Quickening the pulse: Fractal tempos in continental arc magmatism

Shanaka L. de Silva[1], Nancy R. Riggs[2], and Andrew P. Barth[3]

The magmatic history of a continental arc can be characterized as punctuated equilibrium, whereby long periods of low-level activity are interrupted periodically by short bursts of high-volume magmatism ("flare-ups"). Geochronological records, most notably from zircons, reveal episodicity in volcanism, pluton formation, and detrital sedimentation in, and associated with, arc segments and volcano-plutonic suites. Distinct tempos can be recognized at all resolvable spatial and temporal scales and are broadly fractal, with each scale reflecting the timescale of processes occurring at different levels in the arc crust. The tempos of continental arc magmatism thus reflect modulation of the mantle-power input as it is progressively filtered through the continental crust.

KEYWORDS: continental arc flare-ups, magmatic history, episodes, tempos, U-Pb in zircon geochronology

INTRODUCTION

This thematic issue of *Elements* is centered on the recognition that magmatic processes in volcanic arcs vary in space and time. Much of the lifetime of an arc is characterized by the "steady-state" magmatism that builds both the andesitic composite cones, which define the arc, and their intrusive equivalents, tonalitic plutons. This steady-state magmatism is thought to be characterized by low mantle power (i.e. thermal-energy and volatile influx to the base of the crust by basalt intrusion from the mantle.), low magmatic addition rates (termed MARs in this thematic issue), and normal geothermal gradients. At the surface, these conditions produce small-volume, largely effusive eruptions, with only occasional explosive caldera-forming events (Hildreth 1981; de Silva 2008).

The "steady state" is periodically punctuated by short-lived, high-volume magmatic events termed "flare-ups" (FIG. 1). It is during flare-ups that primarily granodioritic Cordilleran batholiths and their eruptive equivalents, dacitic ignimbrites, form (Ducea et al. 2015 this issue). DeCelles et al. (2009) suggested that flare-ups are periods of increased rates of magma production, perhaps up to 3 or 4 times greater relative to the steady-state rates of

---

[1] College of Earth, Ocean, and Atmospheric Sciences
Oregon State University
Corvallis, OR 97333, USA
E-mail: desilvas@geo.oregonstate.edu
[2] School of Earth Sciences and Environmental Sustainability
Northern Arizona University
Flagstaff, AZ 86011, USA
[3] Department of Earth Sciences
Indiana University–Purdue University Indianapolis
Indianapolis IN 46202, USA

This is the author's manuscript of the article published in final edited form as:
de Silva, S. L., Riggs, N. R., & Barth, A. P. (2015). Quickening the pulse: fractal tempos in continental arc magmatism. Elements, 11(2), 113-118. http://dx.doi.org/10.2113/gselements.11.2.113

arc-magma production in the mantle wedge. Flare-ups are probably triggered by major changes in the geometry and geodynamics of subduction zone and lithospheric processes. Advection of mantle power through the crust sets up a series of feedbacks that lead to elevated geotherms and prodigious "upper-plate" ("crustal") magmatism (Brown 2001; de Silva and Gregg 2014). Upper-plate magmatism may be imbued with an enriched chemical and isotopic character quite distinct from periods of steady-state magmatism (e.g. Ducea and Barton 2007). Volcanic activity during arc flare-ups is dominated by the eruption of tens of thousands of cubic kilometers of ignimbrites ("ignimbrite flare-up") and by the formation of multiple spatially and temporally related caldera complexes. These collectively define the ignimbrite plateaus that are understood to be the surface expressions of incrementally constructed granodioritic to granitic batholiths (Lipman et al. 1972; Bachmann et al. 2007) and that are integral to the formation and stabilization of the continental crust. Closely associated with the magmatic history is a geomorphic evolution where erosion of the volcanic elements and exhumation of the plutonic roots leads to a sedimentary record that should, in principle, integrate the volcanic and plutonic records. Adequate integrated records are rare; however, zircons can act as robust recorders of magmatic time-scales and tempos, which can be determined through high-resolution zircon geochronology. The rare adequate records that do exist reveal the episodic nature of flare-ups at a variety of space–time–volume scales. We characterize this episodic nature as fractal because the episodicity recurs at progressively smaller scales (see de Saint Blanquat 2011) each with characteristic tempos (FIG. 1).

ZIRCON AS A RECORDER OF MAGMATIC TEMPOS IN CONTINENTAL ARCS

Zircon has long been recognized as an excellent geochronometer (U–Pb system) because of its high partition coefficients for uranium and thorium radionuclides, which are used in radio-isotopic dating, and its low affinity for nonradiogenic lead. Additionally, zircon is a common, readily obtained, accessory phase in the silicic magmas that dominate during continental arc flare-ups, and zircons are thought to record a significant period of the magmatic history of the system. These characteristics, combined with the development of high-resolution isotopic dating techniques, have revolutionized the science of determining magmatic time scales (e.g. Schmitt 2011; Schmitz and Kuiper 2013). The data we discuss here rely on high-precision/low-spatial-resolution isotope-dilution thermal-ionization mass spectrometry (ID-TIMS; used for volcanic/plutonic records; error <1%) and the lower-analytical-precision, but much finer spatial resolution (tens of microns), in situ techniques of sensitive high-resolution ion microprobe (SHRIMP) mass spectrometry (used for volcanic/plutonic/sedimentary records; error 2–5%), and laser ablation inductively coupled mass spectrometry (LA-ICPMS; used for sedimentary records; error 2–5%). The magma systems that we discuss range in age from 200 Ma to 1 Ma. At the 1 Ma age range, age differences of 0.1 to 0.05 Ma can be resolved; but in 200 Ma old systems the errors may be 4 to 10 Ma. Events of ~0.1 Ma are unlikely to be recorded, and probability density functions, statistical representations of probability distributions of ages, derived from LA-ICPMS and SHRIMP detrital data tend to smooth out the error on individual grains. The variation in precision between systems may lead to offset in apparent derived ages.

One important caveat when using zircon ages is that they may not reflect the entire magmatic history. Zircon will rapidly crystallize once Zr-saturation conditions are met, but will dissolve slowly in a Zr-undersaturated melt. Furthermore, larger zircon phenocrysts preferentially survive over smaller ones. Thus, depending on magmatic conditions, some history may not be recorded. Alternatively, multiple histories may be recorded: in magmas with complex multistage histories, surviving zircon crystals provide nucleation sites for additional zircon growth. Thus, zircons can record multiple events or cyclicity in magmatic systems (e.g. Folkes et al. 2011; Lima et al. 2012).

INTEGRATING VOLCANIC, PLUTONIC, AND DETRITAL RECORDS TO IDENTIFY TEMPOS IN CONTINENTAL ARC MAGMATISM

Episodic behavior during flare-ups in continental arcs is often inferred from the volcanic record of ignimbrite plateaus. Eruptions occur sporadically. By examining the space–time–volume record of volcanic activity, the episodic nature and variability of intensity of eruptions can be identified. Particularly in young arcs, or in environments where erosion is minimal and the volcanic record is well preserved, relatively robust extrusive fluxes (if the area through which a magma flows is known) can be delineated through mapping, stratigraphic correlation, and extensive geochronology (McIntosh et al. 1992; de Silva and Gosnold 2007; Lipman 2007; Best et al. 2013). Magmatic addition rates, or fluxes, are determined by assuming the commonly quoted volcanic-to-plutonic ratios of 3:1, 5:1, and 10:1. However, it is important to understand that the eruptive record is not a complete record of the magmatic activity. Moreover, the largest silicic systems are often difficult to interpret because they are older, cyclic, incompletely preserved or exposed, and may be "resolution limited" because the ability to resolve absolute age differences decreases as age increases. Finally, most studies have focused on segments of arc or on individual volcanic complexes, so data for complete arcs are lacking. Sampling bias also creeps in: studies commonly focus only on a few specific eruptions in preference to the entire regional record. We refer to this as the "petrologist's effect (FIGURE 2).

The plutonic record that is exposed in broadly exhumed arcs are also examined to retrieve apparent intrusive magmatic fluxes. Systematic mapping and abundant geochronologic sampling allow us to illustrate the apparent flux as preserved on an inclined section through the upper crust. Such areal representation of flux, as estimated either by U–Pb zircon age or by area, is highly variable due to pulses and lulls in intrusive activity (Bateman 1992; Ducea 2001; DeCelles et al. 2009). Caution is warranted for three reasons when assessing for magmatic flux. First, geochronologic data are generally not collected in a spatially systematic manner. Second, inclined sections are incomplete exposures of less than fully exhumed plutonic arcs. Third, translation of such data into a volume typically relies on poorly constrained estimates of the thickness of intrusions. Similar to the volcanic record, the petrologists effect is apparent in plutonic studies.

The detrital-zircon record would be assumed to provide the most complete assessment of magmatic activity, owing to the very common occurrence of zircons in igneous rocks and the nature of sedimentation (e.g. Gehrels 2012). By extension, detrital zircons should record magmatic addition rates and provide a first approximation of the volume of zircon-bearing magmatic rock, with short-lived magmatic pulses and lulls also being apparent (e.g. Barth et al. 2012; Laskowski et al. 2013). Nonetheless, caution is warranted when using the zircon record as a proxy because seldom does the sedimentary record isolate a single part of a magmatic arc: sedimentary successions probably represent longer-term integrated "average" records.

MAGMATIC TEMPOS IN CONTINENTAL ARCS – THE RECORD IN FLARE-UPS

The Mesozoic Sierra Nevada–Salinia–Mojave arc of the western USA and Mexico (Dickinson 1981; Saleeby 2003) provides an example of how plutonic and volcanic zircon records, together with the derivative sedimentary record, show the episodicity apparent on a scale of several tens of millions of years (FIG. 3). Remnants of the Jurassic parts of the Salinia–Mojave arc cover a region about 200 km across strike by 300 km along strike, comparable in scale to the aforementioned ignimbrite plateaus. A relatively extensive plutonic age dataset shows a distinct primary pulse lasting 40–60 My with a peak at 166 Ma, reflecting the assembly of a typical Sierran granodiorite to granitic intrusive suite during a flare-up (FIG. 3B). The more defined/pronounced peaks in the volcanic record may implicate shorter windows when conditions for eruption are met, while the plutonic record presents a more continuous history of magma accumulation and batholith construction. The detrital data from the fore-arc and back-arc sections of this Mesozoic arc complex show a broad correlation depending on whether the sedimentary basin records a volcanic or plutonic terrain uniquely or dominantly. The back-arc signature closely matches the plutonic record, whereas the fore-arc signature shows a much younger dominant peak that matches the 150 Ma volcanic peak (FIG. 3C). The sample base in both the fore-arc and back-arc regions is hundreds of zircons from several units spanning several hundred kilometers parallel to the arc; this contrasts with the Salinia–Mojave portion as represented by the plutonic and volcanic zircons. The double peak in the volcanic record together with the correlative peak in the detrital fore-arc data, when contrasted with the irregular plutonic curve, also illustrates the longitudinal asymmetry of the arc. Over a longer time scale, as much as 100 My, the distal back-arc record possibly mimics the greater flux curve for the Sierra Nevada batholith in FIGURE 3B (Laskowski et al. 2013).

FRACTAL TEMPOS IN CONTINENTAL ARC MAGMATISM

Similar, but not necessarily identical, patterns of arc magmatic activity that recur at progressively smaller scales define fractal tempos in continental arc magmatism. Within the primary 40–60 My *p2* pulse (FIG. 3C), it is clear that there are finer-scale episodes or secondary pulses. Further insight into these requires data of higher resolution that could be readily available in the space–time–volume patterns of ignimbrite plateaus. Among the best documented are those of the Altiplano–Puna Volcanic Complex (APVC) of the Central Andes (de Silva et al. 2006), and the various middle Cenozoic volcanic fields of the North American cordillera (e.g. McIntosh et al. 1992; Bryan et al. 2007; Lipman 2007; Best et al. 2013). The primary feature of the time–volume pattern of these ignimbrite flare-ups is that the eruptive history is episodic and in three distinct stages: first, a waxing period of relatively low eruptive flux; second, a climactic stage (the peak of the flare-up) when the largest eruptions happen and the eruptive flux is at its highest; third, a waning stage that returns the arc to a steady state (de Silva and Gosnold 2007; Lipman 2007).

In the APVC, over 15,000 km^3 of largely high-K, crystal-rich dacitic magma was erupted from five distinct caldera systems and smaller ignimbrite shields during an ~10 My ignimbrite flare-up. The spatiotemporal pattern of volcanism, its concordance with a negative residual gravity anomaly and a seismic low-velocity zone, are inferred to map out the incremental construction of an upper-crustal granodioritic batholith, which reflects the remnant plutonic roots of the erupted magmas. A clear pattern that emerges from the space–time–volume data of the APVC is that magmatic activity is episodic: activity clusters at approximately 2 My intervals (FIG. 4), and these define tertiary (third-order) pulses. Furthermore, the volume–time pattern of eruptions is defined by an initial waxing stage of relatively small eruptions clustered around 10 ± 0.5 Ma, followed by a climactic stage ~4 My long during which clusters of supereruptions define third-order pulses of activity at 8 ± 0.5, 6 ± 0.5, and 4 ± 0.5 Ma, with a final waning stage, less than 3 My in duration, of successively smaller eruptions (de Silva et al. 2006).

Volume-normalized SIMS U–Pb age data for the APVC eruptions show a similar pattern to the eruptive record, with distinct pulses of zircon ages coincident with the pulses of eruptive activity (FIG. 4). The broader peaks in zircon crystallization reflect two things. First, because zircon ages record a period of crystallization prior to eruption, the zircon ages from a single ignimbrite may define a relatively broad age-population extending from hundreds of thousands to a million years before eruption right up to the eruption age. Secondly, these data show that each tertiary pulse of ~2 My consists of three or more quaternary (fourth-order) pulses, defined by distinct magmatic histories of several hundred thousand years that culminated in eruptions. In summary, the secondary pulse of the 10 My ignimbrite flare-up of the APVC consists of four tertiary pulses of intrusion/eruption with a periodicity of ~2 My. The tertiary pulses, in turn, consist of three or more distinct quaternary pulses each of <1 My duration.

While no direct plutonic record is available for the APVC, a plutonic record of similar temporal scale is that of the Tuolumne Intrusive Suite (TIS) and John Muir Intrusive Suite, which are part of the Mesozoic Sierra Nevada arc in California (FIG. 2; Bateman 1992). Here, a large number of high-precision zircon ages (~140) are available from multiple samples. If most zircon growth records solidification at the level of emplacement (e.g. Coleman and Glazner 1997), then the accumulated zircon analyses could be used as a proxy for emplacement rates of these intrusive suites, which occupy areas of ~10^3 km^2 and depths of up to 5 km. These nested intrusive suites might be the plutonic equivalent of a composite volcanic field (analogous to the APVC or a large nested caldera system), but it is not clear how these mappable compositional units may record discrete "plutons." The available zircon data set for the TIS, if taken as collectively defining a secondary pulse, clearly indicates zircon growth over an integrated period of ~9 My (FIG. 2, 5). The zircon data for this secondary pulse are then suggestive of three or more tertiary pulses of zircon growth of perhaps 1 to 2 My duration each with comparable lulls. If so, the pulses of growth roughly correspond to the nested suites as mapped and these would be equivalent to the tertiary pulses for the

APVC. Resolution of quaternary pulses, evident in the volcanic record, is not possible with the current data for the TIS.

Correlation between ages derived from the TIS plutonic rocks and the detrital signature (FIG. 5) highlights that, at the scale of 5–10 My (i.e. the secondary pulses), the plutonic and detrital records are not as well correlated as they are at the broader scale of the primary pulses (cf. FIG. 3). Probability curves from the fore-arc and back-arc have broadly similar shapes. At first glance these are different from the curve for the TIS, suggesting that the 10+ My scale is best for understanding how detrital zircons reflect the tempo of magmatism. At this scale, however, the errors assigned to grains can become important. The probability curve smooths out error on individual grains, which is 1–2%, but the error on CA-TIMS data is <1%. Thus, some of the offset of plutonic and detrital data apparent in FIGURE 4 may be due to errors on grains. Other discrepancies, for example the pronounced trough in TIS data at 92 Ma, which is not reflected in either fore-arc or back-arc data, points out the potential for detrital data to reflect multiple sources, arc migration, or other factors that would blur distinctions.

MAGMATIC TEMPOS AND HOW CONTINENTAL ARCS WORK

The hierarchy of pulses in continental arcs can be considered as successively coupled space/time scales related to specific scales of continental-arc magmatic processes. The primary pulse, which is the high-volume event or flare-up, reflects the largest space/time scale of an excursion in mantle-power input from steady-state magmatism, possibly coupled to deformation patterns in the upper plate (DeCelles et al. 2009). This primary 40–60 My mantle signal may occur over a large area: examples include the entire Mesozoic Californian arc, in which flare-ups were driven by delamination events (Ducea 2001); or the middle Cenozoic of the western United States, where the flare-up appears to have been triggered by a regional transition from low-angle plate convergence to an increasingly extensional regime and where peak volcanism largely preceded the bulk of the extension (Lipman 1972; Best et al. 2013).

Secondary pulses are most readily defined on a smaller spatial scale than the primary pulses, reflecting the localization of magmatism into regional “nodes.” This suggests that the primary pulse can be modulated by processes of melting, segregation, and transfer through the crust, along with local upper-plate tectonics to produce secondary pulses in smaller regions. For instance, each of the various volcanic fields of the middle Cenozoic flare-up of the western United States, or the plutonic and volcano-plutonic suites of the Mesozoic California arc, define the individual components of much larger flare-ups. The APVC and the TIS are the examples used here. These secondary pulses, ~10–20 My in duration, must reflect the time-scale of melt production and delivery from the melting and assimilation (MASH) zone at or near the mantle/lower crust boundary and its interaction with upper plate tectonics over the area of each component. The magmatic histories of many individual volcano-plutonic systems tend to be characterized by an ~10 My time-scale (Grunder et al. 2008), which suggests that this is a fundamental signal in continental magmatism.

The tertiary pulses in the APVC, and perhaps the TIS, indicate processes that not only divide the secondary pulse into shorter pulses (2 My magmatic events in the APVC that culminate in eruptions) but produce the characteristic space–time–volume pattern of waxing, climax, and waning. The tempo of these tertiary pulses may ultimately reflect the influence of a combination of mantle, crustal, and upper-plate tectonic modulation (or other nonmagmatic upper-crustal process) (FIG. 6). The waxing–climax–waning pattern seen in these tertiary pulses may reflect the evolution of crustal melt production with time, thereby mimicking the mantle pulse topology. Alternatively (or additionally), it may reflect a progressive evolution of crustal rheology resulting from the thermal signal from the mantle progressing through the crust by intrusion and advection (FIG. 1). This may result in the formation of a mid- to upper-crustal MASH zone and magma "staging" area and an elevation of the brittle–ductile transition to shallow levels in the crust. Over time, these conspire to allow successively larger magma bodies to be built in the uppermost crust before they erupt (e.g. de Silva and Gosnold 2007).

Quaternary pulses are defined by individual eruptions from the magma bodies that were produced during the tertiary pulses. Quaternary pulses have time-scales of ~1 My, based on zircon crystallization time-scales for large calderas in the APVC. This tempo is controlled by the thermomechanical evolution of the upper-crustal magma reservoirs. As magma accumulates in the upper crust, feedbacks between temperature, host-rock mechanics, and chamber pressurization results in ductile host-rock rheologies, which promotes storage and growth over eruption (de Silva and Gregg 2014). Eventual eruption is due to crossing a mechanical threshold. Putting aside any tectonic overprint, the eruptive tempo of a flare-up may be dominantly modulated by the thermomechanical properties of upper-crustal magma reservoirs.

SUMMARY AND RECOMMENDATIONS FOR THE FUTURE

The time–volume evolution of continental arcs can be described as punctuated equilibria where high-volume events, ("flare-ups" of 40–60 My duration) interrupt steady-state arc activity or lulls. Combined volcanic, plutonic, and detrital U–Pb zircon records from flare-ups reveals a fractal tempo to the magmatism. From the examples in this paper, a hierarchy of pulses is identified, which define 4 successively faster tempos. These represent how the magmatic front, driven by the primary mantle-power input, is transmitted through the crust. This modulation of mantle power is reflected by sequentially smaller spatial and temporal scales that progress from arc-segment (first-order), to volcano-plutonic suites (second-order), to individual plutons or magma reservoirs (third-order) to caldera-forming eruptions (fourth-order).

Future research should aim at better defining the hierarchy of pulses and the resulting tempos, their apparent fractal character. and the link between these temporal patterns and magmatic processes. Particularly important will be efforts to understand magmatic tempo in the context of rates of mantle-power input and the intrinsic and structural properties of the crust and of upper plate tectonics. Linking volcanic, plutonic, and detrital records are the way forward, but challenges remain in understanding how multiple sources and arc migration might affect the mutual correlations of these records.

ACKNOWLEDGMENTS

The authors thank the guest editors for their invitation to contribute this article and for their deft handling of the manuscript, which benefited from thoughtful reviews by Olivier Bachmann and Keith Putirka for *Elements*. Discussions over the years with A. Schmitt, R. Economos, A. Grunder, J. Miller, D. Coleman, C. Jacobson and J. Wooden have been invaluable. Our research on continental arc magmatism in the Andes and California is funded by National Science Foundation grants EAR-0711119, EAR-0838536, and EAR-0908324.

REFERENCES

Bachmann O, Miller CF, de Silva SL (2007) The volcanic–plutonic connection as a stage for understanding crustal magmatism. Journal of Volcanology and Geothermal Research 167: 1-23

Barth AP and 6 coauthors (2012) Petrogenetic connections between ash-flow tuffs and a granodioritic to granitic intrusive suite in the Sierra Nevada arc, California. Geosphere 8: 250-264

Barth AP, Wooden JL, Jacobson CE, Economos RC (2013) Detrital zircon as a proxy for tracking the magmatic arc system: the California arc example. Geology 41: 223-226

Bateman PC (1992) Plutonism in the central part of the Sierra Nevada batholith, California. U.S. Geological Survey Professional Paper 1483, 186 pp

Best MG, Christiansen EH, Gromme S (2013) Introduction: the 36–18 Ma southern Great Basin, USA, ignimbrite province and flare up: swarms of subduction-related supervolcanoes. Geosphere 9: 260-274

Brown M (2001) Crustal melting and granite magmatism: key issues. Physics and Chemistry of the Earth Part A: Solid Earth and Geodesy 26: 201-212

Bryan SE and 6 coauthors (2007) New insights into crustal contributions to large-volume rhyolite generation in the Mid-Tertiary Sierra Madre Occidental province, Mexico, revealed by U-Pb geochronology. Journal of Petrology 49: 47-77

Coleman DS, Glazner AF (1997) The Sierra Crest magmatic event: rapid formation of juvenile crust during the Late Cretaceous in California. International Geology Review 39: 768-787

de Saint Blanquat M and 6 coauthors (2011) Multiscale magmatic cyclicity, duration of pluton construction, and the paradoxical relationship between tectonism and plutonism in continental arcs. Tectonophysics 500: 20-33

de Silva S (2008) Arc magmatism, calderas, and supervolcanoes. Geology 36: 671-672

de Silva SL, Gosnold WD (2007) Episodic construction of batholiths: insights from the spatiotemporal development of an ignimbrite flare-up. Journal of Volcanology and Geothermal Research 167: 320-335

de Silva SL, Gregg PM (2014) Thermomechanical feedbacks in magmatic systems: implications for growth, longevity, and evolution of large caldera-forming magma reservoirs and their supereruptions. Journal of Volcanology and Geothermal Research 282: 77-91

de Silva S and 5 coauthors (2006) Large ignimbrite eruptions and volcano-tectonic depressions in the Central Andes: a thermomechanical perspective. Geological Society London Special Publications: 269: 47-63

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

Dickinson WR (1981) Plate tectonics and the continental margin of California. In: Ernst WG (ed) The Geotectonic Development of California. Prentice-Hall, Englewood Cliffs, New Jersey, p 1-28

Ducea M (2001) The California arc: thick granitic batholiths, eclogitic residues, lithospheric-scale thrusting, and magmatic flare-ups. GSA Today 11: 4-10

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

Folkes CB, de Silva SL, Schmitt AK, Cas RAF (2011) A reconnaissance of U-Pb zircon ages in the Cerro Galán system, NW Argentina: prolonged magma residence, crystal recycling, and crustal assimilation. Journal of Volcanology and Geothermal Research 206: 136-147

Gehrels GE (2012) Detrital zircon U-Pb geochronology: current methods and new opportunities. In: Busby C, Azor A (eds) Tectonics of Sedimentary Basins: Recent Advances. John Wiley & Sons, Ltd., Chichester, UK, p 47-62

Grunder AL, Klemetti EW, Feeley TC, McKee CM (2008). Eleven million years of arc volcanism at the Aucanquilcha Volcanic Cluster, northern Chilean Andes: implications for the life span and emplacement of plutons. Transactions of the Royal Society of Edinburgh: Earth Sciences 97: 415-436

Hildreth W (1981) Gradients in silicic magma chambers: implications for lithospheric magmatism. Journal of Geophysical Research 86: 10153-10192

Laskowski AK, DeCelles PG, Gehrels GE (2013) Detrital zircon geochronology of Cordilleran retroarc foreland basin strata, western North America. Tectonics 32: 1027-1048

Lima SM, Corfu F, Neiva AMR, Ramos JMF (2012) Dissecting complex magmatic processes: an in-depth U-Pb study of the Pavia Pluton, Ossa-Morena Zone, Portugal. Journal of Petrology 53: 1887-1911

Lipman PW, Prostka HJ, Christiansen RL (1972) Cenozoic volcanism and plate-tectonic evolution of the western United States. I. Early and Middle Cenozoic. Philosophical Transactions of the Royal Society of London A 271: 217-248.

Lipman PW (2007) Incremental assembly and prolonged consolidation of Cordilleran magma chambers: evidence from the Southern Rocky Mountain volcanic field. Geosphere 3: 42-70

McIntosh WC, Chapin CE, Ratté JC, Sutter JF (1992) Time-stratigraphic framework for the Eocene-Oligocene Mogollon-Datil volcanic field, southwest New Mexico. Geological Society of America Bulletin 104: 851-871

Saleeby J (2003) Segmentation of the Laramide Slab: evidence from the southern Sierra Nevada region. Geological Society of America Bulletin 115: 655-668

Schmitt AK (2011) Uranium series accessory crystal dating of magmatic processes. Annual Reviews of Earth and Planetary Sciences 39: 321-349

Schmitz MD, Kuiper KF (2013) High-precision geochronology. Elements 9: 25-30

FIGURE CAPTIONS

FIGURE 1 Contrasting behavior of steady-state and flare-up arc-magmatic systems and the resulting caldera-forming eruptions. Arcs may switch between these modes due to changes in plate tectonic forcings. **(A)** Steady state refers to the low magmatic addition rate (flux) that characterizes the long-term evolution of the volcanic setting (see Jicha et al. 2015 this issue). **(B)** Flare ups are transient events of high magmatic-production rates that punctuate the steady state magmatism. Depth is scaled to an ~40-km-thick crust. AFC—assimilation and fractional crystallization; MASH—melting, assimilation, storage and homogenization. **(C)** Schematic representation of the hierarchy of magmatic tempos that is imparted at various depths in the system. Modified from de Silva (2008)..

FIGURE 2 Zircon U–Pb age data from the Tuolumne Intrusive Suite (TIS) illustrating sampling bias or the "petrologists effect". **(A)** This data set clearly illustrates some nuances of interpreting and presenting zircon age data in regards to sample bias and size of sample bins. The light red line is the raw representation of the relative probability of the various members of the TIS. In this representation, the dominant peak between 89 and 92 My represents the data from the equigranular Half Dome granodiorite (*HDe*), which has been extensively studied. However, when the data are weighted in terms of exposed area, the heavy line (normalized) clearly shows the areal dominance of the Cathedral Peak (*CP*) pluton. This illustrates the effect of "sample bias" on age data representation, the petrologists effect. We consider the "area-weighted" as the best available approximation to the growth of zircon during assembly of the suite, although we caution against taking the next step from area to volume. The "jaggedness" of the data is largely artificial depending on how "bins" are set. Smoothing is a more realistic way of presenting these data. Data sources can be found in the electronic supplement at *Elements* online.

FIGURE 3 **(A)** Palinspastic map of the Mesozoic southwestern Cordillera, showing distribution of arc rocks of the Sierra Nevada and Salinia–Transverse Ranges, together with the fore-arc and back-arc regions, the major segments and components of the Mesozoic California arc. {what are FTB, LAS, PHX? – please define]} **(B)** Pluton ages from the Sierra Nevada and Salinia–Mojave arc segments define three first-order magmatic pulses: *p*1 in Triassic, *p*2 in

Middle and Late Jurassic, and *p*3 in mid-Early to Late Cretaceous time, with magmatic "lulls" in between, *l*1 beginning in Late Triassic and *l*2 in latest Jurassic time (adapted from Barth et al. 2013). **(C)** An extensive plutonic zircon U–Pb dataset from the *p*2 pulse of the continental Salinia–Mojave arc segment compared with a smaller data set from contemporaneous volcanic activity shows strong correlation of peaks. Detrital zircon data from the fore-arc and back arc show a broad correlation. Data sources are given in the electronic supplement.

FIGURE 4 **(A)** The Altiplano–Puna Volcanic Complex of the Central Volcanic Zone of the Andes showing the areal distribution of the major ignimbrites that define a recent flare-up (1–12 Ma). Colors correlate with age data. **(B)** Age versus erupted volume for each ignimbrite is shown as vertical lines from ^{40}Ar/^{39}Ar data. Red line is the volume normalized relative frequency curve for zircon U–Pb age from all of these eruptions . Correlation between the ^{40}Ar/^{39}Ar data and the zircon age data is strong with zircon data representing accumulation of magma, leading the eruption ages. These data demonstrate that the secondary pulse of the APVC flare-up consists of four tertiary pulses representing clusters of eruptions. **(C–F)** The smaller plots break out the volume-normalized frequency curves for each eruption within the respective age clusters, revealing further episodes defining quaternary pulses. Data sources are given in the electronic supplement.

FIGURE 5 Plutonic and detrital zircon signature of the Tuolumne Intrusive Suite. Red line is the "smoothed" plutonic data from A. Blue line represents data from back-arc sedimentary units; surprisingly, in this case, more detail is apparent in the detrital record. Green line represents data for fore-arc sedimentary units; although smoother in shape than the back-arc, peaks and troughs generally agree with data from the back-arc. Age ranges of the other main plutons Half Dome porphyritic (*HDp*) and Kuna Crest (*KC*) are shown as bars between A and B. [Data sources for A and B can be found in the electronic supplement at *Elements* online.]

FIGURE 6 Three possible scenarios that might account for tertiary pulses in flare-ups. **LEFT PANEL** shows that pulsing in the plutonic and volcanic record is due to source (mantle/lower crustal) tempo. Crust is inert and the source tempo is translated through to the surface. **(MIDDLE PANEL)** Mantle pulse is smooth and episodic behavior is due to crustal processing in a mid- to upper crustal "MASH" zone (see FIG. 1). **(RIGHT PANEL)** Mantle pulse is smooth and the crust has little modulating effect. In this case episodic behavior in the volcanic, and maybe plutonic record, are due to external modulation by tectonic forcing (see Lima et al. 2012) or other nonmagmatic process. The most likely scenarios are crustal modulation and external (tectonic) forcing.