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The association of lava dome growth with major explosive activity (VEI ≥ 4): DomeHaz, a global dataset

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Abstract

Investigation of the global eruptive records of particular types of volcanoes is a fundamental and valuable method of understanding what style of activity can be anticipated in the future, and can highlight what might be expected or unusual in particular settings. This paper investigates the relationship between large explosions (Volcanic Explosivity Index, VEI ≥ 4), and lava dome growth from 1000 AD-present and develops the DomeHaz database. DomeHaz contains information from 397 dome-forming episodes, including duration of dome growth, duration of pauses in extrusion, extrusion rates, and the timing and magnitude (VEI) of associated large explosions. Major explosive activity, when associated with dome growth, is more likely to occur before dome growth rather than during, or at the end of, dome-forming eruptions. In most cases where major explosive activity has been associated with dome growth, the eruptions occurred at basaltic andesite to andesitic volcanoes (the most common type of dome-forming volcano), but a greater *proportion* of dacitic and rhyolitic dome growth episodes were associated with large explosions. High extrusion rates (>10 m^3s^{-1}) seem to be associated with large explosions, and may inhibit degassing or destabilize existing domes, leading to explosive decompression. Large explosions may, alternatively, be followed by dome growth, which represents the clearing of residual magma from the conduit. Relationships extracted from the global record can be used to construct probability trees for new and ongoing dome-forming eruptions, or can be used in conjunction with other types of event trees to aid in forecasting volcanic hazards during a crisis, especially for volcanoes where data are sparse.

1. Introduction

Lava dome-forming eruptions vary in style and can produce a variety of extrusive features from blocky Peléan-type domes (typically andesite to dacite), thick coulées and tortas (typically dacite to rhyolite), to low-viscosity coulées and flows (typically basalt to basaltic andesite) (Calder et al. in press). These eruptions are associated with a suite of hazards including dome-collapse pyroclastic density currents (PDCs), column-collapse PDCs, lateral blasts, lahars, and debris avalanches. Ninety-five percent of dome-forming eruptions reported by Newhall and Melson (1983) were associated with some degree of explosive activity. Most of this explosive activity was VEI ≤ 3 (Newhall and Melson 1983). Nevertheless, major explosive activity, i.e. large explosions VEI ≥ 4, also occurs in association with dome growth and some of the most significant and deadly eruptions of the twentieth century have been of this type. These include the VEI 4 eruption of Mt. Pelée, Martinique on 8 May 1902 (Lacroix 1904); the VEI 4 eruption of Kelut, Indonesia on 19 May 1919; the VEI 5 eruption at Mount St. Helens (MSH), USA on 18 May 1980 (Carey & Sigurdsson 1985; 1989); and the VEI 6 eruption of Mt. Pinatubo, Philippines on 15 June 1991 (Newhall & Punongbayan 1996). More recently, the 2008-2009 VEI 5 eruption of Chaitén, Chile was followed by dome growth (Major & Lara 2013); and the 2010 VEI 4 eruption at Merapi, Indonesia occurred during rapid dome growth (Jousset et al. 2013; Pallister et al. 2013a). While each of these are considered unusual events in the context of the individual volcano concerned, on a global scale it is clear that large explosions associated with dome growth occur with some regularity. In fact, of the 13 eruptions responsible for the majority (74%) of recorded fatalities since 1600 AD (Auker et al. 2013), 9 occurred at dome-forming volcanoes.

Volcano observatories need to be able to easily access historical data in order to assess the potential for rapid escalation from precursory seismic or phreatic activity to explosions (of any magnitude) or to consider the likelihood that effusive dome growth may switch to major explosive activity. Global historical analyses provide a useful evidence base for decision-making alongside volcano monitoring and knowledge of the geological history of a volcano. Indeed, in the absence of monitoring data or significant knowledge of a volcano's eruptive history, global analysis can provide a range of possible outcomes for which a community can prepare.

In this study, all relevant data regarding the association of dome growth and explosive activity (of any magnitude) is collated into a database. DomeHaz forms one component of a wider initiative to develop global databases of volcanic hazards, several components of which have been completed, including the Large Magnitude Explosive Eruptions (LaMEVE) database (Ortiz-Guerrero, 2008; Deligne et al., 2010; Crosweller et al., 2012; Auker et al. 2013; Brown et al. 2014).

The rationale behind the present work is the following:

1) To build upon and add to previous work (e.g. Newhall & Melson 1983; Loughlin et al. 1998), by including newly available data about more recent dome-forming eruptions or those previously not included in analyses (Fig. 1).

2) To carry out a detailed investigation into the occurrence of major (VEI ≥ 4) explosive activity which can be considered an infrequent, yet possible, event associated with dome growth.

3) To interpret the findings within the context of the significantly improved understanding of lava dome systems over the last 30 years (Melnik & Sparks 1999, 2005; Barmin et al. 2002; Diller et al. 2006) developed on the basis of exceptionally well-studied recent eruptions, e.g. MSH, USA (Lipman & Mullineaux 1981; Sherrod et al. 2008), Soufrière Hills Volcano (SHV), Montserrat (Druitt & Kokelaar 2002; Wadge et al. 2014a), Merapi, Indonesia (Newhall et al. 2000; Surono et

al. 2012; Jousset et al. 2013), Unzen, Japan (Sato et al. 1992), and Pinatubo, Philippines (Newhall & Punongbayan 1996).

One of the driving questions for this work is to estimate the likelihood, based on previous eruptions, that a period of dome growth may transition to major explosive activity. In particular, two pertinent questions are: *When during a given dome-forming eruption is the likelihood of large explosions highest? To what extent does this likelihood vary based on composition, extrusion rate, or dome growth duration?*

2. DomeHaz: a global database of dome-forming eruptions

The Smithsonian Institution Global Volcanism Program (GVP) database (Siebert and Simkin 2002-) and the Bulletin of the Global Volcanism Network (BGVN) (Venzke et al. 2002-) were used to compile an initial list of dome-forming eruptions. Peer-reviewed literature and volcano observatory data sources for particular eruptions or volcanoes were used wherever possible to validate the initial list and to extract eruption dates, composition, VEI and timing of major explosive activity, dates and duration of dome growth, extrusion rates, etc.; and were the preferred data sources. The database contains a total of 223 dome-forming eruptions with 397 recorded discrete episodes of dome growth (Fig. 1). The eruptions date from 1000 AD to the most current update as of publication, August 2014 (DomeHaz 2.1, currently available in spreadsheet format at https://vhub.org/groups/domedatabase, with the full relational database online soon).

2.2 Terminology and data constraints

2.2.1 Eruptions, dome-forming episodes, and explosions

There is always some subjectivity in defining what constitutes an 'eruption'; this was discussed in Simkin et al. (1981), where it was assumed that no observed activity for periods of ≤ 3 months probably constituted a *pause* in an eruption, whereas longer periods without observed extrusion or other activity were considered to be gaps *between eruptions*. Improved monitoring means that the ends of eruptions may now be defined based on a return to baseline of the geophysical and/or remote sensing monitoring data rather than the end of extrusion. The beginning of an eruption is sometimes much easier to define than the end. Dome-forming eruptions, which can be long-lived and are often characterized by cyclical dome growth episodes, are particularly difficult to define consistently and present a challenge when compiling global databases. For example, the SHV eruption from 1995-present is generally considered (e.g. Loughlin et al., 2010) as one eruption with pauses (also known as quiescence) between episodes of dome growth of usually no more than 2 years (Fig. 2a). At the time of this publication, there has been no lava extrusion at SHV for more than 4 years. However, the end of the eruption has not been announced and this quiescence in dome growth is currently considered to be a pause (SAC 2014), but could potentially be redefined in the future. In the GVP database, however, this period was split into three different eruptions. Santiaguito (Santa María), Guatemala has a record of distinct episodes of dome growth (Fig. 2b) (Harris et al., 2003), but short days-long pauses between these episodes were not recorded by the GVP. Merapi (Fig. 2c) has had numerous episodes of dome growth since 1768 with pauses in dome growth lasting up to 5 years, but with otherwise consistent extrusion rates and eruptive styles, so many refer to it as a long-lived continuous dome-forming eruption (Siswowidjoyo et al. 1995; Voight et al., 2000). The GVP lists many separate eruptions for Merapi in this period. The start and end dates of an 'eruption' recorded in the GVP may therefore incorporate several discrete episodes of dome growth (e.g. SHV 1995-2003 and 2005-present; Santiaguito), coincide with a single episode of dome growth (e.g. Merapi), or refer to discrete explosive events (e.g. SHV 2004). It is important to note that the way in which the GVP defines these eruptions, mainly in relation to explosivity, is not necessarily incorrect, but is just one way of categorizing often difficult to define, ongoing, dome-forming eruptions based on information available at the time. Indeed, explosive intervals are important to discriminate, as these may be the most hazardous. The GVP database is largely based upon volcano observatory reports during ongoing eruptions, making discrete explosions easier to record than ongoing dome growth. There may be significant uncertainty about the status of a lava dome in daily to weekly reports from volcano observatories for a variety of reasons, including poor visibility. Start and end dates of dome growth (with quantified uncertainties) may be easier to record retrospectively, rather than during an eruptive episode. A clear, holistic picture of eruptive activity may, therefore, only be apparent retrospectively.

Different definitions of an ‘eruption’ clearly pose a problem for examining the relationship between large explosions and dome growth, as they potentially skew the number of recorded eruptions and distort the timing of the explosive activity in relation to the ‘eruption’. For our purposes, we consider that a dome-forming eruption may have only one period of dome growth, or that one *continuous dome-forming eruption* (e.g. Fig 2) may have multiple *episodes* of dome growth with pauses in extrusion (quiescence) in-between. In this paper, cases where any of the following conditions are met are considered to be *continuous dome-forming eruptions*: 1) the literature refers to a volcano as “continuously active” for a given time period, 2) dome quiescence lasts less than 2 years, 3) dome quiescence is shorter than the longest period of dome growth, and/or 4) there is continuous observed volcanic activity or monitored unrest during dome quiescence. We note that this perspective on what constitutes an eruption was necessitated by the nature of our inquiry, and does not suggest that it is the only way to categorize or define cyclical dome-forming eruptions. In this study, we focus on dome growth *episodes* within *continuous dome-forming eruptions*, and in particular how they relate in terms of timing and extrusion rates to large explosions (VEI ≥ 4).

With respect to how we define the relative timing, large explosions occur *before* dome growth when they precede the onset of lava extrusion; large explosions occur *during* dome growth when they occur during a period of active lava extrusion; and large explosions occur *after* a dome growth when they follow the complete cessation of dome-growth (rather than during a brief pause between dome-forming episodes).

This work is concerned with potentially hazardous large magnitude explosions associated with dome-forming eruptions. There are some challenges with using VEI as an identifier of large magnitude explosive events, as VEI is based primarily on erupted tephra volume or plume height, and as a quantitative measure is subject to significant uncertainties (Brown et al. 2014). As such, this work only investigates two categories of dome-forming eruptions: those associated with large explosions (VEI ≥4) and those that are not (0-3). VEI also assumes that eruption magnitude and intensity are related, which may not be the case (Carey & Sigurdsson 1989). However, VEI has the advantage over other measures in that it can be relatively easily assigned from quantitative and qualitative data, allowing even poorly studied eruptions to be classified (Crossweller et al. 2012).

2.2.2 Extrusion rates

Extrusion rate information was collected from a variety of sources, including explicit statements of extrusion rates from volcano observatory-derived activity reports in the BGVN (Venzke et al. 2002-) or peer-reviewed literature, calculations of weekly or monthly extrusion rates from reported dome volumes in BGVN activity reports, or longer-term averaged extrusion rates reported by Newhall & Melson (1983) or other literature.

It is important to note that all extrusion rate data is necessarily time-averaged, over a variety of time scales and was collected using different methods. These time scales tend to be longer at poorly instrumented or difficult to observe lava domes, and with older data. Extrusion rates themselves can vary considerably over even short time periods (minutes to hours) so time-averaging misses much detail. Because of the dearth of extrusion rate information in general (i.e. only available for 129 out of 397 dome growth episodes), the wide variation in time-scales over which extrusion rate information is averaged, and the lack of reporting of the length of these time-scales, it is extremely difficult to ensure proper comparison of extrusion rates between episodes, eruptions and volcanoes. Wherever possible, we have recorded both the *representative* longer time-averaged extrusion rates, as well as any *relevant* information regarding extrusion rates immediately preceding or following large explosions (if they are higher than *representative* rates). Because more *representative* rates are available than *relevant* rates, the extrusion rate data is skewed toward lower extrusion rates.

2.2.3 Completeness of the data

Investigations of the global catalog of large explosions shows that under-recording of events is a serious problem, and that under-recording increases with age but decreases with magnitude (Coles & Sparks 2006; Furlan 2010; Brown et al. 2014). Under-recording is shown to decrease rapidly beginning in 1000 AD (Coles & Sparks 2006), and to largely disappear after 1600 AD (Furlan 2010). On the other hand, accurate frequency-magnitude distributions for very large explosions can only be obtained with sufficiently long time-scales (Deligne et al. 2010). Deligne et al. (2010)

estimated that the probability of a large explosive eruption being recorded steadily decreases from nearly 100% for eruptions occurring today to roughly 20% for eruptions occurring in 1000 AD. Thus, the decision of the recording interval for DomeHaz is a tradeoff between adequately capturing large magnitude events, and avoiding the under-recording of smaller magnitude events. A comparison of DomeHaz with the GVP list of Holocene large explosions and LaMEVE (version 2) shows that all *known* large explosions associated with dome growth since 1000 AD are contained in DomeHaz. However, it is assumed that DomeHaz does not capture all large explosions or all dome-forming episodes. The rate of under-recording for dome growth is currently unknown, and more difficult to quantify than under-recording of explosions, which follow a well-studied frequency-magnitude distribution. It is likely that DomeHaz under-records dome-forming episodes with smaller magnitudes (VEI 0-3), and thus may overestimate the overall likelihood of associated large explosions.

All dome-forming episodes in DomeHaz have compositional information. However, dome- or eruption-specific compositional information was not always available, and the characteristic composition of the volcano was used instead. Of the 397 dome-forming episodes, 384 have VEI information (the remaining 13 with unknown VEI are, however, known to be VEI < 4), 255 have duration information, and 129 have extrusion rate information. Of 51 dome-forming episodes associated with large explosions, 41 have information regarding the timing of the large explosion in relation to dome growth.

3. Results

The frequency with which different types of volcanoes developed different eruption scenarios are presented here as histograms and event trees. These results are based on data contained in

DomeHaz, and as such, are a reflection of the frequency of known past occurrences (1000 AD to the time of publication) alone.

The overview results (Fig. 3) indicate that major explosive activity (VEI ≥ 4) was associated with a small, but not insignificant, number of dome-forming episodes (51/397 dome-forming episodes had a total of 54 large explosions, 13%). An alternative view shows that ~20% of the VEI ≥ 4 eruptions compiled by the GVP were associated with dome growth. Volcanoes of andesitic composition produced the greatest *number* of dome-forming episodes as well as the greatest *number* of large explosions associated with dome growth (29/296 cases; 10%) (Fig. 4a). However, dacitic and rhyolitic volcanoes had a greater *proportion* of large explosions associated with dome growth (17/59 cases, 29%; 5/10 cases, 50%, respectively) (Fig. 4a). Large explosions most commonly occurred *before* the onset of dome growth at volcanoes of all compositions (28/51 cases, 55%) (Fig. 4b). However, major explosive activity *during* dome growth episodes was not unprecedented (10/51 cases, 20%). Basaltic andesite to andesitic volcanoes had the greatest *number* (Fig. 4b) of large explosions to occur during or after dome growth, but more silicic volcanoes had similar *proportions* of large explosions during dome growth or cryptodome intrusion (Fig. 4b).

In terms of duration of dome growth episodes, the vast majority lasted less than 5 years (237 of 255 dome growth episodes with duration information), and as a result, this was also the class associated with the greatest *number* of large explosions (Fig. 5a). However, a greater *proportion* of dome-forming episodes lasting longer than 5 years were associated with large explosions (Fig. 5a). When large explosions did occur, they most commonly preceded dome growth episodes (Fig. 5b). *Proportionally*, however, many large explosions associated with intermediate duration dome growth episodes (1-15 years) occurred during dome growth (Fig. 5b). Large explosions associated with shorter duration (< 10 year) dome growth episodes commonly occurred at higher silica volcanoes (Fig. 5c).

Extrusion rate information is available for 129 dome-forming episodes. Wherever possible, *relevant* shorter-term extrusion rates directly associated with explosive activity were used rather than *representative* longer-term extrusion rates. Higher extrusion rates (> 10 m^3s^{-1}) carried an elevated likelihood of being associated with large explosions (Fig. 6a). Sample sizes were too small to make firm conclusions about the relationship between extrusion rate and the relative timing of large explosions (Fig. 6b) or volcanic composition (Fig. 6c), although explosions occurring before the onset of dome growth were the most common. Very high (>30 m^3s^{-1}) and low (<10 m^3s^{-1}) extrusions rates had the greatest proportion of large explosions occurring during dome or cryptodome growth (Fig. 6b). Large explosions associated with the highest extrusion rates occurred most commonly at higher silica volcanoes (Fig. 6c).

4. Probability Trees and Case Histories

Probability trees were constructed from DomeHaz (after Newhall and Hoblitt, 2002) and used to illustrate a number of relevant case studies. The trees represent the probabilities of mutually exclusive events (e.g. VEI $\geq$ 4) or conditions (e.g. dacitic composition), whose branches are logical steps from more general events/conditions (e.g. dacitic volcano) to increasingly specific events (e.g. VEI $\geq$ 4 explosion during dome growth). Probabilities and conditional probabilities based on observed cases are presented. A conditional probability, P($n|n$-x), is the probability of event n, given that event n-x has occurred (Newhall & Hoblitt, 2002). The absolute total probability for a specific outcome is the product of the probability of the initial event P(1) multiplied by all conditional probabilities (Newhall & Hoblitt, 2002) such that $P(n) = P(1) \cdot P(2|1) \cdot P(3|2) \cdot \ldots \cdot P(n|n-1)$.

Three separate probability trees are presented: One for dome-forming episodes of different compositions (Fig. 7), one for dome growth episodes of different durations (Fig. 8), and one for dome growth episodes of different extrusion rates (Fig. 9). The probability of an associated large explosion and its relative timing is investigated in each case. These probability trees can use the global record of dome-forming eruptions to make inferences about the likelihood of large explosions at individual volcanoes, rather than only considering the eruptive histories of the volcano in isolation. This allows the probability trees to better capture the probability of infrequent events which may not have been recorded or have even occurred at a specific volcano in the past. This is the main value of a global database: to enhance the ability to make evidence-based decisions both at volcanoes with abundant data or at volcanoes where local datasets may be very sparse; the latter condition may be the case for the great majority of the world's volcanoes. For example, Fig. 10a shows a probability tree constructed only from the eruptive history of SHV, which has had 5 recorded dome growth episodes, with no VEI ≥ 4 explosions. Fig. 10b uses the global record of dome-forming eruptions to show that 13% of recorded dome growth episodes since 1000 AD have been associated with large explosions, behavior that, while not recorded at SHV, ought not to be ruled out. The other probability trees (Figs. 7-9) allow one to examine subsets of the global record which may serve as useful analogs to a particular volcano, such as SHV. For example, about 10% of SHV analogs in terms of composition and dome growth episode duration were associated with large explosions, while 25% of extrusion rate analogs were associated with large explosions.

Finally, it is important to note that because these probability trees are based on historical data, it is possible that they do not capture ALL plausible, but not yet observed, eruptive scenarios. Statistical modeling of recurrence rates using extreme value theory or other methods (e.g. Deligne et al. 2010) may prove a useful future step.

The event paths taken by the Santiaguito (Santa María) 1922-present, MSH 1980, Chaitén 2008-2010, and Merapi 2010 eruptions are indicated on the probability trees, as well as the most likely paths that may be taken by ongoing eruptions at SHV and Sinabung, Indonesia (case studies are introduced below).

Santiaguito (Santa María), Guatemala: In 1902, an intense explosive eruption (VEI 6) of Santa Maria volcano produced voluminous clouds of dacitic ash, killed several thousand people, and left a large crater (Stoiber & Rose 1969). A new eruption (VEI 3) began in 1922 with the formation of a dacitic lava dome, Santiaguito (Rose 1973). Since 1922, the Santiaguito dome complex has exhibited periods of relatively high extrusion rates (0.6-2.1 m^3s^{-1}) lasting > 5 years, followed by ~10 year periods of lower extrusion rates (0.2 m^3s^{-1}) (Rose 1973, 1987; Harris et al. 2003) (Fig. 2b).

The orange path on the probability trees shows the event history of the Santiaguito eruption. Santiaguito's composition (dacitic) (Fig. 7), duration of dome growth (>20 years) (Fig. 8), and extrusion rate (0.07 – 2.06 m^3s^{-1}) (Fig. 9), were associated with fairly low frequencies of large explosive activity based on DomeHaz (15%, 0%, and 5% respectively). However, the relatively low extrusion rates recorded for Santiaguito are long term averages over entire episodes of dome-growth, with possibly more *relevant,* shorter-term extrusion rates unrecorded.

MSH, USA: Of the two recent dome-forming eruptions at MSH (1980-86 and 2004-08), only one was associated with a large explosion. On 18 May 1980 rapid intrusion of a cryptodome (42 m^3s^{-1}; calculated from Moore & Albee 1981), triggered the failure of MSH's northern slope, forming a debris avalanche, followed by a directed blast, devastating a 600 km^2 area (VEI 5). Extrusive dome growth began on 12 June 1980, and continued with 19 subsequent short episodes of dome growth until the end of the eruption. The small domes or dome-lobes that were produced during this period each had volumes of a few million m^3, with low extrusion rates (0.24-0.69 m^3s^{-1}; Swanson & Holcomb 1990).

The purple path on the probability trees (Fig. 7-9) shows the event history of the MSH 1980 eruption. Fifteen percent of dome-forming episodes at dacitic volcanoes exhibited large explosions, and 18% of those that did occur, had large explosions during dome growth (including cryptodome intrusion) (Fig. 7). Short (< 1 year) duration episodes of dome growth (as at MSH) were very common (64%), with 7% associated with large explosions, 8% of which were associated with cryptodomes (Fig. 8). However, the extrusion rate probability tree (Fig. 9) shows that 55% of dome-forming episodes with extrusion rates >$30m^3s^{-1}$ were associated with large explosions, most of which occurred during dome growth or cryptodome intrusion.

Chaitén, Chile: Prior to 2008, Chaitén was considered an inactive caldera, formed during a rhyolitic eruption ~10000 years ago (Naranjo and Stern 2004; Lara et al. 2013), with a possible unconfirmed eruption ≤ 3000 years ago (Lara et al. 2013). Little precursory activity was detected before the eruption of Chaitén in 2008 which comprised explosive, transitional, and effusive phases (Pallister et al. 2013b). The explosive phase began on 2 May 2008 with a Plinian VEI 4 explosion (Major and Lara 2013). A second Plinian explosion occurred on 6 May 2008. Only minor PDCs were produced during the explosive phase (Major and Lara 2013). The transitional phase (11-31 May 2008) was characterized by Vulcanian explosions and simultaneous lava extrusion (Pallister et al. 2013b). This was followed by an exogenous lava flow phase (June-September 2008), spine extrusion and endogenous dome growth (October-February 2009). A final phase of endogenous dome growth began with the collapse of a spine on 19 February 2009 and lasted until the end of the eruption in late 2009 or early 2010 (Pallister et al. 2013b). Dome growth extrusion rates averaged 66 m^3s^{-1} during the first two weeks of the eruption, and 45 m^3s^{-1} for the first 4 months (Pallister et al. 2013b).

The yellow path on the probability trees shows Chaitén's 2008 eruptive history (Fig. 7-9). Half of the dome-forming episodes at rhyolitic volcanoes were associated with large explosions, and in most cases (40%), these occurred before dome growth began (Fig. 7). When large explosions were associated with short duration dome growth (< 1 year), they often (75%) occurred before dome growth (Fig. 8). Dome-forming episodes with high extrusion rates (>30 m^3s^{-1}) also commonly (55%) had large explosions, usually before or during dome growth (Fig. 9).

Merapi, Indonesia: Since 1768 there have been 50-60 reported basaltic andesite eruptions (Voight et al., 2000; Costa et al. 2013) at Merapi, nearly all of which have involved dome growth (Fig. 2c). Based on our assumptions (set out in section 2.2.1) we consider these dome-growth episodes as part of one continuous dome-forming eruption. On 15 April 1872, a 5 day explosive phase (VEI 4) occurred (Voight et al., 2000); dome-forming episodes have been frequent since that time, but with pauses up to 5 years between dome growth episodes (Fig. 2c). Since at least 1890, magma eruption rates have been relatively steady, indicating a constant supply of magma (Siswowidjoyo et al., 1995), providing a rationale for considering this activity as one continuous, ongoing eruption. Merapi's case illustrates the importance of defining what constitutes an eruption in a meaningful and consistent way, as well as the effects that different definitions can have on results such as presented here.

The dome growth episode from October 2010-July 2012 at Merapi was also associated with a VEI 4 explosion. Dome growth initiated around 26 October 2010, with extrusion rates averaging 25 m^3s^{-1} (Surono et al., 2012; Pallister et al., 2013a). This rate is substantially higher than the 2006 dome extrusion rates (average 2.4 m^3s^{-1}, peak 4 m^3s^{-1}; Ratdomopurbo et al., 2013) as well as the long-term average magma eruption rate (0.1 m^3/month; Siswowidjoyo et al., 1995). The VEI 4 explosion on 4 November 2010 produced PDCs that traveled 16 km radially around the volcano, necessitated the evacuation of about 400,000 people, and resulted in 367 deaths (Surono et al. 2012; Mei et al. 2013). Extrusion rates increased to 35 m^3s^{-1} after the paroxysmal explosion, but no further explosive activity occurred (Surono et al., 2012; Pallister et al., 2013a). The increase in extrusion rate after the 4 November 2010 explosive event caused considerable alarm, and understandably so.

The blue path on the event trees (Fig. 7-9) corroborates this intuitive relationship, showing that given an extrusion rate of 25 m^3s^{-1}, the frequency of a VEI $\geq$ 4 explosion was around 33%, and that given an extrusion rate >30m^3s^{-1}, the frequency of a VEI $\geq$ 4 explosion was 55% (Fig. 9). However, extrusion rates over 20 m^3s^{-1} were rarely recorded amongst lava domes. The sample size for 20-30 m^3s^{-1} extrusion rates was 6 occurrences, and 11 occurrences were recorded for >30 m^3s^{-1} extrusion rates (from 129 sampled).

SHV, Montserrat: The 1995-ongoing eruption has been characterized by episodes of dome growth and quiescence, often lasting several years (Fig. 2a), accompanied by PDCs, Vulcanian explosions and lahars (Wadge et al. 2014b). At several points during the eruption (e.g. 1997, 2006), extrusion rates rapidly escalated to several tens of m^3s^{-1} (Sparks et al. 1998; Loughlin et al., 2010; Wadge et al. 2010; Odbert et al. 2014), often associated with the onset of minor Vulcanian explosivity (Odbert et al. 2014), causing concern that the volcano might enter a phase of major explosive activity.

Using the red path on the probability trees to estimate probability of a large explosion at SHV, we show that it would be unusual, based on previous occurrences, for a large explosion to occur during the current eruption or for the current eruption to terminate in a large explosion. Given the andesitic composition of SHV, the probability of a VEI ≥ 4 explosion is ~10% based on past frequencies (Fig. 7), but the probability of a VEI ≥ 4 explosion occurring at an andesitic volcano *during* or *after* dome growth is low (2% and <1%, respectively). The vast majority of dome growth episodes of SHV's duration (90%) and extrusion rate (75%) were *not* associated with large explosions (Fig. 8-9). Large explosions much more commonly occurred *before* the onset of short dome growth episodes with extrusion rates < 30 m^3s^{-1}; again reinforcing the fact that the probability is low that SHV would experience such an event (Fig. 9).

Sinabung, Indonesia: The current eruption at Sinabung (basaltic andesite to andesite) began in July 2013, and a dome was observed on 24 December, 2013. Extrusion rates have ranged from < 5 m^3s^{-1} to occasionally more than 20 m^3s^{-1}, with several increases in extrusion rate followed by dome or lava-front collapses that generated significant PDCs (written communication J. Pallister; Wright et al. 2014). By January 2014 hundreds of PDCs were being generated, traveling up to 4.5 km, with over 22,000 people displaced by evacuations. On 1 February 2014 a large dome collapse produced PDCs reaching 4.5 km, killing 15 people who had reentered the evacuated zone. The lack of historic eruptions, and evidence of previous domes and PDCs (Yoshimoto et al. 2013; Wright et al. 2014), has necessitated the use of global records to anticipate future activity through the use of by the Indonesian Center for Volcanology and Geologic Hazard Mitigation (CVGHM) and the USGS Volcano Disaster Assistance Program (VDAP) (Wright et al. 2014).

The green path on the probability trees (Fig. 7-9) indicates the most likely activity to be expected at the ongoing eruption of Sinabung based on previous frequencies. About 10% of basaltic andesite to andesitic dome-forming episodes were associated with large explosions, with most of these large explosions preceding dome growth (Fig. 7). 27% (6 of 22 cases) of dome-forming episodes with extrusion rates between 10-30 m^3s^{-1} were associated with large explosions (Fig. 9), most of which (83%) preceded dome growth. Only 5% of dome-forming episodes with extrusion rates < 10 m^3s^{-1} were associated with large explosions.

5. Discussion

5.1 Composition

Most dome-forming episodes occur at andesitic volcanoes and most (in absolute terms) of the large explosions are also associated with these andesitic volcanoes (Fig. 4a). *Proportionally*, however, more dome-forming episodes at dacitic and rhyolitic volcanoes are associated with large explosions (Fig. 4b). For volcanoes of any composition it is significantly more common to have explosions *before* dome growth, rather than during dome growth or after dome growth has ceased. High silica content magmas are more commonly associated with explosive activity, so the trends observed might be expected. The propensity for large explosions to be more frequently associated with the onset of dome growth is clearly demonstrated and is an important finding in relation to potential hazards at persistently degassing or dormant silicic volcanoes where lava domes have formed in the past. Perhaps an unexpected outcome is that only andesitic dome-forming eruptions have exhibited large explosions after dome extrusion has completely ceased, although we record only one case (Egmont, New Zealand, 1655). Due to the age of the Egmont eruption, it is possible that the timing of the explosion is erroneous, and that it may in fact, have occurred during some residual dome growth. It is already known that lava domes remain hazardous long after extrusion has ceased (e.g. Norton et al. 2002) but more data is required to discount the possibility of large magnitude explosions occurring after the cessation of dome growth.

It is also important to note that during an ongoing eruptive crisis, it is difficult to know if dome quiescence signals a pause in dome growth or the cessation of dome growth, and it is important to examine probability trees for large explosions both *during* and *after* dome growth. Additionally, magma compositions can evolve (although usually only subtly) during an eruption. For example, the 1991 Pinatubo eruption began with a short period of mingled andesite dome extrusion, followed by a series of explosions with an increasingly dacitic composition culminating in the 15 June 1991 VEI 6 explosion (Wolfe & Hoblitt 1996). The explosion was eventually followed by the eruption of a residual mingled andesite lava dome roughly a year (July-Oct. 1992) after the paroxysmal explosion (Daag et al. 1996). This explosion is categorized as *during* a pause in andesite dome growth, rather than *after* the complete cessation of dome growth.

5.2 Dome growth duration

Large, VEI ≥ 4, explosions are more commonly associated with dome-forming episodes of short duration. This is, in part, due to the fact that short duration (< 5 years) dome-forming eruptions are the most frequent type. However, longer duration episodes of dome growth are, *proportionally,* more likely to have large explosions during dome growth. Again, for dome-forming episodes of any duration, large explosions are more commonly observed before the onset of dome growth, rather than during or after dome growth. These trends can be rationalized in the context that most dome-forming episodes that follow large explosions are short lived, because the extrusion of lava in many of these cases represents the expulsion of residual, volatile-depleted magma following the volatile-rich explosive phase (e.g. Chaitén, Castro et al. 2013). It is also worth noting that two cases of large explosions associated with short duration dome growth episodes involved cryptodome intrusion and subsequent decompression (MSH 1980-86; Bezymianny 1956-2012).

5.3 Lava extrusion rate

The extrusion rate data are not sufficiently complete to comprehensively assess relationships between extrusion rates and the timing of large explosive activity in relation to dome growth, with less than 5 large explosions associated with each extrusion rate band. However, higher extrusion rates do seem to be associated with a *proportionately* higher number of large explosions. Again, this effect may actually be stronger than recorded due to the skew towards lower extrusion rates caused by *representative*, long-term average extrusion rates. There were 33 dome growth episodes with extrusion rates > 10 m^3s^{-1}, and of these, 12 (36%) were associated with large explosions, with extrusion rates >30 m^3s^{-1} most likely to be associated with large explosions (6/11 cases, 55%). In fact, high extrusion rates (>30 m^3s^{-1}) were the only investigated condition more likely to be associated with a large explosion than not. Explosions generally occurred either before the onset of dome growth, or during dome or cryptodome growth. This association of large explosions during dome growth episodes with high extrusion rates is supported by theoretical work by Jaupart & Allègre (1991) and Sparks (1997), which notes that conditions favor explosive activity when extrusion rates are high (>10 m^3s^{-1}). High extrusion rates are also known to favor explosive decompression (Melnik & Sparks, 2005).

While the small sample size and incompleteness of the extrusion rate dataset makes the robustness of the observed trends questionable, the data do raise an important flag of caution to monitoring institutions: low extrusion rates do not *necessarily* preclude a large explosion during dome growth. All extrusions rates were associated with at least 1 instance of a large explosion associated with dome growth, and both very low (<10 m^3s^{-1}) and very high (>30 m^3s^{-1}) extrusion rates have high proportions of large explosions occurring during dome-forming episodes.

Additionally, extrusion rates are themselves difficult to measure and require frequent unobstructed observation to produce accurate measurements (Sparks et al. 1998). Extrusion rates can also vary considerably over time, and any measurement is necessarily time-averaged. It seems increasingly clear that shorter-term *relevant* extrusion rates leading up to or following explosive phases (of any magnitude) of eruptions may be more useful than longer-term *representative* extrusion rates when it comes to estimating explosive potential. Methods that allow more frequent high resolution observations of lava domes (e.g. radar satellite measurements at Merapi, Pallister et al. 2013a) can capture these short-term extrusion rates and, in combination with effective ground monitoring, facilitate appropriate and timely risk management measures such as evacuation (Surono et al., 2012; Pallister et al. 2013a).

5.4 Explosive regimes

It is clear from this work that patterns emerge when comparing composition and extrusion rate of lava domes with timing of large explosions. We present a regime diagram where we attempt to 'map' these associations in the context of composition and extrusion rate variations (Fig. 11).

The apparent association, in this analysis, of very low extrusion rates with large explosions may be an effect of the inclusion of longer-term, eruption-averaged extrusion rates which mask extrusion rate variations, in particular, short-term elevated extrusion rates. This paucity of *relevant* data reflects the logistical and scientific challenges inherent in collecting extrusion rate data. However, the association of large explosions *during* dome-forming episodes with low extrusion rates (Fig. 11a) may be explained by theoretical work that has considered processes which might lead to explosions in these circumstances. For example, very low extrusion rates may promote the formation of a solidified dome "cap" or the attachment of magma to conduit walls (Collombet 2009), limiting degassing and increasing pressurization in the conduit (Denlinger & Hoblitt 1999; Collombet 2009).

Based on analysis of DomeHaz, large explosions most commonly precede the extrusion (at a variety of rates) of residual melts (Fig. 11b), at volcanoes of nearly all compositions. Indeed, while Fig. 11 plots cases with associated extrusion rate information, 55% (28/51) of large explosions occurred before the onset of dome growth. In these cases, a large explosion may be necessary to remove high-viscosity, degassed magma from the upper conduit and lava from a previously existing dome, clearing the way for dome extrusion, explaining the prevalence of large explosions that *precede* the onset of dome growth (Barmin et al. 2002). Barmin et al. (2002) posited that dome growth after large explosions could be caused by shortened conduit lengths and plug removal caused by large explosions.

At rhyolitic dome-forming volcanoes, large explosions are common and may be associated with the rapid extrusion of obsidian domes as a byproduct of collapsed foams (Fig. 11c). Work at rhyolitic volcanoes (e.g. Chaitén and Cordón Caulle) demonstrates that the effusion of obsidian domes and lavas may *require* explosions to sufficiently degas the magma to enable flow, and that explosions and rapid extrusion of obsidian domes and flows are the result of the cyclical collapse of magmatic foams (Castro et al., 2013). DomeHaz contains no record of the growth of rhyolitic domes at low extrusion rates.

DomeHaz also contains examples of rapid dome extrusion preceding large explosions (Fig. 11d), possibly because high extrusion rates limit degassing, triggering explosions; or because rapid decompression of a dome triggers an explosion. High extrusion rates are known to lead to large explosions (Jaupart & Allègre 1991; Sparks 1997; Melnik & Sparks, 2005). Melnik and Sparks (2005) modeled magma flow through conduits and noted that if extrusion rates are high, there is not sufficient time for gas to escape during ascent, and the volume fraction of bubbles can increase to over 70%. This can directly lead to explosivity *during* dome growth, or result in explosions triggered by rapid decompression through the removal of the dome by gravitational collapse. High extrusion rates also make dome-collapse more likely, by mechanically destabilizing domes by increasing internal shear strain, increasing loading on support structures, and by steepening the dome slope (Calder et al., 2002; Pallister et al., 2013a).

Basaltic dome eruptions are rare, mainly effusive, and not associated with large explosions (Fig. 11e).

While this work only explores the relationship of large explosions (VEI ≥ 4) and dome growth, less extreme explosive activity is both common and hazardous. Explosive activity reported as VEI 3 occurred with 33% of dome-forming episodes since 1000 AD, and VEI 2 activity (which may include minor explosive activity) was associated with 38% of dome-forming episodes. Solely effusive (VEI 0 or 1) dome-forming episodes (13%) were as rare as those associated with large explosions (13%). Additionally, even in the absence of explosivity, dome-collapse PDCs are a common feature of dome growth episodes, and constitute one of the most dangerous volcanic hazards (Auker et al. 2013)

6. Conclusions and recommendations

Based on this study it appears that:

1. Most dome-forming episodes occurred at basaltic andesite to andesitic volcanoes, lasted less than 5 years, and had extrusion rates less than 10 m^3s^{-1}.
2. In most cases where major explosive activity (VEI $\geq$ 4) has been associated with dome growth, the eruptions occurred at basaltic-andesite to andesitic volcanoes. However, a greater *proportion* of dacitic and rhyolitic dome growth episodes were associated with large explosions, usually accompanied by high extrusion rates.
3. Large explosions, when associated with dome growth (at volcanoes of any composition), are more likely before dome growth rather than during or at the end of the dome-forming eruptions. In these cases, explosions clear degassed magma from the conduit and old degassed lava dome rock from the vent area. Subsequent dome growth probably represents the clearing of residual magma from the conduit or the expulsion of a collapsed foam.
4. Short (< 1 year) dome growth episode durations are most likely (by number) to be associated with large explosions, but a greater *proportion* of longer duration dome-forming episodes (>5 years) are associated with large explosions.
5. While sample sizes are small, higher extrusion rates (>10 m^3s^{-1}, and especially > 30 m^3s^{-1}) seem to be associated with large explosions, either because these high extrusion rates inhibit degassing, destabilize existing domes, or directly aid in the rapid extrusion of obsidian domes. However, all extrusion rates have at least some association with large explosions during dome

growth. Better methods that allow more frequent observations of lava domes (e.g. radar satellite measurements at Merapi, Pallister et al. 2013a) can capture critical indicators such as *relevant* short-term pulses in extrusion rate, which may be key for constructing more accurate probability trees.

6. This type of information has been and can be directly used to inform Expert Judgment Elicitation (Aspinall 2006) for hazard estimations. Preliminary DomeHaz results were presented to the Montserrat Volcano Observatory (Ogburn and Calder, 2006), and were used by the Scientific Advisory Committee to estimate the probability of the SHV eruption ending with a large explosion (SAC 2006).
7. Retrospective activity reporting or summarizing by volcano observatories in their regular reports would greatly improve the data on dome growth episodes and extrusion rates in DomeHaz. For example, retrospective summaries could more clearly define the end dates of dome growth periods. A clear, holistic picture of eruptive activity may only be apparent retrospectively and this would need to be included in volcano observatory reports to ensure timely update of global databases.
8. While DomeHaz does not categorize domes based on morphology or type, this may prove useful for future analyses of the association of large explosions with different styles of dome growth or of the investigation of dome-collapse PDC frequency-magnitude relationships. As many volcanoes exhibit transitions from lava domes to short lava flows or coulées (e.g. Sinabung, Cordón Caulle), which differ only in morphology and retain many of the same hazards as traditional domes (e.g. dome/flow-front collapse PDCs, large explosions), it is important to capture and categorize these different styles of dome growth. Additionally, certain types of lava domes are often not reported in the GVP or other literature sources as ‘dome

growth' (e.g. large volume dacite coulées, common in the northern Andes) and may be underrepresented in DomeHaz.

9. Short-term eruption forecasting and risk management could be improved at many volcanoes using open-access global databases, such as DomeHaz. When combined with other global databases such as WOVOdat, which includes monitoring data (Venezky and Newhall 2007), there's potential for a powerful resource. To increase the value of such databases it is imperative that future eruptions are well monitored and documented thus providing more high quality data for analysis.

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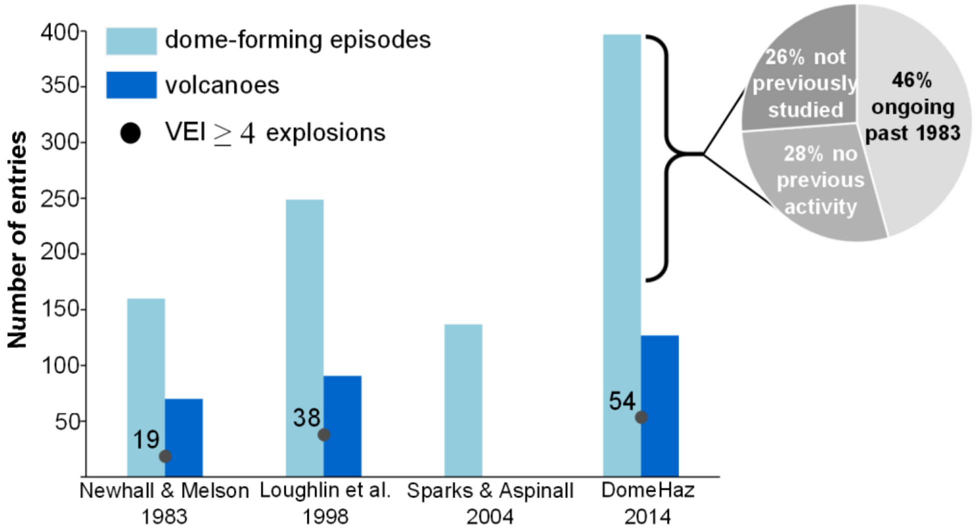

Fig. 1: The DomeHaz database as compared to previous studies. DomeHaz contains 397 dome-forming episodes, at 127 volcanoes, with 54 large explosive (VEI ≥ 4) events. Of the additional 237 more dome-forming episodes that DomeHaz contains in addition to Newhall & Melson (1983), 46% were part of ongoing dome-forming eruptions which continued past 1983, 26% were not studied by Newhall & Melson (1983), and 28% were new dome-forming episodes at volcanoes with no previous dome growth.

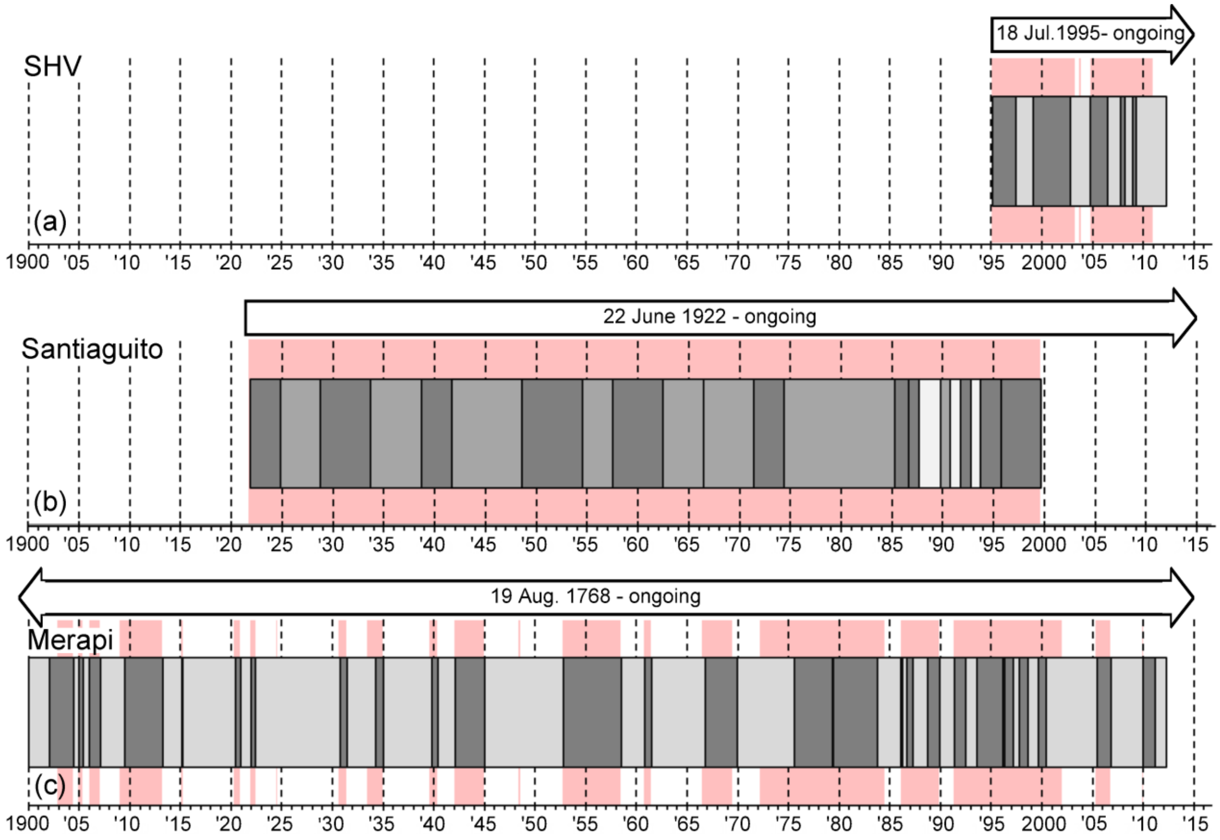

Fig. 2: Periods of dome growth (dark grey) and quiescence (light grey) compared with recorded eruptive history (eruptions in pink) from the Smithsonian GVP for a) Soufrière Hills Volcano, Montserrat; b) Santiaguito Volcano, Guatemala; and c) Merapi Volcano, Indonesia. Santiaguito has alternating periods of high extrusion (darkest grey), low extrusion (medium grey), and quiescence (lightest grey). In our database, frequent episodes of dome growth and quiescence have been grouped together (white rectangles/arrows) into continuous dome-forming eruptions for the sake of consistency.

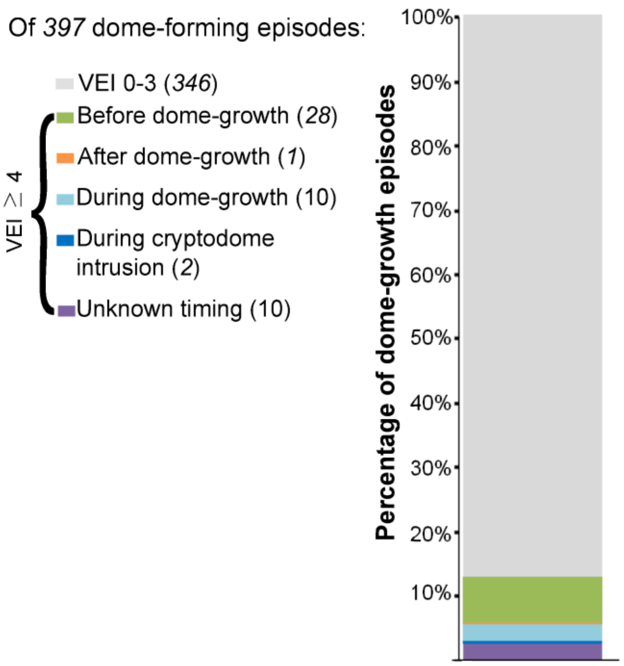

Fig. 3: Overview of the DomeHaz database. Of the 397 dome growth episodes, 51 dome growth episodes were associated with 54 large explosions (three episodes had more than one large explosion). Dome growth episodes which were not associated with a large explosion (VEI 0-3) are shown in grey; the relative timing of VEI ≥ 4 explosions in relation to dome growth are indicated in various colors.

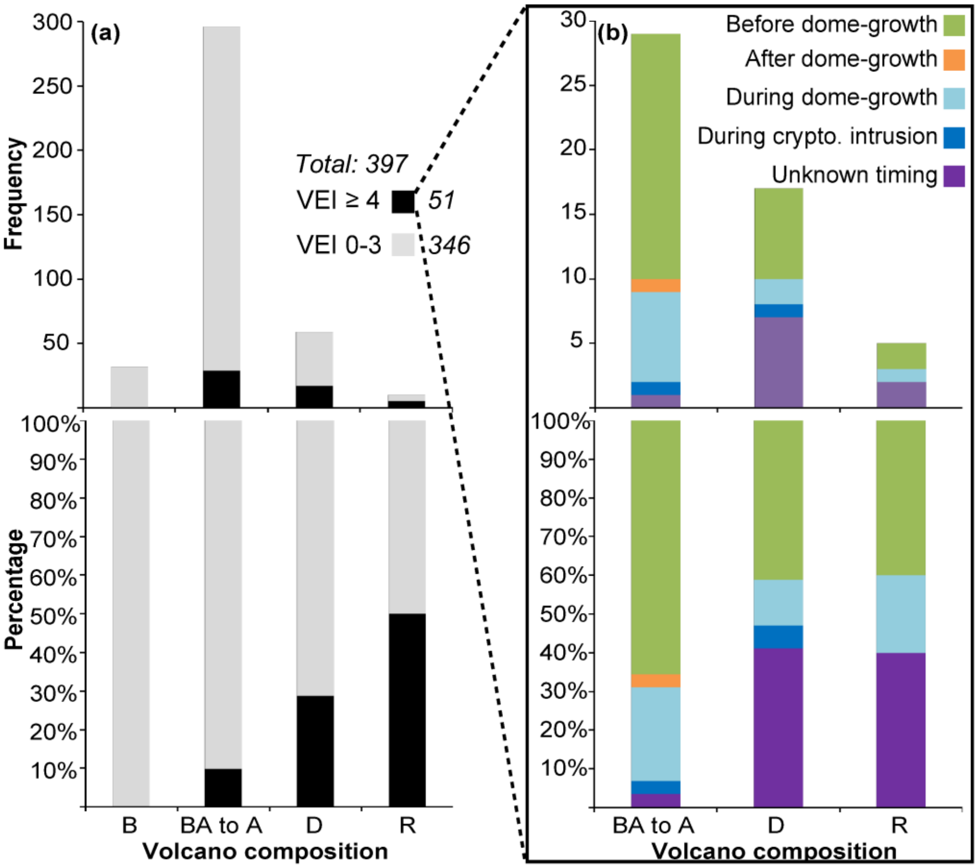

Fig. 4: The a) overall frequency (top) and percentage (bottom) of dome growth episodes associated with explosions varying VEI, with respect to lava composition (B, basaltic, BA to A, basaltic andesite to andesitic; D, dacitic; R, rhyolitic); and b) the timing of the VEI ≥ 4 explosions with respect to dome growth (crypto = cryptodome). Large explosions were not associated with basaltic dome-forming episodes. All 397 dome-forming episodes had compositional information.

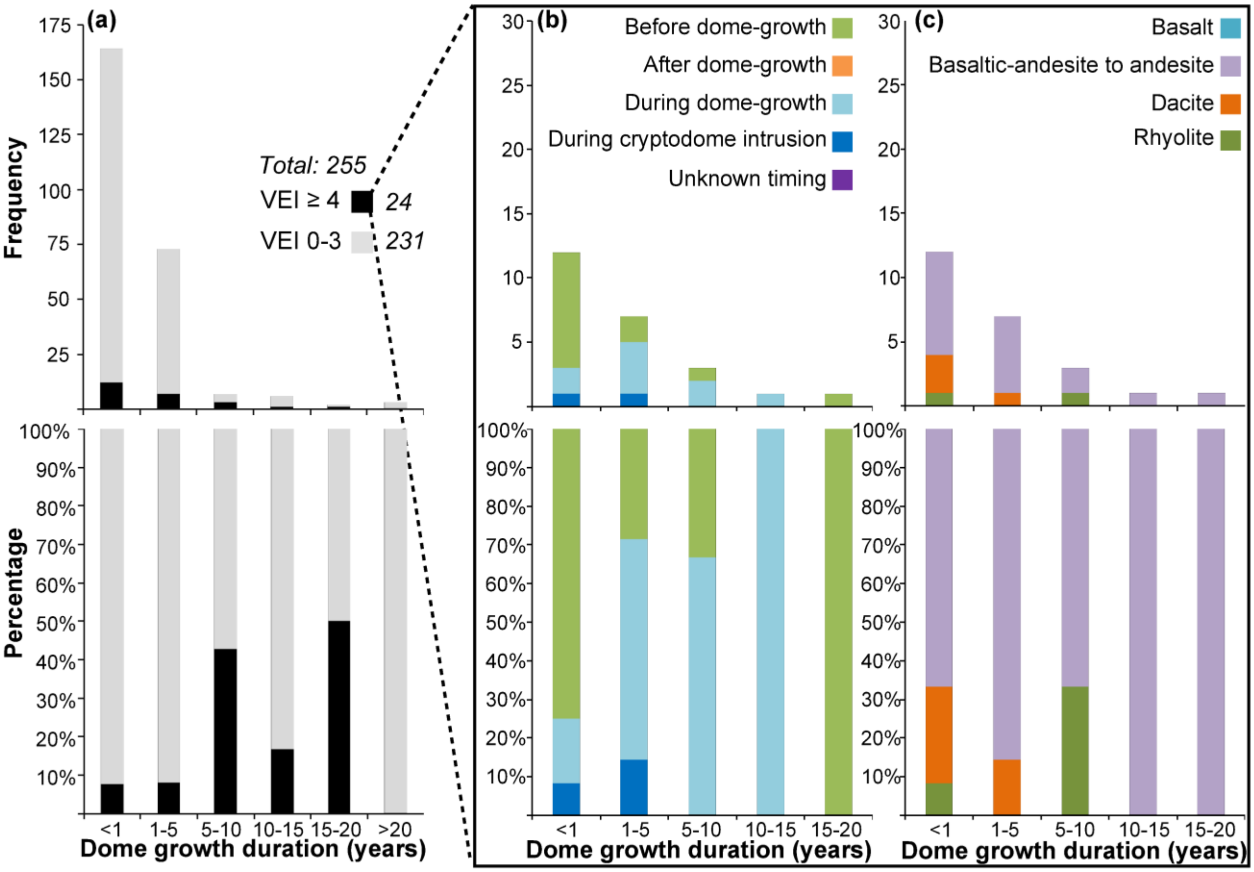

Fig. 5: The a) overall frequency (top) and percentage (bottom) of dome growth episodes of associated with explosions varying VEI, in relation to dome growth duration; b) the relative timing of VEI ≥ 4 explosions with respect to dome growth; and c) the composition of the volcano which produced VEI ≥ 4 explosions. Large explosions were not associated with very long duration (>20 years) dome-forming episodes. Of 397 dome-forming episodes, 255 had duration information.

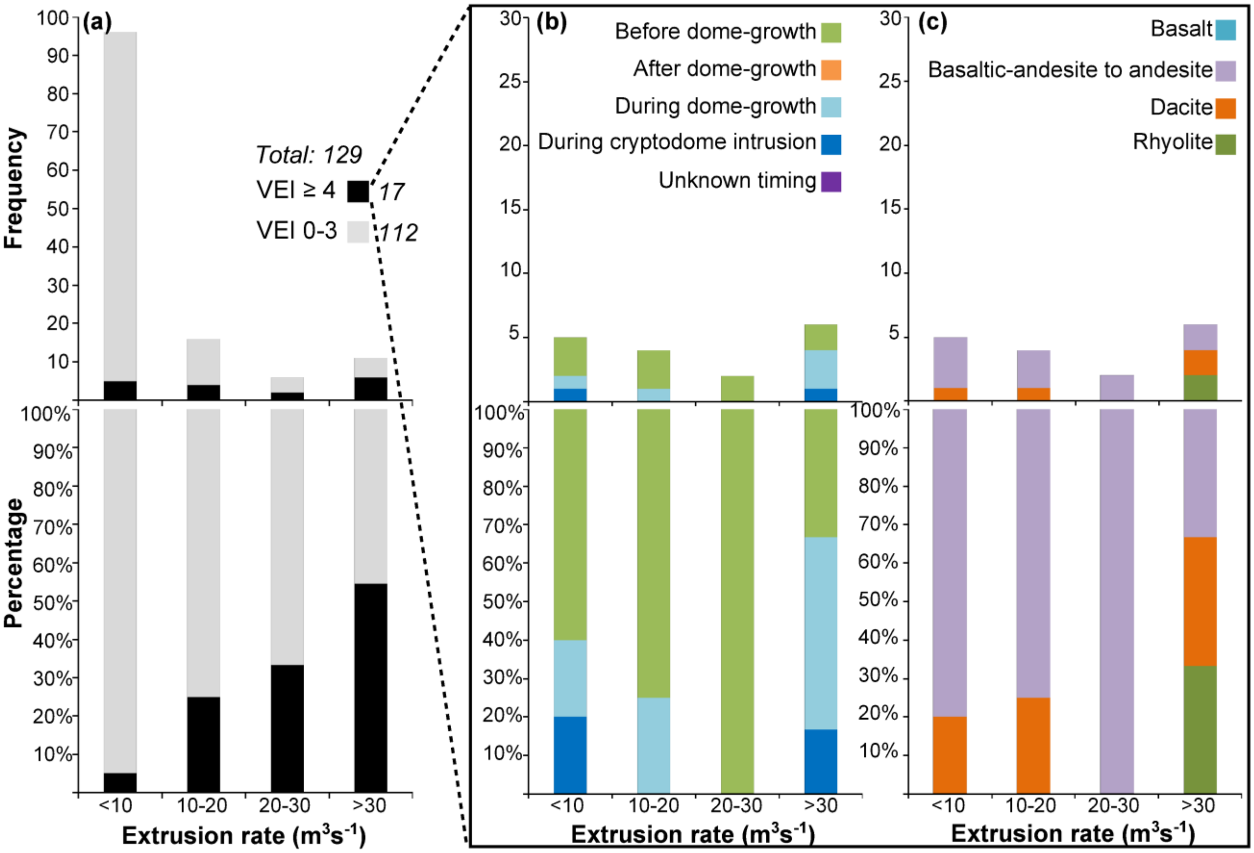

Fig. 6: The a) overall frequency (top) and percentage (bottom) of dome growth episodes of associated with explosions varying VEI, in relation to extrusion rate; b) the timing of VEI ≥ 4 explosions with respect to dome growth; and c) the composition of the volcano which produced the VEI ≥ 4 explosions. Large explosions were associated with all extrusion rates. Of 397 dome-forming episodes, 129 had duration information.

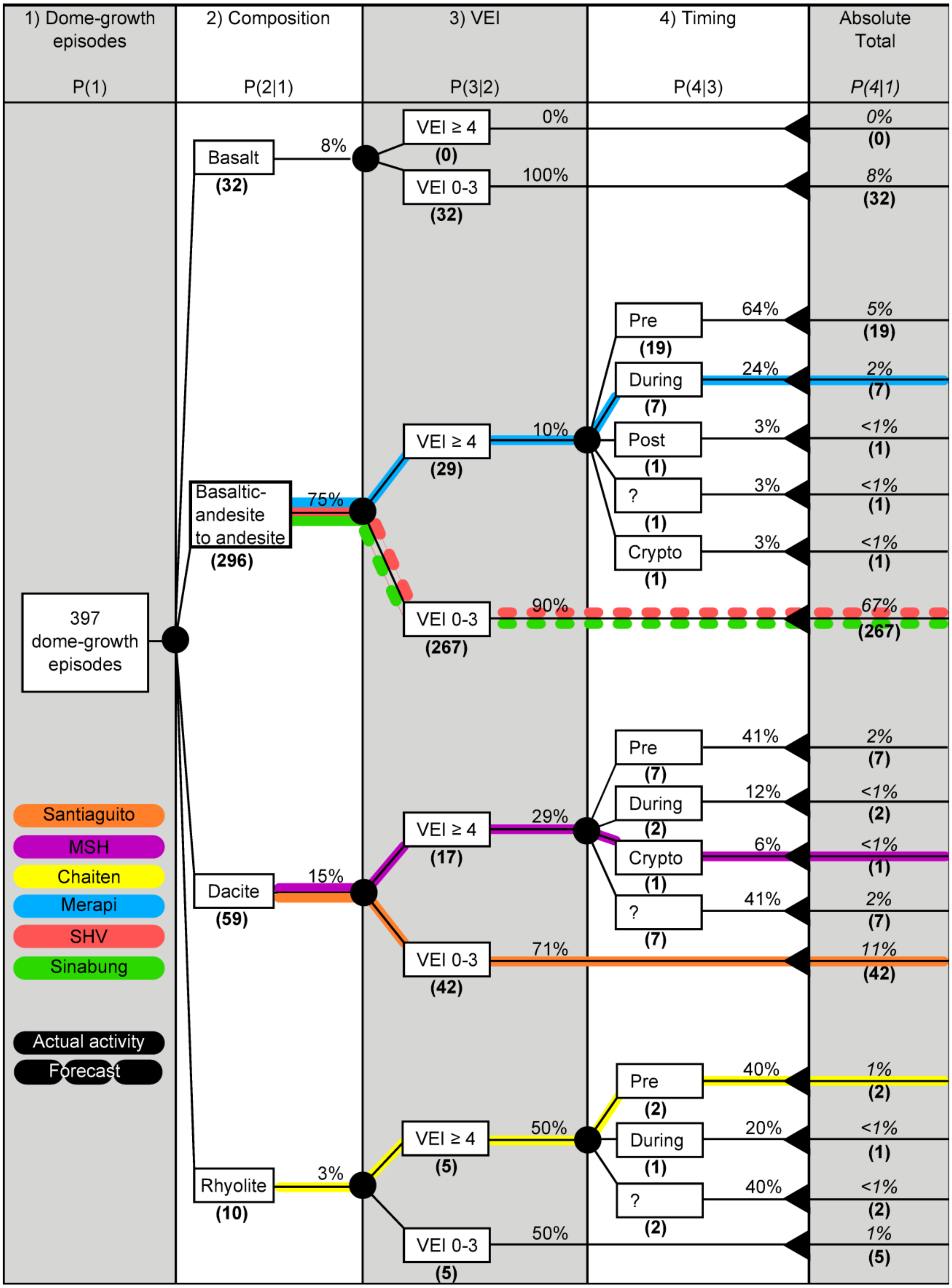
1) Dome-growth episodes
P(1)
2) Composition
P(2|1)
3) VEI
P(3|2)
4) Timing
P(4|3)
Absolute Total
P(4|1)
397 dome-growth episodes
Basalt (32)
8%
VEI ≥ 4 (0)
0%
0%
(0)
VEI 0-3 (32)
100%
8%
(32)
Basaltic-andesite to andesite (296)
75%
VEI ≥ 4 (29)
10%
Pre (19)
64%
5%
(19)
During (7)
24%
2%
(7)
Post (1)
3%
<1%
(1)
? (1)
3%
<1%
(1)
Crypto (1)
3%
<1%
(1)
VEI 0-3 (267)
90%
67%
(267)
Dacite (59)
15%
VEI ≥ 4 (17)
29%
Pre (7)
41%
2%
(7)
During (2)
12%
<1%
(2)
Crypto (1)
6%
<1%
(1)
? (7)
41%
2%
(7)
VEI 0-3 (42)
71%
11%
(42)
Rhyolite (10)
3%
VEI ≥ 4 (5)
50%
Pre (2)
40%
1%
(2)
During (1)
20%
<1%
(1)
? (2)
40%
<1%
(2)
VEI 0-3 (5)
50%
1%
(5)
Santiaguito
MSH
Chaiten
Merapi
SHV
Sinabung
Actual activity
Forecast

Fig. 7: Probability tree for volcanoes of different compositions, where the probability in the absolute total column is equal to the product of each conditional probability: P(composition | total number of events) · P(VEI | composition) · P(explosion timing | VEI).

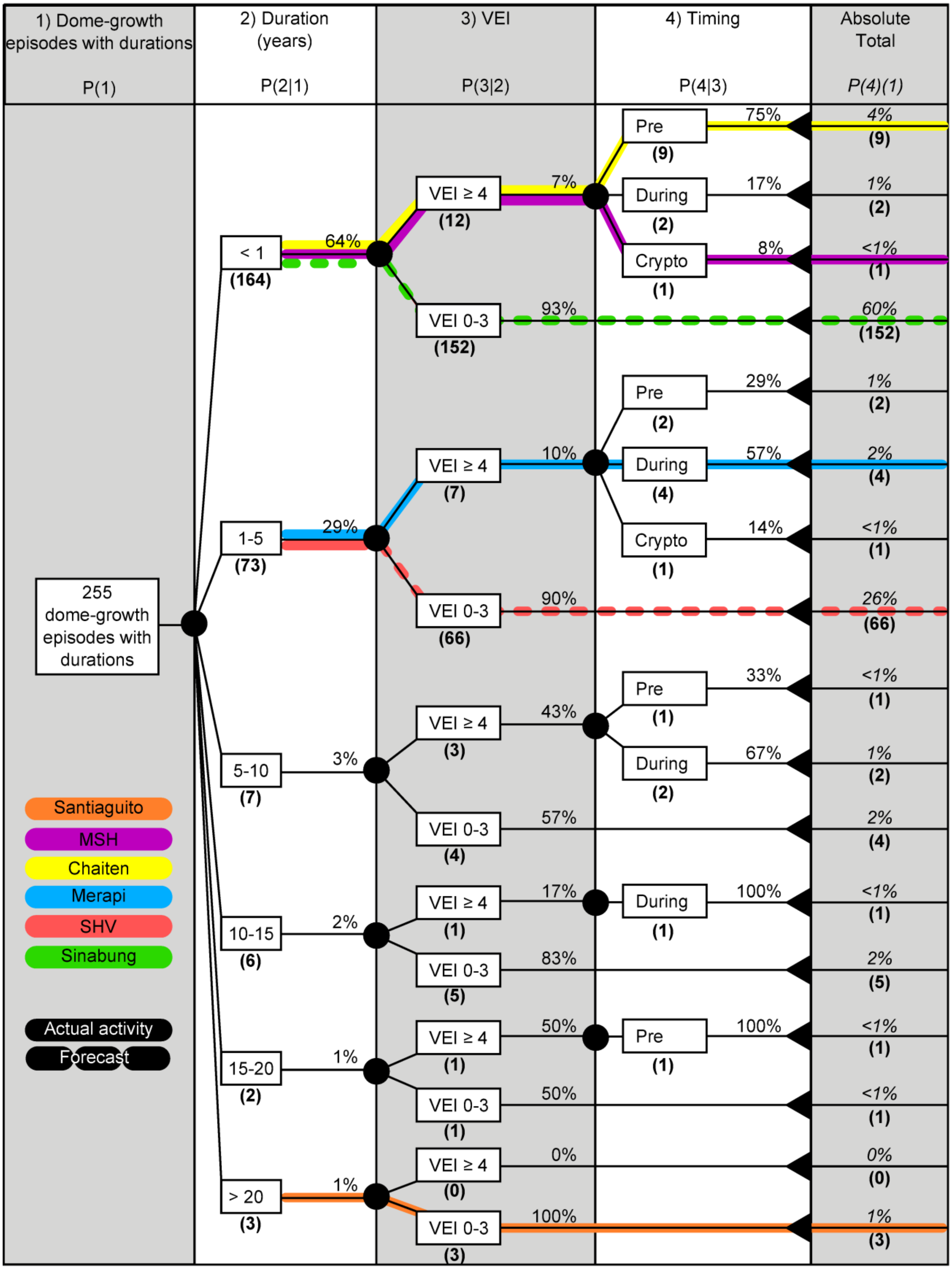
1) Dome-growth episodes with durations
P(1)
2) Duration (years)
P(2|1)
3) VEI
P(3|2)
4) Timing
P(4|3)
Absolute Total
P(4)(1)
255 dome-growth episodes with durations
< 1
(164)
64%
VEI ≥ 4
(12)
7%
Pre
(9)
75%
4%
(9)
During
(2)
17%
1%
(2)
Crypto
(1)
8%
<1%
(1)
VEI 0-3
(152)
93%
60%
(152)
1-5
(73)
29%
VEI ≥ 4
(7)
10%
Pre
(2)
29%
1%
(2)
During
(4)
57%
2%
(4)
Crypto
(1)
14%
<1%
(1)
VEI 0-3
(66)
90%
26%
(66)
5-10
(7)
3%
VEI ≥ 4
(3)
43%
Pre
(1)
33%
<1%
(1)
During
(2)
67%
1%
(2)
VEI 0-3
(4)
57%
2%
(4)
10-15
(6)
2%
VEI ≥ 4
(1)
17%
During
(1)
100%
<1%
(1)
VEI 0-3
(5)
83%
2%
(5)
15-20
(2)
1%
VEI ≥ 4
(1)
50%
Pre
(1)
100%
<1%
(1)
VEI 0-3
(1)
50%
<1%
(1)
> 20
(3)
1%
VEI ≥ 4
(0)
0%
0%
(0)
VEI 0-3
(3)
100%
1%
(3)
Santiaguito
MSH
Chaiten
Merapi
SHV
Sinabung
Actual activity
Forecast

Fig. 8: Probability tree for dome growth episodes of different durations (years), where the probability in the absolute total column is equal to the product of each conditional probability.

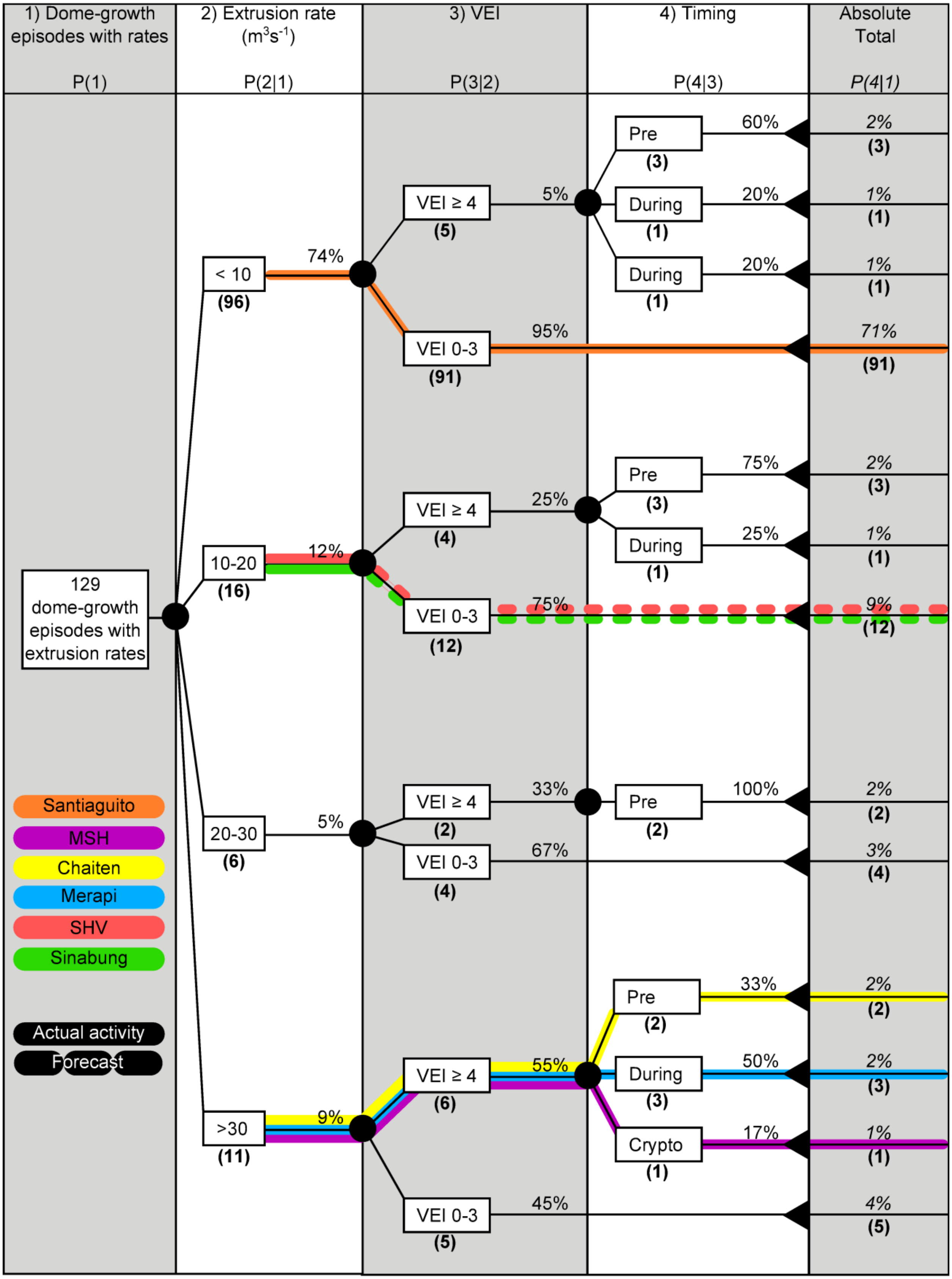
1) Dome-growth episodes with rates
P(1)
2) Extrusion rate (m^3s^{-1})
P(2|1)
3) VEI
P(3|2)
4) Timing
P(4|3)
Absolute Total
P(4|1)
129 dome-growth episodes with extrusion rates
< 10
(96)
74%
10-20
(16)
12%
20-30
(6)
5%
>30
(11)
9%
VEI ≥ 4
(5)
5%
VEI 0-3
(91)
95%
VEI ≥ 4
(4)
25%
VEI 0-3
(12)
75%
VEI ≥ 4
(2)
33%
VEI 0-3
(4)
67%
VEI ≥ 4
(6)
55%
VEI 0-3
(5)
45%
Pre
(3)
60%
During
(1)
20%
During
(1)
20%
Pre
(3)
75%
During
(1)
25%
Pre
(2)
100%
Pre
(2)
33%
During
(3)
50%
Crypto
(1)
17%
2%
(3)
1%
(1)
1%
(1)
71%
(91)
2%
(3)
1%
(1)
9%
(12)
2%
(2)
3%
(4)
2%
(2)
2%
(3)
1%
(1)
4%
(5)
Santiaguito
MSH
Chaiten
Merapi
SHV
Sinabung
Actual activity
Forecast

Fig. 9: Probability tree for dome growth episodes of different extrusion rates, where the probability in the absolute total column is equal to the product of each conditional probability

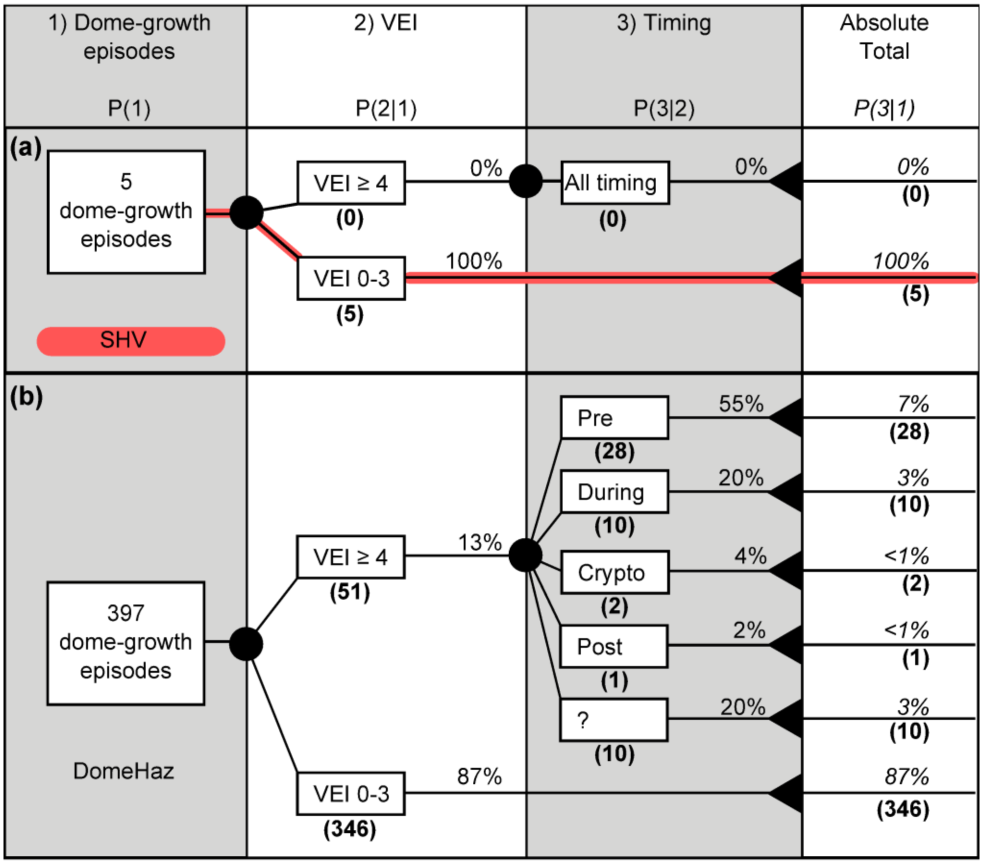

Fig. 10: Probability tree a) using only the eruptive history of SHV, and b) using the entire DomeHaz database to determine the likelihood and timing of large explosive eruptions.

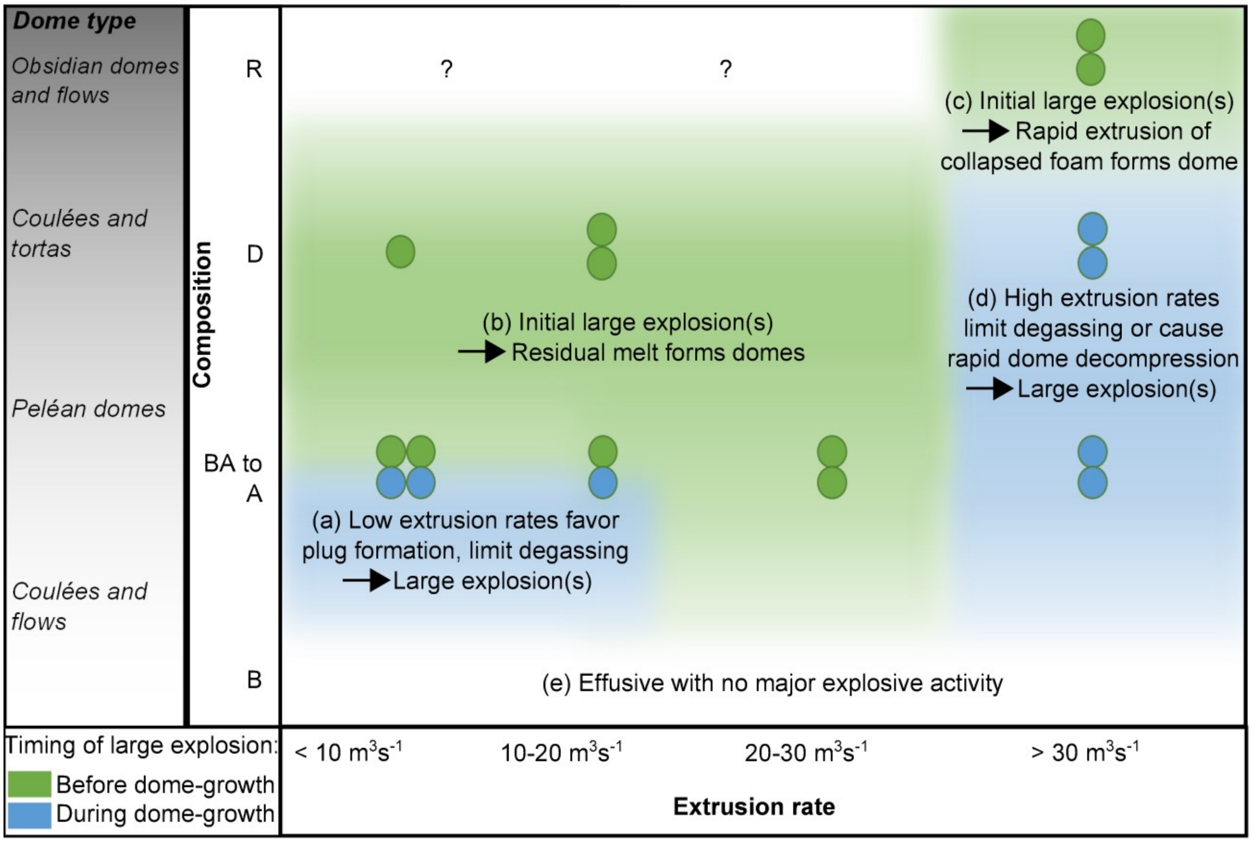

Fig. 11: Schematic diagram of the relationships between lava dome extrusion rate, compositions (B, basaltic; BA to A, basaltic andesite to andesitic; D, dacitic; R, rhyolitic) and dome types, and the timing of large explosions. Green fields indicate large explosions *before* dome growth; blue fields indicate large explosions *during* dome growth. Blue and green dots are data points from DomeHaz, and include the 17 large explosions with extrusion rate information. a) Low extrusion rates at basaltic andesite to andesitic volcanoes may favor the formation of domes that plug the conduit, inhibiting degassing and leading to large explosions during dome growth. Alternatively, very low extrusion rates are a result of long-term averaging. b) Major explosive eruptions at basaltic andesite to andesitic and dacitic volcanoes are followed by the extrusion (at a variety of rates) of residual melts. c) Large explosive eruptions at rhyolitic volcanoes result in the rapid extrusion of obsidian lava domes as the byproduct of collapsing foams. d) Rapid dome extrusion precedes large explosions because high extrusion rates limit degassing or because rapid

decompression of growing lava domes trigger large explosions. e) Basaltic volcanoes do not display an association between large explosions and dome growth. Question marks indicate regions of the regime diagram where extrusion rates are not available.