Eruptible magma

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For those who remember the classic disaster-docudrama *Supervolcano* (BBC-Discovery Channel 2005), the adjective "eruptible" is likely to ring a bell. Set in the near future and generally quite scientifically literate, the movie envisions volcanologists trying desperately to evaluate the near-term threat posed by the giant Yellowstone magmatic system. At the heart of their mission, and of the drama, is their quest to determine the mass of "eruptible magma" under Yellowstone: that is, how much material that is capable of erupting is down there right now? Fortunately, the scientists have at their disposal VIRGIL, a seismic tomography system that is based upon but greatly upgraded from existing systems. VIRGIL can reliably detect eruptible magma but, unfortunately, it is just coming on-line, and when they discover that there is in fact an enormous reservoir beneath them that can erupt, the scientists lack context. Given a gigantic mass of eruptible magma, what if any sort of eruption—or eruptions—is likely to occur, how soon will it begin, how long will it last, how explosive will it be, and how should scientists and the government respond? *Supervolcano* doesn't turn out well, despite the heroism of the scientists. In PNAS, the search for context is at the heart of research presented by Barboni et al. (1).

Geophysical techniques, as represented by VIRGIL and its less-sophisticated present-day tomographic counterparts and by magnetotelluric and gravity surveys, provide a real-time glimpse of where magma is—or may be—stored within the crust (2). Results to date are intriguing but frustrating. Surveys suggest the presence of molten material beneath a growing number of volcanoes. In fact, gigantic volumes of the crust beneath Yellowstone and the Washington Cascade volcanoes, St. Helens, Rainier, and Adams, appear to contain melt (3, 4). However, these zones are interpreted to mostly contain very small melt fractions; that is, they are largely or entirely ineruptible. In fact, no large volumes of eruptible magma have yet been identified anywhere (2): either they don't exist or current resolution is insufficient to reveal them. Increasing scrutiny and improved resolution are called for to confidently locate or rule out giant eruptible bodies. Their absence would not be surprising to investigators who infer that giant eruptible magma assembles and erupts on short timescales (5, 6); because "supereruptions" are relatively rare (on the order of 10^{-5} y^{-1}), it would not be surprising if no eruptible magma bodies of this scale exist today if they are assembled in 10^3–10^4 y or less. Many smaller bodies that feed volcanoes, like those within the Soufrière Volcanic Center (1), should exist today, even if they assemble rapidly, given that such eruptions occur many times per year on Earth, but they might be much more difficult to detect.

Even when, and if, VIRGIL-like reliable, real-time detection of eruptible magma becomes possible, context provided by studies like that of Barboni et al. (1) are critical for understanding volcano behavior in general and hazards in particular. Petrologic studies, broadly defined—that is, the study of rocks and the evidence they provide of the history of magmas—are necessary to enable us to evaluate what threatening volcanoes and detected magma bodies beneath may do: erupt or not? If so, how soon? What sort of eruption? Should authorities go into serious response mode if eruptible magma is detected, or is this simply the expected state of the volcano in question, and should monitoring simply continue?

Eruptible magma includes crystal-poor, melt-rich material and crystal mush [barely eruptible, up to 50–60% crystals (7, 8)] (Fig. 1*A*). The distribution, in space and time, of rheologically distinct materials with differing melt fractions in magma systems (Fig. 1 *B* and *C*) remains controversial and is probably highly variable. Temperature fluctuations are inevitable, but note that, according to Barboni et al. (1), they were more muted than those depicted in Fig. 1*C* (9) for most of the history of the Soufrière Volcanic Center, where Barboni et al. (1) infer that magma remained within the eruptible window for very long periods of time.

Key questions to be addressed if we are to understand magma systems and the eruptions that they produce, most of which are exemplified by the work of Barboni et al. (1), include: (*i*) How long do volcanoes and magmatic systems remain active? (*ii*) For how much of their lifetimes is melt present within these systems? (*iii*) For how much of their lifetimes is eruptible magma present? (*iv*) How are

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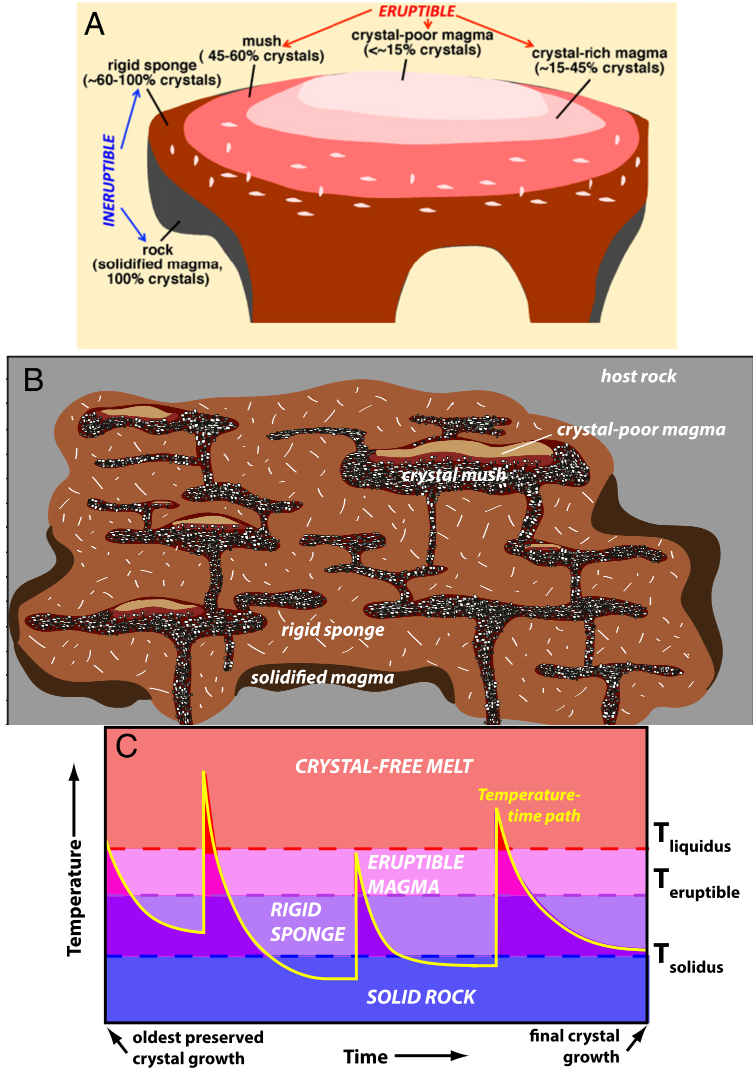

Fig. 1. **Schematic illustrations of upper crustal portion of a magma system. (*A*) Rheologically distinct types of materials (distribution highly simplified): crystal-poor to crystal-rich magma, highly mobile and eruptible; crystal mush, very sluggish but eruptible; rigid sponge, melt present but ineruptible because of abundance of crystals; solidified magma (rock). Modified from refs. 18 and 19. (*B*) Conceptual representation of more complex and realistic distribution of materials; note that the spatial distributions and abundances of the different materials must vary through time (cf. refs. 13 and 20). Illustration courtesy of M. L. Foley. (*C*) Schematic illustration of thermal history of a portion of a magma system and resulting variation in the properties of the magmatic materials as temperature fluctuates. Adapted from ref. 9 with permission from Macmillan Publishers Ltd: *Nature*, copyright 2014.**

melt and eruptible magma distributed within the system in space and time? (*v*) How does the system's temperature fluctuate in space and time? All of these questions require a petrologic approach, and they are addressed by investigations of both erupted magma (volcanic rocks) and intruded magma (plutonic rocks, which comprise magmatic products that remained below the surface) (10, 11). There is wide agreement that magma systems are invariably replenished: that is, they experience repeated injections that bring mass and energy, thus sustaining systems that would otherwise be short lived in the upper crust (e.g., ref. 10), and that both the volcanic and plutonic records of sizeable systems indicate lengthy total longevity [$\sim10^5$ to $>10^6$ y (12–15)]. There is, however, little agreement regarding whether replenishments maintain large, long-lived, magma bodies or rapidly freeze as individual small intrusions (e.g., refs. 12 and 16). Neither is there a consensus regarding whether eruptible magma is ephemeral, extracted and erupted rapidly, or maintained on very long timescales between eruptions.

Among approaches that have been applied to investigate temperature–time-eruptibility histories, the most widely used have been: U-Pb geochronology, mostly with zircon to date crystallization ages >200–300 ka; U-series disequlibria, also mostly for zircon crystallization ages, from a few thousand to ∼300 ka, and for other minerals down to very young ages; geothermometry, estimating temperatures of mineral growth and phase equilibration based on experimentally based thermodynamic models; diffusion profile modeling, which estimates the "relaxation time" required to yield observed concentration profiles in crystals, given known diffusivities of elements within specific minerals as functions of temperature; and modeling crystal size distributions, given established temperature-dependence of crystal growth rates. Each approach yields valuable constraints on potential eruptible magma histories, but none by itself provides answers to more than one or two of the five questions posed in the paragraph above. Any interpretation that goes beyond plausible conjecture requires multiple approaches.

Recent workers aiming to assess histories of eruptible magma and consider consequences for eruption hazards tend to fall into two camps, as described in Barboni et al. (1). In the first camp are the "cold storage" advocates, who suggest that magmatic materials are crystal-rich and ineruptible, perhaps even subsolidus, throughout most of their history, but that they become briefly eruptible as a result of thermal rejuvenation. This interpretation, based on combinations of U-series dating and diffusion profile and crystal size-distribution modeling, has been applied to both supereruptions and modest-scale arc volcanoes; durations within the eruptibility window are interpreted to be short to extremely short (1–10^4 y) (e.g., refs. 6 and 9). The second camp is composed of those who favor "warm storage" and estimate that during much and perhaps most of >10^5 y magma system histories eruptible magma is stored beneath volcanoes (e.g., ref. 17). Proponents of warm storage point to prolonged records of zircon growth revealed by U-Pb and U-series dating. Barboni et al. (1) provide perhaps the most thorough record yet presented of seemingly nearly continuous zircon ages from a magmatic center, together with estimated temperatures of zircon growth (based on Ti concentrations, which are T-sensitive) that in many cases are high enough to suggest a large melt fraction: that is, eruptibility. The authors conclude that eruptible magma storage beneath volcanoes may be the rule and geophysical detection of such magma, therefore, may not indicate near-term eruption.

Studies like that presented by Barboni et al. (1) in PNAS continue to refine our understanding of how volcanoes work and strengthen assessment of hazards that they present. Much remains to be done through continuing refinement of existing analytical and modeling approaches and development of new ones. It remains to be seen whether the cold storage or warm storage view has greater validity; perhaps more likely, different systems have different storage styles, or the reality of typical magma system behavior incorporates elements of both. Eventually, something akin to VIRGIL can be anticipated for real-time geophysical sensing of the presence of eruptible magma. Combining such a technique with petrologically based understanding of how eruptible magma is distributed in space and time in general, and in specific systems, can lead to greatly improved evaluation of volcanic eruptions and their hazards.

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