Studying the initiation of volcanic eruptions: Time for a petrological perspective.

Adam J. R. Kent*

College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA. adam.kent@oregonstate.edu

Christy B. Till

School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA.

christy.till@asu.edu

Kari M. Cooper

Department of Earth and Planetary Sciences, University of California, Davis, CA, USA.

kmcooper@ucdavis.edu

*Corresponding Author

Abstract

Volcano monitoring is essential for mitigating the risks associated with volcanic activity. As monitoring becomes more sophisticated and widespread, there is a growing need for understanding the relationship between different monitoring records and magmatic processes occurring at depth. This is particularly relevant to the processes that initiate eruptions after the extended periods of repose and inactivity that characterize many volcanic systems. Petrological studies of erupted materials are critical to this effort as they provide direct insight into the physical and chemical changes that occur in erupted magmas prior to their eruption, and allow investigation of past eruptions. Crucially, petrological approaches can also constrain the timing of processes involved in eruption initiation, and the time that might be expected to elapse between remote detection of increased activity and eventual eruption. Despite this, petrological studies of eruption initiation mechanisms are rarely systematically applied to monitored and other high-risk volcanoes. A literature compilation suggests there are significant differences in the composition, volume, style and timescales between eruptions initiated by different mechanisms. Knowledge of the processes that initiate eruptions at a given volcano may thus have significant predictive power.

Introduction

Globally almost 800 million people live in regions that are directly exposed to volcanic hazards[1]. Many more are potentially impacted through effects on air travel and communication, and changes to regional and global climate. Volcano monitoring efforts – observations of volcanic behavior through detection of seismic activity, infrasound, deformation, gas emissions and other phenomena – are an essential component of reducing volcanic risk [2-5]. However, monitoring efforts are also inherently limited, as only a small fraction of recognized subaerial volcanoes worldwide are monitored in any form, and fewer are monitored at a level considered adequate [4]. Moreover, monitoring covers only a small fraction of the lifetime of a given volcanic system, and many eruptions – including some of the most serious eruptions of the past century – occur at volcanoes with little or no historic indication of unrest [6-8]. Thus, another important part of mitigating volcanic risk is to develop an understanding of the key physical, chemical and other processes that occur in the subvolcanic magma systems that cause eruptive activity, and how these relate to the geophysical, geochemical and other signals detected by volcano monitoring. However, despite considerable progress in our understanding of magmatic systems in the last decade, associating changes in monitoring signals with specific subsurface processes remains an extant grand challenge [5,9], particularly for volcanoes that erupt infrequently.

Of particular relevance for linking magmatic processes to volcano monitoring signals are the mechanisms by which volcanic eruptions are initiated. Most volcanoes, especially those that erupt intermediate and evolved compositions, experience long periods of quiescence between eruptions, and spend significantly more time in repose than actively erupting [10-13]. Erupted magmas may themselves also be stored in the crust for long periods – thousands of years or more – prior to eruption [14-16]. Thus, magmas and related crystal-rich mush zones can reside in a stable or quasi-stable state within the Earth's crust prior to erupting, and a set of specific and probably quite rare processes may be required to initiate eruption.

Understanding the processes that initiate volcanic eruptions is thus of critical importance to understand volcano behavior and hazards [9], but has seen surprisingly little systematic study – particularly from the petrological perspective. As an example, a monolithic compendium of volcano knowledge, the Encyclopedia of Volcanoes (2nd Ed.) [17] with 71 chapters and 1300 pages, has no discrete chapter dedicated to the processes that initiate volcanic eruptions, and relatively little mention of these processes throughout. Studying the geological history of a given volcano through mapping, geochronology and other means is an established and valuable method for evaluating the likelihood and character of future eruptions [5,18], but it is also rare that this is linked to petrological and other studies that reveal the processes that initiated past eruptions [19].

Classically, the initiation of eruption is considered to result from a magma reservoir attaining the critical overpressure or tensile stress at its boundary with surrounding rock to trigger crustal failure, dike propagation, and magma ascent to the surface [20-22]. However, other factors such as the rate of increases in overpressure, volatile abundance, internal magma dynamics, and the structural, stress, and rheological state of surrounding rocks are also highly important [20,23,24]. Thus eruption initiation is best considered within a framework of the complex transcrustal magma systems that underlie volcanoes [25], and where much of the stored magma may exist as a crystal-rich mush [16,26-30].

As a result of this complexity, the study of eruption initiation requires a multidisciplinary approach. Amongst these, direct studies of erupted material provide some of the most useful insights. The processes that induce eruption leave distinct signatures in terms of the crystallinity, crystal and liquid chemistry, textures, and other features preserved within erupted materials, and often record the last high temperature processes to impact a given magma, which increases preservation potential. In addition, the timing of initiation events can be estimated from the diffusion of major or trace elements in minerals or glasses, as well as crystal growth and dissolution rates, with increasing sophistication and accuracy [31]. Despite this, the use of petrological and related approaches to specifically study the long-term processes of eruption initiation in a given volcanic system remains rare [32,33].

Nomenclature

Currently in the literature there are variations in nomenclature, with both the terms "eruption initiation" and "eruption trigger" being used to describe a broad range of processes and outcomes involved with volcanic eruptions. These include deeper magmatic processes, as well as those that occur more shallowly within a conduit or edifice. Initiation or triggering are also variably applied to changes in eruption intensity or style (such as effusive to explosive transitions) that occur as part of an ongoing eruption, and also surficial events such as collapse events in an eruption column, volcanic edifice, or dome. For this study we consider a useful definition of eruption initiation to be: "the process or set of processes that result in a previously stable or quasi stable accumulation of magmatic material within the crust to commence moving upward and eventually erupt". By "stable or quasi stable", we mean magma bodies or crystal-rich mushes that have recently not been mobile, have not exceeded the critical overpressure or other parameters required to commence upward movement, nor shown previous indication of eruption, with seismicity and other monitoring signals (if known) at baseline levels.

We suggest that a more specific definition of eruption initiation, such as that proposed above, will help focus research on this critical subject, and that the term "eruption triggering" retain a more generic and contextual meaning. The May 18 1980 eruption of Mount St Helens provides an example of this usage. The trigger for the eruption was a magnitude 5.1 earthquake and landslide. However, eruption initiation occurred at several months earlier when magma started to ascend from a crustal reservoir to form a shallow cryptodome after many decades of quiescence.

Processes that initiate volcanic eruptions

Although systematic studies of eruption initiation are rare, there are many studies in the literature that report results and observations that bear on this important topic. We have compiled studies that primarily use petrological, geochemical and related techniques (in some cases this information was also combined with other data from seismicity, ground deformation, gas release and other sources) to infer the processes involved in the initiation of a range of different volcanic eruptions, and that also estimate the time elapsed between the initiation event(s) and eventual eruption. In some cases, these studies do not explicitly identify the eruption initiation mechanism but it is possible to do so from reported data and observations. Our compilation includes volcanoes from a variety of tectonic settings, although it is dominated (90%) by volcanoes from subduction zones. Overall the compilation contains more than 68 individual eruptions, representing 20 different volcanoes. Importantly, although volcanoes exhibit a wide variety of eruption types and styles, the compilation suggests a relatively limited number of eruption initiation mechanisms can be identified (Fig. 1; Supplementary data), and the majority (> 90%) indicate that intrusion of new magma into an existing resident magma occurred immediately prior to eruption. Overall, we recognize four different eruption initiation mechanisms, three relating to intrusion of new magma and one to accumulation of volatile phases.

We also note that there are other mechanisms that have been suggested to initiate eruptions. These include near field phenomena such as roof collapse above large magma chambers [34] and build-up of buoyancy forces [35,36], as well as far field forcing related to large earthquakes [37,38]. Although these mechanisms may be important in some settings, we do not consider them in detail here as they are less likely to leave distinctive petrological or geochemical signatures in erupted products, other than an absence of evidence for other initiation mechanisms. Future work may be able to identify methods whereby these mechanisms can be recognized from studies of erupted materials.

Mafic Recharge

Eruption initiation by addition of mafic magma to a more felsic magma reservoir is identified in 37% of the eruptions in our compilation, and is common in volcanoes in arc settings. Although the term "recharge" has a generic connotation of addition of magma, we recommend that the term *mafic recharge* refer exclusively to cases where significantly more mafic magma (typically basalt or basaltic andesite in composition) is added to a resident more silicic magma (andesite to rhyolite) [39]. The ramifications of this process are known relatively well from analogue and numerical experiments and field and petrological studies, and the petrologic record of this event includes the presence of reversely zoned crystals and different compositional and textural populations of the same mineral derived from distinct mafic and silicic magmas, disequilibrium mineral assemblages (e.g., quartz and olivine), multiple mafic and silicic liquid components in glasses or melt inclusions, and at the field scale hybridized magmas, enclaves, banded pumice, and similar phenomena [21,32,39-47]. Intrusion of mafic material leads to a range of volatile exchange and saturation phenomena, increases in volume and/or internal pressure, and convective overturn. Phenocrysts in this scenario typically show evidence for large temperature contrasts (typically ≥ ~100°C) associated with rim growth [48,49], often associated with extensive mineral dissolution or reaction rims[39]. The presence of microlites or microphenocrysts with mafic signatures within less mafic magmas also suggests magma mixing immediately prior to eruption [32,40,45,50].

Timing constraints for eruptions initiated via mafic recharge typically derive from estimating the timing elapsed between growth of reversely zoned crystal rims and eruption. Such "step function" zoning geometries in major and trace element abundances are well suited to diffusion modelling [32,49,51-53]. Although an outstanding question is how much time elapses during dissolution before new rim growth occurs, this is probably not significantly longer than the time taken to grow the rims as mineral dissolution rates are typically faster than growth rates. Estimates of the timescale associated with mafic recharge can also come from direct observations of modern eruptions [54,55], re-equilibration of Fe-Ti oxides, and estimates of mineral growth and dissolution and melt inclusion preservation [45,50,56-60].

Rejuvenation

The majority (55%) of eruptions in our compilation result from intrusion of magma of broadly similar composition to the resident magma. We term this *rejuvenation*, and given that the compositions of magmas associated with rejuvenation also vary, we further recognize both *mafic rejuvenation* (31% of the compilation) and *silicic rejuvenation* (24%). We also note that differences in composition between introduced and resident magmas vary on a continuum between mafic recharge and rejuvenation. A fourth potential mechanism – *felsic recharge* – could occur when felsic magma intrudes a mafic magma reservoir but appears rare [61].

In contrast to mafic recharge, eruptions initiated via rejuvenation are more likely to result from increased overpressure related to magma addition, together with increased buoyancy forces, and/or decreasing viscosity through changes in temperature and crystallinity. Mineral zoning and mineral populations associated with both mafic rejuvenation and silicic rejuvenation show more subtle differences than in the case of mafic recharge, and the primary difference between the intruding and resident magma may be degree of crystallinity with only minimal temperature differences, as revealed by eruptions that are cryptically zoned in terms of modal crystal proportions [33,44,62,63], or contain glomerocrysts, strained crystals and other evidence for disaggregation of crystal-rich cumulates [64-66]. Crystals from these include phenocrysts with subtle reverse zoning in the outermost rims, often in phases with more limited compositional stability fields such as olivine, sanidine and quartz, indicating that although the replenishing magma was somewhat less evolved in terms of incompatible trace elements, it was broadly similar with respect to phase stability [33,67-69].

Mafic rejuvenation is the dominant mechanism in large shield volcanoes in extensional and arc settings, and felsic rejuvenation appears important for many silicic eruptions, including some of the largest known caldera eruptions [33,70], as well as in arc settings. Eruption timescales for rejuvenation are typically estimated using diffusion in mineral rims. This includes high Ba and high Ti rims on sanidine and quartz for felsic rejuvenation, and high Mg/Fe rims on olivine and orthopyroxene crystals for mafic rejuvenation [31]. In some cases, growth rates of mineral rims can also be used [33,70].

Vapor saturation and exsolution

This mechanism has long been considered important [71-75] but is identified in only ~7% of the eruptions in our compilation, all of which occur in arc settings. Petrologic modelling suggests that volatile accumulation during progressive igneous evolution may be an important eruption initiation mechanism for large silicic magma bodies [72,73,75]. Vapor saturation and increased overpressure can occur related to decompression ("first boiling"), or more commonly when the magma attains vapor saturation during crystallization ("second boiling")[74]. In addition, upward movement of vapor exsolved deeper in a magmatic system or assimilation of hydrothermally-altered wallrocks, could also produce increased vapor pressure and vapor saturation [72,73,75]. Vapor accumulation may be more challenging to definitively identify using petrological means, as most major and accessory phases record normal zoning and other changes corresponding to subtly decreasing temperatures and increased crystallinity. However, minerals that incorporate volatile species, such as amphibole, biotite, or apatite; fluid or melt inclusions hosted in a variety of phases; and/or mineral zoning in trace elements that preferentially partition into an exsolved vapor, can record progressive changes in vapor saturation and vapor composition during progressive crystallization [76-80]. Eruption initiation timescales for volatile accumulation in arc magmas have been estimated using diffusion of volatiles or elements with an affinity for the vapor phase or from mineral rims associated with vapor accumulation [79,80], and from reequilibration (or lack thereof) of melt inclusions [79,80].

Comparison between different eruption mechanisms

Our compilation allows us to compare some key eruption characteristics – the eruption style, erupted volume, erupted composition, and eruption initiation timescale – between eruptions initiated by the different mechanisms we identify above. We classify these characteristics using a categorical variables approach, either because they are already categorical (erupted rock type, eruption style), or because the large uncertainties warrant such an approach (erupted volume, eruption initiation timescale) (supplementary methods). Results, summarized in Figures 1-3, suggest there are systematic differences between eruptions initiated by the different eruption initiation mechanisms we identify. In some cases, these differences are obvious (for example, mafic rejuvenation and felsic rejuvenation are constrained to produce eruptions of mafic and felsic magmas), but for other parameters these systematic variations suggest there are consistent differences related to the processes of eruption initiation. From these data we hypothesize that there are general trends in increasing eruption volumes, longer initiation timescales, more silicic compositions, and more explosive eruption style going from mafic rejuvenation to mafic recharge, silicic rejuvenation and volatile accumulation, as summarized in Figure 3.

To make more rigorous comparisons we apply Fisher's exact test, a statistical significance test for categorical data [81,82], an approach that minimizes the effect of large uncertainties in timescales and erupted volumes (supplementary methods). Using a simplified "dichotomized" categorical variable approach, we test both 4 x 2 contingency tables that compare the distribution of a given characteristic across all of the four different eruption initiation mechanisms, and 2 x 2 contingency tables to directly compare a single characteristic between pairs of eruption initiation mechanisms. In all cases we explore the null hypothesis that no differences exist in the distribution of eruption characteristics between different initiation mechanisms. Results are expressed in terms of P values (Supplemental Data Tables 4-8), which represents the probability of the null hypothesis being true given the observed distribution. We use a P value of ≤ 0.05 as a guide that the null hypothesis can be rejected, but caution against applying this rigidly [83], and simply consider low P values as good candidates for exploration with more comprehensive data sets. Comparison of each characteristic across the four different initiation mechanisms using a 4 x 2 contingency table shows low P values for erupted composition, erupted volume, eruption style and initiation timescale, and thus the probability of the null hypothesis explaining the observed distribution for each of these parameters is considered low. The 2 x 2 contingency tables show P values < 0.05 for comparisons of mafic rejuvenation vs. felsic rejuvenation, mafic rejuvenation vs. mafic recharge and mafic rejuvenation vs. volatile accumulation for erupted volume, erupted composition, and eruption style. Mafic rejuvenation vs. felsic rejuvenation and mafic rejuvenation vs. mafic recharge also have $P < 0.05$ for the eruption initiation timescale. Other comparisons also have relatively low P values (< 0.4): mafic rejuvenation vs. volatile accumulation for eruption initiation timescale; mafic recharge vs. felsic rejuvenation, and vs. volatile accumulation for eruption style; and volatile accumulation vs. mafic recharge and vs. felsic rejuvenation for erupted composition. This may suggest these comparisons are also worth further exploration – particularly those associated with volatile accumulation as the number of studies in the compilation is low ($n = 5$).

Discussion - The utility of petrological studies in understanding eruption initiation

Our results emphasize two important points. Firstly, although further refinements are certainly possible, petrological approaches are one of the best means we have to characterize a given volcanic system in terms of the process or processes that have initiated eruptions, but are also underutilized. Observations from volcano monitoring also provide important insight, but petrological studies of erupted materials allow for the identification of physical and chemical changes associated with eruption, and the associated timescales, and can be applied throughout the available eruptive record. Secondly, having some knowledge of the initiation processes that are likely to occur in a given system offers significant potential for insight into forecasting the initiation timescale and some other characteristics of an eventual eruption. Thus, systematic studies of eruption initiation mechanisms by petrological and other techniques, would seem to offer tremendous promise in some cases for assessing the nature of future eruptions and their associated hazards, and would add value to extant or planned monitoring programs.

To improve and expand on this we make four recommendations for priority areas of work over the next decade.

Increased emphasis on understanding eruption initiation. It is time for a renewed emphasis on the critical subject of eruption initiation mechanisms, including understanding the processes that take volcanic systems from quiescence to eruption and how these processes are recorded (or not) in erupted magmatic products. This research will be multidisciplinary, but there is much to gain from further systematic development and use of petrological and related approaches to identify and constrain initiation mechanisms. Our review reveals that many studies of volcanic systems report sufficient petrological, textural and other information to infer the initiation mechanism, but do not explicitly do so. Introducing consistent nomenclature and classification of eruption initiation mechanisms, as we recommend above, will also help. It may also be possible to further constrain the types of eruption initiation mechanisms beyond the simple categorization we present above.

More data is better than better. We need constraints on the initiation processes and associated timescales for more eruptions. Although we should also aim to improve the accuracy of timescale estimates based on diffusion chronometry and other methods, we argue that progress would be better served at this stage by applying existing techniques to more eruptions. In other words, doubling the number of volcanoes and eruptions studied with the types of techniques exemplified in our literature compilation would provide broader insights than doubling the precision and accuracy of existing chronometers. Our data compilation shows the limits of relatively small numbers for several categories, and greater amounts of available data across different volcano and eruption types and different tectonic environments would open up exciting new opportunities. A more complex categorical scheme, versus the simplified approach we use here, could explore characteristics of eruptions in much greater detail. More data would also provide greater statistical power to address key questions such as the commonality of a particular eruption initiation mechanism over an individual volcano's lifetime, how common specific eruption initiation mechanisms are to particular types of volcanoes and tectonic settings, and the controls on volcanic repose time. Examples of this include the suggestion that estimated eruption initiation timescales may be longer for more silicic (dacite, rhyodacite and rhyolite) eruptions initiated by mafic recharge and silicic rejuvenation (Figure 2), as well as that repose times might also vary with composition[11].

Greater integration with monitoring. Monitoring active and potentially active volcanoes saves lives and property, particularly when integrated with effective hazard mitigation planning. However, there is a need for greater understanding of the relationship between the signals gained from volcanic monitoring methods, and the signals of underlying magmatic processes recorded in the rocks themselves. Petrologic data from modern eruptions is key here, as they allow direct comparison between monitoring signals and the physical and chemical changes recorded by magma in a magma reservoir undergoing initiation. These relationships are actively being explored, aided by increasingly common application of diffusion chronometry [84-86] but much progress remains to be made. To illustrate the importance of this approach, we show a compilation of the timescales of unrest based on various monitoring signals for eruptions with corresponding petrologic initiation timescales from diffusion chronometry or similar approaches in Figure 4. Although we are limited by available data, the results suggest there is not a uniformly simple 1:1 relationship. Mafic rejuvenation is the most frequently identified eruption initiation mechanism in studies where initiation timescales and unrest timescales are both documented, and also appears the most likely to show agreement in the general magnitude of these timescales. However, the limited data suggests the same may not be true for other eruption initiation mechanisms. Improved understanding of the relationship between these two signals will also improve the ability to assess and forecast volcanic hazards.

Increased petrological monitoring. Petrologic studies offer a cost-effective way to understand more about volcanic hazards in understudied volcanoes and to leverage existing monitoring resources. It is relatively common to map the compositions, type, and extent of eruptions through time at a given volcano to gauge hazards, but it is less common to combine this with systematic studies of eruption initiation mechanisms through petrologic studies. In relatively poorly monitored volcanoes this might be one way to understand the likely nature of future unrest episodes. Such observations could be used to augment the monitoring record, and provide a deep time historical context for recognizing the likely mechanism for future eruption initiation and onset of potential eruption episodes, as well as offering the specific potential for understanding the timing of new eruptions. In systems with more comprehensive monitoring programs, such data could also help refine traditionally problematic aspects of monitoring such as recognizing the causes of “failed eruptions” – episodes of instrumental and other unrest that do not result in eruptions. Petrologic research of this type is also a perfect forum for constructive cooperation between academic and government agencies. Importantly, the time to conduct such studies is in the early stages of a monitoring program and prior to the onset of a new eruptive episode.

In conclusion we reiterate that petrologic studies of eruption initiation mechanisms show great promise for improving our understanding of the magmatic processes associated with initiation of volcanic eruptions. A systematic effort at integrating petrologic insights into eruption initiation with monitoring signals offers an excellent opportunity to capitalize on this promise and to make rapid progress into the understanding of volcanic behavior.

Acknowledgements

The ideas for this work stem from NSF-EAR-1654584 (CAREER) to CBT, the 2018 Workshop on Community Volcano Experiments in Albuquerque, New Mexico, and the 2019 CIDER workshop in Berkeley, California, as well as discussions with colleagues at these events and elsewhere. All authors gratefully acknowledge funding support from the National Science Foundation: AJRK NSF-EAR-1654275 and NSF-EAR-1654275; CBT NSF-EAR-1654584; KMC NSF-EAR-1654506. All authors declare no competing financial interests. All three authors jointly conceived the work and collected data from the literature. AJRK took the lead on writing the manuscript, CBT and KMC assisted and edited the document.

References

1 Loughlin, S. C. *et al.* An introduction to global volcanic hazard and risk,in Global

Volcanic Hazards and Risk. p. 1-80 in S.C. Loughlin, R.S.J. Sparks, S.K. Brown, S.F. Jenkins & C. Vye-Brown (eds) Global Volcanic Hazards and Risk, Cambridge: Cambridge University Press. (2015).

2 Auker, M. R., Sparks, R. S. J., Siebert, L., Crosweller, H. S. & Ewert, J. A statistical analysis of the global historical volcanic fatalities record. *Journal of Applied Volcanology* **2**, doi:10.1186/2191-5040-2-2 (2013).

3 Barclay, J. *et al.* Livelihoods, Wellbeing and the Risk to Life During Volcanic Eruptions. *Frontiers in Earth Science* **7**, doi:10.3389/feart.2019.00205 (2019).

4 Moran, S. C. *et al.* Instrumentation Recommendations for Volcano Monitoring at U.S. Volcanoes under the National Volcano Early Warning System. U.S. Geological Survey Scientific Investigations Report 47 (2008).

5 Poland, M. P. & Anderson, K. R. Partly Cloudy With a Chance of Lava Flows: Forecasting Volcanic Eruptions in the Twenty-First Century. *Journal of Geophysical Research: Solid Earth* **125**, doi:10.1029/2018jb016974 (2020).

6 Biggs, J. *et al.* Global link between deformation and volcanic eruption quantified by satellite imagery. *Nat Commun* **5**, 3471, doi:10.1038/ncomms4471 (2014).

7 Luhr, J. F., Carmichael, I. S. E. & Varekamp, J. C. The 1982 eruptions of El Chichon Volcano, Chiapas, Mexico: mineralogy and petrology of the anhydrite-bearing pumices. *Journal of Volcanology and Geothermal Research* **23**, 69-108 (1984).

8 Pallister, J. S., Hoblitt, R. P. & Reyes, A. G. A Basalt Trigger for the 1991 Eruptions of Pinatubo Volcano. *Nature* **356**, 426-428 (1992).

9 National Academies of Sciences, Enghineering, and Medicine. *Volcanic Eruptions and Their Repose, Unrest, Precursors, and Timing*. The National Academies Press, Washionton DC (2017).

10 Deligne, N. I., Coles, S. G. & Sparks, R. S. J. Recurrence rates of large explosive volcanic eruptions. *Journal of Geophysical Research* **115**, doi:10.1029/2009jb006554 (2010).

11 Passarelli, L. & Brodsky, E. E. The correlation between run-up and repose times of volcanic eruptions. *Geophysical Journal International* **188**, 1025-1045, doi:10.1111/j.1365-246X.2011.05298.x (2012).

12 Pritchard, M. E. *et al.* Towards coordinated regional multi-satellite InSAR volcano observations: results from the Latin America pilot project. *Journal of Applied Volcanology* **7**, doi:10.1186/s13617-018-0074-0 (2018).

13 Rougier, J., Sparks, R. S. J., Cashman, K. V. & Brown, S. K. The global magnitude–frequency relationship for large explosive volcanic eruptions. *Earth and Planetary Science Letters* **482**, 621–629 (2018).

14 Claiborne, L. L., Miller, C. F., Flanagan, D. M., Clynne, M. A. & Wooden, J. L. Zircon reveals protracted magma storage and recycling beneath Mount St. Helens. *Geology* **38**, 1011-1014, doi:10.1130/g31285.1 (2010).

15 Cooper, K. M. Time scales and temperatures of crystal storage in magma reservoirs: implications for magma reservoir dynamics. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **377**, 20180009, doi:10.1098/rsta.2018.0009 (2019).

16 Cooper, K. M. & Kent, A. J. Rapid remobilization of magmatic crystals kept in cold storage. *Nature* **506**, 480-483, doi:10.1038/nature12991 (2014).

17 Sigurdsson, H. *The Encyclopedia of Volcanoes, 2nd Edition.* . 1456 (Academic Press, 2015).

18 Condit, C. & Connor, C. Recurrence rates of volcanism in basaltic volcanic fields: An example from the Springerville volcanic field, Arizona. *Geological Society of America Bulletin* **108**, 1225–1241, doi:10.1130/0016-7606(1996)108<1225:RROVIB>2.3.CO;2 (1996).

19 Connor, C., Sparks, R. S., Mason, R. M., Bonadonna, C. & Young, S. R. Exploring links between physical and probabilistic models of volcanic eruptions: The Soufrière Hills Volcano, Montserrat. *Geophysical Research Letters* **30**, doi:10.1029/2003GL017384 (2003).

20 Degruyter, W. & Huber, C. A model for eruption frequency of upper crustal silicic magma chambers. *Earth and Planetary Science Letters* **403**, 117-130, doi:10.1016/j.epsl.2014.06.047 (2014).

21 Eichelberger, J. C., Izbekov, P. E. & Browne, B. L. Bulk chemical trends at arc volcanoes are not liquid lines of descent. *Lithos* **87**, 135-154 (2006).

22 Pinel, V. & Jaupart, C. The effect of edifice load on magma ascent beneath a volcano. *Philosophical Transactions of the Royal Society of London* **A 358**, 1,515-1,532 (2000).

23 Albright, J. A., Gregg, P. M., Lu, Z. & Freymueller, J. T. Hindcasting magma reservoir stability preceding the 2008 eruption of Okmok, Alaska. *Geophysical Research Letters*

46, 8801– 8808, doi:10.1029/2019GL083395 (2019).

24 Gregg, P. M., de Silva, S. L. & Grosfils, E. B. Thermomechanics of shallow magma chamber pressurization: Implications for the assessment of ground deformation data at active volcanoes. *Earth and Planetary Science Letters* **384**, 100-108, doi:10.1016/j.epsl.2013.09.040 (2013).

25 Cashman, K. V., Sparks, R. S. & Blundy, J. D. Vertically extensive and unstable magmatic systems: A unified view of igneous processes. *Science* **355**, doi:10.1126/science.aag3055 (2017).

26 Bachmann, O. & G.W., B. Rhyolites and their Source Mushes across Tectonic Settings. *Journal of Petrology* **49**, 2277-2285, doi:10.1093/Petrology/Egn068 (2008).

27 Bergantz, G. W., Schleicher, J. M. & Burgisser, A. On the kinematics and dynamics of crystal-rich systems. *Journal of Geophysical Research: Solid Earth* **122**, 6131-6159, doi:10.1002/2017JB014218 (2017).

28 Cashman, K. V., Sparks, R. S. J. & Blundy, J. D. Vertically extensive and unstable magmatic systems: A unified view of igneous processes. *Science* **355**, doi:10.1126/science.aag3055 (2017).

29 Edmonds, M., Kohn, S. C., Hauri, E. H., Humphreys, M. C. S. & Cassidy, M. Extensive, water-rich magma reservoir beneath southern Montserrat. *Lithos* **252-253**, 216-233, doi:10.1016/j.lithos.2016.02.026 (2016).

30 Rubin, A. E. *et al.* Rapid cooling and cold storage in a silicic magma reservoir recorded in individual crystals. *Science* **356**, 1154-1156, doi:10.1126/science.aam8720 (2017).

31 Costa, F., Shea, T. & Ubide, T. Diffusion chronometry and the timescales of magmatic processes. *Nature Reviews Earth & Environment* **1**, 201-214, doi:10.1038/s43017-0200038-x (2020).

32 Kent, A. J. R., Darr, C., Koleszar, A. M., Salisbury, M. J. & Cooper, K. M. Preferential eruption of andesitic magmas through recharge filtering. *Nature Geoscience* **3**, 631-636, doi:10.1038/ngeo924 (2010).

33 Shamloo, H. I. & Till, C. B. Decadal transition from quiescence to supereruption: petrologic investigation of the Lava Creek Tuff, Yellowstone Caldera, WY. *Contributions to Mineralogy and Petrology* **174**, doi:10.1007/s00410-019-1570-x (2019).

34 Gregg, P. M., de Silva, S. L., Grosfils, E. B. & Parmigiani, J. P. Catastrophic calderaforming eruptions: Thermomechanics and implications for eruption triggering and maximum caldera dimensions on Earth. *Journal of Volcanology and Geothermal Research* **241-242**, 1-12 (2012).

35 Caricchi, L., Annen, C., Blundy, J., Simpson, G. & Pinel, V. Frequency and magnitude of volcanic eruptions controlled by magma injection and buoyancy. *Nature Geoscience* **7**, 126–130, doi:http://dx.doi.org/10.1038/ngeo2041 (2014).

36 Malfait, W. J. *et al.* Supervolcano eruptions driven by melt buoyancy in large silicic magma chambers. *Nature Geoscience* **7**, 122-125, doi:10.1038/ngeo2042 (2014).

37 Cabaniss, H. E., Gregg, P. M. & Grosfils, E. B. The Role of Tectonic Stress in Triggering Large Silicic Caldera Eruptions. *Geophysical Research Letters* **45**, 3889-3895, doi:10.1029/2018gl077393 (2018).

38 Hamling, I. & Kilgour, G. N. Goldilocks conditions required for earthquakes to trigger basaltic eruptions: Evidence from the 2015 Ambrym eruption. *Science Advances* **6**: eaaz5261 (2020).

39 Eichelberger, J. C. Andesitic volcanism and crustal evolution. *Nature* **275**, 21-27 (1978).

40 Humphreys, M. C. S., Christopher, T. & Hards, V. Microlite transfer by disaggregation of mafic inclusions following magma mixing at SoufriSre Hills volcano, Montserrat. *Contributions to Mineralogy and Petrology* **157**, 609-624, doi:10.1007/s00410-008-03563 (2009).

41 Huppert, H. E., Sparks, R. S. J. & Turner, J. S. Effects of volatiles on mixing in calcalkaline magma systems. *Nature* **297**, 554-557 (1982).

42 Murphy, M. D. *et al.* The role of magma mixing in triggering the current eruption at the Soufriere Hills Volcano, Montserrat, West Indies. *Geophysical Research Letters* **25**, 3433-3436, doi:10.1029/98gl00713 (1998).

43 Ruprecht, P., Bergantz, G. W. & Dufek, J. Modeling of gas-driven magmatic overturn: Tracking of phenocryst dispersal and gathering during magma mixing. *Geochemistry Geophysics Geosystems* **9**, Q07017, doi: 07010.01029/02008GC002022 (2008).

44 Ruprecht, P. & Wörner, G. Variable regimes in magma systems documented in plagioclase zoning patterns: El Misti stratovolcano and Andahua monogenetic cones. *Journal of Volcanology and Geothermal Research* **165**, 142-162, doi:https://doi.org/10.1016/j.jvolgeores.2007.06.002 (2007).

45 Salisbury, M. J., Bohrson, W. A., Clynne, M. A., Ramos, F. C. & Hoskin, P. Multiple

Plagioclase Crystal Populations Identified by Crystal Size Distribution and in situ Chemical Data: Implications for Timescales of Magma Chamber Processes Associated with the 1915 Eruption of Lassen Peak, CA. *Journal of Petrology* **49**, 1755-1780, doi:10.1093/petrology/egn045 (2008).

46 Sparks, S. R. J., Sigurdsson, H. & Wilson, L. Magma mixing - mechanism for triggering acid explosive eruptions. *Nature* **267**, 315-318 (1977).

47 Tepley III, F. J., Davidson, J. P. & Clynne, M. A. Magmatic interactions as recorded in plagioclase phenocrysts of Chaos Crags, Lassen Volcanic Center, California. *Journal of Petrology* **40**, 787-806 (1999).

48 Koleszar, A. M., Kent, A. J. R., Wallace, P. J. & Scott, W. E. Controls on long-term low explosivity at andesitic arc volcanoes: Insights from Mount Hood, Oregon. *Journal of Volcanology and Geothermal Research* **219-220**, 1-14, doi:10.1016/j.jvolgeores.2012.01.003 (2012).

49 Matthews, N. E., Huber, C., Pyle, D. M. & Smith, V. C. Timescales of Magma Recharge and Reactivation of Large Silicic Systems from Ti Diffusion in Quartz. *Journal of Petrology* **53**, 1385-1416, doi:10.1093/petrology/egs020 (2012).

50 Martel, C. Eruption Dynamics Inferred from Microlite Crystallization Experiments: Application to Plinian and Dome-forming Eruptions of Mt. Pelee (Martinique, Lesser Antilles). *Journal of Petrology* **53**, 699-725, doi:10.1093/petrology/egr076 (2012).

51 Barker, S. J., Wilson, C. J. N., Morgan, D. J. & Rowland, J. V. Rapid priming, accumulation, and recharge of magma driving recent eruptions at a hyperactive caldera volcano. *Geology* **44**, 323-326, doi:10.1130/g37382.1 (2016).

52 Martin, V. M. *et al.* Bang! Month-scale eruption triggering at Santorini volcano. *Science* **321**, 1178, doi:10.1126/science.1159584 (2008).

53 Singer, B. S., Costa, F., Herrin, J. S., Hildreth, W. & Fierstein, J. The timing of compositionally-zoned magma reservoirs and mafic 'priming' weeks before the 1912 Novarupta-Katmai rhyolite eruption. *Earth and Planetary Science Letters* **451**, 125-137, doi:10.1016/j.epsl.2016.07.015 (2016).

54 Cassidy, M. *et al.* Volatile dilution during magma injections and implications for volcano explosivity. *Geology* **44**, 1027-1030, doi:10.1130/g38411.1 (2016).

55 Pallister, J. S., Hoblitt, R. P., Meeker, G. P., Knight, R. J. & Siems, D. F. in *Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines* (eds C.G. Newhall & R.S. Punonbayan) p. 687-732. University of Washington Press, Seattle, WA (1996).

56 Chertkoff, D. G. & Gardner, J. E. Nature and timing of magma interactions before, during, and after the caldera-forming eruption of Volc n Ceboruco, Mexico. *Contributions to Mineralogy and Petrology* **146**, 715-735, doi:10.1007/s00410-003-05306 (2004).

57 Nakamura, M. Continuous mixing of crystal mush and replenished magma in the ongoing Unzen eruption. *Geology* **23**, doi:10.1130/0091-7613(1995)023<0807:Cmocma>2.3.Co;2 (1995).

58 Venezky, D. Y. & Rutherford, M. J. Pre-eruption conditions and timing of dacite-andesite magma mixing in the 2.2 ka eruption at Mount Rainier. *Journal of Geophysical Research: Solid Earth* **02(B9)**, 20069-20086 (1997).

59 Venezky, D. Y. & Rutherford, M. J. Petrology and Fe-Ti oxide reequilibration of the 1991 Mount Unzen mixed magma. *Journal of Volcanology and Geothermal Research* **89**, 213-230 (1999).

60 Wotzlaw, J.-F. *et al.* Tracking the evolution of large-volume silicic magma reservoirs from assembly to supereruption. *Geology*, doi:10.1130/g34366.1 (2013).

61 Eichelberger, J. C. & Izbekov, P. E. Eruption of andesite triggered by dyke injection: contrasting cases at Karymsky Volcano, Kamchatka and Mt Katmai, Alaska. *Philosophical Transactions of the Royal Society of London* **358**, 1465–1485, doi:http://doi.org/10.1098/rsta.2000.0599 (2000).

62 Bachmann, O. & Bergantz, G. W. Rhyolites and their Source Mushes across Tectonic Settings. *Journal of Petrology* **49**, 2277-2285, doi: 10.1093/Petrology/Egn068 (2008).

63 Bachmann, O., Deering, C. D., Lipman, P. W. & Plummer, C. Building zoned ignimbrites by recycling silicic cumulates: insight from the 1,000 km3 Carpenter Ridge Tuff, CO. *Contributions to Mineralogy and Petrology* **167**, doi:10.1007/s00410-0141025-3 (2014).

64 Bradshaw, R. W., Kent, A. J. R. & Tepley, F. J. Chemical fingerprints and residence times of olivine in the 1959 Kilauea Iki eruption, Hawaii: Insights into picrite formation. *American Mineralogist* **103**, 1812-1826, doi:10.2138/am-2018-6331 (2018).

65 Clague, D. A. & Denlinger, R. P. Role of olivine cumulates in destabilizing the flanks of Hawaiian volcanoes. *Bulletin of Volcanology* **56**, 425–434 (1994).

66 Thomson, A. & Maclennan, J. The Distribution of Olivine Compositions in Icelandic Basalts and Picrites. *Journal of Petrology* **54**, 745-768, doi:10.1093/Petrology/Egs083 (2013).

67 de Silva, S., Salas, G. & Schubring, S. Triggering explosive eruptions—The case for silicic magma recharge at Huaynaputina, southern Peru. *Geology* **36**, doi:10.1130/g24380a.1 (2008).

68 Till, C. B., Vazquez, J. A. & Boyce, J. W. Months between rejuvenation and volcanic eruption at Yellowstone caldera, Wyoming. *Geology* **43**, 695-698, doi:10.1130/g36862.1 (2015).

69 Viccaro, M., Ferlito, C., Cortesogno, L., Cristofolini, R. & Gaggero, L. Magma mixing during the 2001 event at Mt. Etna (Italy): effects on the eruptive dynamics. *Journal of Volcanology and Geothermal Research* **149**, 139–159. (2006).

70 Chamberlain, K. J., Morgan, D. J. & Wilson, C. J. N. Timescales of mixing and mobilisation in the Bishop Tuff magma body: perspectives from diffusion chronometry. *Contributions to Mineralogy and Petrology* **168**, doi:10.1007/s00410-014-1034-2 (2014).

71 Blake, S. Volatile oversaturation during the evolution of silicic magma chambers as an eruption trigger. *Journal of Geophysical Research: Solid Earth* **89**, 8237-8244 (1984).

72 Fowler, S. J. & Spera, F. J. Phase equilibria trigger for explosive volcanic eruptions. *Geophysical Research Letters* **35**, doi:10.1029/2008gl033665 (2008).

73 Fowler, S. J. & Spera, F. J. A Metamodel for Crustal Magmatism: Phase Equilibria of Giant Ignimbrites. *Journal of Petrology* **51**, 1783-1830, doi:10.1093/petrology/egq039

(2010).

74 Sisson, T. W. & Bacon, C. R. Gas-driven filter pressing in magmas. *Geology* **27**, 613-616 (1999).

75 Tramontano, S., Gualda, G. A. R. & Ghiorso, M. S. Internal triggering of volcanic eruptions: tracking overpressure regimes for giant magma bodies. *Earth and Planetary Science Letters* **472**, 142-151, doi:10.1016/j.epsl.2017.05.014 (2017).

76 Andersen, N. L. *et al.* Petrochronologic perspective on rhyolite volcano unrest at Laguna del Maule, Chile. *Earth and Planetary Science Letters* **493**, 57-70, doi:10.1016/j.epsl.2018.03.043 (2018).

77 Berlo, K., Turner, S., Blundy, J., Black, S. & Hawkesworth, C. Tracing pre-eruptive magma degassing using (210Pb/226Ra) disequilibria in the volcanic deposits of the 19801986 eruption of Mount St. Helens. *Earth and Planetary Science Letters* **249**, 337-349 (2006).

78 Blundy, J., Cashman, K., Rust, A. & Witham, F. A case for CO_2-rich arc magmas. *Earth and Planetary Science Letters* **290**, 289-301 (2010).

79 Budd, D. A. *et al.* Magma reservoir dynamics at Toba caldera, Indonesia, recorded by oxygen isotope zoning in quartz. *Science Reports* **7**, 40624, doi:10.1038/srep40624 (2017).

80 Kent, A. J. R. *et al.* Vapor transfer prior to the October 2004 eruption of Mount St. Helens, Washington. *Geology* **35**, doi:10.1130/g22809a.1 (2007).

81 Fisher, R. A. *Statistical Methods for Research Workers 5th ed.* Oliver & Boyd, Edinburgh, Scotland (1934).

82 Hall, M. & Richardson, T. Basic Statistics for Comparing Categorical Data From 2 or More Groups. *Hospital Pediatrics* **6**, 383-385, doi:10.1542/hpeds.2015-0273 (2016).

83 Wasserstein, R. L. & Lazar, N. A. The ASA Statement on p-Values: Context, Process, and Purpose. *The American Statistician* **70**, 129-133, doi:10.1080/00031305.2016.1154108 (2016).

84 Pankhurst, M. J., Morgan, D. J., Thordarson, T. & Loughlin, S. C. Magmatic crystal records in time, space, and process, causatively linked with volcanic unrest. *Earth and Planetary Science Letters* **493**, 231-241, doi:10.1016/j.epsl.2018.04.025 (2018).

85 Rasmussen, D. J. *et al.* When does eruption run-up begin? Multidisciplinary insight from the 1999 eruption of Shishaldin volcano. *Earth and Planetary Science Letters* **486**, 1-14, doi:10.1016/j.epsl.2018.01.001 (2018).

86 Saunders, K., Blundy, J., Dohmen, R. & Cashman, K. Linking petrology and seismology at an active volcano. *Science* **336**, 1023-1027, doi:10.1126/science.1220066 (2012).

Figure Captions

Figure 1. Summary of the observed characteristics of volcanic eruptions initiated by different mechanisms. Each histogram shows results as percent of total within individual categories: (A) Erupted volume, (B) Eruption style, (C) Erupted composition, (D) Eruption initiation timescale.

Figure 2. Comparison of estimated eruption initiation timescales for different eruption initiation mechanisms. The dominant composition of erupted material is shown by the letter next to each eruption, refer to the inset legend.

Figure 3. Schematic representation of how eruption characteristics (eruption style, volume, composition, and estimated eruption initiation timescale) vary with different eruption initiation mechanisms.

Figure 4. Comparison of petrologic eruption initiation timescales vs. volcano monitoring run-up timescales for eruptions in our literature compilation. Each eruption is represented as the range of relevant timescales recorded by both approaches, color coded by the eruption initiation mechanism. As an initiation mechanism, mafic rejuvenation has the most data available for this comparison, as well the best agreement between the two timescales, suggesting the monitoring signals are more likely recording the same event(s) as the petrologic signals. The limited data for mafic recharge suggests the monitoring signals records events prior to the petrologic signals. There is insufficient data on eruptions initiated by either felsic rejuvenation or volatile accumulation to make a similar assessment.

Figures

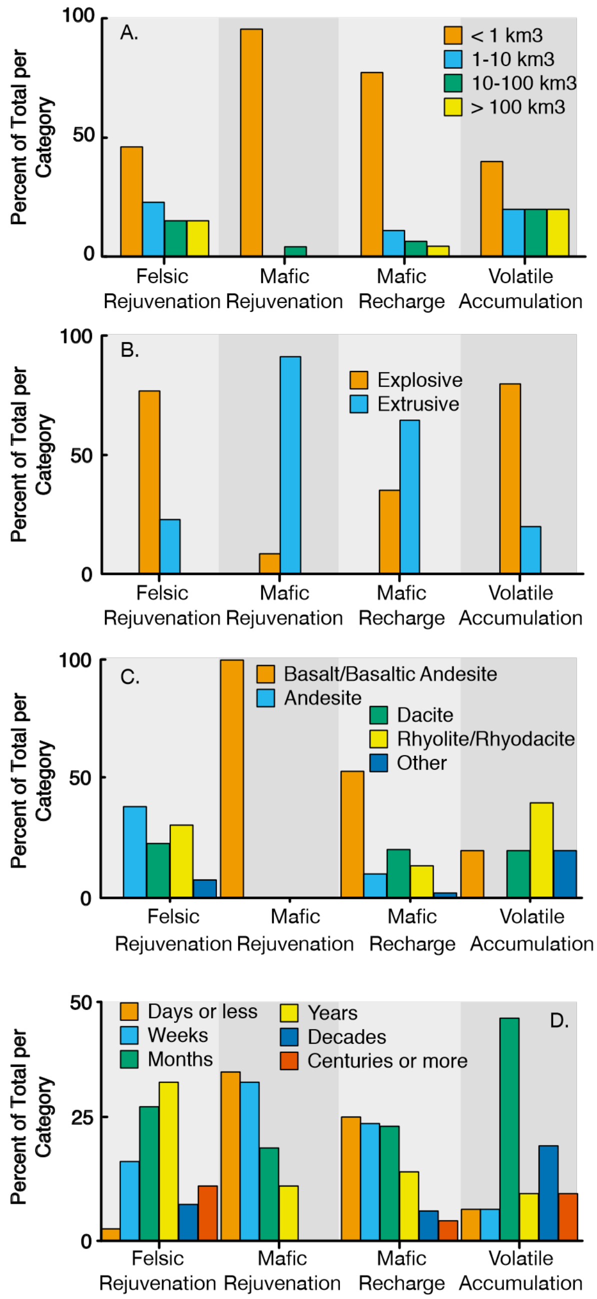

Figure 1. Summary of the observed characteristics of volcanic eruptions initiated by different mechanisms. Each histogram shows results as percent of total within individual categories: (A) Erupted volume, (B) Eruption style, (C) Erupted composition, (D) Eruption initiation timescale.

Days Weeks Months Years Decades
Centuries or less or greater

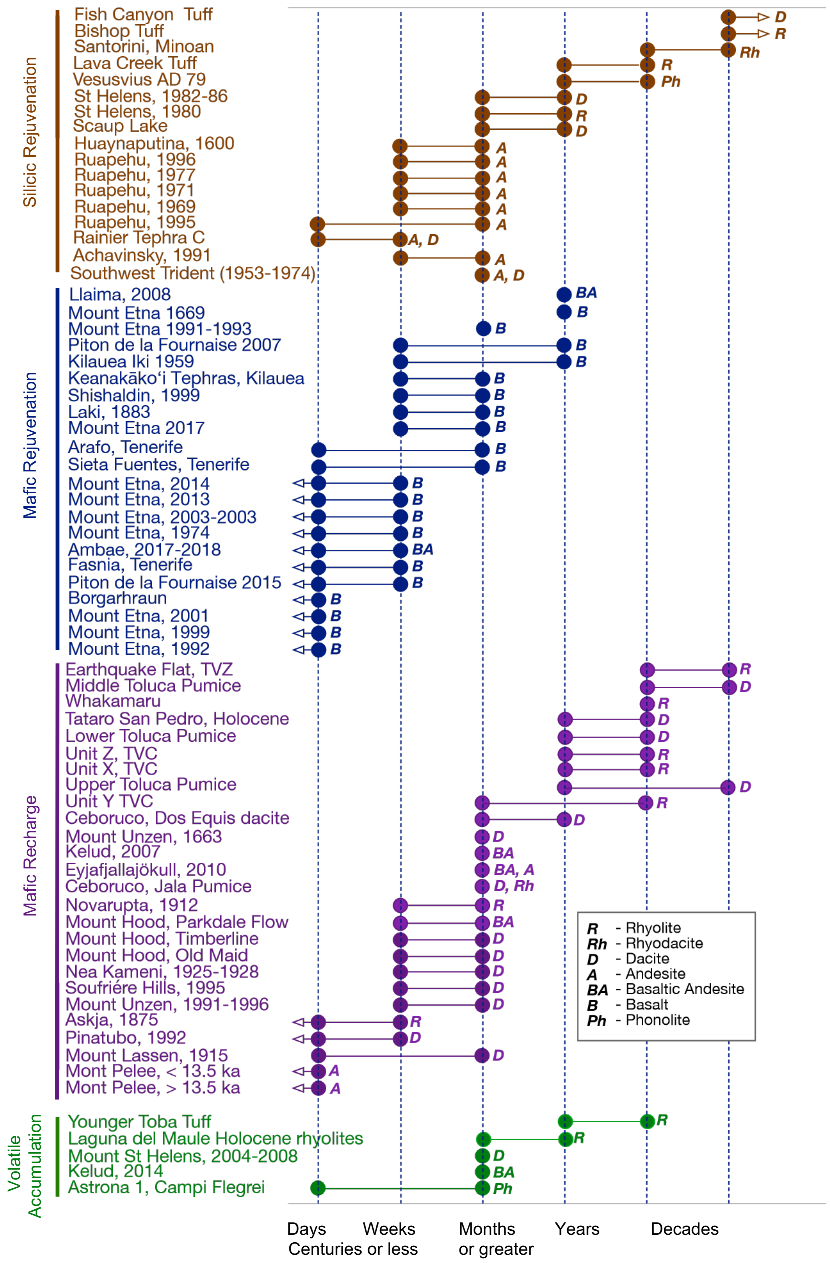

Figure 2. Comparison of estimated eruption initiation timescales for different eruption initiation mechanisms. The letter next to each eruption refers to the dominant composition of erupted material (see legend).

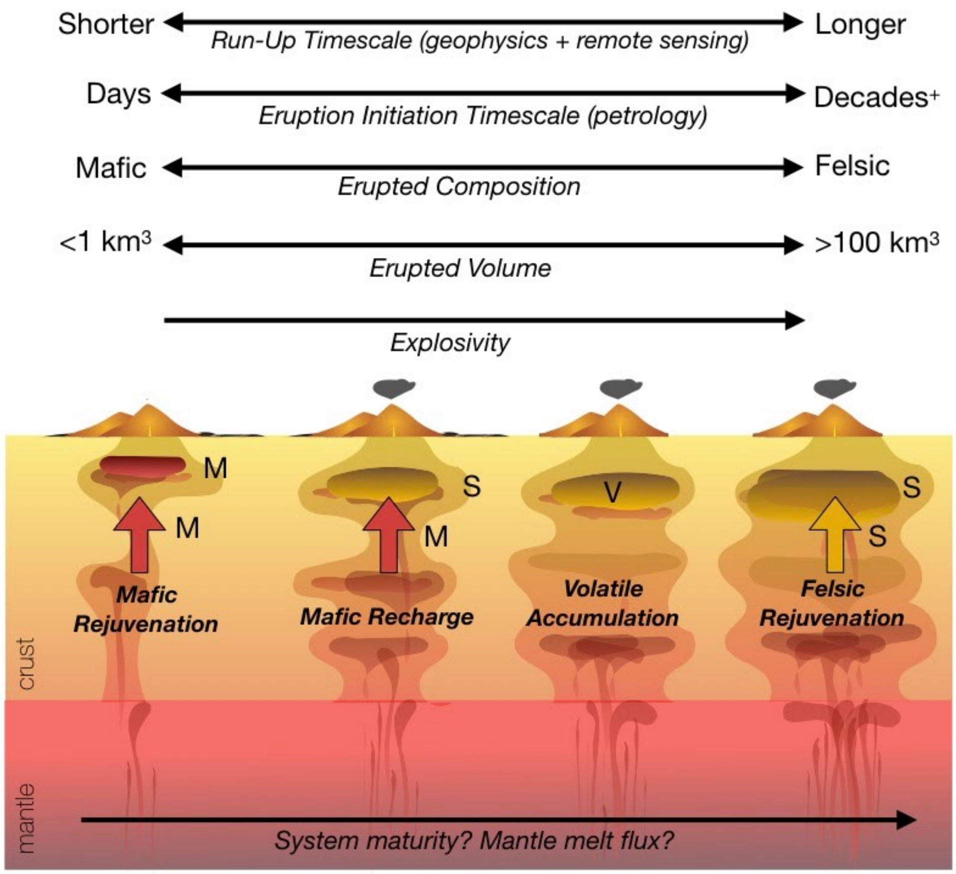

Figure 3. Schematic representation of how eruption characteristics (eruption style, volume, composition, and estimated eruption initiation timescale) vary with different eruption initiation mechanisms.

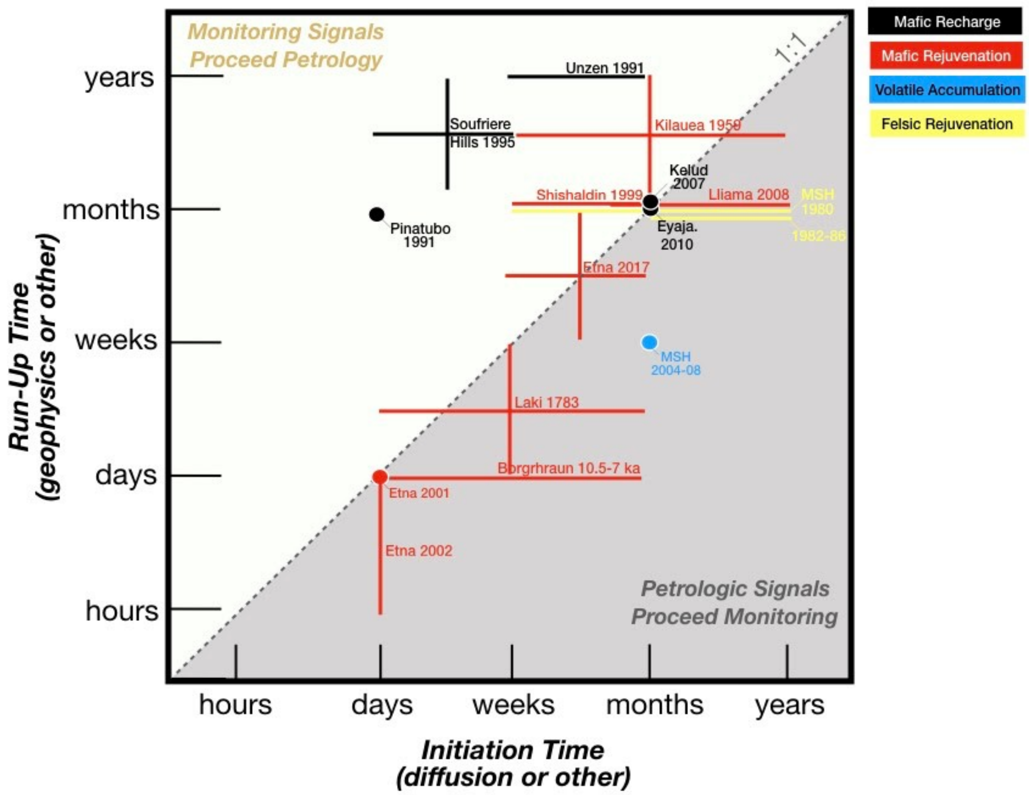

Figure 4. Comparison of petrologic eruption initiation timescales vs. volcano monitoring run-up timescales for eruptions in our literature compilation. Each eruption is represented as the range of relevant timescales recorded by both approaches, color coded by the eruption initiation mechanism. As an initiation mechanism, mafic rejuvenation has the most data available for this comparison, as well the best agreement between the two timescales, suggesting the monitoring signals are more likely recording the same event(s) as the petrologic signals. The limited data for mafic recharge suggests the monitoring signals records events prior to the petrologic signals. There is insufficient data on eruptions initiated by either felsic rejuvenation or volatile accumulation to make a similar assessment.

Supplementary Methods

Statistical Comparison of Eruption Initiation Mechanisms

The details of our compilation and sources are shown in Supplemental Data Table 1. To maximize the amount of available data our data includes both single historic eruptions, as well as prehistoric eruptive sequences. For each eruption in our compilation, we have also recorded the dominant erupted composition(s), dominant eruption style, erupted volume, and estimated timescale for eruption initiation using published information. Where multiple compositions or eruptions styles were observed within a single eruption, we selected the most volumetrically dominant. All variables are recorded as categorical variables using the rubric outlined in Supplemental Data Table 2. Some of the variables in our data compilation are already categorical (eruption style, rock type), and we have elected to treat other variables such as erupted volume and initiation timescale as categorical, even where they are nominally continuous, as this minimizes the effects of the large uncertainties that are often apparent in these quantities. For the timescale, there was still some overlap between some categories, so each study was assigned the six points, and these were assigned to relevant categories (i.e., a timing estimate that ranged from weeks to years was given two points in each of the 'years', 'months' and 'weeks' categories). Points were then summed for each category and expressed in percent of total.

To investigate whether there are significant differences in timescales, eruption type, and erupted volume between different initiation mechanisms we have investigated our categorical data using the two tailed Fisher Exact Test, a statistical significance test used for the analysis of categorical data in contingency tables (Fisher, 1922, Hall and Richardson, 2016). This test is valid over a range of sample sizes and is preferred over the χ^2 test where, as in our case, individual categories may be small ($n < 5$-10). To do this we reassigned our data for all parameters into two “dichotomized” categories, selected to minimize overlap between categories for individual studies (Supplemental Data Table 2). For the very small number of cases where there was still some overlap between these simplified categories, we placed the individual study into the most likely category based on available data.

We use the Fisher Exact test by testing a series of null hypotheses (H_o) that there are no differences between different eruption mechanisms in terms of individual categories. For example, for erupted volumes the null hypothesis states that there is no difference between two eruption initiation mechanisms in terms of the proportions of eruptions that are ≤ 1 km^3 and > 1 km^3:

$$\pi_{\text{Mafic Recharge}} = \pi_{\text{Felsic Rejuvenation}} \qquad (1)$$

and an alternate hypothesis (H_1) states:

$$\pi_{\text{Mafic Recharge}} \neq \pi_{\text{Felsic Rejuvenation}} \qquad (2)$$

Where π represents the proportion of eruptions initiated by mafic recharge and felsic rejuvenation that have volume < 1 km^3. We then determine from our observed data if we have enough evidence to reject the null hypothesis at a reasonable level of significance.

We have implemented this approach using both 2 x 4 contingency tables to compare all identified eruption initiation mechanisms, and have also conducted further focused hypothesis testing between pairs of eruption mechanisms for a specific characteristic using 2 x 2 contingency tables (Supplemental Data Tables 4-7). Calculations for 2 x 2 and 2 x 4 contingency tables were done using the ‘fishertest’ routine and ‘MyFisher24’ function (Cardillo, 2020) respectively in MATLAB™. Results are reported in terms of P values in Supplemental Data Tables 4-7, where P represents the probability of getting the observed distribution, assuming that the null hypothesis is correct. In accordance with recommended usage (Wasserstein and Lazar,

2016) we do not use $P < 0.05$ as a rigid criterion to reject the null hypothesis, but as a guide to suggest where important relationships may exist. Where comparisons show P values that are relatively low, but not less than 0.05, these may also be further tested with more data.

Parameters	**Categories**					
Volume	< 1 km^3	1 - 10 km^3	10 - 100 km^3	> 100 km^3		
Dichotomized Volume	< 1 km^3	≥ 1 km^3				
Timescale	Days or less	Weeks	Months	Years	Decades	Centuries or greater
Dichotomized Timescale	Months or less	Years or greater				
Eruption Type	Extrusive	Explosive				
Composition	Basalt	Andesite	Dacite	Rhyodacite and Rhyolite	Other	
Dichotomized Composition	Mafic (Basalt + Basaltic Andesite)	Silicic (Andesite, Dacite, Rhyodacite, Rhyolite)				

Supplemental Data Table 2. Selected categorical variables for recorded parameters.

Comparison	**P**
Eruption Style	< 0.001
Erupted Volume	0.003
Initiation Timescale	0.050
Erupted Composition	<0.001

Supplemental Data Table 3. Results of Fisher Exact test of the 4 x 2 contingency table. P represents the probability of generating the observed distribution of a given characteristic between different eruption initiation mechanisms if the null hypothesis is correct.

Eruption Initiation Timescale

	Felsic Rejuvenation	Mafic Rejuvenation	Mafic Recharge
Mafic Rejuvenation	0.026		
Mafic Recharge	1.000	0.024	
Volatile Accumulation	1.000	0.144	1.000

Supplemental Data Table 4. Summary of P values determined for the 2 x 2 contingency table for eruption initiation timescale (≤ months vs. ≥ years). P represents the probability of generating the observed distribution in each pairwise comparison if the null hypothesis (that no difference in proportions between each pair of eruption initiation mechanisms) is correct. Grey highlights comparisons where P < 0.05.

Erupted Volume

	Felsic Rejuvenation	Mafic Rejuvenation	Mafic Recharge
Mafic Rejuvenation	0.005		
Mafic Recharge	0.753	0.006	
Volatile Accumulation	1.000	0.013	0.625

Supplemental Data Table 5. Summary of P values determined for 2 x 2 contingency table for erupted volume (< 1km^3 vs. ≥ 1km^3). P represents the probability of generating the observed distribution in each pairwise comparison if the null hypothesis (that no difference in proportions between each pair of eruption initiation mechanisms) is true. Grey highlights comparisons where P < 0.05.

Eruption Style

	Felsic Rejuvenation	Mafic Rejuvenation	Mafic Recharge
Mafic Rejuvenation	<0.001		
Mafic Recharge	0.347	0.002	
Volatile Accumulation	1.000	0.004	0.368

Supplemental Data Table 6. Summary of P values determined for 2 x 2 contingency table for eruption style (extrusive vs. explosive). P represents the probability that the observed data supports accepting the null hypothesis that no difference in eruption type exists between the pairs of eruption initiation mechanisms shown. Grey highlights comparisons where P < 0.05

Erupted Composition

	Felsic Rejuvenation	Mafic Rejuvenation	Mafic Recharge
Mafic Rejuvenation	<0.001		
Mafic Recharge	1.000	<0.001	
Volatile Accumulation	0.200	0.002	0.133

Supplemental Data Table 7. Summary of P values determined for 2 x 2 contingency tables for erupted composition (mafic vs. silicic). P represents the probability that the observed data supports accepting the null hypothesis that no difference in erupted composition exists between the pairs of eruption initiation mechanisms shown. Grey highlights comparisons where P < 0.05

Supplemental References

Albert, H., Costa, F. & Martí, J. Timing of Magmatic Processes and Unrest Associated with Mafic Historical Monogenetic Eruptions in Tenerife Island. Journal of Petrology 56, 1945-1966, doi:10.1093/petrology/egv058 (2015).

Andersen, N. L., Singer, B. S. & Coble, M. A. Repeated Rhyolite Eruption From Heterogeneous Hot Zones Embedded Within a Cool, Shallow Magma Reservoir. Journal of Geophysical Research: Solid Earth 124, 2582-2600, doi:10.1029/2018jb016418 (2019).

Barker, S. J., Wilson, C. J. N., Morgan, D. J. & Rowland, J. V. Rapid priming, accumulation, and recharge of magma driving recent eruptions at a hyperactive caldera volcano. Geology 44, 323-326, doi:10.1130/g37382.1 (2016).

Browne, B. L. et al. Generation of porphyritic and equigranular mafic enclaves during magma recharge events at Unzen volcano, Japan. Journal of Petrology 47, 301-328 (2006).

Budd, D. A. et al. Magma reservoir dynamics at Toba caldera, Indonesia, recorded by oxygen isotope zoning in quartz. Scientific Reports 7, 40624, doi:10.1038/srep40624 (2017).

Cardillo, G. MyFisher24 v. Retrieved September 27, 2020. (GitHub, 2020).

Cassidy, M. et al. Volatile dilution during magma injections and implications for volcano explosivity. Geology 44, 1027-1030, doi:10.1130/g38411.1 (2016).

Chamberlain, K. J., Morgan, D. J. & Wilson, C. J. N. Timescales of mixing and mobilisation in the Bishop Tuff magma body: perspectives from diffusion chronometry. Contributions to Mineralogy and Petrology 168, doi:10.1007/s00410-014-1034-2 (2014).

Chertkoff, D. G. & Gardner, J. E. Nature and timing of magma interactions before, during, and after the caldera-forming eruption of Volc□n Ceboruco, Mexico. Contributions to Mineralogy and Petrology 146, 715-735, doi:10.1007/s00410-003-0530-6 (2004).

Conway, C. E., Chamberlain, K. J., Harigane, Y., Morgan, D. J. & Wilson, C. J. N. Rapid assembly of high-Mg andesites and dacites by magma mixing at a continental arc stratovolcano. Geology 48, 1033-1037, doi:10.1130/g47614.1 (2020).

Coombs, M. L., Rutherford, M. J. & Eichelberger, J. C. Magma storage and mixing conditions for the 1953-1974 eruptions of Southwest Trident volcano, Katmai National Park, Alaska. Contributions to Mineralogy and Petrology 140, 99-118 (2000).

Costa, F. & Chakraborty, S. Decadal time gaps between mafic intrusion and silicic eruption obtained from chemical zoning patterns in olivine. Earth and Planetary Science Letters 227, 517-530, doi:10.1016/j.epsl.2004.08.011 (2004).

de Silva, S., Salas, G. & Schubring, S. Triggering explosive eruptions—The case for silicic magma recharge at Huaynaputina, southern Peru. Geology 36, doi:10.1130/g24380a.1 (2008).

Druitt, T. H., Costa, F., Deloule, E., Dungan, M. & Scaillet, B. Decadal to monthly timescales of magma transfer and reservoir growth at a caldera volcano. Nature 482, 77-80, doi:10.1038/nature10706 (2012).

Fisher, R. A. Statistical Methods for Research Workers 5th ed. (Oliver & Boyd, 1934).

Hall, M. & Richardson, T. Basic Statistics for Comparing Categorical Data From 2 or More Groups. Hospital Pediatrics 6, 383-385, doi:10.1542/hpeds.2015-0273 (2016).

Hartley, M. E., Morgan, D. J., Maclennan, J., Edmonds, M. & Thordarson, T. Tracking timescales of short-term precursors to large basaltic fissure eruptions through Fe–Mg diffusion in olivine. Earth and Planetary Science Letters 439, 58-70, doi:10.1016/j.epsl.2016.01.018 (2016).

Kahl, M., Chakraborty, S., Costa, F. & Pompilio, M. Dynamic plumbing system beneath volcanoes revealed by kinetic modeling, and the connection to monitoring data: An example from Mt. Etna. Earth and Planetary Science Letters 308, 11-22, doi:10.1016/j.epsl.2011.05.008 (2011).

Kahl, M., Viccaro, M., Ubide, T., Morgan, D. J. & Dingwell, D. B. A Branched Magma Feeder System during the 1669 Eruption of Mt Etna: Evidence from a Time-integrated Study of Zoned Olivine Phenocryst Populations. Journal of Petrology 58, 443-472, doi:10.1093/petrology/egx022 (2017).

Kent, A. J. R., Darr, C., Koleszar, A. M., Salisbury, M. J. & Cooper, K. M. Preferential eruption of andesitic magmas through recharge filtering. Nature Geosciences 3, 631-636, doi:10.1038/Ngeo924 (2010).

Kilgour, G., Blundy, J., Cashman, K. & Mader, H. M. Small volume andesite magmas and melt–mush interactions at Ruapehu, New Zealand: evidence from melt inclusions. Contributions to Mineralogy and Petrology 166, 371-392, doi:10.1007/s00410-013-0880-7 (2013).

Kilgour, G. N. et al. Timescales of magmatic processes at Ruapehu volcano from diffusion chronometry and their comparison to monitoring data. Journal of Volcanology and Geothermal Research 288, 62-75, doi:10.1016/j.jvolgeores.2014.09.010 (2014).

Lynn, K. J., Garcia, M. O., Shea, T., Costa, F. & Swanson, D. A. Timescales of mixing and storage for Keanakāko‘i Tephra magmas (1500–1820 C.E.), Kīlauea Volcano, Hawai‘i. Contributions to Mineralogy and Petrology 172, doi:10.1007/s00410-017-1395-4 (2017).

Magee, R., Ubide, T. & Kahl, M. The Lead-up to Mount Etna’s Most Destructive Historic Eruption (1669). Cryptic Recharge Recorded in Clinopyroxene. Journal of Petrology 61, doi:10.1093/petrology/egaa025 (2020).

Martel, C. Eruption Dynamics Inferred from Microlite Crystallization Experiments: Application to Plinian and Dome-forming Eruptions of Mt. Pelee (Martinique, Lesser Antilles). Journal of Petrology 53, 699-725, doi:10.1093/petrology/egr076 (2012).

Martin, V. M. et al. Bang! Month-scale eruption triggering at Santorini volcano. Science 321, 1178-1178 (2008).

Matthews, N. E., Huber, C., Pyle, D. M. & Smith, V. C. Timescales of Magma Recharge and Reactivation of Large Silicic Systems from Ti Diffusion in Quartz. Journal of Petrology 53, 1385-1416, doi:10.1093/petrology/egs020 (2012).

Morgan, D. J. et al. Magma chamber recharge at Vesuvius in the century prior to the eruption of AD 79. Geology 34, 845-848 (2006).

Moussallam, Y. et al. Fast ascent rate during the 2017–2018 Plinian eruption of Ambae (Aoba) volcano: a petrological investigation. Contributions to Mineralogy and Petrology 174, doi:10.1007/s00410-019-1625-z (2019).

Mutch, E. J. F., Maclennan, J., Shorttle, O., Edmonds, M. & Rudge, J. F. Rapid transcrustal magma movement under Iceland. Nature Geosciences 12, 569-574, doi:10.1038/s41561-019-0376-9 (2019).

Myers, M. L. et al. Replenishment of volatile-rich mafic magma into a degassed chamber drives mixing and eruption of Tungurahua volcano. Bulletin of Volcanology 76, doi:10.1007/s00445-014-0872-0 (2014).

Nakamura, M. Continuous Mixing of Crystal Mush and Replenished Magma in the Ongoing Unzen Eruption. Geology 23, 807-810 (1995).

Pallister, J. S., Hoblitt, R. P. & Reyes, A. G. A Basalt Trigger for the 1991 Eruptions of Pinatubo Volcano. Nature 356, 426-428 (1992).

Ruth, D. C. S. et al. Crystal and melt inclusion timescales reveal the evolution of magma migration before eruption. Nature Communication 9, 2657, doi:10.1038/s41467-018-05086-8 (2018).

Salisbury, M. J., Bohrson, W. A., Clynne, M. A., Ramos, F. C. & Hoskin, P. Origin of the 1915 Lassen Peak eruption by magma mixing: Evidence for formation of chemically distinct plagioclase populations from crystal size distributions and in situ chemical data. Journal of Petrology 49, 1755-1780 (2008).

Sparks, S. R. J., Sigurdsson, H. & Wilson, L. Magma mixing - mechanism for triggering acid explosive eruptions. Nature 267, 315-318 (1977).

Singer, B. S., Costa, F., Herrin, J. S., Hildreth, W. & Fierstein, J. The timing of compositionally-zoned magma reservoirs and mafic 'priming' weeks before the 1912 Novarupta-Katmai rhyolite eruption. Earth and Planetary Science Letters 451, 125-137, doi:10.1016/j.epsl.2016.07.015 (2016).

Rasmussen, D. J. et al. When does eruption run-up begin? Multidisciplinary insight from the 1999 eruption of Shishaldin volcano. Earth and Planetary Science Letters 486, 1-14, doi:10.1016/j.epsl.2018.01.001 (2018).

Rae, A. S. P. et al. Time scales of magma transport and mixing at Kīlauea Volcano, Hawai'i. Geology 44, 463-466, doi:10.1130/g37800.1 (2016).

Saunders, K., Blundy, J., Dohmen, R. & Cashman, K. Linking petrology and seismology at an active volcano. Science 336, 1023-1027, doi:10.1126/science.1220066 (2012).

Shamloo, H. I. & Till, C. B. Decadal transition from quiescence to supereruption: petrologic investigation of the Lava Creek Tuff, Yellowstone Caldera, WY. Contributions to Mineralogy and Petrology 174, doi:10.1007/s00410-019-1570-x (2019).

Stock, M. J., Humphreys, M. C. S., Smith, V. C., Isaia, R. & Pyle, D. M. Late-stage volatile saturation as a potential trigger for explosive volcanic eruptions. Nature Geosciences 9, 249-254, doi:10.1038/ngeo2639 (2016).

Sundermeyer, C., Di Muro, A., Techmer, K., Gordeychik, B. & Wörner, G. Heritage and residence of olivines based on Fe-Mg diffusion from the August-November 2015 eruption at Piton de la Fournaise, La Réunion. Geophysical Research Abstracts 20, 6194 (2018).

Till, C. B., Vazquez, J. A. & Boyce, J. W. Months between rejuvenation and volcanic eruption at Yellowstone caldera, Wyoming. Geology 43, 695-698, doi:10.1130/g36862.1 (2015).

Ubide, T. & Kamber, B. S. Volcanic crystals as time capsules of eruption history. Nature Communication 9, 326, doi:10.1038/s41467-017-02274-w (2018).

Venezky, D. Y. & Rutherford, M. J. Preeruption conditions and timing of dacite-andesite magma mixing in the 2.2 ka eruption at Mount Rainier. Journal of Geophysical Research 102, 20069-20086 (1997).

Venezky, D. Y. & Rutherford, M. J. Petrology and Fe-Ti oxide reequilibration of the 1991 Mount Unzen mixed magma. Journal of Volcanology and Geothermal Research 89, 213-230 (1999).

Viccaro, M., Giuffrida, M., Nicotra, E. & Ozerov, A. Y. Magma storage, ascent and recharge history prior to the 1991 eruption at Avachinsky Volcano, Kamchatka, Russia: Inferences on the plumbing system geometry. Lithos 140, 11-24, doi: 10.1016/J.Lithos.2012.01.019 (2012).

Viccaro, M. et al. Violent paroxysmal activity drives self-feeding magma replenishment at Mt. Etna. Scientific Reports 9, 6717, doi:10.1038/s41598-019-43211-9 (2019).

Wasserstein, R. L. & Lazar, N. A. The ASA Statement on p-Values: Context, Process, and Purpose. The American Statistician 70, 129-133, doi:10.1080/00031305.2016.1154108 (2016).

Weber, G., Arce, J. L., Ulianov, A. & Caricchi, L. A Recurrent Magmatic Pattern on Observable Timescales Prior to Plinian Eruptions From Nevado de Toluca (Mexico). Journal of Geophysical Research: Solid Earth 124, 10999-11021, doi:10.1029/2019jb017640 (2019).

Wotzlaw, J.-F. et al. Tracking the evolution of large-volume silicic magma reservoirs from assembly to supereruption. Geology 41, 867-870, doi:10.1130/g34366.1 (2013).