition rates will be used in this issue.

Quantity	Units	Sometimes referred to as
Total added volume	km^3	Magma addition
Volume addition rate	km^3 My^{-1}	Magma flux; magma production rate
Volumetric flux	km^3 km^{-2} My^{-1} = km My^{-1}	
Areal addition rate	km^2 My^{-1}	Areal flux, apparent addition rate
Volume addition rate per arc-length	(km^3 My^{-1})(km^{-1})	Apparent intrusive flux; Armstrong unit; magma addition rate

A number of interesting questions arise when examining any temporal plots of igneous ages, MARs, or any other means (e.g. tectonic or chemical changes) of measuring the histories of an arc or an individual magmatic system. Do these histories reflect episodic tectonic forcing events? Or do they reflect linked, cyclic internal arc processes (e.g. DeCelles et al. 2009)? Evaluating potential causes of the episodic histories can be significantly advanced by doing the following four things: (1) examining the wavelength, amplitude, and asymmetry of temporal patterns of the above data sets (e.g. Figs. 1–5), with "asymmetries" including not only temporal patterns but also changes with depth, differences between volcanic and plutonic histories, and spatial variations; (2) determining the temporal and spatial scales over which the events/cycles occurred (e.g. Fig. 2); (3) establishing the links between the magmatic and tectonic histories in both the lithosphere (Fig. 5) and the mantle; and (4) comparing continental arcs (upper plate with thick continental crust) to oceanic arcs (upper plate with thin oceanic crust) to determine to what degree lower- and upper-plate processes control arc tempos (e.g. compare de Silva et al. 2015, with Jicha and Jagoutz 2015). Even in the case where external-forcing events are driving these histories, existing data clearly show that arcs don't respond instantaneously. Instead, arcs show gradual increases and decreases of MARs, changes in chemistry, changes in tectonism, and so on that often appear to be at least somewhat decoupled from continued subduction.

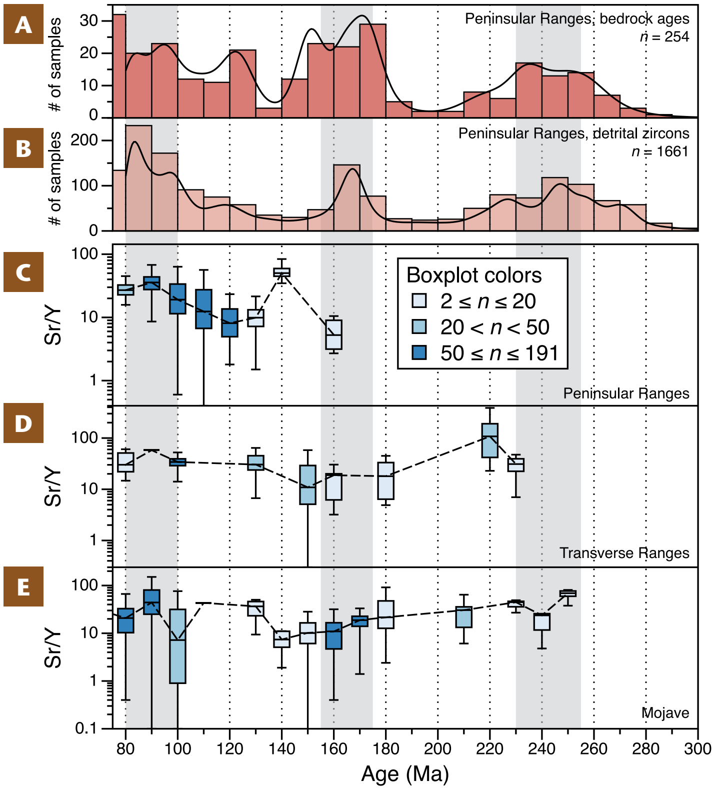

Figure 4 Temporally and spatially controlled averages of different Sr/Y ratios compared to bedrock and detrital U–Pb zircon ages from the Peninsular Ranges Batholith in southern California, USA. References of data sources are available online at elementsmagazine.org/supplements.

Figures 1–5 illustrate the application of the above approaches. Figure 1B shows magmatic ages grouped by depth (surface volcanic rocks, <15 km depth, >15 km depth) in the Sierra Nevada arc. Although the number of ages available for the deepest levels is limited, present data show that there is no depth variation at the times of peak surges and lulls, a result consistent with the limited age data from other continental arcs, such as the Famatinian arc in Argentina (Otamendi et al. 2012) and the Gobi–Tienshan arc in Mongolia (Economos et al. 2012). Inspection of Figures 1B and 1C also shows another example of potential asymmetries in patterns: the maxima of volcanic MARs occurs slightly earlier than the peak of plutonic MARs, at least for the Jurassic and Cretaceous flare-ups.

Figure 2 compiles bedrock and detrital zircon igneous ages (400–80 Ma) from about 15,000 km of Cordilleran Mesozoic arcs from the Coastal Batholith, British Columbia to the southern Andes (Argentina/Chile). The data illustrate how we can begin to examine the spatial length-scales of flare-ups and lulls and their temporal spacing. The arc, it appears, never entirely "turned off" and events/cycles were scale dependent: several magmatic peaks and lulls were roughly synchronous over a distance of >3000 km, others were synchronous over <1000 km, and local variability occurred at ~100 km scales. The durations (wavelengths) of magmatic cycles averaged ~60–70 My during much of the Mesozoic but appear to shorten to ~20–30 My during the Cenozoic. Thus, there are probably several reasons, which are scale and age dependent, why magmatism may be episodic.

Distinct changes in isotope and trace element chemistry in continental arcs correlate with high MAR episodes in many arcs (Fig. 4). Importantly, most high MAR events in continental arcs are accompanied by high Sr/Y and La/Yb ratios, measured at a SiO_2 of 60%, suggesting that these events took place while the crust was thicker than normal (Girardi et al. 2012). The initiation of high MAR events are characterized by an increased spread of radiogenic isotope ratios that are indicative of a greater input from the upper plate's lithosphere; oxygen isotope ratios are consistent with a greater input from the crust (Ducea and Barton 2007; Lee and Lackey 2015). Many other geochemical trends need to be investigated in more detail, but it is clear that the geochemical variations in arc magmas are coupled with the tempo of the magmatism itself.

PROPOSED MODELS FOR ARC TEMPOS

Moresi and colleagues have developed movies that help visualize what happens during subduction beneath arcs (found at elementsmagazine.org/supplements). van Hunen and Miller (2015) use seismic tomography and modeling studies to further explore mantle–lithosphere interactions within and beneath active arcs, emphasizing the temporally complex evolution of these systems (particularly before, during, and after the closure of oceanic basins) and the temporal and spatial scales of processes at crustal depth. Increasing our knowledge about the temporal evolution of both lithospheric and aesthenospheric mantle beneath arcs will greatly improve our ability to test the roles played by the mantle–lithosphere interactions that drive episodic magmatism in overlying arcs.

What other processes might drive episodic magmatism in arcs? We need to keep in mind that tectonic events that cause external forcing and/or internally linked, cyclic processes may be responsible for magmatic episodicity. For example, the Cordilleran Jurassic flare-up has been related to the break-up of Gondwana and its associated change in plate motions. And the Late Cretaceous Cordilleran flare-up has been related to an increase in oceanic crust production rates and/or plate reorganizations (Matthews et al. 2012). These imply that there is a direct link between some aspect of plate motions and magma surges/lulls in arcs; however, this link has not been observed (Ducea 2001; DeCelles et al. 2009).

Ducea and Barton (2007) and DeCelles et al. (2009, 2015) have developed an elegant model that involves feedback between linked tectonic processes (foreland shortening, underthrusting of foreland material into lower crustal parts of arcs, crustal thickening and mountain building), sedimentary erosion, and magmatic processes (flare-ups, loss of mafic–ultramafic plutonic roots). Cao et al. (2015) modified this model by noting that tectonic and erosional processes are also episodic within an arc (Fig. 5), resulting in upper crustal rocks in the arc being moved downward into the mantle wedge where they may be partially melted and recycled into rising magmas. These models need no external forcing, although they may partly reflect how an arc responds to an external forcing event.

It has been suggested that magmatic flare-ups in arcs, particularly those in continental arcs, may result from decompression melting within the mantle wedge and modulated by the thickness of the upper plate. Plate thickness is, in turn, controlled by cycles of magmatic thickening and tectonic thinning (Lee and Lackey 2015).

Other potential processes, such as episodic volatile fluxing into the mantle wedge, episodic melting scenarios, and the modulating effects of thick continental crust on rising magmas, may all play a role. But to date, long-term temporal records of such processes have not been established. Thus, it remains difficult to determine what role these latter processes play in influencing arc tempos.

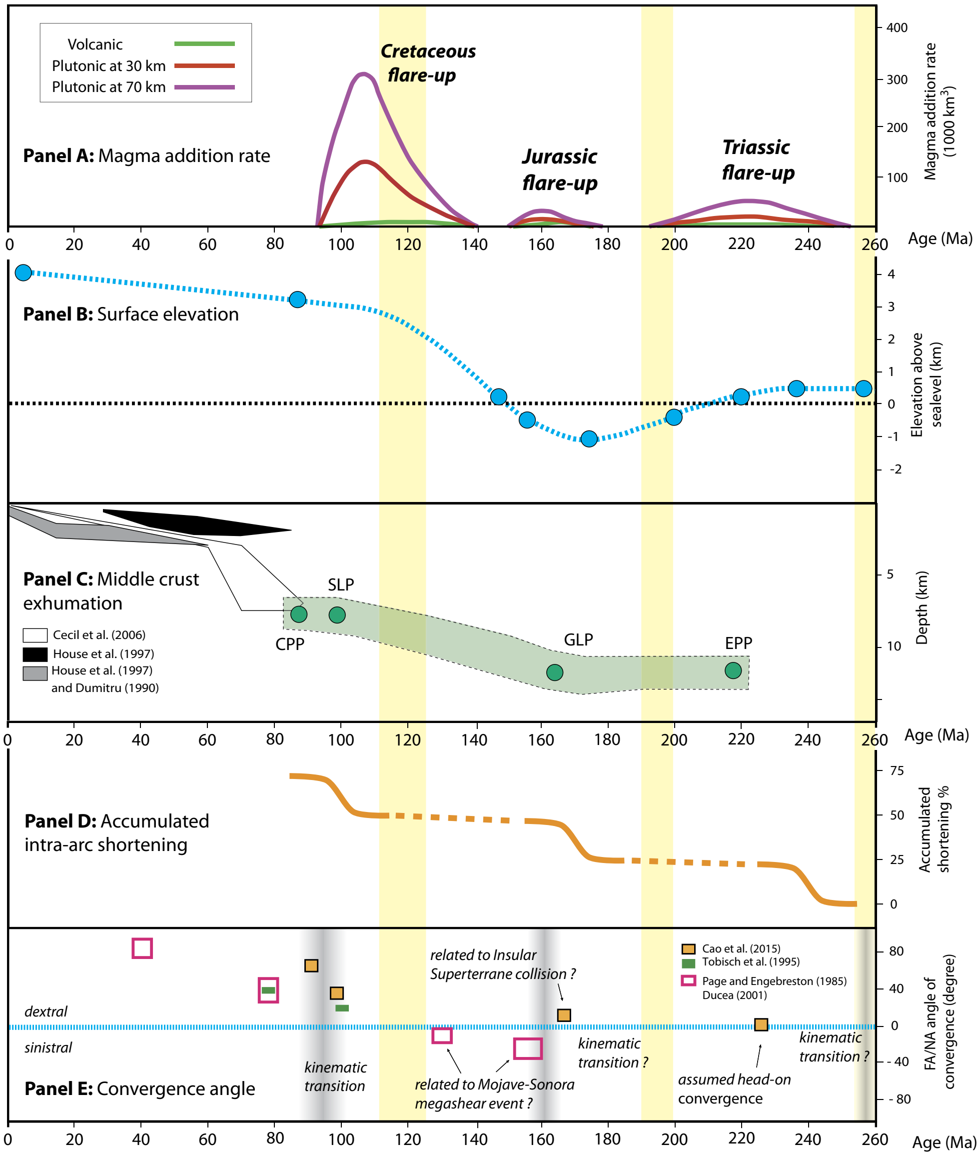

FIGURE 5 (**A**) Tectonic history of Mesozoic Sierra Nevada (USA) in comparison to the MAR plot (1000 km^3; for plutonic and volcanic sections of 1° arc length in central Sierras) from FIGURE 1C. (**B**) Estimated surface elevations for highest peaks in central Sierra Nevada versus time: dots are times where we have geologic controls on elevation. (**C**) Mid-crustal exhumation curve with green showing pluton emplacement depths determined from the aluminum-in-hornblende geobarometer. CPP = Cathedral Peak pluton, SLP = Soldier Lake pluton, GLP = Green Lake pluton, and EPP = Eagle Peak pluton. (**D**) Inferred accumulated bulk shortening of the arc. (**E**) Tectonic summary of North American–Farallon (NA/FA) plate convergence angles. Yellow shaded zones = regional unconformities. For further discussion of this plot see Cao et al. (2015). References of data sources are available online at elements-magazine.org/supplements.

Most of the above models are developed for continental arcs. One common denominator to these models is that any reorganization (e.g. tectonic reorganization, change in structural configurations, change in bulk compositions or environmental conditions) of the lower crust–mantle lithosphere regions beneath arcs will lead to a rejuvenation of melting and, potentially, a magmatic flare-up. A thermal lag likely occurs after the initial tectonic reorganization of the lithosphere as magma conduits reorganize, latent heat of fusion is added to the new rocks, latent heat of crystallization is removed from fresh magmas, and crustal rheologies shift. These four latter processes may lead to some of the asymmetries discussed above. Whether this reorganization is due to internal feedback, external forcing, or is due to coupling with mantle processes remains unclear.

CONCLUSIONS AND SOCIETAL IMPACTS

Magmatism in continental arcs is clearly episodic. Why it is so, remains an exciting question to investigate. We hope that the papers in this issue of *Elements* provide a useful introduction to the topic, and will motivate young scientists to research further the likely causes. We particularly encourage the continued development and synthesis of large databases that establish the long-term history of tectonic, magmatic, and sedimentary processes for both oceanic and continental arcs. The creation of geochemical and geochronologic databases are well underway (e.g. GEOROC, NAVDAT, Pet DB, EARTHCHEM), but structural databases are still lacking. It is also critical that all "arc databases" be evaluated over a range of spatial and temporal scales. Too often our ideas and resulting models for arc behavior are based on single sections through a laterally extensive arc system or on a single type of study (e.g. just plutons or just volcanoes or just tectonics). Studies of limited focus will not be sufficient to unravel the causes of episodic magmatism (or tectonism) along arc sections such as that shown in FIGURE 2 where the episodic behavior is variable along the arc.

Understanding the spatial and temporal history of arcs is also an exciting endeavor for society, and for our educational system. These episodically evolving arc systems play an important role in the building of mountains, the formation of ore deposits, the evolution of water resources, climate change, and in a variety of geologic hazards (e.g. volcanic eruptions, earthquakes, rock fall, landslides and floods in mountainous regions). If arcs display a variety of episodic behaviors, does this imply that all of the above processes are episodic as well? If so, we can improve our ability to predict and/or respond to geologic hazards that may catastrophically impact our communities. These evolving arc systems are dynamic and visible examples to our society of "alive" geologic systems that shift their behavior as our planet evolves. Magmatic arcs are, thus, an outstanding and easily accessible teaching resource, and they provide a fitting setting by which to discuss how we, as humans, interact with an evolving Earth.

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DEFINITIONS OF COMMONLY USED TERMS IN DISCUSSION OF MAGMA ADDITIONS TO ARCS

Apparent flux: Rate of magma input (plutonic) or output (volcanic) inferred from areal size of mapped igneous units. Units measured in km^2 My^{-1} (Table 1).

Arc residue: Materials located in the lower crust of arcs. They comprise the low-silica cumulates after fractional crystallization and/or restites after partial melting of intermediate melts (e.g. tonalites, granodiorites). They are rich in ortho- and clinopyroxenes, amphiboles, and depending on the depth below surface, also contain plagioclase and/or garnet as major minerals.

Arc roots: The lower part of magmatic arcs (crust and mantle lithosphere) considered to be dominated by magmatic residual (restitic from partial melt and cumulate materials) mixed with new additions from the mantle. Arc roots have an average silica composition lower than basalt.

Arc tempo: A measure of cadence or rhythm of processes operating within magmatic arcs. In cases where these tempos can be defined by a wave-like pattern, then the following terms help describe the wave pattern and thus processes:

- *Amplitude*: vertical distance from a background to peak height.
- *Asymmetry*: Instead of sinusoidal wave patterns, measured values define asymmetrical patterns which may change with time, with depth or with respect to other variables.
- *Wavelength*: Distance between any two points with the same phase, such as between crests, or troughs of a wave.

Back arc: A secondary line of magmatic products, sometimes present at subduction margins, more scattered on the upper plate than the frontal arc products.

Batholith: Areas of plutonic rock larger than 100 km^2 that represent the magmatic portion of arcs. The term is used both for single solidified magma bodies (plutons) and areas of multiple, closely spaced plutonic bodies (e.g. Sierra Nevada Batholith).

Bedrock zircon ages: U–Pb ages of zircon grains obtained from bedrock units.

Benioff zone: Planar zone of deep (~35–700 km) earthquakes corresponding to location of the subducted slab in the mantle.

Continental arc: Subduction-related magmatic arc in which the lower plate is oceanic lithosphere whereas the upper plate is continental lithosphere. Note that some upper plates, while made of continental lithosphere, may be under extension and thus form at low elevations and can sometimes be submarine.

Crust production rates: The rate at which arc crust is produced per unit of time. Long-term, time-averaged, crust production rates for arcs are typically determined by estimating an existing volume of crust and dividing by its age. These rates are expressed in units of volume (km^3) per km of arc length per unit of time, which is typically expressed in millions of years (km^3 km^{-1} My^{-}1).

Cyclic processes: Processes that repeat in a regular fashion due to internal feedback mechanisms.

Detrital zircon ages: U–Pb zircon ages from sedimentary rocks. These zircon grains formed in igneous units elsewhere and were deposited at the sampling location.

Episodic processes: Series of loosely connected parts or events occurring at repeated (can be regular or irregular) intervals. It does not assume that there are internal feedback mechanisms driving the repeated events.

External forcing: Events external to systems that change boundary forces and thus potentially drive a change of behavior within the system.

Flare-up: Period where the volume of magmatism added to the crust is much greater than average amounts.

Frontal arc: The first line of volcanoes and underlying batholiths away from the subduction trench; always present at subduction margins and parallel to the trench.

Ignimbrite flare-up: Period of volcanic activity dominated by eruption of ignimbrites, with volume at least an order of magnitude greater than steady-state volcanic activity.

Lithospheric delamination: The removal and sinking of a portion of the lowermost lithosphere into the mantle below.

Lower plate: a subducting oceanic plate and all rock units below this plate

Lull: Period where the volume of magmatism added to the crust is much less than average.

Magma addition rate (MAR): Amount of plutonic material added to the examined area measured in km^3 My^{-1} (Table 1).

Magma production rates: The total volume of magma produced for a given arc or ridge segment per unit of time. Magma production rate estimates take into account the volume of the arc crust produced *and lost* since inception. Crust can be lost via any number of processes including rifting, subduction erosion, delamination, and surficial erosion. These rates, like crust production rates, are expressed in units of volume (km^3) per km of arc length per unit of time, which is typically expressed in millions of years (km^3 km^{-1} My^{-1}) (Table 1).

Mantle-power input: Thermal-energy and volatile influx to the base of the crust by basalt intrusion from the mantle.

Mixed arc: Long-lived, continental arcs that incorporate coeval island arcs that collided and accreted to the continental upper plate.

Oceanic arc: Subduction-related magmatic arc in which both the lower and upper plates are oceanic (made of oceanic crust and oceanic mantle lithosphere).

Paleo- and Neo-Tethys: Ancient Paleozoic oceans located between the continents of Gondwana and Laurasia.

Regional "nodes": Concentrations or foci of magmatism or volcanism within a broader area.

Seismic anisotropy: A phenomenon that occurs when a polarized shear-wave travels through an anisotropic medium. The incident shear-wave splits into two separately polarized shear waves. The two waves travel at different speeds and the delay time difference between the two arrivals provides an estimate of the amount of anisotropy in the material. The orientation of the faster shear-wave records the orientation of the anisotropic fabric and can be used to infer mantle flow.

Slab rollback: The process where sinking oceanic lithosphere (or slab) subducts into the mantle and sweeps backwards causing the hinge or trench location to migrate away from the arc in the direction of the subducting plate.

Slab window: A gap or tear in the subducted oceanic lithosphere.

Tertiary pulses: Third-order temporal peaks of volcanic activity; part of a hierarchy of temporal peaks.

Upper plate: All rock units above a subducting oceanic plate.

Volume-normalized U–Pb age data: Number of U–Pb analyses weighted by estimated volume of the geologic unit analyzed.