

The Pace of Plutonism

Trango Towers,
Gilgit-Baltis

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Beneath volcanoes are magmas that never erupt but that become frozen into feldspar- and quartz-rich rocks broadly called granite. Where the crystallized magmas form bodies with distinctive textures, they are grouped into named units—plutons. The rate (pace) at which magmas accumulate into plutons is fundamental to understanding both how room is made for the magmas and how unerupted and erupted magmas are connected. Dating plutonic rocks suggests that plutons accumulate slowly. Although the pace of magma accumulation does not preclude direct connections between plutons and small volcanic eruptions, it appears to be far too slow to support connections between most plutons and supereruptions.

KEYWORDS: granite, pluton, U–Pb, Ar–Ar, geochronology

INTRODUCTION

As recently as the early nineteenth century, the controversy surrounding the origin of plutons was staged as a metaphorical battle between the Roman gods. The Neptunists (championed by German pioneering geologist Abraham Werner [1749–1817]) believed that granites—along with all rocks—were precipitated from the oceans. According to the Neptunists, the granitic layer of the Earth was the oldest layer, upon which younger fossil-bearing layers were deposited. The Plutonists (originally proposed by Italian abbot and naturalist Anton Moro [1687–1764], but ultimately championed by the great Scottish geologist James Hutton [1726–1797]) posited that plutonic rocks had their origin in fire and were crystallized from magmas. Ultimately, it was the recognition of dikes (tabular bodies of rock that crosscut older rocks) that vanquished the Neptunists. Plutonists successfully argued that these rocks could not have been deposited from the sea, and Pluto, Roman god of the underworld (FIG. 1), won the day. Fittingly, understanding the rates of magma movement and accumulation in dikes and other tabular plutonic bodies remains key to understanding the pace of plutonism.

During a 1947 conference organized by the Geological Society of America (Gilluly 1948), the origin of plutons had evolved to a debate between a melt-dominated mechanism (crystallization from a magma—magmatism) or a metasomatic mechanism with minor melt (the dominantly solid-state alteration of preexisting rock—migmatism). The conundrum of granite formation arose because, unlike volcanic rocks that can be witnessed to erupt as crystal-

liquid mixtures (clearly igneous), the evolution of plutonic rocks is not directly observable. Although he ultimately fell on the losing side of the debate, migmatist advocate Prof. Herbert H. Read of Imperial College, London (UK) emphasized two important themes in his 1947 presentation. The first theme was the room problem: If granites intrude as magmas, how are the wall rocks displaced in order to make space for the granite? The second theme was the importance of time in understanding the origin of granites. Read later devoted an entire paper to this

second theme, his “A Contemplation of Time in Plutonism” (Read 1949). In it, Read made the intriguing suggestion that

Death, I agree, is an important event to a man, but his life is much more important to posterity – and so it is with plutonic rocks. Besides, just as all members of a family do not usually die on the same day, so genetically related granites may complete their courses at widely different ages...

In many ways, our drive to understand the pace of plutonism follows from this quote. Much of the modern debate circles around the questions, “How do plutonic magmas accumulate?” and “In the life and death cycle of a pluton, what event(s) are dated? How are those ages interpreted?”

DATING PLUTONIC ROCKS

Techniques for determining the age of plutonic rocks have focused in the past 20 years on the decay of uranium to lead (U–Pb geochronology), and the decay of ⁴⁰K to ⁴⁰Ar. Dating with Ar includes the modification of measuring ⁴⁰K through the proxy of the isotope ³⁹Ar, which can be produced artificially from ³⁹K in a nuclear reactor: thus, it is an ⁴⁰Ar–³⁹Ar (or simply Ar–Ar hereafter) age. The details of modern U–Pb and Ar–Ar chronology are beyond the scope of this contribution (see for example, “One Hundred Years of Isotope Geochronology” [Elements v9n1]). However, several key facts about the methods bear mention here.

For plutonic rocks, the most commonly dated mineral by U–Pb is that particularly robust time capsule, zircon (ZrSiO₄). It can retain its daughter Pb at temperatures in excess of magmatic crystallization temperatures (>900 °C). Consequently, a zircon age is generally thought to reflect the integrated magma history between the time zircon began to crystallize (the zircon saturation temperature, typically >800 °C) through the time when the magma becomes completely solid. The mineral titanite (CaTiSiO₅)

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FIGURE 1 *Pluton* (French for “Pluto”) as sculpted by Henri Chapu and photographed by Mel22. LICENSED UNDER CREATIVE COMMONS ATTRIBUTION 3.0.

is also commonly used in U–Pb geochronology; however, unlike zircon, titanite leaks daughter Pb down to temperatures of ~680°C (the closure temperature). The relatively low closure temperature of titanite is useful in evaluating the pace of plutonism because comparison of U–Pb zircon ages to titanite ages from a single sample offers insight into the cooling rate of the pluton in the interval between >800°C and 680°C.

Dating with Ar–Ar can be done using any potassium-bearing mineral in a rock. For plutonic rocks, this commonly includes hornblende and biotite. Because the daughter isotope in this decay scheme is a noble gas, it tends to diffuse out of crystals at magmatic temperatures. Consequently, like U–Pb in titanite, the age determined using Ar–Ar is the time since the mineral dropped (and stayed) below its closure temperature. The closure temperatures of hornblende and biotite vary somewhat depending on the composition and size of each mineral, as well as the rate of cooling, but are nominally 550°C for hornblende and 350°C for biotite. Like the comparison of U–Pb ages for zircon and titanite, comparison of Ar–Ar ages between hornblende and biotite offer insights into the cooling history of the rock. It is ideal to combine U–Pb and Ar–Ar ages for a sample to get a nearly complete thermal history from zircon saturation through biotite closure.

THE SIGNIFICANCE OF THE PACE

Until recently, the rate of magma accumulation to form plutons received little attention. Generally, it was thought that magmas rose through the Earth’s crust as diapirs (picture the ascending blobs in a lava lamp) and ultimately crystallized into plutons, requiring ascent and accumulation rates that were faster than crystallization. During the early days of geochronology, dating a single sample from a pluton was considered sufficient to know the entire pluton’s age. Discrepancies between zircon U–Pb and hornblende or biotite Ar–Ar ages were presumed to result from slow cooling histories deep in the crust, or subsequent reheating that resulted in resetting the Ar clock.

The effort to resolve the pace of plutonism began in earnest with the effort to resolve the room problem. Understanding how the solid earth moves in order to accommodate space for an intruding magma is clearly linked to knowing the rate at which the solid earth has to move. Also linked to the room problem, however, were entrenched ideas about the nature of magma chambers and the connection between plutonic and volcanic rocks. Because texturally similar plutonic rocks were thought to be frozen magma chambers capable of wholesale convection and mixing, and because large silicic eruptions were thought to require extensive chemical evolution in shallow crustal magma chambers, rapid assembly of such bodies was required by basic petrology tenets. It is fair to say that there is no consensus in the granite community about many of the issues, but a look into the room problem and plutonic–volcanic connections provides a good view into why it is critical to understand the pace of plutonism.

THE ROOM PROBLEM

During the late 1980s to early 1990s, there was a revival of interest in the room problem for granite plutons (Hutton 1988; Tikoff and Teyssier 1992). Most approaches to understanding the problem focused on the structural mechanisms for moving rocks out of the way of the rising magmas and on the tectonic settings that might best facilitate space-making. One of the most straightforward settings where links between the pace of magmatism and plate tectonics can be made is at mid-ocean ridges. There, new oceanic crust is made by intrusion and eruption of magmas at a pace dominantly determined by the spreading rate of the ocean plates on either side of the ridge. On the continents, however, most plutons are formed where one plate is subducted beneath another. Whereas the room problem for gabbro plutons (formed under the oceans) was easily solved and the pace of gabbro plutonism was well-determined, making room for granite plutons (formed in continents) and the pace at which that might happen were more problematic. A link had to be made between magma intrusion rates and reasonable rock deformation rates in collisional settings.

Fortunately, at this same time, there was rapid advancement in U–Pb analytical techniques. Prior to the late 1980s, the analysis of zircon required large amounts of the mineral and, consequently, large amounts of rock. Zircon is an accessory mineral commonly comprising less than 0.05% of a granitic rock and, depending on the age of the sample, obtaining enough zircon for dating could mean collecting 50 kg of rock or more. Thus, sampling a pluton was often restricted to one sample per map unit, and usually from easily accessible locations. However, in order to understand the rates of magma accumulation, multiple samples are necessary. The development of cleaner laboratory techniques and instrumentation capable of measuring smaller masses of daughter isotopes of Pb allowed for single-crystal analysis, with commensurate reduction in rock mass to less than a kilogram and the possibility to better date plutons. This led to advances in attempts to solve the room problem (and other problems).

Surprises from the Tuolumne Intrusive Suite (California, USA)

One of the first studies to suggest age variations in mapped plutons was done by Kistler and Fleck (1994) of the US Geological Survey on the Tuolumne Intrusive Suite—best known as the bedrock for most of Yosemite National Park in California (Fig. 2). This work combined ages that were determined by several techniques (K–Ar, Ar–Ar, Rb–Sr and U–Pb) on a host of rocks and mineral phases. Focusing

on just hornblende Ar–Ar ages (for which there are the most samples for direct comparison), the plutons of the suite preserve a 6 My history from approximately 89 Ma to 83 Ma. This study included only three zircon U–Pb ages, which were clustered around 88–86 Ma and were tighter than the spread in Ar–Ar ages. The data also include biotite Ar–Ar ages that are younger than hornblende Ar–Ar ages by up to 4 My. Taken together, these suggested the possibility that the dispersed Ar–Ar ages reflect cooling rather than crystallization. The results called for more zircon ages.

It is no accident that the Tuolumne Intrusive Suite has been the focus of understanding the dynamics of plutons and magma chambers for decades. Glaciers have carved a spectacular 3-D exposure of the plutons, leaving almost nothing to the imagination (Fig. 2). Thus, the suite provides an ideal opportunity to unravel the pace of plutonism. The first comprehensive zircon U–Pb investigation of the Tuolumne Intrusive Suite was completed by Coleman et al. (2004), who published U–Pb zircon results for eleven samples from across the suite. These authors concluded that the magmas had accumulated and solidified over a 10 My interval between 95 Ma and 85 Ma. Additionally, they were able to document that an individual pluton, the Half Dome Granodiorite, had assembled over at least 4 My. Subsequent studies confirmed these results (e.g. Memeti et al. 2010).



FIGURE 2 Granitic rocks of the Tuolumne Intrusive Suite, Yosemite National Park (California, USA). Essentially, everything in the photo that is not green or blue is a plutonic rock that accumulated by the incremental addition of magmas over millions of years. The double peak just left of center is Cathedral Peak. PHOTO BY ALLEN GLAZNER

How Do Plutons Form?

Work in the Tuolumne Intrusive Suite revealed that some individual map units—rocks once thought to represent single injections of magma, or multiple upwellings within a single large injection of magma—accumulated and crystallized over millions of years. Work on many plutons now demonstrates that the results from Yosemite are typical of plutons from a variety of times and tectonic settings, and incremental assembly of plutons is now widely accepted. That plutons are amalgamated from multiple pulses of magma is an old idea (Pitcher 1979); however, the inferred small volume of pulses and long times during which they

accumulate challenged most of what was thought about pluton assembly. Most relevant to solving the room problem is the question, “How do magmas ascend and accumulate to form plutons if not as large diapirs?”

The key to understanding the ascent and assembly of plutons may go back to the same observations that sunk the Neptunists. It is widely recognized that intrusion through fractures as tabular bodies—dikes and sills—is an efficient mechanism for moving granitic magmas through the crust (Clemens and Mawer 1992; Petford et al. 1993). Few would argue against the idea that the sheeted dike complexes that characterize the plutonic rocks of the oceanic crust comprise a significant volume of the mafic crust formed in that extensional setting. Extrapolating that result to granitic rocks has been significantly more controversial because, for the most part, granitic plutons do not preserve dike-like structures. The Main Donegal Granite of north-west Ireland is perhaps the best known example of a pluton thought to be assembled by the incremental intrusion of tabular bodies (Pitcher and Berger 1972). There, preservation of numerous screens of the rocks into which the pluton intruded (wall rocks) defines a series of dike intrusions.

Bartley et al. (2008) proposed that such features were more common than appreciated and that most granitic plutons could form through the amalgamation of many dikes and/or sills. However, they suggested that preservation of contacts between increments was most likely to be near the contacts between the earliest intruding granites and their nongranitic wall rocks. They noted that the earliest intrusions have the greatest contrast between wall-rock and magma temperature, enhancing the likelihood that they would cool quickly and preserve contacts. Furthermore, with the recognition that in an incrementally assembled pluton, early intruding granites *become* the wall rocks for later intruding granites, the lack of nongranitic wall rocks screens in the youngest portions of granitic plutons is not surprising. Additionally, they argued that an incrementally assembled granite pluton spends significant intervals at or near magmatic temperatures, helping to erase contacts between increments. This is less probable in an oceanic setting where intrusive depths are generally shallower and the magmatic temperatures are significantly higher than those for granites. That hypothesis can be tested with thermal modeling and by taking advantage of the contrast in closure temperatures of the U–Pb and Ar–Ar systems.

Cooling Rates

Comparing temperature–time paths constructed from dating multiple minerals in individual samples with those predicted from thermal models can help in understanding the assembly of plutons. Incrementally assembled plutons slowly add heat to the system over the duration of pluton assembly, but individual pulses initially cool quickly. Thus, high-temperature chronometers may yield a tight age cluster and low-temperature chronometers may yield a spread in ages (Fig. 3). The Ar–Ar data from the Tuolumne Intrusive Suite suggest that at least some of those plutons spent millions of years at temperatures above ~350°C. Subsequent studies have combined U–Pb zircon and titanite data, or Ar–Ar hornblende and biotite, to quantify the temperature–time histories of plutonic rocks.

At the high-temperature end of the spectrum, it is useful to compare U–Pb zircon saturation ages with U–Pb titanite closure ages. These can provide an estimate of the time between temperatures in excess of 800°C and 680°C. Work in the Adamello batholith of Italy reveals indistinguishable ages for the youngest zircon and magmatic titanite from individual samples. This is consistent with rapid cooling of the magmas from zircon crystallization to below 680°C, respectively. Curiously, the Adamello batholith also includes a second population of titanite (nonmagmatic) intergrown with chlorite that probably grew at lower temperatures (Schoene et al. 2012). These titanite crystals are significantly younger than the magmatic crystals and suggest that the plutons remained (or were reheated) above 300°C to 400°C for hundreds of thousands of years after magma intrusion.

The Ar–Ar system is, perhaps, better suited for exploring the thermal history of plutons at, or just below, solidification temperatures (Zimmerer and McIntosh 2012). The closure temperature of hornblende is near that of granite solidification, and the closure temperature of biotite is near that

where secondary titanite is likely to form (FIG. 3). Davis et al. (2012) were able to show that plutons in the Sierra Nevada batholith of California recorded up to a 5 My difference between hornblende and biotite ages. Moreover, they noted that biotite ages were more clustered than higher-temperature (zircon) ages and suggested that this clustering resulted from a relatively rapid decrease of temperature once pluton accumulation had stopped.

The Crux is the Flux

Knowing the age range, potential intrusion and assembly mechanisms, and cooling rate brings us closer to being able to estimate the flux of magma into plutons. The last remaining variable (i.e. question) requires some subjectivity: “What is the volume of the pluton?” Whereas the surficial area of a pluton can be known fairly accurately, evaluating what happens in the third dimension is more problematic and two end-member approaches have been taken. The first recognizes that plutons are typically tabular or wedge-shaped and that the thickness can be roughly predicted by the area (Cruden and McCaffrey 2001). Thus, a pluton with a mean width of 20 km may be reasonably estimated to be approximately 3.5 km thick—a flat disk. The second recognizes that the contacts between wall rocks and plutons tend to be steep, and plutonic rocks of broadly the same composition may extend for tens of kilometers below surface exposures (e.g. Lipman 2007). Thus, that same 20 km wide disk may be a 20 km tall cylinder. Neither of these approaches accounts for loss of volume to erosion. Regardless, application of the first approach yields magma volume estimates that can be an order of magnitude less than those obtained by using the second approach.

Another complicating factor for estimating magma flux into plutons is recognition that some of the magma might have erupted. Given that exposures of demonstrably related plutonic and volcanic rocks are sparse, knowing the volume of magma that a pluton lost to an eruption is difficult, if not impossible. Systematic study of intrusive:extrusive ratios suggests a range of between 3:1 and 10:1 (White et al. 2006), once again adding a factor of three to the uncertainty in knowing the magma volume. Quantifying this relationship is presently a hot topic of research.

A final complication in calculating magma flux is that the number of samples dated is finite. Consequently, the time interval of magma accumulation is always a minimum. At some level, this mitigates problems introduced with knowing the volume. In our work, we have chosen to estimate the flux for the exposed volume. That is, if we have sampled a 20 km wide pluton over 1 km of relief, we calculate the volume of a disk with a diameter of 20 km and a height of 1 km. We recognize that this is likely to be an underestimate of the flux for all the reasons outlined above, but it avoids making the assumptions that unseen rocks are present and are the same age as exposed rocks. Despite these difficulties, however, and considering reasonable variations in the assumptions made, estimated magmatic fluxes are consistently between 10^{-3} to 10^{-4} km³ y⁻¹ for plutons with volumes estimated to be from 10^1 to 10^4 km³ (FIG. 4).

The apparent flux of magmas into plutons is slow. It is orders of magnitude slower than fluxes required to sustain a dominantly liquid magma chamber, and much more in line with known tectonic strain rates. With geodetic imaging techniques, it is possible to detect inflation of active volcanoes and estimate the flux of magma beneath them. These estimates tend to be higher than long-term estimates for plutonic systems; however, long-term pluton fluxes likely mute higher short-term, observable fluxes under modern volcanoes (Pritchard and Gregg 2016 this

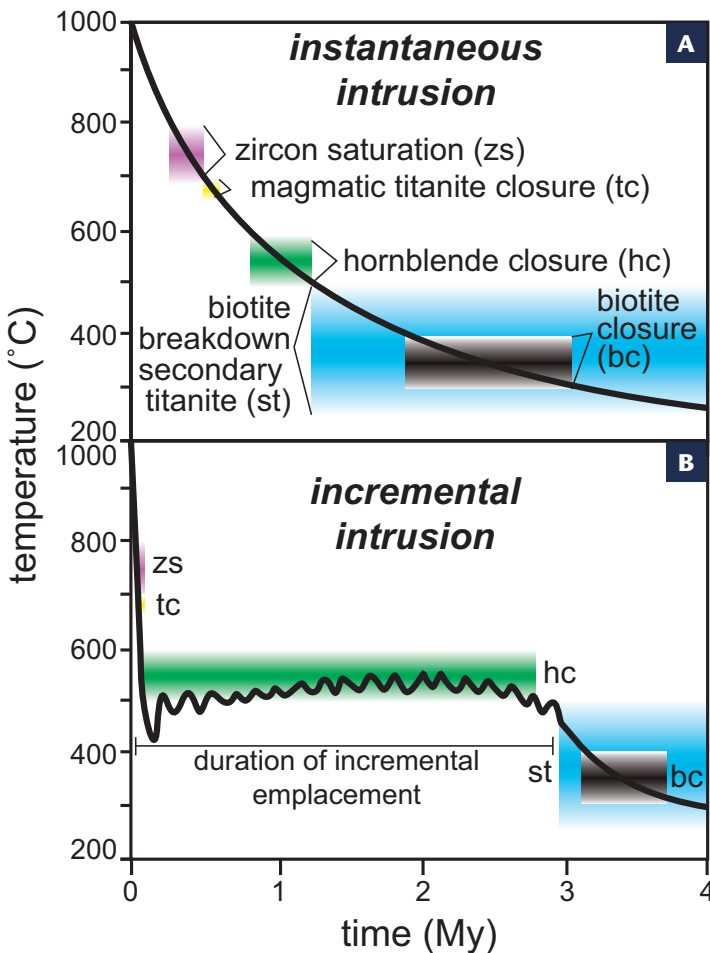


FIGURE 3 Examples of how chronometers can be used to decipher the pace of plutonism using HEAT 3-D models by Ken Wohletz. Both models show a pluton intruded at a depth of 5 km with a final diameter of 30 km and a final thickness of 10 km. Colored horizontal bars show the range of ages potentially recorded by different chronometers. These are at the same temperature in each panel. (A) Instantaneous emplacement of the entire volume. The pluton cools slowly and chronometers yield a range of ages. (B) Incremental assembly of the same volume as (A) over a 3 My period. Note that zircon, magmatic titanite and (potentially) hornblende ages will overlap. However, many hornblende and biotite ages as well as titanite growth ages will be significantly younger. Many variables will play a role in determining a pluton's thermal history and different chronometers may yield different results, depending on those variables.

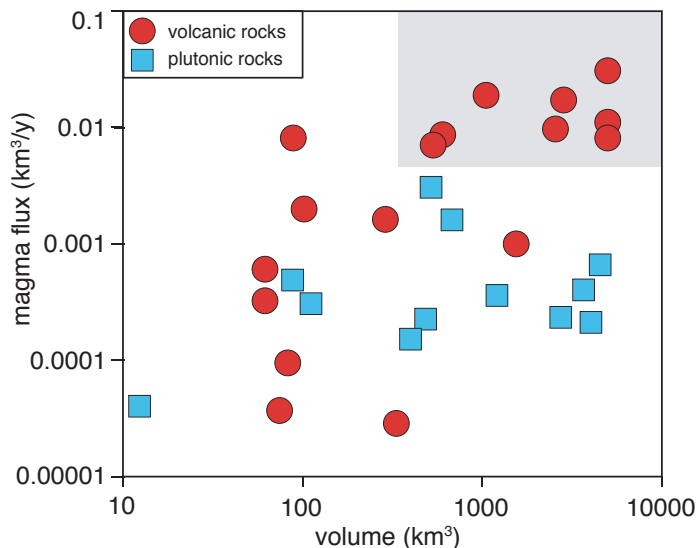


FIGURE 4 Magma volume and flux estimates for granitic plutons (blue squares) and volcanic rocks (red circles). Deposits noted in the literature as supereruptions fall in the gray shaded area. One other high volume field with low flux includes multiple units and is therefore not considered a supereruption. Supereruption magmas appear to accumulate orders of magnitude faster than comparable volumes of plutonic rocks. MODIFIED FROM MILLS AND COLEMAN (2013) AND FRAZER ET AL. (2014).

issue). Slow magma accumulation rates were recognized by geophysical techniques for oceanic magma systems (Detrick et al. 1990) around the same time that geologists studying granites began earnestly searching for a solution to the room problem. As in mid-ocean ridge settings, geophysical analysis of continental magma systems has yet to reveal the presence of large volumes of liquid magma beneath Earth's largest active volcanoes. Even Yellowstone—with a record of supereruptions, and often cited as having potential for future supereruptions—is sitting above partially molten rock with only 2–15% melt present (Farrell et al. 2014; Huang et al. 2015).

PLUTONIC-VOLCANIC ROCK CONNECTIONS

The apparently slow pace of magma accumulation in plutonic environments is at odds with the dominant paradigm linking plutonic and volcanic rocks. Smith (1960) noted the likely “kinship” between large volcanic ash flows and shallow plutonic rocks. This relationship was further developed by many authors, and Lipman (1984) championed a direct link between the two on the basis of field, petrologic, and chemical relationships. The spatial connection between plutons and huge volcanic ash-flows is undeniable, but the calculated magma fluxes for the two are quite different. A compilation of data for plutons and ash-flows shows that most magmas that lead to supereruptions (> 450 km³) are generated at rates between 1 and 2 orders of magnitude faster than similarly sized plutons (Fig. 4). This tipping point for supereruptions seen from the geochronologic data is in accord with the thermal models of Annen (2009), which predict a minimum flux

of 0.01 km³ y⁻¹ needed to sustain a magma chamber that leads to supereruptions. The comparison between small eruptions and plutons shows the opposite—the paces of small volume volcanism and plutonism are comparable (Fig. 4).

An excellent example of the disparity between large plutons and supereruptions comes when comparing zircon ages for the Mount Givens Granodiorite (Sierra Nevada, USA) and the Fish Canyon Tuff (Southern Rocky Mountain Volcanic Field, USA). These rocks are comparable in composition and volume (with all the caveats inherent in estimating volumes). However, the Mount Givens Granodiorite preserves a record of at least 7 My of zircon growth, in contrast to less than 0.5 My of zircon growth recorded by the Fish Canyon Tuff (Fig. 5).

The contrast in ages preserved in this pluton and tuff suggests either dramatically different paces of magma accumulation or significant differences in zircon crystallization and/or preservation between the two environments. A commonly invoked explanation for the discrepancy is efficient zircon dissolution prior to tuff eruption (Miller et al. 2007). In this scenario, prior to eruption, the tuff existed as a slowly accumulated (pluton-pace) shallow magma body that, if completely crystallized, would have preserved millions of years of zircon growth. The reheating that triggered eruption is proposed to be sufficient to take the magma body back above the zircon saturation temperature for a long enough interval that all of the preexisting zircon dissolved, and the narrow time recorded by the zircon in the tuff represents new growth. The difficulties

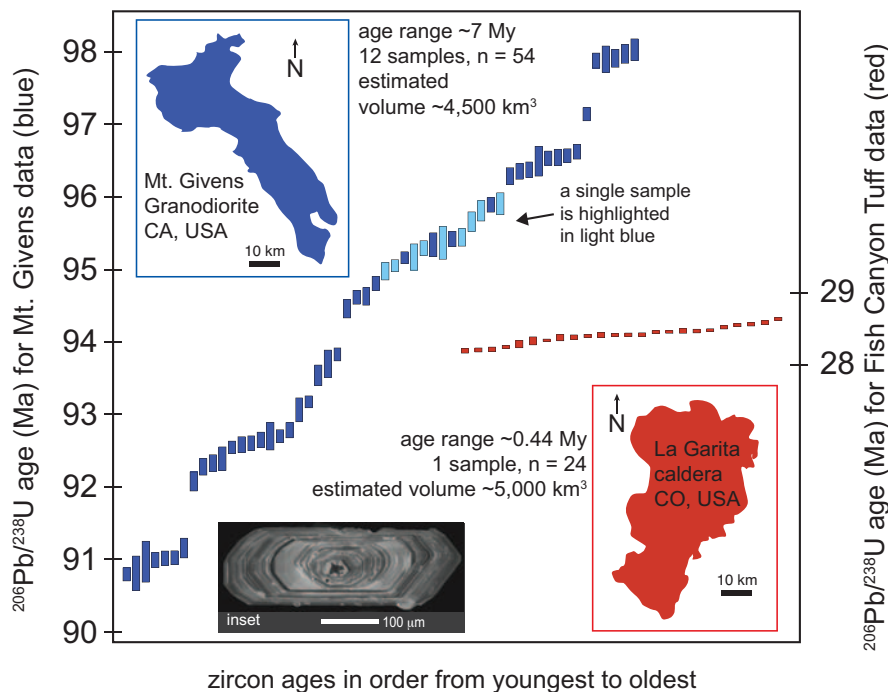


FIGURE 5 Comparison of single grain U–Pb zircon analyses from the Mount Givens Granodiorite (blue; Frazer et al. 2014) and the Fish Canyon Tuff (red; Wotzlaw et al. 2013). Horizontal axis sequences analyses from youngest to oldest for one Fish Canyon Tuff sample and twelve Mount Givens samples distributed throughout the intrusion. These two rock units are comparable compositionally and likely comparable volumetrically. The scale for both samples is the same, but note the difference in absolute age for the Mount Givens Granodiorite (left axis) and Fish Canyon Tuff (right axis). Maps show outlines for the Mount Givens pluton and the La Garita caldera (the source of the Fish Canyon Tuff) at the same scale. INSET: A typical zircon from the Mount Givens Granodiorite. The Mount Givens Granodiorite records an age range that is over an order of magnitude greater than that for the Fish Canyon Tuff.

with this scenario are that zircon dissolution is inefficient and not likely to happen at the timescales for remobilization and eruption (Frazer et al. 2014). Direct evidence against the efficacy of zircon dissolution in tuffs includes the common preservation of zircons inherited from slightly older (<1 My) parts of the same magma system and, in some cases, zircons that record crystallization ages millions to billions of years prior to the eruption. There are no geochronologic data to suggest that supereruptive tuffs represent large chambers that accumulated at rates comparable to plutonic rocks.

SUMMARY

Understanding the origin of plutonic rocks, and specifically the room problem and plutonic–volcanic rock connections, has been the subject of vigorous debate for over a century. The solution to the room problem was revealed when magma accumulation rates in plutonic environments were discovered to be far slower than previously consid-

ered. Whereas the slow pace of plutonism is not at odds with a direct connection to geologically common small-volume volcanic eruptions, it is apparently far too slow to permit a direct connection between most plutons and (fortunately!) rare massive supereruptions.

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