Do high lava-dome extrusion rates foreshadow explosive eruptions?

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Satellite radar, LIDAR, and photogrammetry provide improved measurements of erupting lava domes. Data from these sources combined with petrologic data and historical records raise the question of whether high extrusion rates can be used to forecast explosive eruptions.

Lava dome extrusion takes place both before and after large explosive eruptions (as well as interspersed between explosive eruptions). Examples include Pinatubo (1991), Chaitén (2008-2009), and Merapi (2010). At Pinatubo, mingled magma lava domes were extruded both before and a year after the paroxysmal Plinian eruption on 15 June 1991 (Daag et al., 1996; Pallister et al., 1996). At Chaitén, rapid (>45 m3s-1 extrusion of low viscosity rhyolite followed an initial Plinian eruptive phase (Pallister et al., in press). At Merapi, rapid (25 m3s-1) lava extrusion followed an initial phreatomagmatic eruption on 26 October 2010 and formed a 5 Mm3 lava dome before the main Plinian eruption on 5 November 2010. Rapid (35 m3s-1) extrusion then resumed for a brief period on 6 November, forming a 1.5 Mm3 lava dome that initially inflated and then subsided as the eruption waned (Surono et al., 2012; Pallister et al., 2013).

At both Pinatubo and Merapi intrusion of new gas-rich magma into pre-existing crustal reservoirs triggered the eruptions, and in both cases, ascent was retarded by transit through these viscous crystal-rich reservoirs. However, there are distinct differences in the Pinatubo and Merapi situations. Prior to 1991, Pinatubo was a closed system lacking a conduit to the surface. Gas-rich recharging basalt magma mingled with crystal-rich dacite in Pinatubo's crustal reservoir. It was this mingled magma that augered a new conduit to the surface to form the 7-12 June 1991 lava dome (extrusion rate unknown) and it was dacite that powered the paroxysmal eruption. At Merapi, an unusually large and gas-rich batch of magma invaded and pressurized a dominantly andesitic magmatic system with a pre-existing conduit to the surface. In both cases, the erupted magmas bear petrologic evidence of a difficult passage (e.g., mingled or mixed magmas with varied crystal cargos). Consequently, large or particularly gas-rich replenishing magma batches are most likely to break through these shallow crustal filters (Costa et al, 2013) and trigger eruptions. Such magmas are the vanguards that create and pressurize conduits and thereby generate seismic swarms and near-surface deformation.

Anomalously high rates of dome extrusion, accompanied by increasing and accelerating levels of shallow seismicity and inflation (as seen at Merapi) are a warning sign that a more explosive eruption may ensue. However, when seismicity and inflation are flat or declining, despite a high rate of extrusion (as seen at Chaitén and Merapi following their initial Plinian phases), pressure in the conduit system has declined and the threat of a more explosive eruption has diminished.

Revealing shallow magmatic ascent processes during the 2006 and 2010 eruptions of Merapi volcano: evidence from textural and compositional variations of feldspar microlites

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The interplay between magma ascent, degassing and changing magmatic properties are widely recognized as critical factors controlling the style of silicic volcanic eruptions. Microlite textures in samples from the prolonged dome-forming eruption of Merapi in 2006 provide a record of changing magmatic ascent conditions and shallow conduit processes throughout the eruption. Analysis of microlite textural parameters, including measurements of areal number density (N_A), mean microlite size, crystal aspect ratio and groundmass crystallinity (ϕ), combined with the monitoring record and field observations, indicate that magma ascent paths change between continuous ascent at varying rates from a deeper magma storage region, to ascent being temporarily stalled at shallow depths in the latter stages of the eruption [1]. Plagioclase microlite compositions show evidence of decompression-induced degassing, often displaying rims of anorthoclase and more K-rich alkali feldspar (sanidine). Anorthite contents also support the textural data of later erupted magma being temporarily stalled at shallow depths. Crystal size distributions (CSDs) are interpreted to show that both growth-dominated and nucleation-dominated crystallisation regimes existed during the 2006 eruption, resulting from changing conditions of undercooling (ΔT) during variable magma ascent paths. By contrast, microlite textural analysis and feldspar microlite compositions of samples from the fast-growing lava dome of the second phase of the 2010 eruption prior to the cataclysmic events on 5 November indicate faster ascent rates, a crystallisation regime more strongly dominated by nucleation due to high ΔT and possible interaction of the 2010 magma with more mafic magma from depth.
The differences in ascent processes have key implications for determining the eruptive behaviour at Merapi, i.e. effusive vs. explosive activity, as well as the associated hazards.

Reference: [1] Preece *et al.*, (2013) J. Volcanol. Geotherm. Res. (in press)

Petrology and geochemistry of the large-magnitude 2010 eruption of Merapi volcano, Central Java, Indonesia: insights into magma dynamics

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The devastating eruption of Merapi that started on 26 October 2010 was the volcano's largest since 1872 and the deadliest event since 1930. The eruption was unusual in many respects: (1) it started, after nearly two months of increased seismicity and summit deformation, with an explosive phase that was not preceded by lava dome extrusion at the summit; (2) between 30 October and 4 November, a lava dome appeared and grew rapidly within the newly formed summit crater, exceeding growth rates observed at the peak of the penultimate eruption in 2006 by a factor of 7.5 [1]; (3) during the paroxysmal eruption phase on 5 November, high-energy PDCs were generated and at least one PDC travelled more than 15 km (more than twice the distance of the largest flows in 2006) beyond the summit along the Gendol river valley, causing widespread devastation on Merapi's south flank [2, 3]; (4) in a later phase on 5 November, PDCs were produced that incorporated conspicuous light-coloured pumice clasts; (5) ash emissions from sustained eruption columns resulted in ash fall tens of kilometres from the volcano, affecting, amongst other areas, the city of Yogyakarta 25 km to the south of Merapi; and (6) the total non-DRE volume in 2010 is thought to have been at least 4 times higher than that of the preceding 2006 eruption [3, 4]. Despite the unusual eruptive behaviour of Merapi in 2010, whole-rock major and trace element compositions, Sr-Nd-O isotopic data, pre-eruptive melt volatile concentrations, as determined by electron and ion microprobe analysis of pyroxene-hosted melt inclusions, for the eruptive products from the various stages of the 2010 eruption are remarkably similar to other recent and historical eruptions, which were predominantly characterised by periods of slow lava dome extrusion punctuated by gravitational dome failures. By contrast, notable petrographical differences are the presence of unaltered amphibole phenocrysts and microphenocrysts without reaction (breakdown) rims as well as variations in groundmass textures in the juvenile component(s) of the 2010 eruption, which, in combination with short-lived U-series isotope systematics (^{210}Po-^{210}Pb-^{226}Ra), provide a detailed picture of pre-eruptive magma dynamics characterized by fast ascent and temporary shallow stalling of magma (or batches of magma) that fed the eruption.

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Modelling the frequent transitions between explosive and effusive activity at Volcán de Colima, Mexico

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During the past 14 years Volcan de Colima has transitioned between a large variety of eruptive styles whilst showing a remarkable consistency in the magma composition. The volcano has produced 6 distinct periods of dome growth with mean effusion rates varying over 2 orders of magnitude from 0.02 to 8 m3 s-1. Several domes were destroyed by subsequent Vulcanian explosions with a variation in the interval dividing the two types of activity (from days to several months). In 2005 the explosions were of sufficient magnitude to produce pyroclastic density currents from column collapse which reached up to 5.4 km. However, the largest run-out distances (6.1 km) were achieved by flows resulting from dome collapse in Oct. 2004. Superimposed on top of this activity the volcano has demonstrated a very efficient sealing mechanism preventing continuous gas release and resulting in small Vulcanian explosions on the time-scale of a few hours.

Different data has been used to understand the upper edifice processes controlling magma degassing and crystallization. Seismicity has enabled the tracking of magma ascent rates with precursory swarms of LP events associated with brittle fracturing along the margins of fractures. Variation in fumarole temperatures has reflected the variation in degassing pathways and magma ascent rates, whilst thermal images of domes has given an insight into their emplacement mechanism. The SO2 flux has shown a decreasing trend throughout the 1998-2013 eruptive period, however, there is evidence for relatively large volumes of gas-rich magma which decompressed to drive the sporadically occurring larger explosions. Further insight has been obtained from the comparison between column ascent rate of the explosions and associated seismic and thermal energy release.

Physical evidence in the form of widespread tuffesites found on the dome gives us further insight into the explosive mechanism. These represent fractures that were filled with gas-rich magma prior to the eruption. Failure of the capping dome-rock, lead to rapid decompression and fragmentation within these zones. Some ash entered the eruption column, whilst some re-crystallized to close the cracks, increasing the permeability once more with a new Vulcanian sequence following. A slow growing dome was emplaced between 2007 and June 2011, when there was a moderate explosion, which destroyed a portion and marked the end of its growth. Then there was a remarkable quiet period, but after only a 1.5 year hiatus, it resumed activity during January 2013, with further moderate explosions with magma emplacement within the newly formed crater.

Volcan de Colima represents an excellent case study due to its frequent transitions and interplay between explosive activity of different magnitudes and effusive eruptions. The understanding of these transitions is critical for the interpretation of precursory signals and the evaluation of possible eruptive scenarios and their associated hazards.

Does magma rheology control eruption style? The case of Fuego, Guatemala

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Volcán Fuego, Guatemala, is a basaltic andesitic stratovolcano that has been in semi-continuous eruption for more than 500 years. The past decade has been characterized by vulcanian explosions with minor ash emission, punctuated by strombolian episodes with extrusions of lava flows and rare larger eruptions with pyroclastic flows, most recently in September 2012. We have investigated 9 samples (4 lava flows, 1 air-cooled bomb, and 4 blocks transported in pyroclastic flows) erupted or deposited in 2003 and in 2008-9, and all collected from the Barranca Santa Teresa on Fuego's western flank, to see if the type of activity (lava flow vs pyroclastic flow generation) can be correlated with varying physical and chemical properties of the magma. In particular we test the hypothesis that magma rheology controls eruptive style, i.e. blocks and bombs should be more viscous than lava flows.

All the samples are highly crystalline, with similar basaltic andesite bulk compositions (52-53 wt.% SiO_2) comprising matrix glass of andesitic to dacitic composition (62-67 wt.% SiO_2) with abundant plagioclase, olivine and pyroxene phenocrysts together with minor Fe-Ti oxides. One lava flow "2003c" has a rhyolitic matrix glass ($\sim$74 wt.% SiO_2). Phenocryst compositions vary little, and show no systematic variation with eruption style. The matrix (dense-rock) density of the samples also varies little, from $\sim$2810-2850 kgm^{-3}), while bulk density varies from $\sim$1480 to $\sim$2680 kgm^{-3}, due to porosity. Lava flow samples contain 11-16 vol.% vesicles, while the bomb contains 16 vol.% and blocks range from 5 vol.% (dense) to 48 vol.% (vesicular). Water contents of matrix glasses vary from $\sim$0.25 wt.% (bomb) to less than 500 ppm (breadcrust block in a pyroclastic flow). The rheology of all samples was measured by uniaxial compression at $\sim$1020°C and 1 atm. In all experiments, regardless of porosity, the viscosity increased from $\sim10^{10}$ to $\sim10^{12}$ Pa.s in a few hours, then increased only slightly for the next $\sim$80 hours. Lava flow sample 2003c has a slightly ($\sim$0.5 log unit) higher viscosity than other samples. These experiments never exceeded 2% total strain, and overall changes in porosity were negligible, but the proportion of isolated porosity increased during the experiment, which we attribute to early crack closure.

Despite large variations in vesicularity, and modest variations in matrix glass chemistry and dissolved water content, the rheology of blocks, bombs and lava flows is generally identical. We conclude that changes in eruption style do not reflect changes in magma properties. The most likely alternative controls are magma supply rate, and/or mechanisms related to how lava and hot erupted material accumulates near the summit region, and how this material may be remobilized as either lava or pyroclastic flows.

Reassembling a volcanic conduit using bombs at Cordón Caulle, Chile

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Active volcanic conduits are not directly observable, however, snapshots of the state of magma feeding varied eruption styles can be reconstructed from pyroclasts. During the opening weeks of the June, 2011 Cordón Caulle eruption, hundreds of large (cm's to m's) bombs were ejected and deposited up to 2.5 km from the vent. At this time, activity changed from being explosive to hybrid, involving effusion of obsidian lava along side a pyroclastic fountain. The bombs at El Caulle provide an unprecedented view into an active conduit that fostered simultaneous explosive and effusive volcanism.

We examined the physical characteristics of >70 bombs from the flanks of Cordón Caulle, and based on these observations group them into two general categories. Type I bombs were erupted as dense magma and quenched to form either obsidian or breadcrusted blocks. The dense, flow banded blocks have incipient surface cracks and etched outer surfaces. Type I breadcrusted bombs occur as many separate fragments that individually vesiculated after the bomb impacted and broke. Both dense and breadcrusted bombs have white, ash- and pumice-laden tuffisite veins (mm to cm's) adjoined to their surfaces, indicating that some of the Type I bombs were actually composites of dense obsidian and juxtaposed ash and pumice domains at the time of their eruption.

Type II bombs are pumiceous with <5 vol% obsidian clasts. These bombs may be partly or wholly brecciated, comprising angular pumice clasts (cm to dm's) suspended in fine to coarse ash and pumice lapilli. Some Type II bombs are homogenous pumice blocks that also contain red tuffisite veins cutting through them. Pumice breccia bombs often have large (dm's) coalesced vesicles at their centers that cracked the outer bomb surface due to their expansion after the bomb erupted. These features indicate that despite the bomb's clastic and porous nature, brecciated conduit magma must weld to the point of having low permeability—this may, in turn, impede outgassing to the point of explosive release in the conduit.

The glassy and pumiceous bombs found at Cordón Caulle represent juxtaposed regimes of magma movement and degassing. Type I facies develops during coherent magma flow through the conduit, while Type II records multiple fragmentation events and gas-driven flow of clastic bubbly magma. That overlap exists between these facies—this evidenced by the mixing (inclusion) of pyroclastic and dense elements in Type I and II bombs—suggests that the bombs are sourced from a boundary zone/layer that separates effusively and explosively erupting magma. This boundary zone must allow not only physical exchange of pyroclastic and coherent elements, but also chemical transfer of exsolved gases between the different magma domains.

Explosive expansion of a slowly-decompressed magma analog: evidence of delayed bubble nucleation

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Slow decompression of magma generally results in an effusive or mildly explosive expansion of the magma, but counterexamples of sudden switches from effusive to explosive eruptive behaviour have been documented at various volcanoes worldwide. The mechanisms involved in this behavior are currently debated, in particular regarding basaltic magmas. Here, we explore the interplay between decompression rate and vesiculation vigour by decompressing a magma analog obtained by dissolving pine resin into acetone in varying proportions. Our mixtures contain solid particles and upon decompression experience the nucleation of acetone bubbles. We find mixtures high in acetone, containing smaller and fewer solid particles, experience strong supersaturation and fragment for very slow decompressions, despite having low viscosity, while mixtures low in acetone, with more and larger solid particles degas efficiently. We interpret our results in terms of delayed bubble nucleation due to a lack of efficient nucleation sites. We discuss how a similar mechanism might induce violent, explosive expansion in volatile-rich and poorly crystalline low-silica magmas, by analogy to previous inferences for rhyolitic magmas

Explosive versus effusive eruptive activity at Merapi volcano, Java, Indonesia.

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1872 Merapi volcanic activity was even more violent and explosive than the 2010 events (VEI 4). Here we examine Merapi past explosive versus effusive activity through a detailed analysis of selected lava flows and domes, juvenile components from different types of pyroclastic flow deposits and lapilli ejecta from sub-plinian-style eruptions, ranging in age from Proto-Merapi to the recent activity.

The textures, petrology and geochemistry of the older Merapi units are revisited giving particular attention to the contrast in crystal sizes of the volcanics relative to those of the inclusions and xenoliths as well as to the associated mineral assemblages and compositions in order to identify the various stages of magma genesis and evolution. Moreover, special attention is given to the 1872 eruptive products and their comparison to the 2010 ejecta.

Crystal size distribution (CSD) theory is applied to obtain information on growth and residence times of plagioclase crystals in the various magma storage zones in the sub-volcanic plumbing system and to gain insight on open-system processes such as the frequency of magma replenishment and possible rates of crustal assimilation. From Intercept-Slope (I-S) relations, in comparison to other large magmatic systems, the staging zones for some Merapi eruptives appear to be similarly extensive in terms of volume and longevity. This suggests that, in addition to understanding eruption mechanics, the eruptive record of Merapi may also be valuable in understanding the ongoing evolution of other major magma chambers.

Coupled with petrographic results, like a freshly-crystallized amphibole observed in the 2010 deposits (Costa et al., 2013 and Preece et al., 2013) and in older deposits, it may provide a clue to the identification of precursors for very explosive events (VEI 4) by carrying the signature of a large, undegassed magmatic batch from a source deeper than where 20thcentury lava dome magmas were stored before extrusion.

Textural and Mineral Chemistry Constraints On Evolution of Merapi Volcano, Indonesia

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We analyze and compare the textures of Merapi lavas (basalts and basaltic andesites) ranging in age from Proto-Merapi through modern activity, with the goal of gaining insights on the temporal evolution of Merapi magmatic system. Analysis of textural parameters, such as phenocryst and microphenocryst crystallinity, coupled with crystal size distribution theory, provides information about the storage and transport of magmas. We combine textural analyses with geochemical investigations for a comprehensive comparison of erupted lavas over time. The chemical analyses identify crystal growth processes in the magma chamber and underline differences between sample groups. We analyze also the textures and mineralogy of Merapi tephra generated during explosive eruptions with VEI 3-4, and compare these data to those observed for Merapi dome and flow lavas. We find that the Merapi tephra and lava textures differ significantly with respect to small-size crystal populations, but that phenocryst textures are generally similar. A similar initial phase of crystallization is indicated for tephras and lavas in mid-crustal reservoirs. Subsequent textural differences are mainly affected by ascent rate and degassing during ascent, and, for dome lavas, with temporary storage in a shallow reservoir. These differences correspond to different eruptive styles. In general, comparison of the crystal size distributions and calculated residence times among the effusive and explosive eruptive styles indicates that the two magma types resided for a similar length of time in a mid-crustal reservoir, before ascending toward the surface and either erupting (tephra), or stagnating in a shallow magma chamber (lava). The interpretation is supported by the occurrence of amphibole in pristine condition (tephra) or altered state (lava). Dome lavas from the 20th century eruptive activity indicate steady-state, open-system behavior, while samples from the stratigraphic history of Merapi record both repeated attainment and loss of steady-state conditions. This observation suggests that the relatively benign activity of the 20th century will be interrupted from time to time by more explosive eruptions such as that of 2010.

Effects of magma and conduit conditions on transitions between effusive and explosive activity: A numerical modeling approach to illuminate the 2006-2010 activity at Merapi Volcano, Indonesia

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Transitions between effusive and explosive eruptions, common at silicic volcanoes, can occur between distinct eruptive episodes or can occur with switches between effusive and explosive phases in a single episode. The precise causes of these transitions are difficult to determine due to the multitude of mechanisms and variables that can influence fragmentation thresholds. Numerical modeling of magma ascent within a volcanic conduit allows the influence of key variables to be extensively tested. We use a conservative, 1-D, two-phase, steady-state model that allows for lateral gas loss at shallow depths to study the effect of different variables on the mass eruption rate at the vent. We use a fragmentation criteria based on gas volume fraction. We are able to generate a number of regime diagrams for a variety of magma and conduit conditions that constrain transitions from effusive to explosive episodes. For constant conduit geometry, initial magma crystal content and chamber overpressure have the greatest effect on the mass eruption rate. We apply our model to the recent activity at Merapi Volcano in Indonesia. We constrain model input and output parameters using current petrologic, seismic, and geodetic studies of the Merapi system, and vary critical parameters over reasonable ranges as documented in the literature. Our model is able to reproduce eruption rates observed during both the 2006 effusive and 2010 explosive/effusive eruptions. Our modeling suggests a combination of overpressure, increased volatile content, and decreased crystal content due to the voluminous injection of new magma into the shallow Merapi system is the plausible cause of explosivity in the 2010 eruption, the most violent at Merapi since 1872. Transitions in eruptive activity were also observed during the 2010 eruptive sequence, where explosive episodes lasting on a scale of hours alternated with longer periods of rapid effusive dome growth. Our modeling suggests these transitions can be plausibly controlled by (1) the degassing behavior of the shallow conduit system without needing to change the magma supply rate into the conduit from the chamber, or (2) alternating conduit magma batches with different H2O content that reflect converging extraction patterns in a volatile-heterogeneous chamber. The latter condition reflects the inevitability for a large eruption to sample, nearly simultaneously, from a wide vertical and horizontal range of locations in a zoned chamber.

Evolution of conduit flow during the 2011 eruption of Shinmoe-dake, Japan-insights into cyclic sub-Plinian activity and shifting eruption style of andesite magma

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The climactic phase of the 2011 eruption of Shinmoe–dake is characterized by sub–Plinian eruptions (Jan 26–27) and lava accumulation in the crater (Jan 28–31), both of which accompanied vulcanian eruptions (Nakada et al., in review). Referring real–time observatory data on crater image, tremor and infrasound (Ichihara et al., in review) and tilt variation (e.g. Kozono et al., in review), a geological study (Maeno et al., in review) showed three sub–Plinian events (26PM, 27AM and 27PM, the most intense phase of each lasted 2.5–1.7 hours) occurred every 12 hours with a decrease of erupted magma volume and with a constant mass discharge rate. This study reveals evolution of conduit flow through the climactic phase, by combining, a) records in groundmass microlite and vesicle textures and b) the above–mentioned, time–resolved observatory results. Based on a petrological result (Suzuki et al., in review JVGR), we judge that variable groundmass textures among the samples reflect different conditions in syneruptive magma ascent, not different characteristics of the magma at the reservoir. Although most ejecta (gray and brown ones as to pumice clasts) are products of magma mixing that resulted from syneruptive injection of basaltic andesite magma into a silicic andesite magma reservoir, the mixed magmas were homogeneous in the reservoir (SiO_2 57–58 wt.%, 30vol.% phenocrysts, 960–980C, 4wt.% H_2O) owing to constant mixing ratio. The volcanological questions we would like to address after we reveal evolution of conduit flow through the climactic phase are, 1) mechanisms that led to the cyclic sub–Plinian eruption, including triggering processes of each event, 2) timing and conditions of syneruptive magma ascent that are responsible for the shifting eruption intensity and the eruption style (explosive and effusive). We expect this groundmass textural study also helps us newly define a boundary between the 26PM and 27AM pumice deposits. The corresponding deposit exhibits reverse and normal gradings, as if it was generated in a single event (Maeno et al., in review, Nakada et al., in review). Regardless of that, the groundmass textures of the samples may record waxing and waning phases of conduit magma flow in each sub-Plinian event.

Unsteady and steady phases of the Kaharoa 1314 eruption, Tarawera volcano, New Zealand

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The 5 km3 Kaharoa eruption of AD1314 was a prolonged rhyolitic eruption (ca. 5 years) involving at least 7 source vents located along an 8 km long fissure transecting a pre existing dome complex. Following vent opening explosions, seven early powerful pyroclastic fall phases formed tephra lobes dispersed to the SE with minor pyroclastic explosive activity. The eruption deposits have characteristics typical of both subplinian-Plinian (absolute intensity, duration) and Vulcanian styles (multiple explosive phases, dense juvenile clasts, grain size fluctuations). These characteristics are not compatible with end-member models of either rapid ascent (Plinian), or short lived, low intensity (Vulcanian) explosions. Each pumice fall unit is separated by partings rich in fine ash, interpreted to represent short quiescence intervals between eruptive phases. Within fall units, grainsize and juvenile clast density measurements taken on a bed by bed basis provide a high-resolution eruption chronology that implies the degree of "steadiness" (or instantaneous mass discharge rates) of the eruptive phases.Two fallout units were chosen to represent "unsteady" and "steady" eruption conditions. We use clast microtextures combined and analytical measurements to evaluate the parameters that drive steady vs. unsteady silicic explosive eruptions. Initial microtextural observations reveal that the partial outgassing of the magma column in the conduit was a critical factor in driving unsteady eruptions. Additionally, high density (greater than 1600 kgm-3) juvenile clasts increase in size and abundance during unsteady phases suggesting evacuation of stagnant melt within the conduit, plug or dome. Our juvenile clast density analysis also shows evidence for the existence of a protodome or plug in the active vent at an earlier stage of the eruption than initially postulated.