Title: Similarities and differences in the historical records of lava dome-building volcanoes: implications for understanding magmatic processes and eruption forecasting.

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Abstract:

A key question for volcanic hazard assessment is the extent to which information can be exchanged between volcanoes. This question is particularly pertinent to hazard forecasting for dome-building volcanoes, where effusive activity may persist for years to decades, and may be punctuated by periods of repose, and sudden explosive activity. Here we review historical eruptive activity of fifteen lava dome-building volcanoes over the past two centuries, with the goal of creating a hierarchy of exchangeable (i.e., similar) behaviours. Eruptive behaviour is classified using empirical observations that include patterns of SO_2 flux, eruption style, and magma composition. We identify two eruptive regimes: (i) an *episodic* regime where eruptions are much shorter than intervening periods of repose, and degassing is temporally correlated with lava effusion; and (ii) a *persistent* regime where eruptions are comparable in length to periods of repose and gas emissions do not correlate with eruption rates. A corollary to these two eruptive regimes is that there are also two different types of repose: (i) inter-eruptive repose separates episodic eruptions, and is characterised by negligible gas emissions and (ii) intra-eruptive repose is observed in persistently active volcanoes, and is characterised by continuous gas emissions. We suggest that these different patterns of can be used to infer vertical connectivity within mush-dominated magmatic systems. We also note that our recognition of two different types of repose raises questions about traditional definitions of historical volcanism as a point process. This is important, because the ontology of eruptive activity (that is, the definition of volcanic activity in time) influences both analysis of volcanic data and, by extension, interpretations of magmatic processes. Our analysis suggests that one identifying exchangeable traits or behaviours provides a starting point for developing robust ontologies of volcanic activity. Moreover, by linking eruptive regimes to conceptual models of magmatic processes, we illustrate a path toward developing a conceptual framework not only for comparing data between different volcanoes but also for improving forecasts of eruptive activity.

Keywords: Lava-dome volcanoes; Exchangeable behaviours; Persistent; Episodic; Magmatic processes; Forecasting.

1. Introduction

Volcanic activity can be manifested in many different ways. From a volcanic risk perspective one important variety of eruptive activity is extrusion of lava domes at intermediate and silicic volcanoes. Recurrent hazards associated with dome-building activity include: pyroclastic flows and volcanic blasts associated with the collapse of lava domes and edifice instability; fountain-fed pyroclastic flows associated with Vulcanian to sub-Plinian explosions; and copious tephra fall . Worldwide, such volcanic activity has been responsible for over two thirds of volcanic fatalities since 1600 C.E. (Auker et al., 2013).

Within the Smithsonian Global Volcanism Program (GVP) database there are 205 recorded dome-building volcanoes that have been active in the Holocene (Siebert et al., 2010). Of these, 117 have erupted in the last millennium and 89 have erupted since 1900 C.E. (Ogburn et al., 2015). Historical eruptions have lasted many months, years or even decades (Newhall and Melson, 1983; Sparks, 1997; Ogburn et al., 2015). Over historical timescales volcanic activity can be regarded as continuous, albeit fluctuating, but may also include complex episodic and sometimes cyclic fluctuations in intensity, duration, frequency and eruptive style.

Lava dome formation requires particular conditions, which suggests that magmatic processes at dome-building volcanoes have shared characteristics. Specifically, the lavas of dome-building volcanoes have low average eruption rates (~10^{-1} to 10^{-2}

km^3 yr^{-1}) and high viscosities (10^6 to 10^{11} Pa s; Yokayama, 2005) that are commonly associated with high groundmass crystallinity (Cashman, 1992) and, consequently, substantial yield strength (Calder et al., 2015). Nevertheless, dome-building volcanoes can exhibit markedly different eruptive histories, including both the duration of individual eruptive episodes and the potential for explosive activity. This variability reflects the general conceptual tensions in volcanology where: (1) there is a belief that individual volcanoes are unique, as exhibited by the complex nature of their eruptive records, and (2) the concept that eruptive activity is driven by common magmatic processes that produce certain eruptive styles and volcano morphologies (Cashman & Biggs, 2014).

In this review we identify characteristics of fifteen lava-dome building volcanoes that are similar (exchangeable) or unique (not exchangeable), as well as those that are common only to a sub-group of volcanic records. In volcanology, for example, the concept of exchangeable characteristics can be used to define the common traits for all volcanoes, and to infer the conceptual system that this definition represents. Using this idea, the basic exchangeable characteristics of a volcanic system - implied by the definition of a volcano by Borgia et al. (2010) - are simply magma, eruption, and edifice. We ally to this the idea that the volcanic system (and thus the conceptual construct of volcanism) should be hierarchically organized, such that identifying and characterizing different hierarchies allows individual volcanoes to be distinguished in space and time (Szakács, 2010). For this reason, we develop a hierarchy of different eruptive behaviours using observations from the historical records of fifteen well-characterised dome-building volcanoes. By characterising exchangeable behaviours we can assess inaccessible elements (e.g., the magmatic system) from observed elements (e.g., surface phenomena). A similar approach is employed in medical sciences, where individuals (i.e. humans) are unique, but different groups of humans are known to have similar health traits (Spiegelhalter, 1986; Best et al., 2013).

Using a hierarchical construct for eruptive behaviours at dome-building volcanoes we consider the conceptual system that can explain the different sets of shared traits and characteristics. Specifically, we ask whether the diversity in behaviours can be explained by subsystems of the magmatic system (e.g., shallow crustal reservoirs) or whether it requires a more holistic view of crustal magmatic processes (i.e., a transcrustal reservoir system that extends from the surface through the crust and into the mantle). This approach allows us to evaluate emerging paradigms for eruptive activity based on the destabilisation and reorganisation of igneous mush systems (e.g., Cashman and Giordano, 2014; Christopher et al., 2015), and to interpret the role of connectivity within a magmatic system on the pattern and style of eruptive activity at dome-building volcanoes.

An additional application of our study relates to the implications of a hierarchical construct on the analysis of volcanic datasets. An important issue relates to the concept of volcanic activity as a point-process of discrete events as this influences how magmatic processes are interpreted and how probabilistic forecasts are made.

We also examine the implications of different patterns of eruptive behaviour on forecasting the activity of one volcano using observations from other (perhaps better characterized) volcanoes of the same type. We discuss the issues when selecting evidence to make eruptive forecasts and contextualize this in regards of forecasting the onset of eruptive activity.

2. Data

The fifteen dome-building volcanoes selected for this review are listed in Figure 1. Our selection is governed by the quality of available data and relevant observations, and guided by the principle that our dataset should contain volcanoes that are well-characterised, have long records of activity and have been recently active. All fifteen volcanoes sit in arc environments, and erupt magmas that are hydrous and intermediate in composition. As volcanic gas emissions are an important aspect of dome-building volcanism, we also include one volcano characterised by persistent gas emissions but no recent eruptive activity.

To enable comparison of similar dome-building behaviour, we restricted the selection to volcanoes of intermediate composition, thus omitting domes formed by the eruption of crystal-poor rhyolites (e.g., Chaiten 2008: Pallister et al., 2013). To ensure that the eruptive records are complete and not affected by recording biases (Coles and Sparks, 2006; Deligne et al., 2010), we review patterns of eruptive activity only back to 1800 C.E. (Fig. 2), as prior to this date each of the individual eruptive records is assumed to be incomplete. However, recent advances in the ability to monitor and observe eruptive activity (Cashman and Sparks, 2013) mean that much of the data derive from eruptive activity in the late 20th and early 21st centuries. Data sources include eruption databases (Siebert et al., 2010; Ogburn, 2013), peer-reviewed publications (e.g., journal articles, professional publications), and observatory data and databases of volcanic unrest (e.g., WOVOdat; http://www.wovodat.org/). Detailed profiles for the volcanoes can be found in the supplementary material.

Data are collated for two purposes: (i) as empirical evidence of long-term behaviours at dome-building volcanoes, and (ii) as a semi-quantitative measure of their behaviour. Empirical evidence includes observations of phenomenological behaviour, magmatic degassing, and the bulk rock characteristics of erupted products. In contrast to focussed studies at the individual volcanoes, we do not use the observations as direct evidence of specific magmatic processes or characteristics of the respective magmatic systems. Instead, we use them only to subdivide individual volcanoes into groups that reflect their long-term eruptive behaviour. We then examine geophysical (seismicity and deformation) and petrological observations within groups to compare the behaviour of the magmatic systems within and between volcano groups.

2.1. Phenomenological behaviour

Dome-building volcanoes exhibit a range of effusive and explosive behaviours (Newhall and Melson, 1983; Sparks, 1997; Ogburn et al., 2015). By definition, however, the main eruptive activity involves protracted lava dome extrusion, with extrusive phases that may last from months to many years; our reference volcanoes have also experienced periods of quiescence of months to decades. During times of activity, lava discharge rates can be estimated from ground-based and satellite-based techniques (e.g., Sparks, 1997; van Manen et al., 2010) and used to characterise the intensity of dome growth phases. The effusion rate, together with the magma viscosity, determines whether lava moves away from the vent as a lava flow or builds either an ever-larger dome and talus apron or a near-solid lava spine (Watts et al., 2002; Cashman et al., 2008). Where lava accumulates over the vent, the increase in magma-static head creates a backpressure that can resist extrusion and influence the longer-term dynamics of the magmatic system (Stasiuk et al. 1993; Scandone et al., 2007).

Phases of extrusive activity can be interspersed with more explosive activity, including Strombolian, Vulcanian and sub-Plinian eruption styles. The intensity and explosivity of eruptive activity can be characterised using phenomenological observations such as ash column height, pyroclastic run-out, tephra fall deposit volumes, some of which can serve as proxies for magnitude, intensity and explosion style (Newhall and Self, 1982). Infrequently, dome-building volcanoes also have large-magnitude explosions, including Plinian eruptions and lateral blasts (Ogburn et al., 2015).

2.2. Magmatic degassing

As magma ascends through the crust, volatiles exsolve and rise to the surface (Wallace, 2003; 2005; Oppenheimer et al., 2011). The most abundant volatile species are H_20 and CO_2. SO_2, however, is the most commonly monitored volatile because it is a trace gas in the atmosphere and thus its concentration can be readily measured using remote sensing techniques (Rose et al., 2000; Edmonds et al., 2003; Galle et al., 2003; Carn et al., 2013). SO_2 fluxes are quantified using ultraviolet absorption spectra and measured in tonnes per day (t/d); some data for the last few decades are sporadically available for most of the study volcanoes.

Prior to the development of ultraviolet spectroscopic techniques, gas fluxes were estimated by sampling fumarolic gases (Giggenbach, 1996). Introduction of the correlation spectrometer (COSPEC) in the 1970s allowed SO_2 flux measurements, although early measurements were prone to large errors (Oppenheimer et al., 2011). More recently, fluxes have been estimated from differential optical absorption spectroscopy (DOAS; Platt and Stutz, 2008). A major advantage of this method is that spatially distributed multi-beam instruments can provide precise estimates for plume velocity, which significantly reduces measurement errors of flux (Oppenheimer et al., 2011, and references within). Importantly, however, measurements are restricted to sunlight hours only and the quality of gas data from all remote sensing techniques depends on meteorological conditions (e.g., low humidity and no clouds).

Terrestrial-based spectroscopic measurements are not feasible for measuring volatile emissions in major explosive events because abundant ash masks the signals. Consequently, the mass of gas released during large eruption events is measured using satellite-based techniques and then converted to fluxes (Carn and Prata, 2010; Carn et al., 2013).

2.3. Bulk rock observations

In our data set, the products of dome building volcanoes range in composition from basaltic andesite (~52-57 wt.% SiO_2) to dacite (~64-69 wt.% SiO_2; Table 1). Whilst it is impossible to observe the long-term dynamics of magmatic systems directly, macroscopic observations and bulk rock analysis can be used to interpret the compositional, and potentially the physical, structure of magmatic systems (e.g., Barclay et al., 2010; Larsen et al., 2010; Coombs et al., 2013; Scott et al., 2013; Turner et al., 2013).

Magma rheology is a major determinant of physical behaviour, particularly at shallow depths where flow at the surface may be inhibited by high yield strength. Magma is a multiphase system and consequently its rheology is complex (Mader et al., 2013). Rheology is strongly controlled by the crystallinity of the magmas, which is typically high in intermediate arc magmas. Crystallization is further increased by syn-ascent decompression and degassing and is thus modulated by eruption rate, the pressure of shallow storage prior to eruption, the bulk composition of the magma and kinetic factors associated with bubble dynamics (Jaupart and Vergniolle, 1989; Geschwind and Rutherford, 1995; Nakada and Motomura, 1999; Hammer et al., 2000; Cashman and McConnell, 2005; Divoux et al., 2009; Wright et al., 2012). Exsolved gas can also lead to marked rheological variations as functions of bubble size distribution and bubble content (Manga et al., 1998; Mader et al., 2013). The interplay between magma ascent, decompression, gas exsolution, crystallization and rheology can lead to complex episodic behaviours (e.g., Jaupart and Allegre, 1991; Melnik and Sparks, 1999; Michaut et al. 2013).

2.4. Geophysical observations

For each volcano we report common geophysical observations; for consistency, we omit specialised observations (e.g., strain meters, broadband seismicity) made at only one or two volcanoes. Geophysical monitoring observations are susceptible to spatial and temporal biases associated with network capacities and technological constraints at volcano observatories (Sparks et al., 2012). Therefore, it is important to understand these biases and thus the robustness and validity of comparing records. Spatial biases arise from variations in monitoring capacities due to both resource availability and accessibility. Temporal biases are associated with advances in technology that improve observation thresholds and the precision of measurements. These are discussed in more detail with reference to the particular observables.

2.4.1. Seismicity

Volcanic seismicity can be categorised either by its physical cause, if occurring at the surface (e.g., rockfalls, lahars, pyroclastic flows, etc.), or its waveform and frequency content if originating from within the crust (e.g., high or low-frequency signals; Chouet, 1996; Neuberg, 2000; McNutt, 2005; Chouet and Matoza, 2013). High-frequency (volcano-tectonic) events have recognisable P and S wave first arrivals and are attributed to brittle fracturing related to opening of new pathways for either magma or magmatic fluids (Kilburn, 2003). Low-frequency (long-period and hybrid) events are associated with movement of magma and magmatic fluids (McNutt, 2005). Seismicity is most commonly associated with eruptive activity but is also observed during periods of quiescence, that is, when a volcano is in a non-eruptive state, and can be diagnostic of incipient unrest (Phillipson et al., 2013) or post-eruptive tectonic stress recovery (e.g., Barker and Malone, 1991).

Although seismicity can be characterised using a range of metrics, we focus on the number of events (daily counts) as this is the most commonly recorded observation across the volcanoes in the dataset. We do not compare absolute numbers of seismic events or cumulative seismic moment between volcanoes due to recording biases associated with variations in network capacities and sensitivities (e.g., number of and type of instruments). Instead we compare patterns of total seismicity and the relative frequency of different types of events, primarily long-period and volcano-tectonic earthquakes.

2.4.2. Deformation

The episodic and sometimes repetitive nature of eruptive activity at many dome-building volcanoes commonly manifests as time-varying deformation of the crust that can be monitored at the surface using geodetic techniques. Great variability in instrumentation and network design in the near-field monitoring of ground deformation, however, makes direct comparisons difficult. For this reason, we focus only on far-field deformation (> 5 km from the vent). These data also provide useful constraints on deeper magmatic processes. Far-field deformation can be measured by geodetic networks (using GPS), although these measurements require ground-based support and are restricted to only a few of the volcanoes in our dataset. On the other hand, Interferometric Synthetic Aperture Radar (InSAR) techniques using satellite-based instruments provide a global approach for observing far-field deformation (Biggs et al., 2014). By combining observations from these two methods we compare patterns of deformation (i.e. whether the volcano is inflating, deflating or neither) between different volcanoes and relate deformation behaviour to eruptive and non-eruptive phases of activity.

2.5. Petrology

Petrologic data provide information on the homogeneity of the magmatic system, temporal changes of magma composition and the extent to which eruptive activity is influenced by the ascent of discrete magma batches. Of particular interest is evidence for the interaction of different magmas, which can occur at a range of scales. Macroscopic evidence for magma mingling includes enclaves or compositional banding in erupted products. Microscopic details of geochemical interactions provide information on the nature and timing of mingling events. Analysis of individual crystals and their melt inclusions provides information on both intrinsic and extrinsic properties (e.g., temperature, pressure and volatile inventories) of magma storage regions (e.g., Nakamura, 1995; Zellmer et al., 2003a; Dirksen et al., 2006; Humphreys et al., 2006; Costa et al., 2013). Finally, petrological analyses and U-series geochemistry can constrain the timescales of magmatic processes (e.g., Volpe and Hammond, 1991; Zellmer et al., 2003b; Cooper and Reid, 2008; Dosseto et al., 2008; Claiborne et al., 2010) that control and sustain eruptive activity at dome-building volcanoes. Quantification of groundmass characteristics (crystallinity, crystal size and shape) can further constrain rates of magma ascent to the surface (e.g., Hammer et al., 2000; Toramaru et al. 2008; Wright et al., 2012).

3. Patterns of eruptive activity at dome-building volcanoes

We identify in our dataset two types of long-term behaviour defined by the relative time a volcano remains in a state of eruption or repose (i.e. non-eruption): (1) activity is *episodic* when time scale of eruption is much less than the time scale of repose; and (2) activity is *persistent*, when the time scale of eruption is comparable to that of repose (Fig. 3a). Identification of episodic and persistent regimes represents the first sub-level in our hierarchical construct of historical dome-building volcanism (Fig. 4).

Episodic and persistent behaviour can be manifested over different timescales (Fig. 4) and, over time, individual volcanoes can show both types of behaviour (Fig. 3c). Over the examined time period of the past 200 years, for example, many dome-building volcanoes are characterised by episodic behaviour; however, within that broad description, some have remained in a persistent regime for multiple decades. We characterise these volcanoes as belonging to a mixed regime. Over very long time periods, all the volcanoes in our sample can be viewed as mixed.

Patterns of SO_2 degassing also provide additional insight into long-term patterns of volcanic activity. The largest volumes of SO_2 emissions are always associated with major explosive events (e.g., Carn and Prata, 2010; Werner et al., 2013). Two patterns of less energetic degassing can be defined as: (1) SO_2 flux that is closely correlated with eruptions (Fig. 3b) and (2) degassing that is not correlated with eruptive activity (Fig. 3a). Correlated degassing is common at volcanoes in an episodic regime; here both gas and magma fluxes decrease with time after an initial (often explosive) maximum (Fig. 5a). Poor correlation between degassing and eruptive activity, in contrast, is typical of persistent activity (Fig. 5b). The correlation of degassing patterns with eruptive behaviour suggests that magmatic degassing constitutes an important distinction between persistent and episodic regimes (e.g., Whelley et al., 2015).

Finally, we use differences in degassing behaviour to distinguish two states of repose: (1) inter-eruptive repose separates episodic eruptions and is characterised by negligible degassing (Fig 3a;5a); and (2) intra-eruptive repose occurs in the persistent regime and is characterised by sustained degassing (Fig 3b;5b). We also identify a non-eruptive degassing regime to describe dome-building volcanoes that remain in a state of long-term repose (~decades) characterised by low levels of persistent degassing.

3.1. Episodic regime

Volcanoes in an episodic regime are characterised by periods of eruptive activity separated by much longer periods of repose. The onset of eruptive episodes is explosive, with high magma discharge rates. Both magma discharge rates and SO_2 fluxes decrease with time during eruptive periods (e.g., Fig. 6). During eruptive periods, the later stages of activity are typically characterised by low extrusion rates and associated extensive syn-eruptive crystallisation that combine to produce lava spines (e.g., Watts et al., 2002; Cashman et al., 2008). We distinguish two different timescales for episodic activity in historical records (Fig 4): (1) volcanoes where eruptive episodes last several years, and (2) volcanoes where eruptive episodes last a few months at most. These two subgroups can be further distinguished by the homogeneity or heterogeneity of erupted magma compositions.

3.1.1. Eruptive episodes lasting years

Two volcanoes in this review have experienced episodic activity lasting several years (Fig. 2; UNZ, PEL). In both cases, lava compositions are broadly homogeneous. The duration of inter-eruptive periods of repose is multiple decades or longer.

(a) *Mount Unzen*, Japan (UNZ), is a complex dacitic volcano that last erupted near-continuously from 1991-1995 (Fig. 2). No previous historic activity is known although a major sector collapse event of an older dome occurred in 1792 (Ui et al., 2000). Between 1991 and 1995, the composition of eruptive products was ~65 wt.% SiO_2 (Nakada and Motomura, 1999) and the average lava effusion rate was ~1 m^3s^{-1}, with higher rates (~4-6 m^3s^{-1}) during the eruption onset. Extrusion rates generally diminished with time, although a secondary peak was observed in 1993 (Nakada et al., 1999; Fig. 6). SO_2 fluxes averaged 137 t/d, were correlated with extrusion rate and diminished soon after eruptive activity ceased (Hirabayashi et al., 1995).

(b) *Mont Pelée*, Martinique (Fig. 1), is an andesitic volcano that has erupted infrequently (Fig. 2). The best-recorded eruptive activity occurred in the early part of the 20*th* century, between 1902-05 and 1929-32 (Lacroix, 1904; Perret, 1937; Tanguy, 1994). During both periods, lava fluxes decreased from >10 m^3s^{-1} to ~1 m^3s^{-1} (Tanguy, 2004), with later stages characterised by spine extrusion (Lacroix, 1904; Perret, 1937). The composition of eruptive products from Mont Pelée is quite homogeneous at 62 wt.% (Fichaut et al., 1989b; Gourgaud et al., 1989; Smith and Roobol, 1990).

3.1.2. Eruptive episodes lasting months

Two volcanoes in this review have experienced eruptive episodes lasting a few months (Fig. 2; RED, AUG). In contrast to the volcanoes in the previous group, the duration of inter-eruptive periods of repose is several years to a few decades. Additionally, lavas of different composition are erupted contemporaneously.

(c) *Mount Redoubt*, USA (RED), is an andesitic volcano that has erupted intermittently on four separate occasions since 1902 (Fig. 2). The most recent eruptive episodes have been in 1989-90 and 2009, each lasting for several months (Miller and Chouet, 1994; Bull and Buurman, 2013). During each eruptive episode eruptive products ranged from 57 to 63 wt.% SiO_2, with the later stages involving the more silicic lava (Nye et al., 1994; Coombs et al., 2013). SO_2 degassing is highly correlated with periods of eruptive activity. In 1989 -1990, extrusion rates varied from 2.1 to 26 m^3s^{-1}, with average dome growth occurring at ~5.8 m^3s^{-1} (Miller, 1994). Similar extrusion rates were observed in 2009 (2.2 -35 m^3s^{-1}) although the average rate was slightly higher at ~9.5 m^3s^{-1} (Diefenbach et al., 2013). In both cases the initial activity was the most explosive and the extrusion rate declined during eruptive activity (Miller, 1994; Diefenbach et al., 2013). Initial explosive activity in 2009 was associated with the largest SO_2 fluxes (~3000 to ~17000 t/d). Subsequent activity involved more continuous extrusion with SO_2 fluxes ≤3000 t/d (Hobbs et al., 1991; Casadevall et al., 1994; Werner et al., 2013). In both 1990 and 2009, it took several years for SO_2 fluxes to return to undetectable levels after eruptive activity ceased (Doukas, 1995; Werner et al., 2013).

(d) *Mount Augustine*, USA (AUG), is an andesitic volcano that has had nine known eruptive episodes since 1812, with the most recent in 1976, 1986 and 2006 (Fig 2), each lasting for several months (Swanson and Kienle, 1988; Power et al., 2006; Power and Lalla, 2010). The composition of the erupted magma has ranged from 56 to 64 wt.% SiO_2, with more silicic magma preferentially erupted later in each eruptive episode (Harris, 1994; Roman et al., 2006; Larsen et al., 2010). During the 2006 eruptive activity, magma fluxes varied from 2 to 22 m^3s^{-1} (Coombs et al., 2010). Notably, in contrast to other volcanoes in episodic regimes, the final stages of eruptive activity at Augustine in 2006 were characterised by elevated discharge rates and the formation of lava flows, although discharge rates were still lower than at the onset of eruptive activity (Coombs et al., 2010). Magmatic degassing is correlated with eruptive activity, with the largest fluxes commonly associated with explosive activity (Stith et al., 1978, Rose et al., 1988; McGee et al., 2010). In 2006, however, the highest SO_2 fluxes (~9000 t/d) were associated with a brief hiatus in eruptive activity, although SO_2 fluxes were high (~3000 t/d) throughout the eruptive episode (McGee et al., 2010), and it took 1-2 years after the end of eruptive episodes in 1986 and 2006 for SO_2 fluxes to return to undetectable levels (Symonds et al., 1990; Doukas, 1995; McGee et al., 2010).

3.2. Persistent regime

We identify eight volcanoes in this review that have remained in a persistent regime for decades or longer. Volcanoes in a persistent regime exhibit broadly consistent behaviour associated with stable long-term lava fluxes. For example, although rates of lava effusion at Bezymianny, Kamchatka, have varied over the short term, they have been approximately constant over the past several decades (Fig. 5). The eruptive activity of an individual volcano can also show ‘typical’ (repeatable) patterns of behaviour, as illustrated by Santiaguito, Guatemala, where typical behaviour comprises “small to moderate explosions of steam and ash, small pyroclastic flows... and effusion of blocky lava domes and flows” (Scott et al., 2012). Typical intermittent behaviour at Merapi, Indonesia, in contrast, is characterised by eruptive activity that is “low in explosivity with VEI-3 or less ... [that] involve the formation of a lava dome” (Ratdomopurbo et al., 2013).

We distinguish two different variants of long-term persistent behaviour (Fig. 4). Firstly, there are volcanoes that have remained in a persistent regime at least the 19th century. These volcanoes produce lavas with an approximately constant bulk composition. Secondly, there are volcanoes that have entered a persistent regime following a long period of in a state of repose. Volcanoes in this group typically have bulk compositions that show a decrease in SiO_2 content with time.

3.2.1. Long-term persistent regimes

Four of the dome-building volcanoes in this study have been in a persistent regime throughout the 19th, 20th and 21st centuries; these volcanoes are characterised by frequent, intermittent phases of dome-growth (Fig. 2; MER, COL, LAS, SHI). The style of eruptive activity is generally consistent through time and characterised by definable 'typical' behaviour, except for rare large-magnitude explosions (Fig. 2). Interestingly, these explosive events commonly involve magma that is more mafic than erupted during the effusive phases. Activity at each volcano is described in detail below.

(a) *Merapi*, Indonesia (MER), is a basaltic andesite volcano that has been in an eruptive state every few years since at least the 18th century. Eruptive activity is characterised by minor explosions associated with the extrusion of viscous lava domes and coulées that can collapse to form block-and-ash pyroclastic flows (Voight et al., 2000). Lava extrusion rates are approximately constant over historical records at ~0.5 m^3s^{-1} (Siswowidjoyo et al., 1995). Persistent effusive activity has been punctuated by at least two major explosions that have produced high-energy pyroclastic density currents (Surono et al., 2012). The bulk rock lava composition ranges from 52 to 56 wt.% SiO_2 (Andreastuti et al., 2000; Gertisser and Keller, 2003) and shows no temporal trend, although explosive events appear to involve deeply sourced, volatile-rich magmas (Costa et al., 2013), which may be more mafic (Gertisser and Keller, 2003). SO_2 degassing is continuous with fluxes between 50 and 250 t/d (Humaida, 2008), although instantaneous fluxes can be much larger (~10,000's t/d) during major explosive events (Surono et al., 2012). Importantly, SO_2 fluxes and eruptive activity appear decoupled, with SO_2 flux peaks observed during inter-eruptive periods, and sometimes associated with ash venting (Ratdomopurbo et al., 2013).

(b) *Colima*, Mexico (COL), is an andesite volcano that has been erupting intermittently since the 18th century. Periods of intra-eruptive repose normally last on the order of years, although longer periods without apparent eruptive activity have followed major explosive events in 1818 and 1913. These longer periods of repose probably involved endogenous growth below the crater rim (Robin et al., 1991; González et al., 2002), so we infer that Colima remained in a persistent regime during post-explosion periods. Eruptive activity is characterised by lava dome extrusion, Vulcanian explosions and occasional block-and-ash flows (Zobin et al., 2002). Short-term lava effusion rates vary from <1 to >5 m^3s^{-1} (Varley et al., 2010), but long-term averages are poorly constrained. The lava composition ranges from 59 to 62 wt.% SiO_2 with no clear temporal trend (Luhr and Carmichael, 1980; 1990; Savov et al., 2008), except that products of major explosive events are more mafic (SiO_2 = 55-58 wt.%; Luhr and Carmichael, 1990; Reubi and Blundy, 2009; Crummy et al., 2014). SO_2 degassing is continuous, with fluxes typically between 50 and 1000 t/d (Casadevall et al., 1984; Engberg, 2009), although sometimes as high as 5000 t/d (Taran et al., 2002; Varley and Taran, 2003). Magmatic degassing appears decoupled from eruptive activity (Zobin et al., 2008), but the largest SO_2 fluxes are associated with more explosive events (Taran et al., 2002).

(c) *Lascar*, Chile (LAS), is an andesitic volcano that has been erupting intermittently at yearly to decadal timescales throughout much of its history. Lava dome growth has been confined within a large summit crater. Four periods of near-continuous dome growth occurred between 1984 and 1993; each culminated in lava dome subsidence and explosive events, including a Plinian explosion in April 1993 (Matthews et al., 1997). Long-term lava extrusion rates are poorly constrained but are likely to be < 0.1 m^3s^{-1} (Matthews et al., 1997). Since 1993, activity has comprised episodic Vulcanian explosions that have decreased in both intensity and frequency; the last explosion occurred in 2007. Juvenile pyroclasts from 1993 can be separated by composition into two groups: 57.6-58.7 or 60.4-61.4 wt.% SiO_2 (Matthews et al., 1999); similarities to previously erupted lavas (Deruelle, 1985) suggest that the magma composition has remained constant throughout its history. Lascar has exhibited continuous fumarolic activity (Casertano, 1963; Gardeweg & Medina, 1994) with recent SO_2 fluxes sustained between 150 and 940 t/d (Henney et al., 2012, Menard et al., 2014). During more explosive activity, fluxes have reached 2300 t/d (Andres et al., 1991; Mather et al., 2004). SO_2 fluxes have shown an irregular pattern of degassing during periods of intra-eruptive repose and therefore appear decoupled from magma flux (Menard et al., 2014).

(d) *Shiveluch*, Russia (SHI) is an andesitic volcano that has been erupting intermittently since a major explosive event in 1854. Even prior to 1854, sparse observations suggest that periods of repose lasted no more than a few decades. Recent phases of eruptive activity have varied in duration from months to several years, and Shiveluch has been in a near-continuous eruptive state since 2000 (Belousov, 1995; Zharinov and Demyanchuk, 2008). Between 1980 and 2007 the average lava discharge rate was ~ 0.4 $m^3 s^{-1}$, although fluxes fluctuated considerably (Zharinov and Demyanchuk, 2008). Explosive activity has been of variable magnitude, with major Plinian events in 1854 and 1964 (Belousov, 1995). The eruptive products contain 56-62 wt.% SiO_2 and show no temporal trends (Dirksen et al., 2006; Humphreys et al., 2006; Gorbach and Portnyagin, 2011). Fumarolic activity has been sustained throughout both eruptive activity and intra-eruptive repose (Belousov, 1995; Gorelchik et al., 1997; Zharinov and Demyanchuk, 2008), but SO_2 fluxes have not been documented.

3.2.2. Long-duration repose preceding a long-term persistent regime

Two volcanoes in this study have initiated persistent behaviour after explosive eruptions that followed a long period in a state of repose (~millennia; Fig. 2; SAN, BEZ). The onset of a persistent regime at these volcanoes is characterised by Plinian and lateral blast explosions. In contrast to the previous group, the most evolved pyroclasts in this group are associated with major explosive events; the SiO_2 content of subsequent lavas decreases systematically through time.

(e) *Santiaguito (Santa Maria)*, Guatemala (SAN), is a dome complex that has been active since 1922; effusive activity followed the Plinian eruption of its parent volcano, Santa Maria, in 1902 (Rose, 1972). Effusive activity has been nearly continuous at long-term rates of ~ 0.46 m^3s^{-1}, with marked fluctuations that have been classified into eight distinct phases (Rose, 1973; Harris et al., 2003; Scott et al., 2013). Each phase has initiated with high rates (0.5-2.1 m^3s^{-1}) and has been followed by low, sustained extrusion rates of < 0.2 m^3s^{-1} (Harris et al., 2003; Ebmeier et al., 2012). The lavas are dacitic to silicic andesite in composition, with SiO_2 contents that have decreased systematically from ~66 to ~62 wt.% since 1922. SO_2 degassing is continuous with average fluxes between 80 and 120 t/d (Andres et al., 1993; Rodríguez et al., 2004).

(f) *Bezymianny*, Russia (BEZ), is an andesite volcano that has been erupting near-continuously to intermittently since a lateral blast and associated sector collapse in 1956 (Belousov et al., 2007). Between 1956 and 1977, eruptive activity was limited to periods of endogenous lava dome growth associated with sustained fumarolic activity (Gorshkov, 1959; Bogoyavlenskaya et al., 1985; Belousov, 1996). After 1977, dome growth occurred exogenously and included occasional explosions (van Manen et al., 2010). More recently, eruptive phases have decreased in duration and have become increasingly explosive (West, 2013). The long-term average extrusion rate was 0.6 m^3s^{-1} between 1956 and 1976 (Belousov et al., 2002) and 1993 to 2008 (van Manen et al., 2010). Since 1956 the eruptive products have become steadily less evolved with time, varying from 60.4 to 56.8 wt.% SiO_2 (Bogoyavlenskaya et al., 1985; Turner et al., 2013). SO_2 degassing has been sustained. Fluxes have been measured at 140 to 280 t/d during three campaigns conducted during periods of low eruptive activity (Lopez et al., 2013). These measurements are not sufficient to assess relations between degassing and magma discharge.

3.3. Mixed eruptive regime

Persistent and episodic regimes can manifest over different timescales at individual volcanoes. Consequently, the historical records of some dome-building volcanoes exhibit patterns of eruptive activity that are characteristic of both regimes: they exhibit persistent behaviour over several decades but are also characterised by long periods of inter-eruptive repose. We identify four volcanoes that fit this category and define them as ‘mixed’ regime volcanoes (Fig. 2; MSH, SHV, TUN, POP).

The eruptive behaviour at these volcanoes varies markedly, with persistent activity over short timescales but episodic activity over timescales of decades to centuries and persistent activity over shorter timescales. Mixed activity is sufficiently varied, however, that it cannot be considered exchangeable. For example, Mount St Helens showed persistent activity throughout most of the 1980's with degassing that was well correlated temporally with lava extrusion. Tungurahua, in contrast, has remained in a persistent regime since 1999, with degassing that has been poorly correlated with lava extrusion. A common observation at all of these volcanoes, however, is intermittent ash venting.

(a) *Mount St. Helens*, USA (MSH), is a dacitic volcano that has experienced two eruptive episodes in recent times: 1980 to 1986, and 2004 to 2008 (Swanson and Holcomb, 1990; Scott et al., 2008), following an inter-eruptive period of repose lasting 136 years (Fig. 2). Eruptive activity in 1980 initiated with endogenous growth of the edifice (Lipman and Mullineaux, 1981) that caused a major flank collapse accompanied by sub-Plinian explosive activity (Voight et al., 1983; Glicken, 1998). This was followed by sub-Plinian to Vulcanian explosions in the summer of 1980 that steadily decreased in magnitude and duration (Scandone and Malone, 1985). Subsequent effusive activity transitioned between discrete and continuous eruptions of variably crystalline lavas (Cashman, 1992). Between 1980 and 1986, extrusion rates varied from 1.4 to 40 m^3s^{-1}, with a long-term average of ~ 0.4 m^3s^{-1} (Anderson and Fink, 1990; Swanson and Holcomb, 1990). Renewed continuous effusion in 2004 occurred at rates that decreased steadily until 2008, with a maximum of < 5.9 m^3s^{-1} and a long-term average of 0.1 m^3s^{-1} (Schilling et al., 2008; Major et al., 2009). Between 1980 and 1986 magma compositions were broadly homogeneous at 62-64 wt.% SiO_2 (Cashman, 1992; Pallister et al., 1992; Blundy et al., 2008; Pallister et al., 2008). Lavas erupted between 2004 and 2008 were similarly homogenous at 63-65 wt.% SiO_2 (Blundy et al., 2008; Pallister et al., 2008). During both eruptive periods, degassing was continuous and largely coupled with magma extrusion. The largest SO_2 fluxes were associated with explosive activity in the early 1980's, when they frequently exceeded 1000 t/d (Gerlach and McGee, 1994). The lowest SO_2 fluxes (~70 t/d) were associated with the dome-building activity in 1982-86 and 2004-2008 (Gerlach and McGee, 1994; Gerlach et al., 2008). Following the cessation of each eruptive episode, SO_2 fluxes decreased rapidly to negligible levels. In the 1990's, however, detectable gas emissions (Gerlach et al., 2008) were observed concurrently with elevated shallow VT seismicity and explosive emissions of non-juvenile tephra (Mastin, 1994).

(b) *Soufrière Hills Volcano*, Montserrat (SHV), is an andesitic volcano that erupted in 1995 following several centuries of no eruptive activity. Since 1995 it has exhibited intermittent activity with five phases of eruptive activity lasting several months to years (Young et al., 1998; Sparks and Young, 2002; Wadge et al., 2010; 2014), with the last phase ending in 2010. The eruptive activity has included lava dome extrusion, block-and-ash flows and Vulcanian explosions; periods of repose have been characterised by ash venting and continuous degassing (Wadge et al., 2014). The time-averaged lava extrusion has been 3 m^3s^{-1}, although rates exceeding 10 m^3s^{-1} have characterised some phases of dome extrusion (Wadge et al., 2010; Wadge et al., 2014). The SiO_2 content of historically erupted products has varied from 58 to 62 wt.% (Murphy et al., 2000; Zellmer et al., 2003b; Barclay et al., 2010; Christopher et al., 2014). The average SO_2 emission rate from 1995 to 2010 was ~530 t/d (Christopher et al., 2010) and largely decoupled from eruptive activity (Christopher et al., 2010; Edmonds et al., 2010; Christopher et al., 2015). Soufrière Hills Volcano continues to degas at ~ 430 t/d (Christopher et al., 2015). During periods of intra-eruptive repose, peaks in degassing of several thousand t/d have been associated with bursts in seismicity (VTs) and are sometimes accompanied by ash venting (Cole et al., 2014).

(c) *Tungurahua*, Ecuador (TUN), erupted in 1999 following 81 years of no eruptive activity. Slow lava extrusion and frequent explosive activity during phases of eruptive activity have limited lava dome growth. Between 1999 and 2006 Tungurahua alternated between explosive (Strombolian to Vulcanian) eruptions and relatively quiet periods dominated by ash venting and fumarolic activity. The most explosive activity occurred during July and August 2006 (Arellano et al., 2008), after which activity returned to frequent low-intensity Strombolian explosions (Steffke et al., 2010). Whilst the magma supply rate has varied over timescales of months (Wright et al., 2012), the long-term emission rate of ash has been approximately constant at >0.2 m^3s^{-1}, and possibly >0.4 m^3s^{-1} (Le Pennec et al., 2012). The eruptive products have compositions of 56-59 wt.% SiO_2 and show no systematic variation with time or eruptive style (Samaniego et al., 2011), except that major explosive events in 1866 and 2006 have included a minor dacitic component (Samaniego et al., 2011). Between 1999 and 2006, SO_2 fluxes varied from several hundred to thousands of t/d; degassing has been largely decoupled from eruptive activity (Arellano et al., 2008), although since 2006 daily SO_2 fluxes have decreased and appear to be better correlated with eruptive activity.

(d) *Popocatépetl*, Mexico (POP), has experienced several periods of eruptive activity in the 20th century. Most recently, eruptive activity was renewed in 1994 and has involved repeated periods of dome growth that have culminated in explosive eruptions and dome collapse. Extrusion rates have ranged from 0.5 to 4.1 m^3s^{-1} during dome-growth in 1996 and 1997; the long-term average has been 0.24 m^3s^{-1} (Delgado-Granados et al., 2001). Prior to 1995, Popocatépetl last erupted between 1920 and 1927 (Delgado-Granados et al., 2001) followed by several decades of minor degassing and ash venting (Brennan, 2007). Pyroclasts erupted between 1996 and 1998 ranged in bulk composition from ~ 59 to 64 wt.% SiO_2 (Athanasopoulos, 1997; Straub and Martin-Del Pozzo, 2001), with all compositions erupted contemporaneously (Witter et al., 2005). In 1994, average SO_2 fluxes were several thousand t/d. Similarly high SO_2 fluxes (30,000-50,000 t/d) marked explosive activity between 1996 and 1998 (Goff et al., 1998; Delgado-Granados et al., 2001). DOAS measurements of the plume in 2006 provide an average flux of 2450 t/d, with large daily variations not always associated with eruptive activity (Grutter et al., 2008).

3.4. Non-eruptive degassing regime

At volcanoes that have remained in a persistent regime throughout the 20*th* and 21*st* centuries (section 3.1.1), fumarolic activity may be sustained during periods of repose lasting years or even decades (e.g., Lascar; Gardeweg & Medina, 1994). One volcano in our database has not erupted during the 20th and 21st centuries but has exhibited sustained and persistent degassing of SO_2.

(a) *Kudryavy (Moyorodake/ Medvezhia)*, Russia (KUD), is a basaltic andesite volcano that has been in a persistent state of high temperature fumarolic degassing and phreatic activity since its last magmatic eruption in 1883 (Fischer et al., 1998; Korzhinsky et al., 2002). The only measurements come from a single campaign in 1995, which measured SO_2 fluxes of 73 ±15 t/d (Fischer et al., 1998).

4. Magmatic behaviour in persistent and episodic regimes

Geochemical analysis of erupted products and geophysical observations can provide semi-empirical evidence for different magmatic processes. We summarise these data for the fifteen dome-building volcanoes, with a particular focus on systematic variations in the behaviour of volcanoes in the different regimes.

4.1. Interaction of magmas

Evidence of mixing and mingling between different batches of magma are observed in all 14 volcanoes in our database that have erupted in the 20th century (Table 2 and references therein). Different magma batches typically vary in composition, although interactions are also observed between magmas or melts that are similar in composition but differ in temperature and crystallinity (Cashman and Blundy, 2013; Costa et al., 2013; Troll et al., 2013). Evidence for magma interaction over short timescales (days to years) is ubiquitous and includes: (1) disequilibrium mineral assemblages; (2) disequilibria between mineral assemblages and matrix glass; and (3) phenocryst zoning (Table 2). Zoning patterns, in particular, provide evidence that magma mixing is sustained over a range of times. Discrete magma mixing events may be associated with single explosive events (Pallister et al., 2008; Samaniego et al., 2011; Scott et al., 2013) or individual phases of effusive activity lasting months (Dirksen et al., 2006). Frequent and near-continuous magma mixing may accompany sustained lava effusion (Nakamura, 1995; Barclay et al., 2010; Turner et al., 2013).

The degree of mixing ranges from contemporaneous eruption of different magma compositions to the eruption of lavas that are homogeneous in bulk composition but heterogeneous on a thin section scale. Evidence for incomplete mixing includes banded lava or pumice, or mafic enclaves in more silicic host lavas. Where incomplete mixing is observed, historical activity tends to be episodic with moderate to long periods of inter-eruptive repose. Persistent activity, in contrast, tends to produce homogeneous lavas; here evidence for magma mixing is preserved only at the micro-scale, in melt inclusions, disequilibrium mineral assemblages, polymodal mineral compositions, and phenocryst zonation (Table 2).

4.2. Geophysical observations

4.2.1. Seismicity

Similar patterns of seismicity are observed across all the volcanoes in this review, with no apparent correlation with eruptive regime. Most volcanic earthquakes occur prior to and during eruptive activity. Renewed eruptive activity is generally preceded by elevated VT seismicity, with elevated LP seismicity immediately prior to eruption initiation. Levels of LP seismicity are highest at volcanoes in persistent regimes where degassing rates are high (e.g., Lascar, Popocatépetl; Asch et al., 1996). Hybrid events (LP seismicity with clear P & S wave arrivals) are commonly associated with dome-growth (e.g., Miller et al., 1998; Umakoshi et al., 2008).

Once a volcano has remained in a state of repose for more than a few months, the level of seismicity decreases, although episodic increases in VT seismicity are common and are often associated with elevated degassing and ash venting (Mastin, 1994; Ratdomopurbo et al., 2013; Budi-Santoso et al., 2013; Sernageomin, 2013; Cole et al., 2014). Seismic crises can occur during inter-eruptive repose; these may last for several months to several years with multiple felt earthquakes and no eruption of magma (Japan Meteorological Agency, 1996, Young et al., 1998).

4.2.2. Deformation

Geodetic measurements of far-field deformation are more common at volcanoes in an episodic regime than at those in a persistent regime (Table 3), although this apparent correlation could be coincidental, since many of the volcanoes in our dataset that exhibit episodic behaviour are located in developed countries, which tend to have well-established monitoring and research capabilities (e.g., USA and Japan). Alternatively, volcanoes in a persistent regime may lack far-field observations because only near-field observations are required for short-term forecasting. At episodic volcanoes, periods of repose may show inflation, whereas deflation is primarily associated with phases of dome growth (Table 3). The timescales of inflation vary from years (e.g., Augustine, Redoubt; Cervelli et al., 2010; Grapenthin et al., 2013a) to decades (e.g., Augustine, Unzen; Kohno et al., 2008; Lee et al., 2010). Soufrière Hills Volcano, which has remained in a persistent regime since 1995, also exhibits cycles of far-field inflation and deflation coincident with eruptive and non-eruptive cycles of months to years (Odbert et al., 2014a). Where persistent behaviour includes short phases of lava effusion and explosive eruption (e.g., Bezymianny, Merapi, Colima), InSAR measurements suggest negligible far-field deformation (Chaussard et al., 2013; Grapenthin et al., 2013b).

5. Conceptual magmatic models for dome-building volcanism

The interpretation of magmatic processes and their relation to volcanism requires a conceptual model for volcanic activity. From this perspective, understanding the geometry of pre-eruptive magma storage is critical. A widespread, but not universal, observation about dome-building volcanoes is that magma is supplied from storage regions in the shallow crust (Table 5 and references therein), which has stimulated models of eruptive activity modulated by shallow magma chambers (Gourgaud et al., 1989; Murphy et al., 2000; Mora et al., 2002; Humphreys et al., 2008; Roberge et al., 2009; Larsen et al., 2010; Samaniego et al., 2011; Shcherbakov et al., 2011; Coombs et al., 2013; Turner et al., 2013). There is also evidence, however, for deeper levels of magma storage, including mid- to lower crustal earthquakes associated with volcanism (McNutt, 2005; Power et al., 2013), deep sources of deformation (Pritchard and Simons, 2002; Elsworth et al., 2008), and deep sources of gas (Troll et al., 2013; Hautmann et al., 2014; Christopher et al. 2015). Petrological and geochemical data help to quantify the importance of deep igneous processes (Hildreth, 2004; Troll et al., 2013; Edmonds et al., 2014), including mineral assemblages that record multiple crystallisation depths (Matthews et al., 1994; Martel et al., 1998; Scott et al., 2012; Cashman and Blundy, 2013; Turner et al., 2013) and geochronology evidence for long crustal residence times (Volpe and Hammond, 1991; Zellmer et al., 2003b; Cooper and Reid, 2008; Dosseto et al., 2008; Claiborne et al., 2010). Finally, tomographic images of arc volcanoes suggest magma storage occurs at different depths throughout the crust (e.g., Koulakov et al., 2013).

Here we place geochemical and geophysical evidence for transcrustal magmatic systems in the context of our categorisation of temporal variations in the historical records of lava dome-building volcanoes. Specifically, we address the question of the extent to which observed regimes are consistent with non-linear processes associated with a shallow magma chamber, or whether they require involvement of vertically extensive crustal processes. Importantly, our aim is not to attribute the behaviour of an individual volcano or eruptive event to either paradigm, but instead to investigate the extent to which different eruptive regimes may reflect fundamentally different subsurface conditions, at least with regard to the extent and connectivity of individual magma lenses. We conclude that whilst storage of magma in the upper crust exerts an important control on when and what eruptive activity occurs, over historical timescales different patterns of volcanism can be better ascribed to a conceptual model based on complex behaviours of vertically extensive magma storage regions.

5.1. Shallow chamber paradigm

A common model for eruptive activity at dome-building volcanoes is a shallow melt-dominated magma chamber that is replenished from depth and periodically discharges magma (Fig. 7). In this paradigm, intrusion of mafic magma from depth is assumed to trigger the eruption of shallow magma bodies (Gourgaud et al., 1989; Murphy et al., 2000; Mora et al., 2002; Humphreys et al., 2008; Roberge et al., 2009; Larsen et al., 2010; Samaniego et al., 2011; Shcherbakov et al., 2011; Coombs et al., 2013; Turner et al., 2013). The concept of mafic triggers derives primarily from near-ubiquitous evidence for magma mixing (Table 2). Intruding mafic magma also provides an explanation for observations of excess SO_2 (that is, emission of SO_2 in excess of amounts dissolved in the erupted magma; Andres et al., 1991; Wallace, 2003; Shinohara, 2008; Christopher et al., 2010; Wallace and Edmonds, 2011), as SO_2 is much more soluble in mafic magmas that in silicic magmas (Wallace, 2005). Petrologic evidence for shallow magma storage comes from saturation pressures recorded in melt inclusions, as well as phase assemblages consistent with storage pressures ≤ 200 MPa (e.g., Moore and Carmichael, 1998; Blundy and Cashman, 2001; Couch et al., 2001).

The modulating effect of shallow magmatic systems on eruptive processes is supported by geophysical data. Deflation during eruptive periods can be related to magma discharge from upper- or mid-crustal magma chambers (Nishi et al., 1999; Elsworth et al., 2008; Cervelli et al., 2010; Mattioli et al., 2010; Grapenthin et al., 2013a). Furthermore, most seismicity associated with unrest and eruptive activity is restricted to depths of <10 kilometres (Ratdomopurbo and Poupinet, 2000; Moran et al., 2008; Power and Lalla, 2010; Thelan et al., 2010; Petrosino et al., 2011). Seismicity is commonly inferred to record the stress effects of the formation of magma transport pathways (Kilburn, 2003; Scandone et al., 2007) and rise of magmatic fluids from shallow magma chambers (Neuberg, 2000; McNutt, 2005; Chouet and Matoza, 2013). Shallow seismicity is also associated with shallow magma intrusion (Moran et al., 2011), pressurisation and pre-eruptive inflation.

Patterns of recharge have been used to explain pulsatory and cyclic behaviour (Melnik and Sparks, 1999; Barmin et al., 2002). Indeed it is likely that volcanism is modulated, jointly, by different parts of the volcanic system, including shallow magma chambers. However, because the mechanism for replenishment in the shallow chamber paradigm is poorly understood, it cannot completely explain the hierarchy of common behaviours and similar patterns and styles of eruptive activity.

5.2. Transcrustal destabilisation

A shallow magma chamber can be envisaged as the upper manifestation of a much larger transcrustal system (Marsh, 2000; Cañón-Tapia and Walker, 2004), which may extend throughout the crust and even into the mantle (Fig. 8). Such a conceptual model implies that mechanisms for unrest and eruption may involve more complex processes than discrete intrusions. Specifically, magmatic systems can be viewed as comprising extensive bodies of crystal-rich magma (mush) with interspersed lenses of melt and magmatic fluids that are formed by repeated intrusion of mafic melts from the mantle (Solano et al., 2012; Connolly and Podladchikov, 2013; Christopher et al. 2015). From this perspective, melt and fluid layers are susceptible to destabilisation, and reorganisation of these layers may provide a trigger for eruptive activity in mafic (Tarasewicz et al., 2012; Neave et al., 2013) and large caldera systems (Cashman and Giordano, 2014). Similarly, transcrustal processes can explain apparently anomalous activity in some dome-building volcanoes (Christopher et al., 2015), whilst also providing a source of deep magma and magmatic fluids. Key is the concept of the meta-stability of transcrustal magmatic systems and destabilisation events that involve either all or part of the melt-bearing region (Fig. 8a,b), with or without contemporaneous eruptive activity (Fig. 8c).

Temporal and spatial variations in the susceptibility of vertically extensive magmatic systems to destabilisation can also explain long-term patterns of eruptive activity at dome-building volcanoes. First we return to the question of mafic eruption triggers, particularly as evidenced by varying intensities of magma mixing in the eruptive products. Mixing has long been used to describe the homogenisation of two melts, as manifested in linear two-element geochemical diagrams. Mixing, however, is increasingly viewed as involving complex interactions between melts and crystal mushes (Blundy et al., 2008; Humphreys et al., 2009; Cashman and Blundy, 2013). From this perspective, the role of mixing as a primary mechanism of eruption triggering is less clear. In fact, mixing may be an effect, as much as a cause, of eruptive activity, particularly if triggered initially by destabilisation of the magmatic system. Destabilisation could occur from the bottom up, with deep level disturbances propagating into the upper crust (e.g., Christopher et al., 2015). Alternatively destabilisation could propagate downward, driven by a downward propagating decompression wave caused by early eruptive activity (e.g., Tarasewicz et al., 2012). In either case, destabilisation of a complex magmatic system can force interaction among melt lenses and intervening crystal mush zones (e.g., Cashman and Giordano, 2014).

Another important aspect of dome-building volcanoes in hydrous arc system relates to the evolution and migration of volatiles. Fractionation of deeply sourced arc basalts (Annen et al., 2006) can cause sulphur saturation of more evolved felsic melts in the middle and lower crust (Wallace, 2005). This occurs because, although sulphur is highly soluble in basaltic melts, it is much less soluble in felsic melts (Lesne et al., 2011). As a consequence, SO_2 degassing can start deep within the crust, well below levels of shallow magma storage. The same is true of CO_2, where strong pressure-dependence may promote CO_2 exsolution throughout the crust (e.g., Blundy et al., 2010). Different volatile elements can therefore be fractionated and stored independently at multiple crustal levels during inter-eruptive periods of repose. Separation of volatiles from their parental magmas during these periods of repose can explain both the excess SO_2 degassing and decoupling of gas and magma fluxes observed in dome-building volcanoes in the persistent regime. Ascent of magmatic fluids from depth can also explain decoupling of shallow seismicity from eruptive activity (Moran, 1994; Roman et al., 2004; Girona et al., 2014; Hautmann et al., 2014, Christopher et al., 2015). Similarly, deep (20 to 40 km), long period earthquakes in arcs can be explained by exsolution and migration of insoluble gases like CO_2 (McNutt, 2005; Nichols et al., 2011). Finally, independent rise of magmatic fluids may cause the surface deformation observed at passively degassing volcanoes (Girona et al., 2014), and can help to explain varying timescales of far-field inflation at dome-building volcanoes.

5.3. Persistent dome-building behaviour

The persistent regime combines pulsatory phases of effusive eruption and homogeneous magma compositions with sustained, and decoupled, degassing (section 3.1.1), and is typical of 'open' system behaviour (e.g., Chaussard et al., 2013). These observations appear to require a dynamically connected, through-going magmatic system to sustain a persistent regime, especially over long timescales. Large explosive eruptions in these systems involve magma that is more mafic (deeper, more volatile-rich) than that produced during effusive activity. Transitions between persistent shallow-seated effusive behaviour and intermittent deep-seated explosions thus suggest that magmatic systems at these volcanoes are vertically extensive and (transiently) dynamically connected, at least to mid-crustal levels (Fig. 8a). More generally, rapid transport of deep, mafic and volatile-rich magmas is commonly invoked for paroxysmal events at open-system basaltic volcanoes (e.g., Métrich et al., 2010; Sides et al., 2014).

Eruptive activity at a second group of volcanoes in the persistent regime (section 3.1.2) reactivated with major explosive events that followed long periods of inter-eruptive repose. In these volcanoes, the explosively erupted magma is more evolved than subsequent extrusive lavas, which show gradual decreases in SiO_2 with time. Progressive variation in the composition of erupted products can be explained by a vertically extensive and connected magmatic system, although a more traditional zoned magma chamber model (e.g., Scott et al., 2013) cannot be excluded on the basis of these characteristics alone. Most important from a volcanic hazards perspective, however, are the compositional homogeneity and paucity of mafic enclaves (Scott et al., 2013; Turner et al., 2013) that characterise activity. This suggests that these persistently active volcanoes have relatively stable magmatic systems that are less susceptible to large-scale destabilisation than during inter-eruptive periods of repose.

The observation that explosive eruptions may be either more or less evolved than magma erupted effusively from the same system provides insight into explosive eruption triggers. ‘Top-down’ destabilisation is observed in cases of edifice collapse following either a long duration in a state of inter-eruptive repose (Bezymianny, Santiaguito, Mount St. Helens) or sustained effusive activity and dome growth (Lascar). Top-down triggering taps evolved magma from high in the crust. ‘Bottom-up’ destabilisation, in contrast, explains explosive events that appear to be triggered by the rapid rise of deep-derived magmas (Merapi, Colima, Shiveluch).

Persistent eruptive regimes require that the magmatic system is ‘open’, or vertically connected. Under these conditions, eruptive activity may be neither strictly ‘top down’ nor ‘bottom up’ but instead reflect the intrinsic instability of complex magmatic systems. One mechanism of instability relates to the behaviour of crystal-melt suspensions, which segregate to form separate layers of melt and/or volatiles. We suggest that these (unstable) layers can reorganise rapidly to trigger abrupt changes in eruption patterns. Layer destabilisation may occur because of external triggers, such as regional tectonics or eruptions of neighbouring volcanoes (e.g., Walter et al., 2007; De la Cruz-Reyna et al., 2010; Biggs et al., 2016). Alternatively, passive volatile release during a state of repose may cause the pressure distribution sufficiently to cause replenishment of magma from depth (Girona et al., 2015). Such mechanisms are not restricted to dome-building volcanoes, and have been observed at basaltic arc systems that are vertically well-connected and exhibit complex feedback mechanisms for magma discharge (e.g., Stromboli; Ripepe et al., 2015).

5.4. Episodic dome-building behaviour

Dome-building volcanoes that show episodic behaviour are characterised by diminishing eruption rates with time and correlations between lava extrusion and volatile emission. Both characteristics are indicative of closed system behaviour, which likely reflects the formation and ascent of discrete magma batches. In many of these volcanoes, however, there is evidence for the interaction of different melts (Table 3), which argues against discrete melt batches. In fact, volcanoes in an episodic regime that erupt frequently (e.g., Augustine, Redoubt) erupt a wide range of compositions during any individual eruption. This suggests that small melt batches evolve independently and interact only during eruptions (e.g., Roman et al., 2006). More homogeneous magma compositions produced by volcanoes that erupt less frequently (e.g., Mont Pelée, Unzen), in contrast, suggests that magma mixing may occur prior to, as well as during, eruptive episodes (Browne et al., 2006).

A magmatic model based on the shallow chamber paradigm suggests that if magmas are generated at a constant rate at depth, then the duration a volcano remains in a state of repose will control the volume of magma components (volatiles, melt, and crystal mush) that can accumulate; this time-dependent volume may, in turn, influence the duration a volcano remains in an eruptive state. In contrast, under the transcrustal paradigm, variations in frequency and duration of eruptive episodes could reflect patterns of destabilisation within the deeper system. Stability may be controlled by physical properties, such as the size of magmatic systems, or fundamental parameters such as the flux of magma at depth (Caricchi et al., 2014).

5.5. Large-magnitude explosive eruptions

The dynamic nature of eruptive activity at dome-building volcanoes suggests that past behaviour is likely to influence stability of the magmatic system, and future patterns of eruptive activity. For example, edifice collapse associated with large magnitude explosions is known to reduce storage pressures (Pinel & Albino, 2013) and enable the eruption of denser, more mafic magmas, which would otherwise stall at shallow depths (Pinel & Jaupart, 2000; 2005). Indeed, volcanoes in our dataset where the onset of eruptive activity involved edifice collapse may well have shown different long-term patterns of eruptive activity if the onset of eruptive activity had been effusive. Conversely, where edifice collapse occurred after a long duration in a state of repose (~millenia), persistent activity appears to last for many decades (e.g. Bezymianny, Santiaguito; Fig. 2). Removal of the edifice during these large magnitude events thus appears to destabilise the system (Pinel & Albino, 2013).

A different situation occurred at Mount St. Helens in 1980, where the initial explosive eruption was related to edifice collapse, but the prior repose interval was only slightly more than a century. In this case, persistent behaviour continued for only six years. It is noteworthy that the volcano reactivated between 2004-2008

(Fig. 2) after two intervening episodes of inferred recharge from deeper in the system (Moran, 1994; Musumeci et al., 2002). The limited persistent activity of Mount St. Helens compared to Bezymianny and Santiaguito may be simply a result of shorter inter-eruptive repose, which could limit the accumulation of eruptible magma. Alternatively, it may be related to the dacitic composition of magma at Mount St. Helens, compared to the andesitic magmas of Bezymianny and Santiaguito.

6. Conceptualising volcanism in time

Records of eruptive activity inform our understanding of magmatic processes and are commonly the basis for forecasts of eruptive activity. Traditionally, volcanism is conceptualised as a series of discrete eruptions (Siebert et al., 2010) that are characterised by measureable properties such as magnitude, duration, intensity and eruptive style (Mercalli, 1907; Newhall and Self, 1982; Pyle, 2000). The intervals between eruptions are usually referred to as repose periods and at these times the volcano is commonly interpreted to be in a dormant state. This ontology of volcanic activity as a point process stems from geological records that comprise a punctuated series of distinct deposits, and historical records that are biased towards occasional memorable, and generally explosive, individual events (Szakács and Cañón-Tapia, 2010).

A different perspective emerges from our analysis of long-term eruptive behaviours at fifteen well-studied dome-building volcanoes. Instead of identifying discrete eruptions, we suggest that periods of eruptive activity be classified in the context of the eruptive history. For example, at two different volcanoes, periods of dome extrusion may have similar lava volumes, rates of extrusion, and duration, but can occur in very different situations (e.g., as period of episodic activity or a phase of lava extrusion in a persistent regime). Including time as a key parameter highlights the shortcomings of viewing volcanoes as in only either an “eruptive” or “non-eruptive” state. Critically, this ontology of volcanic activity should influence interpretation of both volcanic data and inferred magmatic processes.

The evidence for different states of repose provided by our case studies suggests that lava dome-building volcanoes can be characterised by three, rather than two, states: (i) a state of dormancy without abnormal geochemical or geophysical signals (inter-eruptive); (ii) an active state in which magma is erupted; and (iii) a state of unrest where perturbations in the system at depth cause marked and measurable departures from a background (dormant) state (intra-eruptive). Historical records allow volcano classification by one, two or all three of these states. Over geological timescales, we assume all volcanoes experience periods of dormancy or inter-eruptive repose periods. Intra-eruptive repose periods can be more difficult to identify, and present the greatest challenges for volcanic hazard assessment.

Inter-eruptive repose occurs at volcanoes that show episodic behaviour, meaning that they conform more closely to the traditional interpretation of volcanism as a sequence of discrete eruptions. The duration of inter-eruptive repose can vary from many years (e.g., Augustine, Redoubt) to centuries (e.g., Mount Unzen), but in all cases the volcano is deemed to be in a dormant state between eruptive periods. Volcanoes classified as dormant can move into the unrest state with increases in geophysical (e.g., seismicity, and deformation) and fumarolic activity. For example, prior to 1992, Soufrière Hills Volcano had been in a dormant state for over 350 years, but had moved into a state of unrest in 1896-97, 1933-37 and 1966-67, as evidenced by elevated fumarolic activity and intermittent seismic crises (Shepherd et al., 1971; Odbert et al., 2014b). Similar seismic crises were also observed throughout the 20th century at Mt Unzen prior to eruption onset in 1991 (Japan Meteorological Agency, 1996).

Intra-eruptive repose is observed at volcanoes in a persistent regime where intervals between pulses of eruptive activity can last for months to years or even decades, especially following major explosive events (e.g., Bezymianny, Colima, Lascar, Santiaguito). At these volcanoes, however, periods of repose are characterised by sustained degassing, intermittent seismicity and ash venting, all of which indicate magmatic unrest that is not consistent with dormancy. Importantly, unrest under these conditions does not imply imminent eruptive activity, as observed in the example of Kudryavy where a persistent state of high temperature fumarolic degassing and phreatic activity is inferred since its last magmatic eruption in 1883 (Fischer et al., 1998; Korzhinsky et al., 2002).

By characterising exchangeable traits of volcanic behaviour, we demonstrate that the case histories in this review challenge the depiction of volcanism as a point process in time, and raise questions about what it means to say that a volcano is dormant and how to view periods of non-eruptive volcanic unrest. Importantly, several of our case study volcanoes show unrest signals that are greatly elevated after eruptive activity, in comparison to unrest signals when a volcano is in a period of longer dormancy (e.g., Merapi, Lascar, Bezymianny). For this reason, we suggest that the state of unrest be used to classify volcanic activity, with the caveat that it is important to recognise when the distinction between unrest and dormancy is determined by a change in detection thresholds and not by true changes in the state of a magmatic system.

The conceptualisation of eruptions as discrete events has been, and still is, fundamental to volcano classification, volcano databases, data selection in probabilistic forecasts and the interpretation of magmatic processes. The GVP database (Siebert et al., 2010) is the only comprehensive global compilation of active volcanoes, and is widely used to characterise volcanism, inform interpretations of volcanic processes and provide evidence for eruptive forecasts. The catalogue is predicated, however, on viewing volcanism as an alternation of two different events, repose period and eruption. The GVP further defines repose as any cessation in eruptive activity that exceeds 3 months. This definition works well for some of our case studies (e.g., Augustine, Redoubt), but is problematic for volcanoes showing prolonged intermittent activity (e.g., Bezymianny, Mount St. Helens, Merapi, Soufrière Hills Volcano). More critically, the GVP database structure does not record information that is useful for both characterising and interpreting states of eruption and unrest.

7. Information exchangeability in forecasting volcanic activity

In recent decades probabilistic methods have become established as the principal approach to forecasting volcanic activity. Importantly, they can capture both aleatory and epistemic uncertainties and include multiple strands of evidence and different kinds of data (e.g., Newhall and Hoblitt, 2002; Aspinall et al., 2003; Marzocchi et al., 2004; Sparks and Aspinall, 2004; Neri et al., 2008; Sobradelo et al., 2013; Aspinall and Woo, 2014; Hincks et al., 2014; Sobradelo and Martí, 2015). Probabilistic approaches, however, have highlighted specific challenges associated with eruptive forecasts at dome-building volcanoes. The most acute problem relates to a lack of data, especially at volcanoes with infrequent eruptive activity in episodic regimes. The issue of sparse data, however, can also manifest at volcanoes in a persistent regime, when forecasting a long period of dormancy. Consequently, an important question in volcanology is whether observations from a number of well-studied volcanoes can be used to reduce uncertainty associated with a lack of data at an individual volcano. This is especially pertinent with the development of global databases (e.g., Smithsonian GVP; La MEVE; WovoDAT) and global approaches to data collection (e.g., Biggs et al., 2014; Carn et al., 2016).

Importantly, the principle of using observations from multiple volcanoes requires an assumption of information or data exchangeability (e.g., Bebbington, 2014; Sheldrake, 2014). From a Bayesian perspective, exchangeability requires a (subjective) level of similarity, but importantly, does not require the behaviours of the objects to be identical (Bernado, 1996; Gelman et al., 2013). Hence, similar behaviours and traits based on phenomenological observations identified in this review could be a basis for assumptions of exchangeability.

7.1. Approaches to assuming exchangeability

One approach to the problem of limited data is through expert judgement (Aspinall and Cooke, 2013), where experienced scientists assess key parameters and likelihoods of future events based upon their own knowledge, experience and judgements. In principle, the experts should also estimate the uncertainty of their likelihood assessment (Aspinall, 2010). Issues of exchangeable data arise when comparisons with other volcanoes enter into these discussions, at least informally. In many volcano emergencies, for example, such assessments are *ad hoc* and executed largely through unstructured discussion within a volcano observatory team. These efforts can be improved by formalised methods for pooling expert judgements, as illustrated by hazard assessments for Soufrière Hills Volcano (Wadge and Aspinall, 2014). Importantly, the experience of an expert in previous volcanic crises will likely influence their views. This illustrates a major disadvantage in the informal approach, where the basis for assessment may be anecdotal and biased towards previously witnessed discrete events. Moreover, even the most experienced volcanologist is unlikely to have witnessed more than a handful of eruptive events, so these comparisons warrant a more rigorous approach to identifying appropriate analogue volcanoes and to what extent comparisons are justified.

Broad classifications for volcano 'type' based on characteristics such as morphology (Rittmann, 1962; Siebert et al., 2010) or eruptive style (e.g., Hawaiian, Strombolian, Peléean, Vulcanian and Plinian; Bullard, 1962) provide a natural framework for assumptions of exchangeability. However, as the analysis in this review has outlined, the historical records of dome-building volcanoes are only partially exchangeable. Thus, whilst exchangeability may be assumed based on volcano 'type' (e.g., lava-dome building), the limitations and sources of aleatory uncertainty of probabilistic forecasts that arise from this assumption must be addressed by identifying both the underlying conceptual model and the common process that together form the basis for exchangeability. It is equally important to recognise key differences when applying exchangeability. This is evident in a cladistics analysis of Japanese arc volcanoes (Hone et al., 2007) that identified three broad volcano types grouped by composition, eruptive products and morphological characteristics. Differences are also identified in a study of magnitude-frequency relations that treats separately closed- and open-vent stratovolcanoes (Whelley et al., 2015).

7.2. Volcanic unrest

The concept of exchangeability can be used to interpret volcanic unrest, which is an almost a ubiquitous precursor to volcanic activity. Signs of unrest are typically monitored using geodetic, geophysical and geochemical surveys (e.g., Swanson et al., 1983; Sparks, 2003; Sandri et al., 2004; Jaquet et al., 2006; Chouet and Matoza, 2013). Critically, these monitoring data are used to infer magmatic processes (e.g., Voight, 1988; Kilburn, 2003; Smith et al., 2007; Lavallée et al., 2008), an approach that requires implicit, if not explicit, comparisons with unrest from previous activity.

The simplest approach to comparing volcanic unrest among volcanoes is to consider all signals of unrest as weakly exchangeable, with variations in the duration, pattern and occurrence the result of aleatory uncertainty, reflecting the natural variability of volcanic systems. A stronger assumption of exchangeability compares signs of unrest between volcanoes of a specific type (e.g., Phillipson et al., 2013), with the underlying assumption that different types of volcanoes should behave in similar ways. Our work shows, however, that even particular volcano ‘types’ can vary greatly in behaviour. In particular, we have shown that intra-repose unrest of a volcano in a persistent regime may reflect a very different state of activity than inter-repose unrest in the episodic regime, which may herald the onset of explosive activity. In this way, our categorization of eruptive activity at dome-building volcanoes as episodic (closed-system) or persistent (open-system) could help to further refine classifications of unrest, particularly with regard to the problem of distinguishing between non-eruptive unrest and unrest related to reawakening of a volcano in repose (e.g., Phillipson et al., 2013). Furthermore, by attempting to understand differences in episodic and persistent behaviour in terms of magmatic processes, this provides an opportunity to interpret patterns of volcanic unrest in terms of these magmatic processes, rather than purely the outcome of eruptive activity (e.g., Hincks et al., 2014).

8. Conclusions

We have shown that dome-building volcanoes show two fundamentally different patterns of eruptive behaviours that we term episodic and persistent. Episodic behaviour is characterised by discrete episodes comprising an explosive onset followed by effusion and dome formation. In this regime, explosively erupted magma may have more evolved compositions than later-erupted lava. Excess gas emissions may be observed during explosive activity, but SO_2 fluxes are correlated with the eruption of lava and diminish to negligible levels following the end of each eruptive episode. Persistent behaviour, in contrast, is characterised by frequent (~yearly) phases of eruptive activity and sustained gas fluxes during periods of intra-eruptive repose. Erupted material is often compositionally homogeneous, except during explosive (paroxysmal) eruptions, which often involve deep, more primitive, magma compositions. Alternatively, at volcanoes that have not erupted for a long time (~millenia), large explosive Plinian eruptions can be followed by persistent behaviour where lava compositions become less evolved with time. Importantly, all volcanic activity is episodic if viewed over sufficiently long times.

We explain the variety of episodic and persistent behaviour through the lens of vertically extensive magmatic systems, where the extent of connectivity within the system dictates episodic or persistent behaviour (e.g., Christopher et al., 2015). Importantly, open-system behaviour involves transient, dynamically triggered magma transfer from depth but continuous gas transfer through the system. Episodic behaviour, in contrast, records eruption and gas loss from a magma batch that is quickly isolated from deeper (mid-crustal) reservoir. An interesting question relates to the importance of volatiles and volatile-rich melts in determining the stability of a magmatic system, particularly transitions between episodic and persistent regimes, and eruption triggering in episodic regimes (e.g., Borisova et al., 2014; Christopher at al., 2015; Girona et al., 2015).

From a hazard forecasting perspective, our 15 case studies show that dome-building volcanic activity cannot be characterised by a point process. This observation highlights a key ontological issue for volcanology. Discrete eruptive events can appear similar in nature in both an episodic and persistent regime, but are associated with different states of repose and long-term behaviour. Therefore, when analysing volcanic data, and interpreting magmatic processes, it is important to characterise eruptive activity in the context of the longer-term behaviour of a volcanic system. We have shown that gas data, in particular, may help to discriminate between inter- and intra-eruptive repose. Also important are patterns of seismicity, which provide information on the depth and volume of magma storage (e.g., White and McCausland, 2016).

Also important for hazard forecasting is developing a method to determine how monitoring data from well-observed volcanoes can be used to inform interpretations of monitoring data from periods of unrest at less-studied volcanoes. Such an approach is feasible, but requires an understanding of the extent to which the monitoring data can be considered exchangeable. We suggest that exchangeability can be formalised by assessing temporal patterns in volcanic phenomena (especially relative patterns of eruption, degassing and repose), even if the datasets have different spatial and temporal data. From a theoretical standpoint, linking assumptions of exchangeability (e.g., episodic vs. persistent) to conceptual models of volcanic systems (e.g., closed vs. open) provides a mechanism to interpret monitoring data using a framework of magmatic processes.

Importantly, the approach employed in this review cannot be used to identify unique magmatic processes at individual volcanoes, and in that sense cannot replace ‘in-depth’ studies of individual volcanic systems. However, it provides a conceptual framework for interpreting common processes at dome-building volcanoes. From a broader perspective, our work demonstrates the value of constructing a hierarchical framework for volcanic activity based on exchangeable behaviours. We suggest that this approach could be extended to volcanoes with other types of characteristic activity, and thus provides a holistic approach to analysing global volcanic records.

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Figure Captions:

(1.5 column)
Figure 1: Locations of the 15 dome-building volcanoes in this study: (a) Augustine; (b) Bezymianny; (c) Colima; (d) Kudryavy; (e) Lascar; (f) Merapi; (g) Mount St. Helens; (h) Mont Pelée; (i) Popocatépetl; (j) Redoubt; (k) Santiaguito; (l) Shiveluch; (m) Soufrière Hills Volcano; (n) Tungurahua; (o) Mount Unzen. They are all found in subduction settings: either oceanic-continental or oceanic-oceanic boundaries.

(1.5 column)
Figure 2: Binary plots indicating whether (magmatic) eruptive activity (ash explosions and lava dome growth) was recording in each year since 1800 C.E, at each of the 15 volcanoes in this study. Importantly, the red bars do not equate to continuous eruptive activity, but instead are meant to indicate the variation in long-term patterns of eruptive activity. Labels are MER - Merapi; LAS – Lascar; COL – Colima; SHI – Shiveluch; SAN – Santiaguito; BEZ – Bezymianny; POP – Popocatépetl; TUN – Tungurahua; SHV - Soufrière Hills Volcano; HEL - Mount St. Helens; AUG – Augustine; RED – Redoubt; UNZ – Unzen; PEL – Pelée; KUD – Kudryavy. Volcanoes with the most persistent behaviour are found towards the top of the figure, and we have highlighted issues with specifically identifying a persistent regime in older records. The record of volcanic activity is based upon the Smithsonian database (Siebert and Simkin, 2002), and references specific to each volcano that can be found in section 3 and the supplementary material.

(Single column)
Figure 3: Representative cartoons for the two different eruptive regimes that are identified in this review; (a) Episodic behaviour, where the duration a volcano remains in an eruptive state is proportionally much shorter that the duration it remains in non-eruptive state. Degassing is temporally correlated with eruptive activity, and the regime is characterised by periods of no eruptive in which degassing is negligible, which we define as inter-eruptive repose; (b) Persistent

behaviour, where the duration a volcano remains in an eruptive state is proportionally similar to the duration it remains in non-eruptive state. Degassing is not necessarily temporally correlated with eruptive activity, and the regime is characterised by periods of no eruptive in which degassing is continuous and sustained, which we define as intra-eruptive repose. (c) A third mixed regime is characterised to identify how a volcano can exhibit both episodic and persistent behaviour in its eruptive record.

(Double column)
Figure 4: A hierarchical construct for historical eruptive activity at dome-building volcanoes. The first sub-level of this construct identifies the two different behaviours, episodic and persistent. The second sub-level of this construct identifies two different styles of episodic and persistent behaviour that are observed in historical records, over identical timescales (i.e. between points a and b). Key characteristics for each behaviour are identified in the boxes below each cartoon.

(Double column)
Figure 5: (a) Episodic behaviour at Augustine between 1970 and 2008, consisting of four eruptive episodes lasting months (red lines represent onsets), adapted from Power and Lalla, (2010). SO_2 degassing (orange) is temporally correlated with the eruptive episodes, as indicated by the data from McGee et al., (2010), overlaid on the lower chart. Black bars represent seismicity, which is elevated prior and during eruptive episodes; (b) Persistent behavior at Merapi between 1990 and 2006, with several phases of dome growth (blue bars) and associated explosions (blue vertical arrows), adapted from Ratdomopurbo et al., (2013). SO_2 degassing (orange) is temporally uncorrelated with eruptive activity, as observed by the overlaid data between 1992 and 1998. Seismicity is correlated with phases of eruptive activity, as indicated by the variation in the cumulative seismic energy (red line).

(Single column)
Figure 6: Estimated effusion rate (blue dots) at Unzen between 1990-1995, from Nakada et al. (1999). This is an example of a single eruptive episode at Unzen that lasted 5 years between 1990-1995 (Fig. 2). The latter stages of the eruptive episode are characterised by crystal-rich lavas and low effusion rates. During the eruptive episode, however, there are periodic increases in effusion rate, such as in 1993.

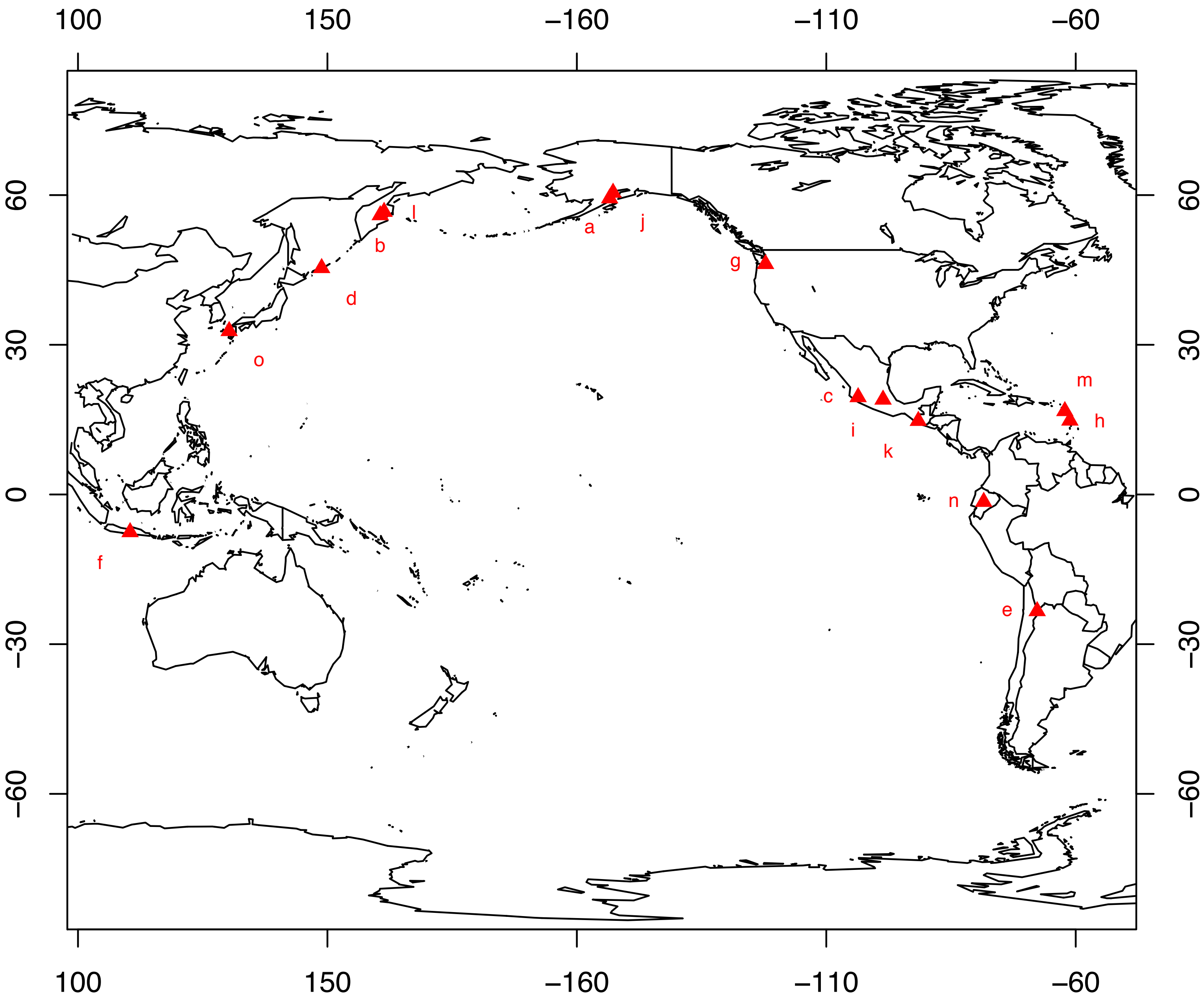
(Single column)
Figure 7: Estimated extrusion rates (blue dots) for 23 phases of dome growth at Bezymianny volcano between 1993 and 2008, from van Manen et al., (2010). This pattern of activity is an example of a persistent regime, in which frequent periods of dome-growth occur, with a consistent long-term extrusion rate. However, the intensity and frequency of phases of dome growth can vary. The red dashed line indicates the cumulative extruded volume, in which periods of dome growth and repose can be observed.

(Single column)

Figure 8: Example of a conceptual model for eruptive activity associated with the shallow chamber paradigm at La Soufrière, Guadeloupe, adapted from Hincks et al. (2014), where geophysical and geochemical observations at the surface are interpreted in terms of shallow crustal magmatic processes.

(Single column)

Figure 9: Schematic for the interaction of melt layers in a transcrustal magmatic system at lava dome-building volcanoes. Possible scenarios for eruptive activity and volcanic unrest; (a) complete destabilisation of the tran- scrustal system, involving deeply sourced mafic melts that provide volatiles and heat, resulting in major explosive activity; (b) partial destabilisation of the transcrustal system involving magma stored in shallow crustal regions resulting in effusive and minor explosive activity; (c) partial destabilisation of the magmatic system resulting in volcanic unrest but not eruptive activity. Importantly, this is in no way a true representation of the structure and dimensions of magmatic systems at lava dome-building volcanoes as they are found in subduction zones. Indeed, perpendicular to tectonic plate margins the arc widths of active volcanism are generally very narrow (~5 km or less).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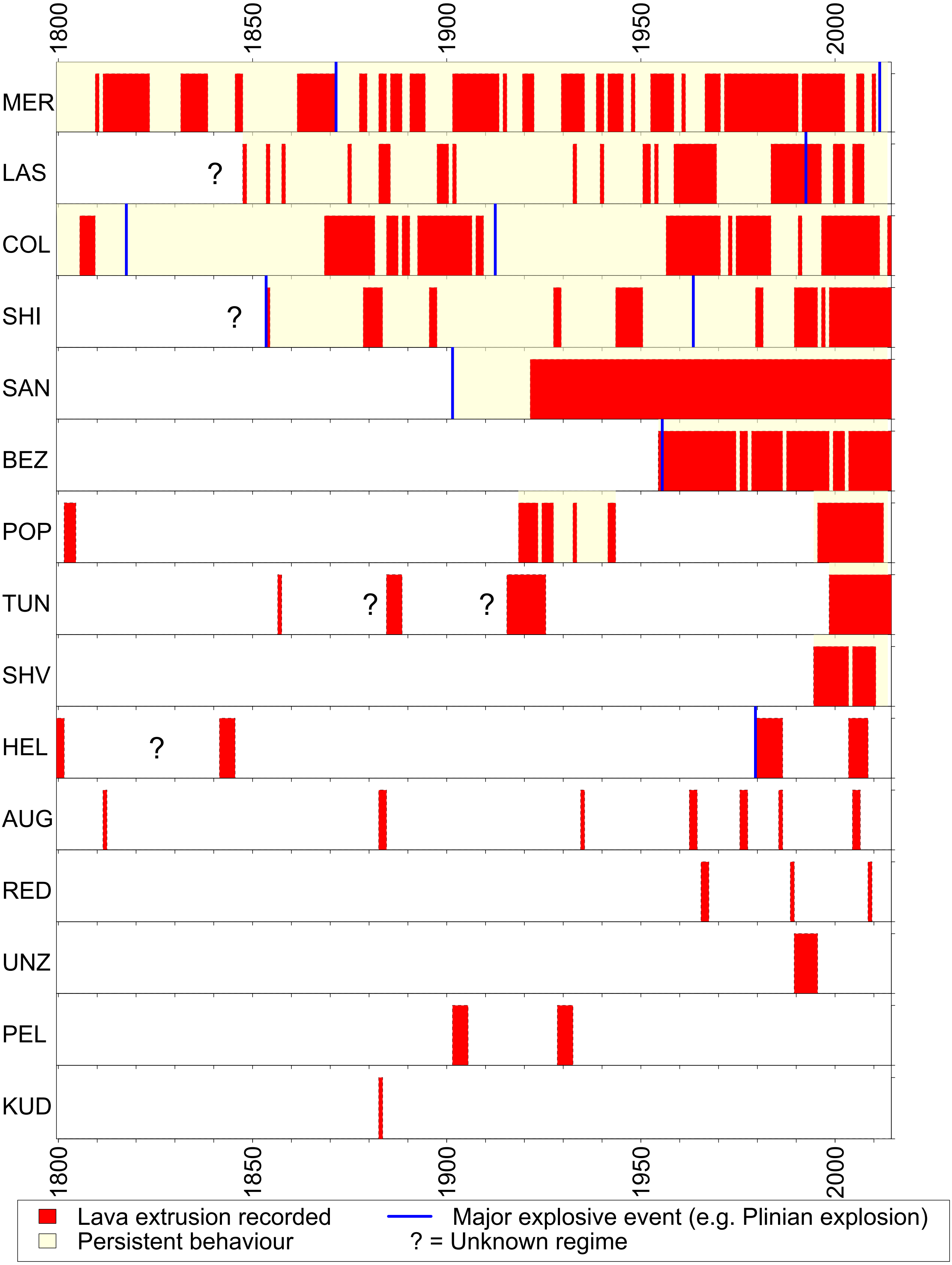
1800
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TUN
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HEL
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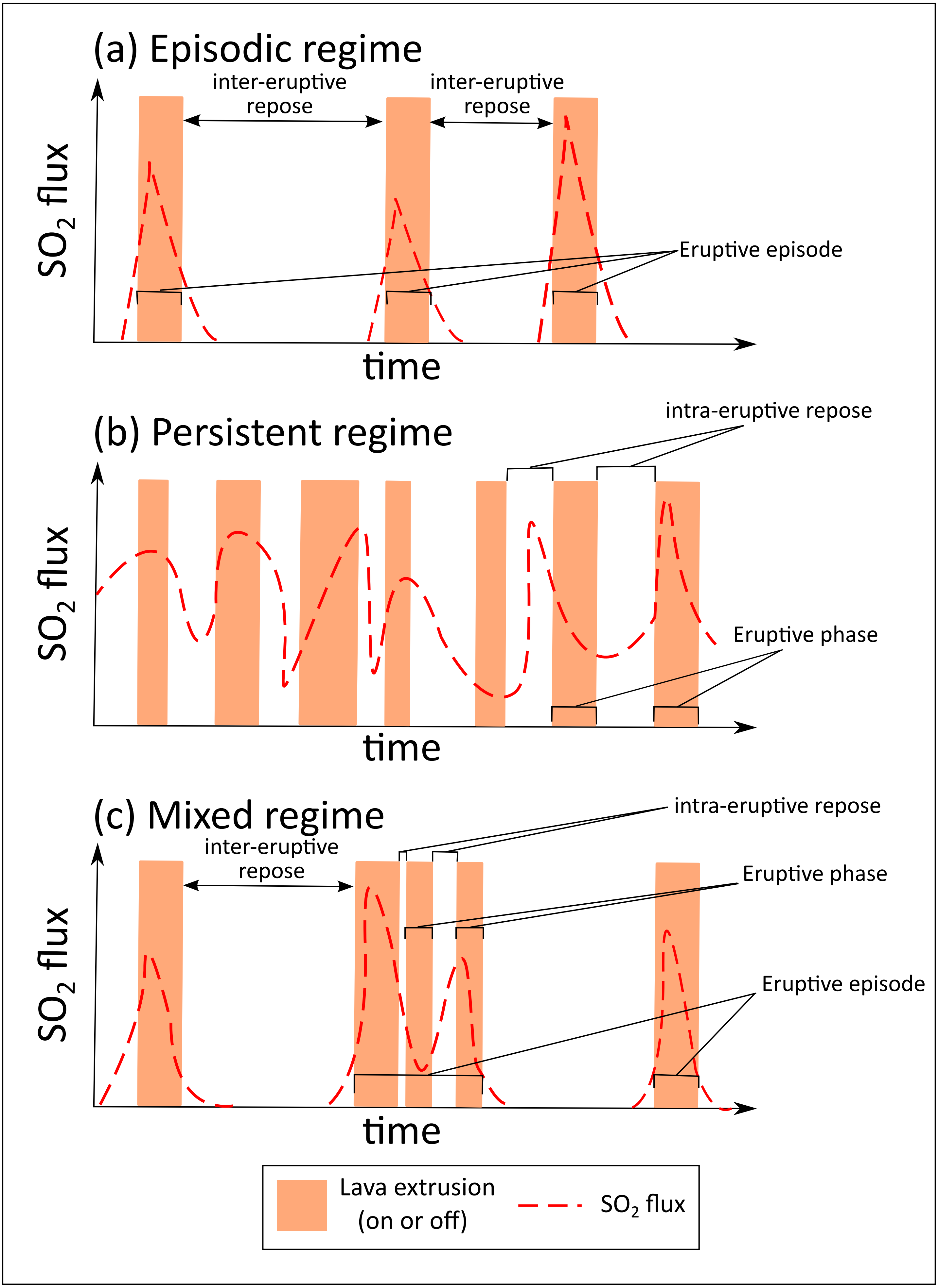
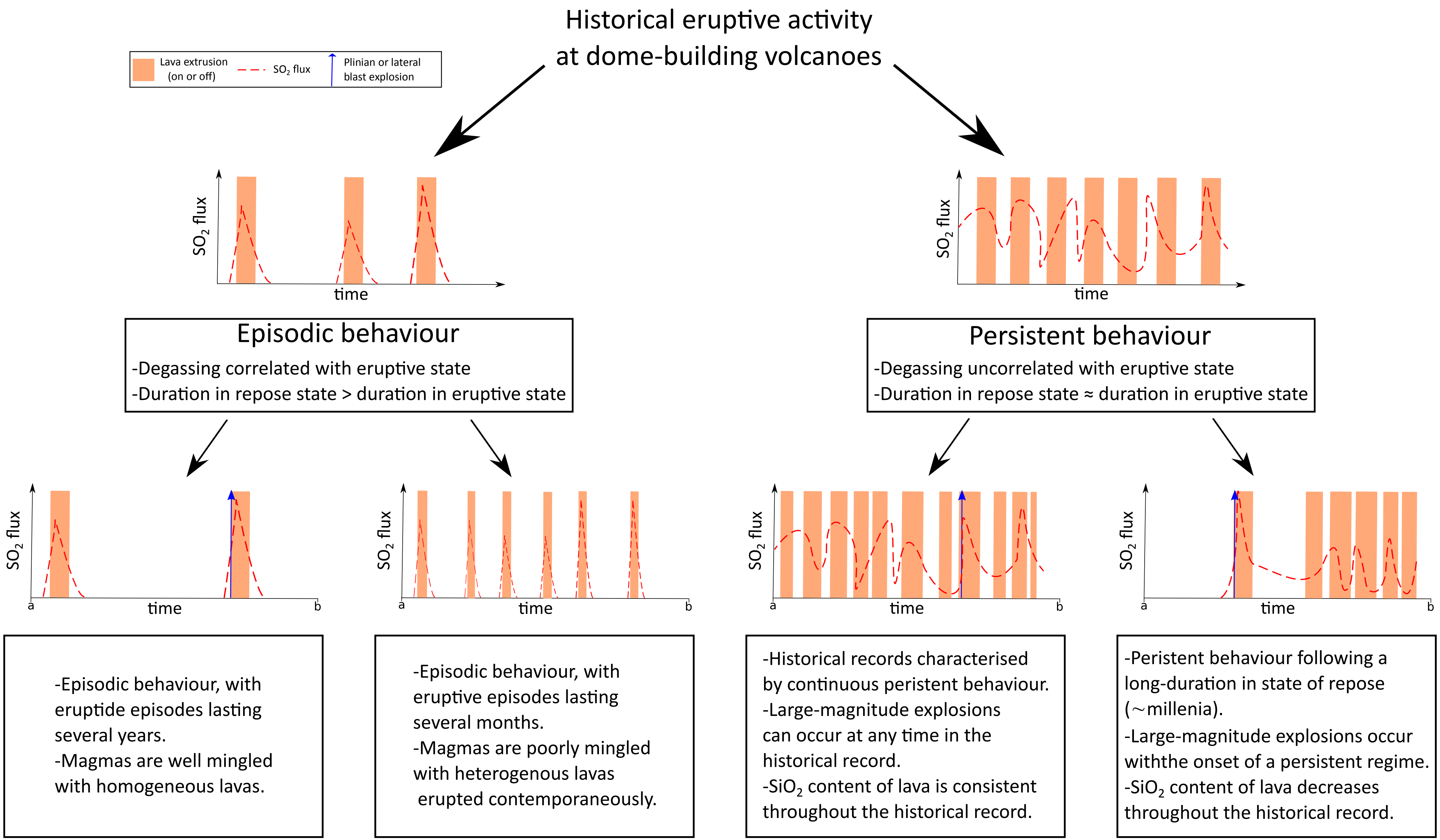
KUD
?
🟥 Lava extrusion recorded
Persistent behaviour
Major explosive event (e.g. Plinian explosion)
? = Unknown regime


(a) Episodic regime
inter-eruptive repose
inter-eruptive repose
SO_2 flux
Eruptive episode
time
(b) Persistent regime
intra-eruptive repose
SO_2 flux
Eruptive phase
time
(c) Mixed regime
inter-eruptive repose
intra-eruptive repose
Eruptive phase
SO_2 flux
Eruptive episode
time
Lava extrusion (on or off)
SO_2 flux



Historical eruptive activity at dome-building volcanoes

Episodic behaviour

-Degassing correlated with eruptive state
-Duration in repose state > duration in eruptive state

Persistent behaviour

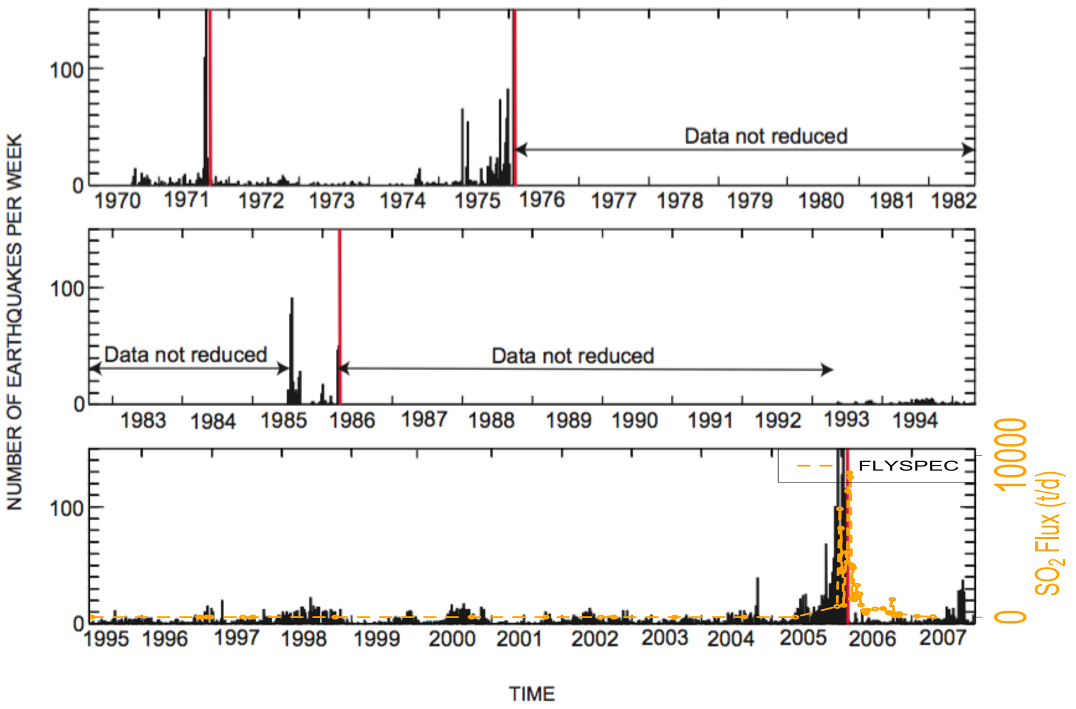
-Degassing uncorrelated with eruptive state
-Duration in repose state ≈ duration in eruptive state

-Episodic behaviour, with eruptide episodes lasting several years.
-Magmas are well mingled with homogeneous lavas.

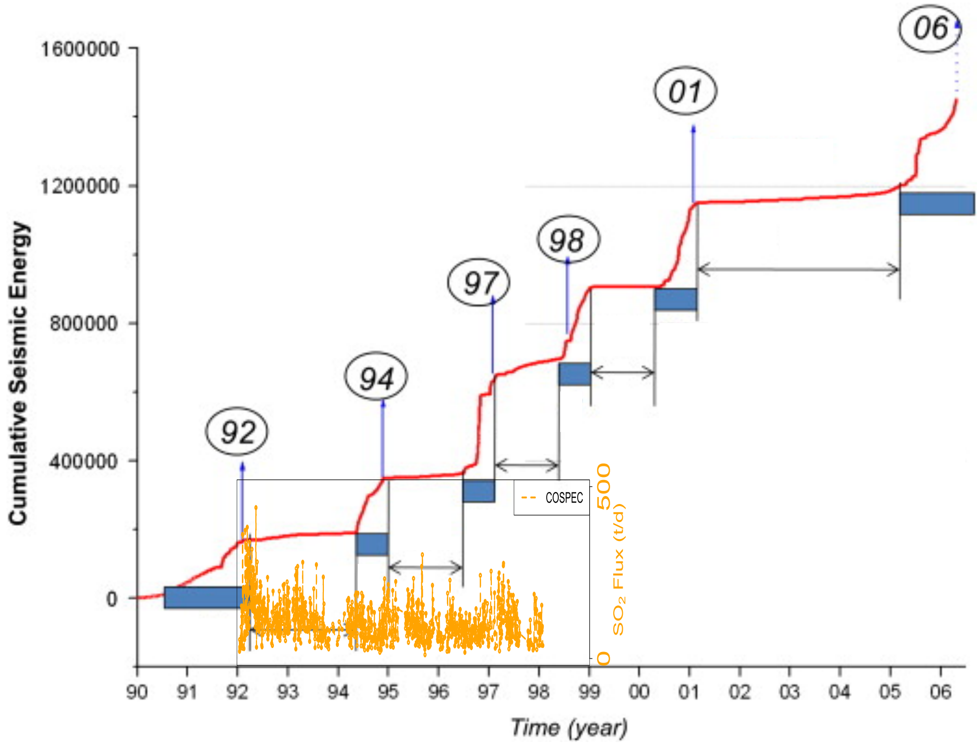
-Episodic behaviour, with eruptive episodes lasting several months.
-Magmas are poorly mingled with heterogenous lavas erupted contemporaneously.

-Historical records characterised by continuous peristent behaviour.
-Large-magnitude explosions can occur at any time in the historical record.
-SiO$_2$ content of lava is consistent throughout the historical record.

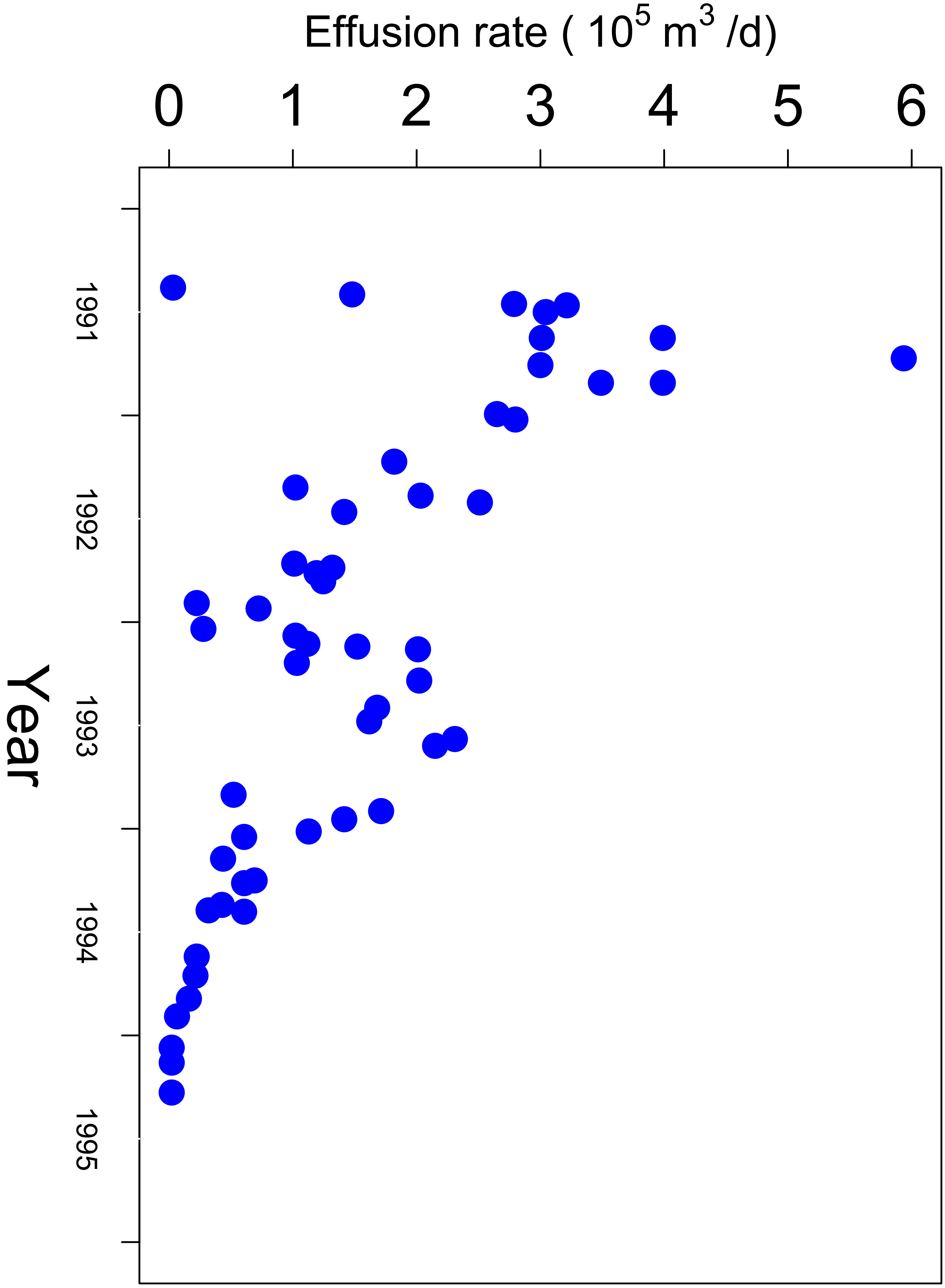
-Peristent behaviour following a long-duration in state of repose (~millenia).
-Large-magnitude explosions occur withthe onset of a persistent regime.
-SiO$_2$ content of lava decreases throughout the historical record.

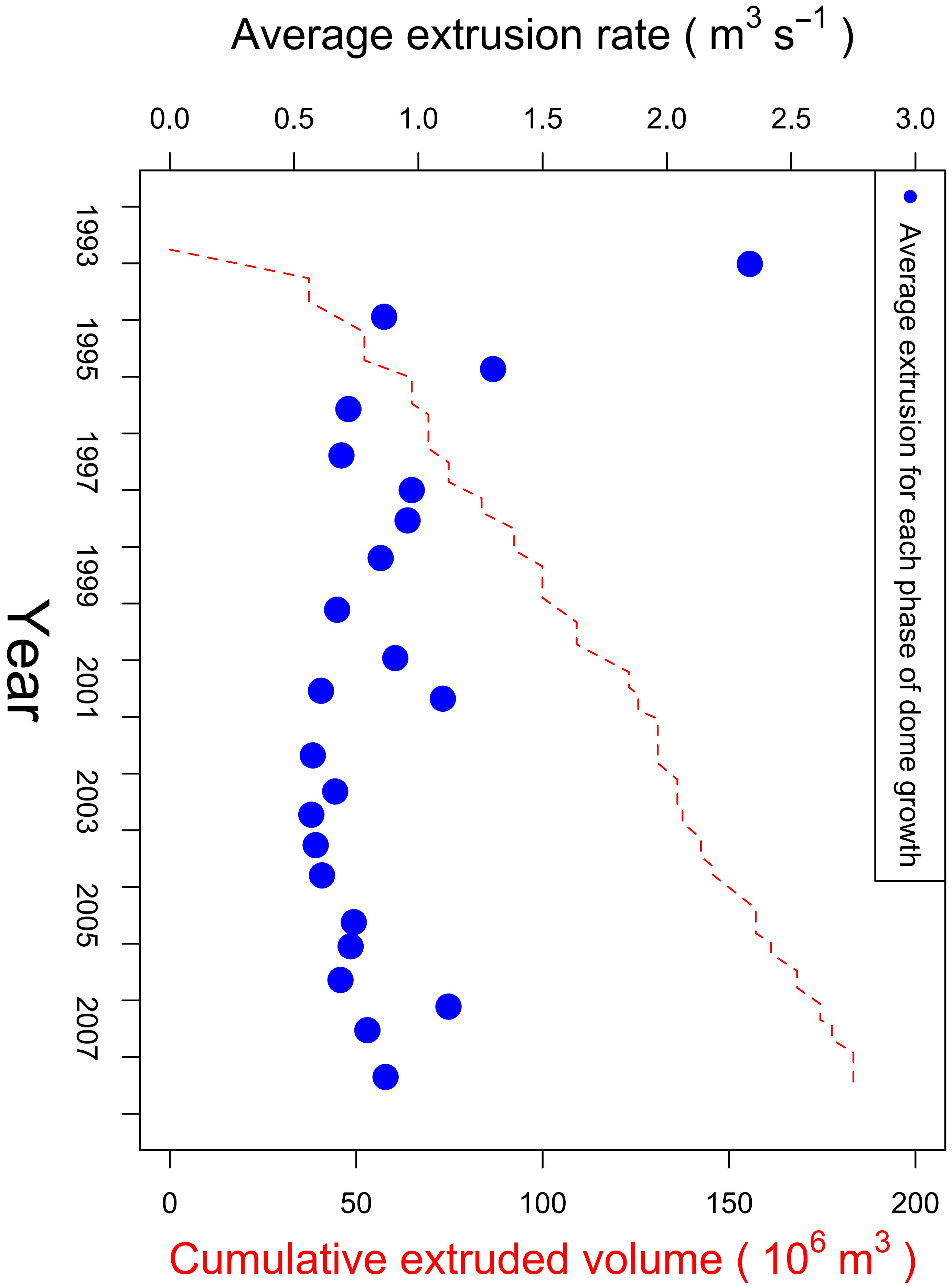


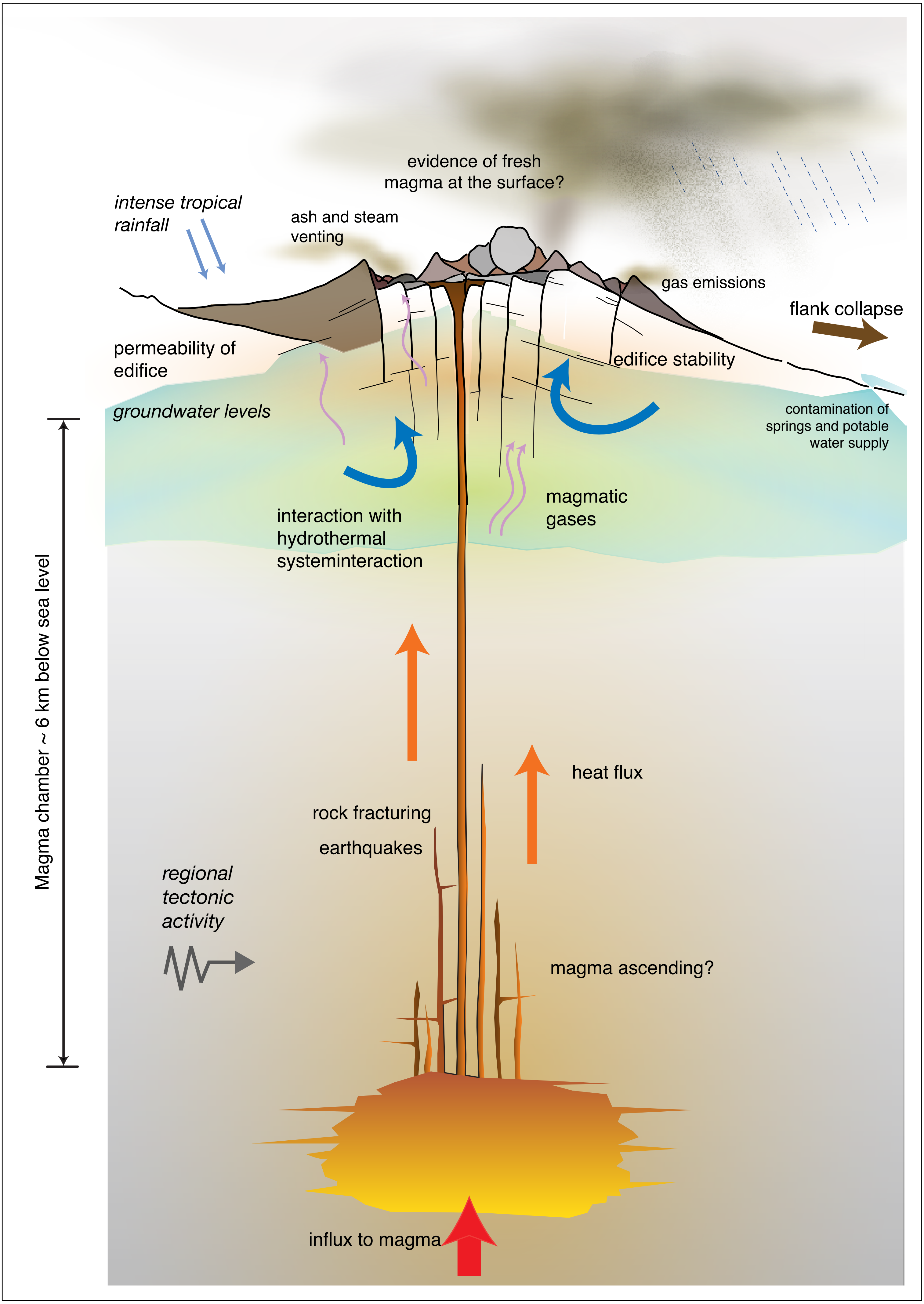
(a) Augustine 1970 - 2008

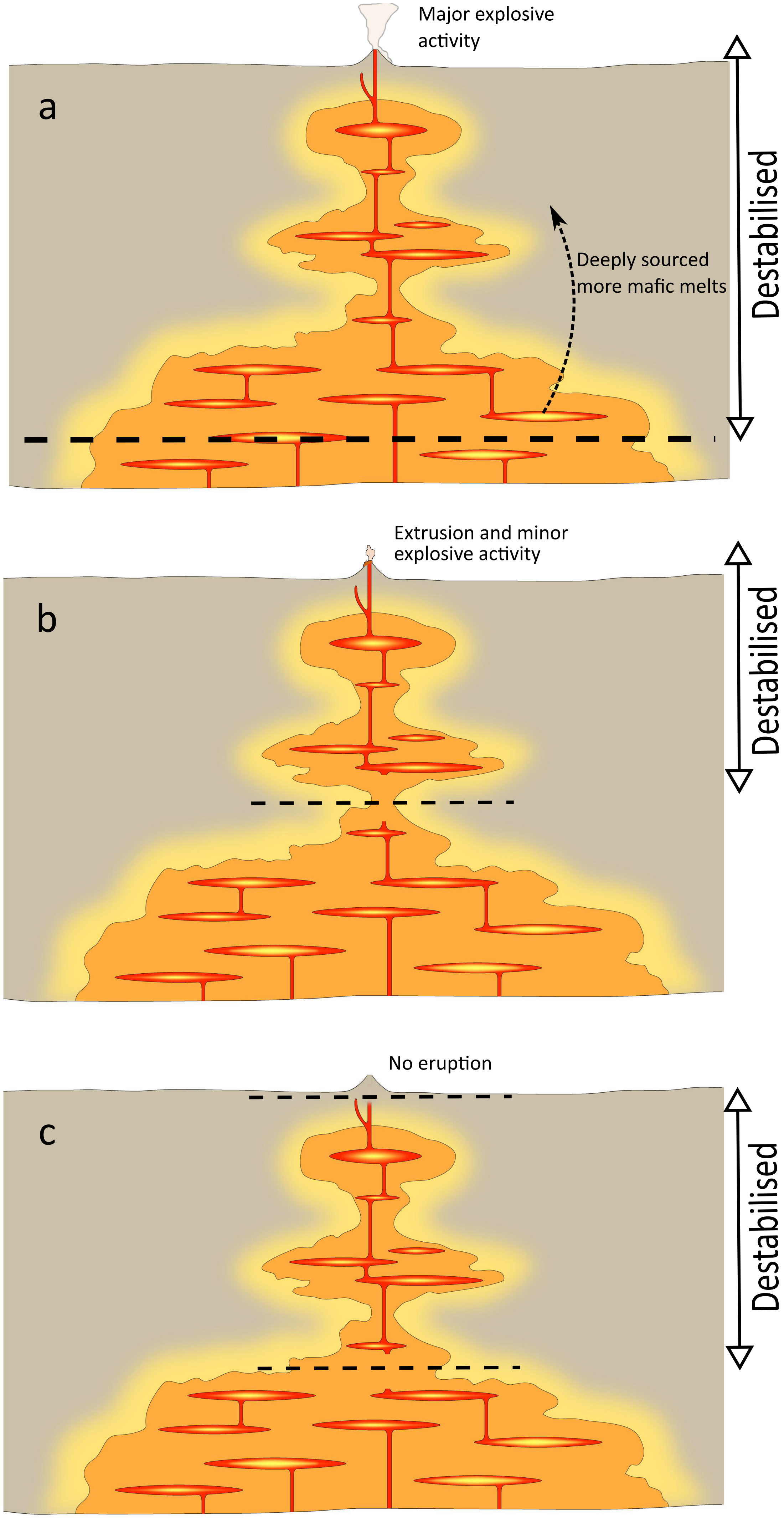


(b) Merapi 1990-2006


Effusion rate (10^5 m^3 /d)
0
1
2
3
4
5
6
Year
1991
1992
1993
1994
1995


Average extrusion rate ($m^3 s^{-1}$)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
● Average extrusion for each phase of dome growth
Year
1993
1995
1997
1999
2001
2003
2005
2007
0
50
100
150
200
Cumulative extruded volume ($10^6 m^3$)


evidence of fresh
magma at the surface?
intense tropical
rainfall
ash and steam
venting
gas emissions
flank collapse
permeability of
edifice
edifice stability
groundwater levels
contamination of
springs and potable
water supply
interaction with
hydrothermal
systeminteraction
magmatic
gases
Magma chamber ~ 6 km below sea level
heat flux
rock fracturing
earthquakes
regional
tectonic
activity
magma ascending?
influx to magma


Major explosive activity
a
Deeply sourced more mafic melts
Destabilised
Extrusion and minor explosive activity
b
Destabilised
No eruption
c
Destabilised