

Tackling supervolcanoes: Big and fast?

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The largest of all explosive volcanic eruptions, the so-called “supereruptions,” eject batholith-scale quantities of magma ($> \sim 450 \text{ km}^3$) into the atmosphere and onto Earth’s surface. No eruptions of such a massive scale have occurred over recorded history, and thus from a human perspective the scale of such an event would be unprecedented. Supereruptions are likely to have dramatic effects on Earth’s habitability, potentially inducing long nuclear winters, and covering continent-scale regions with pyroclastic flow and fall products (e.g., Self and Blake, 2008). For reference, the A.D. 1815 eruption of Indonesia’s Mount Tambora was the largest in recorded history. This event, with an erupted volume of $\sim 50 \text{ km}^3$, produced the 1816 “year without a summer” and ultimately resulted in many tens of thousands deaths worldwide (Oppenheimer, 2003). In stark contrast, the Fish Canyon Tuff from La Garita caldera (Colorado, USA) in the Southern Rocky Mountain volcanic field, one of the largest known Cenozoic eruptions, *ejected more than 5000 km³ of magma* (Bachmann et al., 2002).

It is precisely because of their immense size that supervolcanoes have long held a fascination for volcanologists and petrologists (although the terms supervolcano and supereruption have come into common use more recently). The lack of directly observed supereruptions means that our understanding is primarily based on classical geological methods, particularly careful documentation and examination of volcanic deposits in the field and laboratory (e.g., Smith, 1960; Hildreth, 1981), together with contributions from a range of other disciplines such as experimental petrology and numerical modeling. Increasingly, a raft of sophisticated geochemical techniques are also being used to probe the products of such eruptions at smaller and smaller temporal and spatial scales. A timely example of the latter is the work reported by Pamukcu et al. (2015, p. 947) in this issue of *Geology*. Pamukcu et al. combine chemical and tomographic measurements of quartz crystals with modeling of diffusion process in crystals and melt inclusions to estimate the duration of magma residence prior to eruption for several large volcanic eruptions.

Important questions revolve around the time scales of the magmatic processes occurring within the crustal magma systems that feed supervolcanoes. How long does it take to build up huge quantities of magma? How, and how quickly, can this magma be mobilized to produce an eruption? Such concerns also dovetail closely with the important practical issues. Can we recognize a nascent supervolcano, and if so, how much warning are we likely to get before it blows? There is broad consensus that in supervolcano systems, like most other volcanoes on the continental crust (Chaussard and Amelung 2014), magma accumulates within reservoirs within the shallow crust ($< \sim 10 \text{ km}$) prior to eruption. There is also a growing understanding that, like many large plutonic systems (e.g., Glazner et al., 2004), growth of such magma reservoirs occurs via incremental addition of smaller batches of magma. What is less certain is how fast this incremental addition must occur to produce large quantities of mobile magma (Annen, 2009; Gelman et al., 2013), and what the exact processes are that dictate when this stored magma erupts at the surface (e.g., Degruyter and Huber, 2014).

Pamukcu et al. report data that help constrain the duration of magma accumulation and residence within the shallow crust prior to eruption for the Ohakuri-Mamaku and Oruanui eruptions (both from the Taupo Volcanic Zone, New Zealand, with erupted volumes of $\sim 100 \text{ km}^3$ and $\sim 530 \text{ km}^3$, respectively) and the Bishop Tuff ($\sim 1000 \text{ km}^3$) from Long Valley Caldera, California. Pamukcu et al. use a particularly novel technique, based on ear-

lier work by the same group (Gualda et al., 2012), that utilizes the development of facets in melt inclusions hosted in quartz crystals to constrain the length of time between melt inclusion formation and final eruption and quenching. Melt inclusions are small bubbles of trapped silicate melt \pm vapor that form when minerals crystallize (e.g., Roedder, 1979; Kent, 2008). When formed, inclusions typically show curved interfaces between the trapped melt and host mineral. However, after trapping, in an attempt to minimize free energy, the inclusion may slowly assume internal facets corresponding to the negative crystal shape of the host mineral (Gualda et al. 2012). For melt inclusions trapped in quartz crystals, this requires redistribution of Si, which is mediated by diffusion of Si through the trapped melt. The diffusivity of Si in silicate melts is known, and thus the residence time of a given melt inclusion can be estimated from the degree of faceting apparent. Pamukcu et al. use a sophisticated three-dimensional X-ray tomographic technique for evaluating the shape of melt inclusions, and to document the position of melt inclusions within individual crystals. This allows them to estimate residence times of individual melt inclusions, and growth rates of the host quartz crystals. They also apply another technique, more widely used (e.g., Wark et al., 2007; Matthews et al., 2012), based on the diffusion of Ti in quartz. Quartz incorporates trace quantities of Ti when it is crystallized, and differences in magmatic Ti contents and/or magmatic temperatures can result in dramatic and sharp variations in Ti content within individual crystals. Once such a crystal has formed, diffusion will act to smooth out these differences and thus the shape of Ti variations (or the intensity of cathodoluminescence images, which directly reflect Ti concentration in quartz; e.g., Rusk et al., 2006) between different zones can be used to estimate the length of time the quartz crystal spend in magma.

The time scales that Pamukcu et al. estimate using these techniques are surprisingly short—ranging from decades to centuries for the most part, and are interpreted to reflect magma residence times—the time that has elapsed since crystallization of quartz within the magma until eruption. On the basis of these results, Pamukcu et al. argue that the massive bodies of magma in the subsurface eviscerated by supervolcano eruptions can accumulate on time scales as uncomfortably rapid as decades to centuries. This is a provocative finding and potentially has important ramifications for identifying and gauging the hazards associated with supervolcano systems.

However, this work also highlights an emerging dichotomy between studies that use various radiometric dating techniques to determine magma residence times and those, such as Pamukcu et al., that use methods based on modeling of kinetic processes like diffusion (Turner and Costa, 2007; Cooper and Kent, 2014). Radiometric techniques are based on decay of a radioactive parent isotope to a radiogenic daughter (e.g., ^{238}U decaying to ^{206}Pb) and radiometric ages thus record the time since fractionation of the parent/daughter isotope ratio. The canonical Bishop Tuff, one of the eruptions studied by Pamukcu et al., is a good example. In contrast to Pamukcu et al.’s diffusion-based estimates of magma residence, U-Pb dating of zircon crystals taken from erupted pumice reveal an extended range of ages of zircon formation prior to eruption (interpretations of the exact duration recorded by zircons vary but it is clear that zircon growth occurred for at least several tens of thousands of years prior to eruption; Crowley et al., 2007; Reid and Coath, 2000; Chamberlain et al., 2013). This difference is reflected in many other volcanic systems where U-Pb or U-Th ages of zircon, or ages of major phases determined using U-series disequilibrium,

are typically 10,000 yr or more, whereas residence ages estimated on diffusion or crystallization rates are centuries to millennia (e.g., Turner and Costa, 2007; Cooper and Kent, 2014).

How to reconcile such differences? Well, for a start, there are semantic issues. What exactly is “magma residence time”? Eruptions of large low-crystallinity magmas like the Bishop Tuff are thought to require extraction or assembly of liquid-rich magma from a larger crystal-rich “mush” (e.g., Bachmann and Bergantz, 2004). Thus, radiometric ages might record earlier processes occurring within a long-lived crystal mush system, whereas diffusion-based age estimates record residence more directly relevant to the accumulation of the liquid-rich magmas that ultimately erupt.

However, there may also be deeper issues in play. Use of kinetic processes, such as diffusion, to estimate magma residence times explicitly require that the temperature experienced by the crystal throughout its residence is known. Diffusion follows an Arrhenius relationship, and diffusivity is an exponential function of temperature. Thus any uncertainties or fluctuations in the temperatures experienced during magma residence will translate to considerable uncertainties in the residence time. In particular, if crystals had experienced an extended period of residence at temperatures significantly lower than that used for diffusion calculations, then the result might be apparent residence ages that are shorter than the actual residence. Such an explanation was used by Cooper and Kent (2014) to reconcile younger residence ages estimated from diffusion of Sr in plagioclase relative to ages of plagioclase derived from ^{238}U - ^{230}Th disequilibrium studies at Mount Hood, Oregon. In this case, the difference in ages argue for an extended period of relatively cold magma storage prior to eruption.

Whether such periods of magma residence at relatively cold temperatures also occur in supervolcano systems is an interesting question. For their diffusion calculations, Pamukcu et al. use temperatures based on independent petrological estimates of the temperature of formation of quartz crystals in magma from each of the eruptions they have studied, and have also incorporated uncertainties in these temperatures in their overall residence time estimates. In addition, the temperatures of liquid-rich rhyolite magmas, such as the Bishop Tuff, are largely controlled by eutectic phase relations, and thus, while quartz, alkali feldspar, and plagioclase are present together and in equilibrium with the liquid, temperature should be invariant (e.g., Gualda et al., 2012). Nevertheless, the thermal history of these crystals remains a critical outstanding issue for the interpretation of any diffusion-based chronometry. If the studied crystals spend significant time at near solidus or subsolidus conditions, then the actual time since formation of the crystals would be considerably longer than suggested by diffusion modeling alone, and might even approach the longer durations suggested by U-Pb zircon studies.

Despite these uncertainties, it is becoming increasingly clear is that with advances in instrumentation and applications, such as detailed by Pamukcu et al., we are entering a new era of unprecedented ability to estimate of the time scales of important magmatic and volcanic processes. These techniques are now being widely applied, from supervolcanoes down to the much smaller eruptions that dominate much of Earth’s volcanic output. The result? Important new insights into the behavior of volcanic systems, including those responsible for the largest eruptions of all.

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