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VOLCANICA

Start me up: The relationship between volcanic eruption characteristics and eruption initiation mechanisms

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ABSTRACT

Understanding the processes that initiate volcanic eruptions after periods of quiescence are of paramount importance to interpreting volcano monitoring signals and mitigating volcanic hazards. However, studies of eruption initiation mechanisms are rarely systematically applied to high-risk volcanoes. Studies of erupted materials provide important insight into eruption initiation, as they provide direct insight into the physical and chemical changes that occur in magma reservoirs prior to eruptions. Petrologic and geochemical studies 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. A compilation and analysis of literature data shows that petrological evidence identifies four distinct processes of eruption initiation: mafic recharge (intrusion of mafic magma into a felsic magma storage region), mafic rejuvenation (intrusion of mafic magma into a mafic magma storage region), felsic rejuvenation (intrusion of felsic magma into a felsic magma storage region) and volatile accumulation. Other mechanisms such as roof collapse or increasing buoyant forces may also initiate eruptions but leave little petrological record in erupted material. There are also statistical differences in the composition, volume, style, and timescales between eruptions initiated by these different mechanisms, and these suggest that increasing eruption volumes, longer initiation timescales, more felsic compositions, and more explosive eruption styles occur going from mafic rejuvenation to mafic recharge, felsic rejuvenation and volatile accumulation. Knowledge of the processes that initiate eruptions at a given volcanic system may thus have significant predictive power.

KEYWORDS: Eruption intiation; Mafic recharge; Volcano.

1 INTRODUCTION

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 [Moran et al. 2008; Auker et al. 2013; Barclay et al. 2019; Poland and Anderson 2020]. 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 [Moran et al. 2008]. 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 [Luhr et al. 1984; Pallister et al. 1992; Biggs et al. 2014]. 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 [National Academies of Sciences, Engineering, and Medicine 2017; Poland and Anderson 2020], 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 [Deligne et al. 2010; Passarelli and Brodsky 2012; Pritchard et al. 2018; Rougier et al. 2018]. Erupted magmas may themselves also be stored in the crust for long periods—thousands of years or more—prior to eruption [Claiborne et al. 2010; Cooper and Kent 2014; Cooper 2019]. 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 [National Academies of Sciences, Engineering, and Medicine 2017], but has seen surprisingly little systematic study. As an example, a monolithic compendium of volcano knowledge, the Encyclopedia of Volcanoes (2nd Ed.) [Sigurdsson 2015] 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 [Condit and Connor 1996; Poland and

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Anderson 2020], but it is also rare that this is linked to systematic petrological and other studies that reveal the processes that initiated past eruptions [Connor et al. 2003].

The initiation of an 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 [Pinel and Jaupart 2000; Eichelberger et al. 2006; Degruyter and Huber 2014]. In detail, 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 [Gregg et al. 2013; Degruyter and Huber 2014; Albright et al. 2019]. Thus eruption initiation is best considered within a framework of the complex transcrustal magma systems that underlie volcanoes [Cashman et al. 2017], and where much of the stored magma may exist as a crystal-rich mush [Bachmann and Bergantz 2008; Cooper and Kent 2014; Edmonds et al. 2016; Bergantz et al. 2017; Cashman et al. 2017; Rubin et al. 2017].

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 [Costa et al. 2020]. Despite this importance, systematic studies of the processes that initiate eruption in a given volcanic system over time are less common [Kent et al. 2010; Shamloo and Till 2019; Mangler et al. 2022].

1.1 Nomenclature and definitions

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 have they shown previous indication of eruption. If the volcano in question is being monitored, then this state prior to eruption initiation would also include seismicity and other monitoring signals being 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 (USA) provides an example of this usage. The trigger for the eruption was a magnitude 5.1 earthquake and landslide. However, eruption initiation occurred several months earlier when magma started to ascend from a crustal reservoir to form a shallow cryptodome after many decades of quiescence.

2 MECHANISMS OF VOLCANIC ERUPTION INITIATION

Although systematic studies of eruption initiation are relatively 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 we believe it is possible to do so from reported data and observations. Any errors in these interpretations are our own, and in the future, with greater emphasis on eruption initiation, it may be possible to refine our classification. In total, we have 80 eruptive events in our compilation representing over 40 different volcanoes. Volcanoes in the compilation come from a range of tectonic settings but are mostly commonly from subduction and intraplate environments.

We also focus largely on volcanoes and eruptions that represent mobilization of magma after significant quiescence, as fitting our definition of eruption initiation above. However, we have also included data in our compilation for some so-called open-conduit volcanic systems such as Stromboli and Mount Etna (Italy). These volcanoes exhibit long term eruptive activity with occasional changes in eruptive style due to paroxysmal events [e.g. Andronico et al. 2021]. Although these systems may not strictly fit the definition of eruption initiation above, these events typically reflect major changes in eruptive activity, which is otherwise relatively stable, largely due to arrival of new batches of magma arriving in the shallow magma storage system.

On the basis of our compilation, we recognize four different eruption initiation mechanisms, three relating to intrusion of new magma and one to accumulation of volatile phases. These are discussed in greater detail below. 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 [Gregg et al. 2012] and build-up of buoyancy forces [Caricchi et al. 2014; Malfait et al. 2014], as well as far-field forcing related to large earthquakes [Cabaniss et al. 2018; Hamling and Kilgour 2020]. 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.

2.1 Mafic recharge

Eruption initiation by addition of mafic magma to a more felsic magma reservoir is identified in 41 % 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 felsic magma (andesite to rhyolite) [Eichelberger 1978]. 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 felsic magmas, disequilibrium mineral assemblages (e.g. quartz and olivine), multiple mafic and felsic liquid components in glasses or melt inclusions, and at the field scale hybridized magmas, enclaves, banded pumice, compositionally zoned deposits, and related phenomena [Sparks et al. 1977; Eichelberger 1978; Huppert et al. 1982; Murphy et al. 1998; Tepley III et al. 1999; Eichelberger et al. 2006; Ruprecht and Wörner 2007; Ruprecht et al. 2008; Salisbury et al. 2008; Humphreys et al. 2009; Kent et al. 2010]. 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 [Koleszar et al. 2012; Matthews et al. 2012], often associated with extensive mineral dissolution or reaction rims [Eichelberger 1978]. The presence of microlites or microphenocrysts with mafic signatures within less mafic magmas also suggests magma mixing immediately prior to eruption [Salisbury et al. 2008; Humphreys et al. 2009; Kent et al. 2010; Martel 2012].

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 [Martin et al. 2008; Kent et al. 2010; Matthews et al. 2012; Barker et al. 2016; Singer et al. 2016; Costa et al. 2020]. 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 [Pallister et al. 1996; Cassidy et al. 2016], re-equilibration of Fe-Ti oxides, and estimates of mineral growth and dissolution and melt inclusion preservation [Nakamura 1995; Venezky and Rutherford 1997; 1999; Chertkoff and Gardner 2004; Salisbury et al. 2008; Martel 2012; Wotzlaw et al. 2013].

2.2 Rejuvenation

The majority (53 %) 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 (32 % of the compilation) and felsic rejuvenation (21 %). 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 to be rare [Eichelberger and Izbekov 2000].

Relative 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 felsic 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 [Ruprecht and Wörner 2007; Bachmann and Bergantz 2008; Bachmann et al. 2014; Shamloo and Till 2019], or contain glomerocrysts, strained crystals, and other evidence for disaggregation of crystal-rich cumulates [Clague and Denlinger 1994; Thomson and Maclennan 2013; Bradshaw et al. 2018]. 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 [Viccaro et al. 2006; de Silva et al. 2008; Till et al. 2015; Shamloo and Till 2019].

Mafic rejuvenation is the dominant mechanism in large shield volcanoes in extensional and arc settings, and felsic rejuvenation appears important for many felsic eruptions, including some of the largest known caldera eruptions [Chamberlain et al. 2014; Shamloo and Till 2019], 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 [Costa et al. 2020]. In some cases, growth rates of mineral rims can also be used [Chamberlain et al. 2014; Shamloo and Till 2019].

2.3 Vapor saturation and exsolution

This mechanism has long been considered important [Blake 1984; Sisson and Bacon 1999; Fowler and Spera 2008; 2010; Tramontano et al. 2017] but is identified in only 6 % 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 felsic magma bodies [Fowler and Spera 2008; 2010; Tramontano et al. 2017]. 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") [Sisson and Bacon 1999]. 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 [Fowler and Spera 2008; 2010; Tramontano et al. 2017]. 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 temperature 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 [Berlo et al. 2006; Kent et al. 2007; Blundy et al. 2010; Budd et al. 2017; Andersen et al. 2018]. 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, and from re-equilibration (or lack thereof) of melt inclusions [Kent et al. 2007; Budd et al. 2017].

3 METHODS

3.1 Statistical comparison of eruption initiation mechanisms

Our compilation and sources can be found in Supplementary Material 1 (Table S1). To maximize the amount of available data, our data include 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 Table 1. 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 six points per eruption, and these were distributed among the 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 (Table 1). For the 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_0) 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 $\leq 1\,\mathrm{km}^3$ and $> 1\,\mathrm{km}^3$:

$$\pi_{MaficRecharge} = \pi_{FelsicRejuvenation} \tag{1}$$

and an alternate hypothesis (H_1) is that

$$\pi_{MaficRecharge} \neq \pi_{FelsicRejuvenation} \tag{2}$$

Where π represents the proportion of eruptions initiated by mafic recharge and felsic rejuvenation that have volume $< 1\,\mathrm{km}^3$. 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 2×4 contingency tables (Table 2) to compare a given eruption characteristic (e.g. erupted volume) between all four identified eruption initiation mechanisms, and have also conducted further focused hypothesis testing between pairs of eruption mechanisms for a specific eruption characteristic using 2×2 contingency tables (Table 3, 4, 5, and 6). Calculations for 2×2 contingency tables were done using the `fishertest` routine in `MATLAB`™. Calculations for 2×4 contingency tables used the `MyFisher24` function in `MATLAB`™ [Cardillo 2020] and a `JavaScript` calculator[*], which produce comparable results. Results are reported in terms of P values in Table 3–6, 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.

4 COMPARISON BETWEEN ERUPTION INITIATION MECHANISMS

Our compilation allows us to compare some key eruption characteristics—the eruption style, erupted volume, erupted

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[*] available at `http://vassarstats.net/fisher2x4.html`

Table 1: Selected categorical variables for recorded parameters.

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 style	Extrusive	Explosive				
Composition	Basalt	Andesite	Dacite	Rhyodacite and Rhyolite	Other	
Dichotomized composition	Mafic (Basalt + Basaltic Andesite)	Felsic (Andesite, Dacite, Rhyodacite, Rhyolite)				

Table 2: Results of Fisher Exact test of the 4 × 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.

Comparison	P
Eruption style	0.006
Erupted volume	0.098
Initiation timescale	<0.001
Erupted composition	<0.001

composition, and eruption initiation timescale—between eruptions initiated by the different mechanisms we identify above. These results, summarized in Figure 1, Figure 2, and Figure 3, suggest there are systematic differences in these eruption characteristics between eruptions initiated by the different eruption initiation mechanisms we identify. Although in some cases these differences are obvious, such as the compositional differences between mafic rejuvenation and felsic rejuvenation, for other parameters these systematic variations suggest there are consistent differences between eruptions initiated by different mechanisms. The statistical comparison of each characteristic across the four different initiation mechanisms using a 4 × 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. In addition, the 2 × 2 contingency tables show low P values for the following:

1. Eruption timescale (mafic rejuvenation vs. felsic rejuvenation; mafic rejuvenation vs. mafic recharge);
2. Erupted volume (mafic rejuvenation vs. mafic recharge);
3. Eruption style (mafic rejuvenation vs. felsic rejuvenation; mafic rejuvenation vs. mafic recharge; mafic rejuvenation vs. volatile accumulation);
4. Erupted composition (mafic rejuvenation vs. felsic rejuvenation; mafic rejuvenation vs. mafic recharge; mafic rejuvenation vs. volatile accumulation).

Some other comparisons also have relatively low P values (< 0.4): mafic rejuvenation vs. volatile accumulation for eruption timescale; felsic rejuvenation vs mafic recharge and volatile accumulation vs mafic recharge for eruption style; and felsic rejuvenation vs. volatile accumulation and mafic recharge vs. volatile accumulation 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 ($n = 5$).

Overall, this simple analysis suggests that specific differences in eruption style, volume, composition, and timing are associated with differences in eruption initiation mechanisms that can be identified from petrological observations. Based on this prior knowledge of the eruption initiation mechanisms over the life of a specific volcanic system may thus have useful predictive power for future eruptions. These data also allow us to hypothesize that there are general trends in increasing eruption volumes, longer initiation timescales, more felsic compositions, and more explosive eruption style going from mafic rejuvenation to mafic recharge, felsic rejuvenation, and volatile accumulation, as summarized in Figure 3.

5 THE UTILITY OF PETROLOGICAL STUDIES IN UNDERSTANDING ERUPTION INITIATION

Our results emphasize two important points. Firstly, although further refinements are certainly possible, studies of erupted volcanic products are one of the best means we currently have to characterize a given volcanic system in terms of the process or processes that initiated eruptions. Observations from volcano monitoring also provide important insight, but 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 future eruptions. Thus, systematic studies of eruption initiation mechanisms offer considerable promise in assessing the nature of future

Table 3: Summary of P values determined for the 2 × 2 contingency table for eruption initiation timescale ($\leq$ months vs. $\geq$ 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 $P < 0.05$.

Eruption initiation timescale			
	Felsic rejuvenation	Mafic rejuvenation	Mafic recharge
Mafic rejuvenation	0.004		
Mafic recharge	0.55	<0.001	
Volatile accumulation	1.00	0.06	1.00

Table 4: Summary of P values determined for 2 × 2 contingency table for erupted volume (< 1 km^3 vs. $\geq$ 1 km^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 $P < 0.05$.

Erupted volume			
	Felsic rejuvenation	Mafic rejuvenation	Mafic recharge
Mafic rejuvenation	0.10		
Mafic recharge	1.00	0.03	
Volatile accumulation	1.00	0.59	0.65

Table 5: Summary of P values determined for 2 × 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 $P < 0.05$

Eruption style			
	Felsic rejuvenation	Mafic rejuvenation	Mafic recharge
Mafic rejuvenation	0.004		
Mafic recharge	0.37	0.03	
Volatile accumulation	1.00	0.03	0.37

Table 6: Summary of P values determined for 2 × 2 contingency tables for erupted composition (mafic vs. felsic). 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 $P < 0.05$.

Erupted composition			
	Felsic rejuvenation	Mafic rejuvenation	Mafic recharge
Mafic rejuvenation	<0.001		
Mafic recharge	1.00	<0.001	
Volatile accumulation	0.23	<0.001	0.13

eruptions and their associated hazards, and may add value to extant or planned monitoring programs.

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

1. *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. 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. With more data (see below) it may also be possible to further constrain the types of eruption initiation mechanisms beyond the simple categorization we present above.

2. *More data is better than better data*

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 may be better served at this stage by applying existing techniques to more eruptions. In other words, doubling the number of vol-

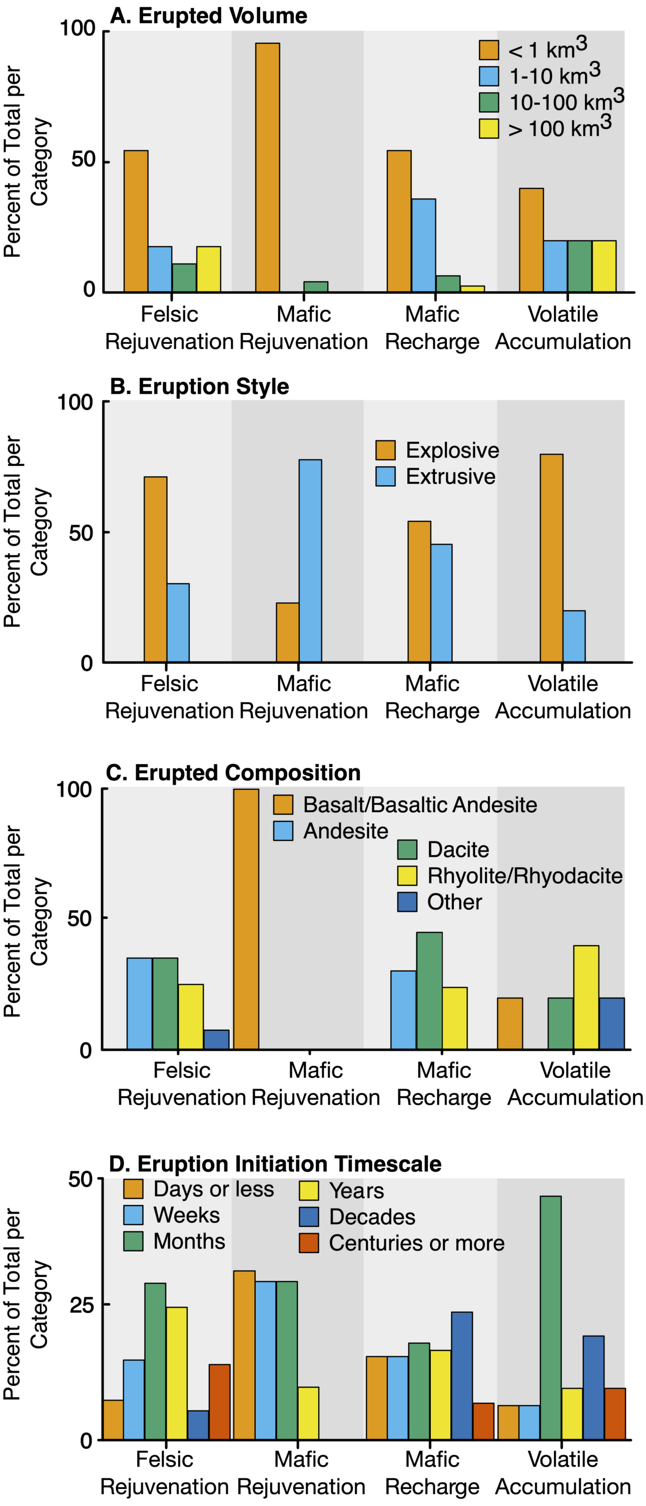

Figure 1: Summary of the observed characteristics of volcanic eruptions initiated by different mechanisms. Each histogram shows results as percent of total within individual categories: [A] Erupted volume, [B] Eruption style, [C] Erupted composition, [D] Eruption initiation timescale.

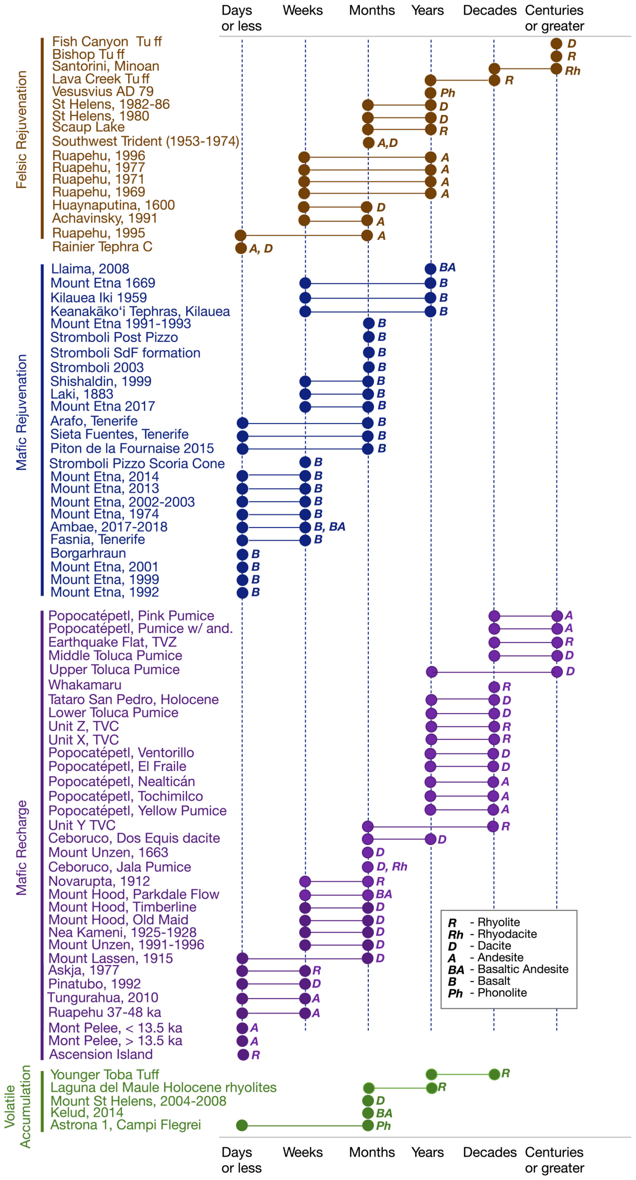

Figure 2: Comparison of estimated eruption initiation timescales for different eruption initiation mechanisms. The letter next to each eruption refers to the dominant composition of erupted material (see legend).

canoes and eruptions studied with the types of techniques exemplified in our literature compilation would provide broader insights than a factor of two improvement in the precision and accuracy of existing chronometers. Our data compilation shows the limits of relatively small numbers for several categories, and greater numbers 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 if larger numbers of eruptions were available for analysis. 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 felsic (dacite, rhyodacite and rhyolite) eruptions initiated by mafic recharge

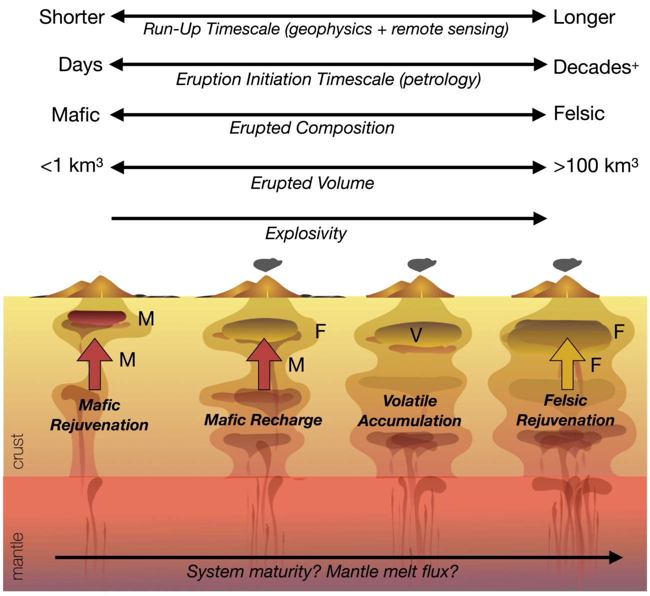

Figure 3: Schematic representation of how eruption characteristics (eruption style, volume, composition, and estimated eruption initiation timescale) vary with different eruption initiation mechanisms. Arrows represent movement of mafic "M" and felsic "F" magma from deeper within the magma plumbing system.

and felsic rejuvenation (Figure 2), as well as that repose times might also vary with composition.

3. *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. This is particularly important where petrological features are used to estimate the timescales leading to eruption initiation, as it is critical to understand exactly what event a given petrological feature records, and what the timescale estimated from that event specifically represents [e.g. Costa et al. 2020]. Studies of modern eruptions are 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 [Saunders et al. 2012; Pankhurst et al. 2018; Rasmussen et al. 2018; Costa et al. 2020] 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.

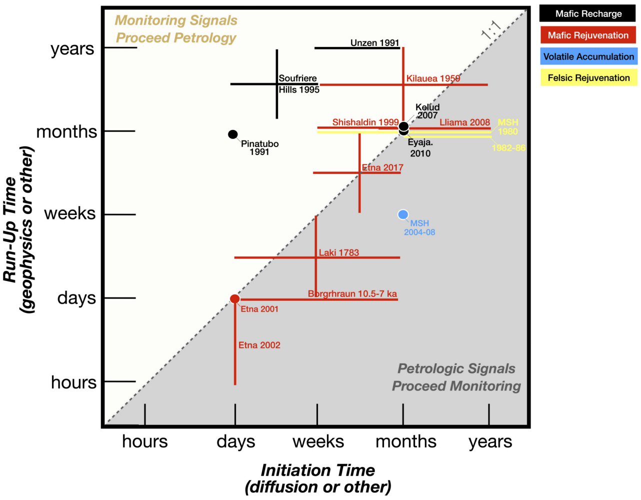

Figure 4: Comparison of petrologic eruption initiation timescales vs. volcano monitoring run-up timescales for eruptions in our literature compilation. Each eruption is represented as the range of relevant timescales recorded by both approaches, color coded by the eruption initiation mechanism. As an 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 are insufficient data on eruptions initiated by either felsic rejuvenation or volatile accumulation to make a similar assessment. Sources for run-up times from geophysical studies are from Passarelli and Brodsky [2012], Rae et al. [2016], Rasmussen et al. [2018], Ruth et al. [2018], and Viccaro et al. [2019]. All initiation times (from diffusion or other) are from our literature compilation for the same eruption.

4. *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. In poorly monitored volcanoes this might be one way to understand the likely nature and timescales of future unrest episodes. Such observations could be used to augment the monitoring record and provide a greater context for recognizing the likely mechanism for future eruption initiation. 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. 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, the links between eruption initiation mechanisms and eruption characteristics shown here indicate there is significant predictive power in a determination of eruption initiation mechanisms for a given volcanic system. Petrologic studies of erupted materials are particularly important for this. Thus, studies of eruption initiation mechanisms using petrological and other approaches show promise for mitigating volcanic hazards, especially when paired with volcano monitoring data.

AUTHOR CONTRIBUTIONS

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.

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DATA AVAILABILITY

All data used in this work are from literature sources and are summarized in Supplementary Material Table S1.

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