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The Emplacement Dynamics of Pumice Lobes Ascertained from Morphology and Granulometry; Examples from the 1993 Deposits at Lascar Volcano, Chile

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Abstract

The work presented here focuses on lobe shapes and clast populations within lobate termini of the 1993 pumice flow deposits at Lascar Volcano, Chile. A new method to analyze a coarse-tail grain size population with field photographs is presented. Using this method, more than 33,000 (>0.5 cm) clasts from the pumice lobes of the 1993 pumice flow deposits were measured at 36 sites, and the resultant grain size distributions were then related to lobe morphology. Lobe margins (i.e., levees, clefts, and snouts) were found to contain significantly larger pumice clasts and be more poorly sorted than lobe central channels (i.e., locations away from the margins). Previous laboratory experiments suggest lobe margins form by the floatation and deflection of larger clasts to the margins of an advancing flow lobe. Results here indicate that the same sorting process efficiently segregates clasts into two flow regimes: 1) a mobile central channel depleted in coarse clasts, and 2) friction-dominated margins enriched in clasts ≥15 cm. The lobe margins, 60% enriched in larger particles and matrix <20%, slow and frictionally freeze from the base up and before the material in the central channel stops flowing. The advancing pumice lobes finally stop when the margins reach ~12 clasts thick and stop flowing and the central channel has insufficient mass flux or momentum to break through or over-top the static margins. These processes form a unique lobe and channel morphology deposit that is diagnostic of granular flow and typical of small to intermediate volume pumice flow emplacement.

1.0 Introduction

Pyroclastic flow deposits range from having a planar sheet-like morphology (e.g., Smith 1960), when pumice concentrations of the parent flow are low and velocities are high, to high-relief, lobate morphology (e.g., Wilson and Head, 1981) when flow pumice concentrations are high and velocities are low (Lube et al., 2007 and references therein). Pumice-rich terminal lobes are common in pumice flow deposits and small-volume ignimbrites (e.g., Lascar 1993 [Calder et al., 2000] and Mount St. Helens 1980 deposits [Wilson and Head, 1981 and Kokelaar et al., 2014]), and are also observed in large-scale ignimbrites (e.g., The Bishop and Bandelier Tuffs [Pittari et al., 2005; and references therein], and the Purico Ignimbrite [unpublished observations, 2009]). Pumice-rich lobes are therefore a recognizable and quantifiable feature of both large and small volume pyroclastic deposits, and both their formation and geometry provide information on the parent flow dynamics shortly before deposition.

A full understanding of pumice lobe emplacement would provide a link between the dynamics of large- and small-scale pyroclastic flow deposits and quantify the similar emplacement mechanism(s). Furthermore, computational models of granular flows commonly have difficulty predicting the inundation extent of pyroclastic density currents (PDCs) because the stopping criteria are not well understood (Yu et al., 2009). By describing, in detail, the flow mechanics at and near the point of flow frictional freezing, results of this work could be used to improve computational models and thereby increase the effectiveness of hazard mitigation. Results here are applicable to any PDC that produces pumice-rich lobate terminal fingers.

Analog experiments (Pouliquen, 1999; Felix and Thomas, 2003) as well as modeling approaches (Mangeney et al., 2007) have been utilized to understand natural deposits and flows, in an attempt to explain how granular lobes form in a moving current of pyroclastic material (summarized in section 2.1). Here, global positioning system (GPS) data are used in conjunction with field studies of the pristine 1993 pumice flow deposits from Lascar volcano, Chile, (Fig. 1) to explore the relationship between lobe formation and grain size evolution to better describe the stopping criteria of a pumice-rich PDC.

2.0 Background

PDCs are produced by the collapse of unstable lava domes (e.g., Soufriere Hills, Montserrat [Calder et al., 1999]), in lateral blasts (e.g., Mount St. Helens, USA [Kieffer, 1981; Druitt, 1992]), or by column collapse (e.g., Lascar, Chile [Gardeweg & Medina, 1999] and Cotopaxi, Ecuador [Wolf, 1878]). PDCs are gravity currents and during transport segregation occurs that produces a turbulent, diffuse, upper suspended *surge* component and a ground-hugging, dense, particle-rich *granular* traction component (Nairn and Self, 1978; Hoblitt, 1986; Yamamoto, 1993; Boudon et al., 1993; Cole et al., 1998; Valentine and Fisher, 2000). In many cases evidence for a transitional regime also exists. The processes that control flow and deposition in each regime are different. Surge deposits are the subject of numerous field, laboratory and modeling efforts (e.g., Fisher, 1979; Wright et al., 1980; Valentine, 1987; Valentine and Fisher, 2000) and are not further addressed here. Instead, the nature of granular flows and their resultant deposits are explored.

The high particle concentration portion of a pyroclastic flow moves as a granular flow (Lowe, 1976; Nairn and Self, 1978; Yamamoto et al., 1993) where interstitial ash and gas reduce clast to clast friction. The amount of gas and ash present dictates where the flow behaves like one of two end members or an intermediate case: 1) low gas and ash concentration, in which flow is hindered by clast-clast friction; and 2) fluidized, in which flow is lubricated by high gas and ash concentrations (Freundt and Bursik, 1998; Lube et al., 2011; Breard and Lube, 2016). The flow deposits discussed here are likely closer to the first *friction-dominated* end member to intermediate in nature, based on their deposits dominantly being coarse grained.

The geomorphology of landforms is studied to gain insights on both lithologic properties and environmental processes (Ritter et al., 2002). Few studies, however, have addressed ignimbrite geomorphology. Usually, primary, positive-relief flow features are most abundant at the distal margins of ignimbrites, with the remainder of the deposit having a typically planar surface (Smith, 1960). Consequently, ignimbrite aspect ratio (i.e., thickness divided by extent) is the only geomorphic measure commonly used to describe large-volume ignimbrites (e.g., Walker et al., 1980; Freundt et al., 2000). Bailey et al. (2007) used geomorphology to investigate the relative importance of fluvial and aeolian processes on ignimbrites in the Altiplano region of Chile, but their study concerned climate evolution rather than emplacement mechanisms of the parent flows. Geomorphic investigations of volcanic mass flow deposits have the potential to assess topographic controls on the transport and emplacement of the parent flows. In addition, quantitative geomorphology can be used to analyze deposit characteristics to determine relevant parameters for understanding flow behavior (Thouret, 1999) and as such represent a very rich and, as yet, under utilized source of information.

Detailed geomorphic investigations of small-volume PDC deposits (summarized in Table 1) began with Wilson and Head (1981) who related lobe dimensions of the 1980 Mount St. Helens pumice-flow deposits to pumice flow rheology. The rheology of the flow, however, ascertained by characteristics of the terminal lobe deposits, is unlikely to be representative of the rheology of the entire flow (Kokelaar and Branney, 1996) but rather the final few seconds as the flow comes to rest. Much caution, therefore, has to be applied when interpreting this type of data.

In analog granular flow experiments, a few specific aspects of flow rheology can be inferred from primary deposit features (e.g., Felix and Thomas, 2004; Kokelaar et al., 2014). Specifically, deposit lobe width is directly proportional to clast mass flux (Mangeney et al., 2007). In addition, detailed field studies of the 1975 Ngauruhoe pumice-flow deposits demonstrate that deposit lobe width is inversely correlated with substrate slope, whereas the levee height is positively correlated (Lube et al., 2007). This simple relationship of substrate slope to deposit morphology reinforces the importance of detailed observations of deposit morphology. The interpretations need to concede that there are differences between the rheology of flows that are beginning to frictionally freeze during deposition and the rheology of flows upstream as they are still propagating. However, a quantitative-disconnect remains between field data and experimental or modeling results. Experimental and computational approaches use simple flows with mono- or bi-dispersed particle distributions, whereas natural flows have far more complex constituents and dynamics.

2.1. Lobe and levee formation

As a high particle concentration flow propagates, instabilities (triggered by a heterogeneous substrate, clast size distribution, or flow thickness) deform the flow front (Poliquen et al., 1997). One model for multiple lobe formation is that large clasts arrive at the flow front and stall, which allows smaller clasts to pass by the obstruction and produce adjacent fingers or lobes (Pouliquen et al., 1997; Pittari et al., 2005). Within each lobe, granular segregation occurs by floatation and kinetic sieving (Lube et al., 2007). A velocity gradient (margins travel slower than the center, and the top faster than the base) deflects larger clasts towards the front and the margins where they stagnate and produce levees and toes (Lube et al., 2007; Baker et al., 2016). Models and experiments suggest that granular flow lobes continue to propagate until they reach a minimum thickness (h_{stop}) where they no longer flow (Pouliquen, 1999; Felix and Thomas, 2004). A major caveat of applying these models to the emplacement of natural granular flows is that the theory is the result of experiments using a monodispersed (or nearly so) clast populations, and the extent to which their results might apply to natural polydispersions is not well understood. Natural PDC's are far more complex, as clasts vary in both size and density. Therefore, although the theory is well developed it remains unclear how to utilize h_{stop} for predicting deposit extents of *natural* PDCs. More fundamentally, it remains unclear if it is appropriate to use h_{stop} for natural systems.

Observations suggest that PDC mobility varies systematically with both generation mechanism (i.e., eruption style) *and* particle support mechanisms (e.g., Calder et al. 1999; Vallance et al., 2010). This implies that natural granular flows have characteristic thinning properties that relate to either of these parameters or a combination of both. Jessop et al. (2012) suggest a link between deposit thickness and flow h_{stop}, however they did not characterize grain size. By quantifying the granulometry and morphology of lobes, at Lascar, this work explores h_{stop} for polydispersed flows, which constrains the extent that they thin before frictionally freezing. This work identifies parameters in small-volume pumice flows that suggest h_{stop} is useful in natural systems, although it is understood that these systems are far more complex than laboratory analogs.

2.2. Lascar pumice lobes

Lascar volcano (23.366° S, 067.733° W; 5590 m) is a stratovolcano in the Andean Central Volcanic Zone (Gardeweg et al., 1998; Fig. 1). In April 1993, Lascar produced a Volcano Explosivity Index (VEI) 4 eruption (Siebert et al., 2010) that culminated with an eruption column as high as 23 km Gardeweg and Medina (1994). Column collapse occurred at least nine times over ~30 hours producing pyroclastic flows down the northwestern and southern flanks of the volcano (Calder et al., 2000). For detailed accounts of the chronology of the 1993 eruption see Guarinos and Guarinos (1993), Gardeweg and Medina (1994) and Calder et al. (1999*)*. A map of the distribution of the 1993 pyroclastic flow deposits is given in Figure 10 *in* Calder et al. (2000), and a general interpretation of flow emplacement mechanisms are provided in Sparks et al. (1997), Calder et al. (2000) and Cassidy et al. (2009). The deposits of the 1993 pyroclastic flows include the Tumbres fan that extends 9 km down the northwestern flank and the Lejia fan that reaches 4 km down the southern flank of Lascar (Fig. 1). Together these fans involve approximately ~0.06 km^3 of material (*in situ*) with an estimated maximum thickness of ~30 m (Calder et al., 2000). In this work we build upon the previous work by explicitly addressing the formation of lobes and levees that are typical of the deposit.

Both the Lejia and Tumbres fans are well-preserved 20 years post-emplacement because of the hyper-arid climate of the high Chilean Altiplano. A network of fractures, however, obscures some of the primary features in the thickest (20-30m) part of the Tumbres fan (Whelley et al., 2012). This paper focuses on the most pristine parts of the deposit (Fig. 1), the Lejia lobes, to the south, and an un-fractured portion of the Tumbres Fan to the northwest.

3.0 Methodology

3.1. Lobe morphology

Global Positioning System (GPS) transects were measured across the Lejia (Fig. 2) and Tumbres fans (Fig. 3) utilizing two Leica AT502 antenna / SR530 receiver units over multiple field seasons in 2006, 2008 and 2009. One reference unit was mounted on a semi-permanent base station located within 500 m of the deposits and one as a backpack-mounted kinematic unit. Approximately 150,000 individual locations were recorded in total. Subsequent post-processing, using *Leica Geo-Office*, removed atmospheric effects on the location observations resulting in points accurate to within 0.025 m (horizontal) and 0.059 m (vertical). Digital Elevation Models (DEMs), with a horizontal resolution of

50 cm, were then interpolated using a standard Kriging algorithm in *Surfer* (version 8). To estimate the surface beneath the fans, substrate DEMs were interpolated in *Arc Map* software using elevation points measured adjacent to the fan and a triangular irregular network (TIN) algorithm. The difference between the fan DEMs and the substrate DEMs are the estimated fan thicknesses. Substrate and fan slope maps were calculated, in *Arc Map*, by comparing each DEM pixel with its neighbors. These data, slope maps and DEMs, were then used to map the outlines of individual lobes and measure morphologic features.

Lobe mapping was achieved by comparing slope and thickness maps with image data (air-photos and field photos). Relative lobe stratigraphy was determined by investigating superposition and embayment relationships (Fig. 2 & 3). Topographic profiles were then interpreted based on the lobe contacts determined through deposit mapping (Figs. 2 & 4). The morphology of pumice lobes is represented by variations in key dimensions for each site (Fig. 5): the entire lobe width (W), the width from levee peak to levee peak (w), the central channel thickness ($h_{channel}$), and the thickness of the levee (h_{levee}). The ratio: $\frac{W-w}{2}$ approximates the levee width, and $\frac{w}{W}$ indicates the fraction of a lobe occupied by the channel. Morphologic measurements were extracted directly from lobe maps as well as topographic profiles. Although the locations of lobe contacts at the surface are well constrained, subsurface contacts are estimates. These data quantify the surface morphology of the most distal tens to hundreds of meters of the 1993 pumice flow deposit.

3.2. Granulometry

Standard sieving techniques are not particularly practical for characterizing coarse constituents of many natural deposits, as large volumes of material are needed to constitute a statistically valid sample. However, the nature of matrix component of the 1993 deposit does not change substantially through the deposit and deposit grain-size variations are largely represented by a varying degree of course-tail grading (Calder et al., 2000). Therefore, the focus here is to quantify the variations of the coarse tail only through an exploratory image analysis technique and relate those variations to lobe morphology.

During a February 2009 field season, systematic photographs of the Lejia Lobes were taken to analyze the coarse-tail that dominates the pumice-rich facies (Fig. 6a-c). The Tumbres lobes were not visited during this field season, so granulometry data were not taken there. For the Lejia lobes, a 7.1 mega-pixel Kodak digital camera was mounted on a tripod such that the field of view was consistently 1 x 1.33 m. Image locations were determined by using GPS and field sketches. For all images analyzed, masks were drawn over each pumice clast that was larger than 0.5 cm in diameter and completely within the image frame (e.g., Fig. 6d-f) using an oval drawing tool in a vector graphics application (Adobe Illustrator CS2). More than 33,000 pumice clasts were identified by visual inspection in 36 images, from 3 pumice lobes. Pumice masks were then exported as binary images where black pixels represented pumice, and white pixels were background. An assumption of this method is that the background constitutes either ash-rich matrix, pumice clasts <0.5 cm, or void space. A particle-counting routine in *Image-J* (a java based image-processing program) was then used to count the number of pixels in pumice clasts (represented by discrete and continuous black masked regions) in each image. Using the known scale of each image, the number of pixels in each mask was converted to pumice area. To analyze the pumice coarse tail, the following statistics were calculated: the 1st and 99th diameter percentiles (D_1 and D_{99} respectively); the median clast diameter; the abundance of large clasts, determined by calculating the area percent occupied by clasts -7Φ (12.8 cm on the Wentworth scale: Krumbein, 1936) and greater ($A_{7\Phi}$); and clast sorting, determined by diameter standard deviation (σ) where high values indicate poor sorting.

The principal source of uncertainty in this form of granulometry analysis results from measurement subjectivity. To constrain this, a consistency test was conducted by repeating the pumice counting routine multiple times and comparing resulting pumice diameters with the Pearson's r test (Burt and Barber, 1996). Calculated clast diameters were found to be within 2% of each other. The location of each image is well known, and the uncertainties are constrained, so these data enable the characterization of subtle changes in pumice size on the surface of the deposit. An important assumption is that the grain-size distribution recorded on the deposit surface is a reasonable proxy for the grain-size distribution internally. Although this method is somewhat labor-intensive, it can show that subtle variations in the pumice lobe coarse-tail are statistically significant, and it provides key information allowing the linking of lobe dimensions to grain size that is otherwise impractical to collect.

4.0 Results: Pumice lobe measurements

4.1. Pumice lobe morphology

Results for the lobes within the Tumbres and Lejia fans are discussed separately. In both cases, the distance from the lobe snout for each observation is normalized by the total length of the flow (from the vent to the most distal margin of the fan).

4.1.1. Tumbres fan

The Tumbres fan is a collection of ~30 individual lobes that are stacked upon each other forming a 250 by 300 m fan ~6 m thick at the base of the headwall scarp and ~1.5 m thick near fan margins (Fig. 1 & 3). The margin of the fan is scalloped, due to adjoining digits of fingering lobes. The lobes in this fan have a mean w/W ratio of 0.6 with a standard deviation of 0.14 (Fig. 7d), generally thin away from the vent (1.3 m mean h_{levee} and 1 m mean $h_{channel}$: Fig. 7e & f) but thicken again at their terminal snouts. Levees are consistently thicker than central channels except in the most distal portions of the lobe (terminal snouts) where channels become 1.0 to 1.4 times thicker than their adjacent levees (Fig. 7e & f).

4.1.2. Lejia fan

The Lejia fan instead comprises long, slender, finger-shaped pumice lobes at the distal end of a 3 km by 1.5 km fan of deposit that is more than 30 m thick at the center (Fig. 1 & 2). Individual lobes are narrower (W) at their snouts than they are closer to the vent, as are central channels (w) and levees (Fig. 8a & b). The mean w/W is 0.7 with a standard deviation of 0.12 (Fig. 8d) similar to the w/W ratio observed in the Tumbres fan. The Lejia lobes also generally thin away from the vent (1.5 m mean h_{leve} and 1.1 m mean $h_{channel}$ Fig. 8e & f) but thicken again at their terminal snouts. Levees are thicker (vertical dimension) than central channels except at terminal snouts where channels are again as thick as their adjacent levees (Fig. 8e & f).

Trends in lobe dimensions are much easier to see in the Lejia morphology data than in the Tumbres plots. The Lejia lobes were deposited on a smooth sloping (~5°) plain (Figs. 1 & 2), whereas the measured Tumbres lobes represent the upper units of a thick package of slightly older lobes (Figs. 1, 3 & 4). Nevertheless, some useful comparisons can be made between the two fans. The Tumbres lobes are generally thinner (Figs. 7 e & f and 8 e & f) and narrower (Figs. 7 a-d & 8 a-d) than the Lejia lobes; but lobes in both fans follow the same narrowing and thinning trends with distance. Given their deposition on such different surfaces, the Lejia and Tumbres lobes are remarkably similar.

4.2. Lejia lobe granulometry

Granulometry data were only systematically collected on the Lejia lobes. Clasts in all three Lejia lobe margins (i.e., levees, clefts and snouts) are larger than in the central channels (Fig. 9a & Table 2) and both are larger than a “bulk” observation made 3 km up slope from the lobes, where the fan exhibits planar sheet morphology. The most distal lobes are characterized by the largest clast sizes (Fig. 9b-d) and poorest sorting (Fig. 9e). Lobe margins are enriched in larger clasts compared to the central channels (Fig. 9f). The ratio of: $\frac{\sigma}{A_{7\phi}}$ (Fig. 9g) relates sorting with clast size and shows that away from the vent, clast size increases to a greater degree than σ does.

5.0 Discussion

5.1. Granulometry

Deposit margins are enriched in coarse clasts by 55% in comparison to the central channel (determined by comparing $A_{7\Phi}$ values in Table 2) as shown if Figure 9a and f. The enrichment in large clasts at lobe margins indicates size segregation in the parent flow, either by kinetic sieving or floatation in a fluidized flow. An increase in clast size in the most distal deposits (Table 2; Fig. 9b & c) suggests that the propagating flow front became progressively enriched in large clasts, consistent with recent laboratory experiments and numerical simulations (e.g., Baker et al., 2016 and references therein). The generally poor sorting in the margins (Fig. 9e) indicates that although the largest clasts (10 to 15 cm: Fig. 9b) are segregated by the flow and concentrated in the levees, smaller (0.5 to 2 cm) clasts remain ubiquitous (Fig. 9d). In other words, the segregation that enriches the levees in large clasts is insufficient to produce levees containing only larger clasts. The differences in pumice population in the levees versus the central channel (Fig. 9 a-g) suggest that these two domains behave differently while the flow is propagating.

5.2. Considering h_{stop}

Flowing granular material shears and thins as it travels away from the source (Pouliquen et al., 1997). Laboratory experiments suggest that as granular flows progresses and the inundation extent widens, thinning continues until frictional forces halt the flow (Pouliquen, 1999; Felix and Thomas 2004). Furthermore, these experiments indicate that there is a critical thickness, h_{stop}, beyond which internal and basal friction precludes further thinning, which is defined by:

$$\frac{v}{\sqrt{gh}} = \beta \frac{h}{h_{stop}} \quad (1)$$

where v is the flow velocity, h the thickness of the current, g is the acceleration due to gravity, and β is a material dependent empirical constant (Pouliquen, 1999). Importantly, the field data from Lascar can now be used to test the applicability of the h_{stop} model to a natural granular flow .

The 1993 Lascar pumice lobes thin with distance; this is expected and consistent with experimental results (Pouliquen, 1999; Felix and Thomas 2004. Near their termini, however, the lobes sharply increase in thickness (Fig. 7e & f; 8e & f). This distal thickening is most pronounced in the central channels in the Lejia lobes. Based on field observations, its is clear that lobe termini thickening has resulted from material in the mobile central channel flow becoming dammed or retained by more static or slowly advancing terminal snout. These interactions between different flowing and static parts of the granular flow that vary over small spatial scales (meters) are difficult to reconcile with flow-averaged concepts like h_{stop}. Further, lobe margins are courser-grained than the material represented in the central channel (Table 12 and Fig. 9a) and therefore would have a different (thicker) h_{stop} than the material of central channel. When mass fluxes are low at the advancing flow front, it is the h_{stop} of the margins (levees and snouts) that is important for stopping granular flows, and when the snouts are sufficiently thick to corral the adjacent moving central channel, the flow will stop. Conversely, larger mass fluxes or simply continued fluxes will overtop or push aside levees and pumice dams at the snout recycling the large clasts (Pouliquen et al., 1997) and continue to flow. Therefore, we suggest that levee thickness (h_{levee}) is the deposit dimension that is analogous to the experimental parameter h_{stop}.

An implication of the h_{stop} model is that there is a characteristic minimum number of clasts (N) that stack upon each other to reach the minimum thickness (Pouliquen, 1999); i.e., the flows, as they are stopping, have a characteristic thickness with regard to their clast size. Pouliquen (1999) defined h_{stop} for monodispersed experimental flows and we will use our observations of natural (polydispersed) deposits to constrain h_{stop} for natural flows. What clast size is the relevant one to consider? For the Lascar deposits, both median clast and D_{99} change systematically with normalized distance from the vent (Fig. 9a-c), so either might be appropriate. However, D_{99} is larger than the median and using it ensures N is minimized. N for the Lejia lobes is defined (after Pouliquen, 1999) as:

$$N = \frac{h_{levee}}{D_{99}} \tag{2}$$

Levee thickness measurements and granulometry observations were collocated at 10 locations (Table 3). The mean N for all ten is $N = 12$ clasts with a standard deviation of 5. This suggests that the flow is unable to propagate once the levee thickness decreases to 7-17 D_{99} clasts thick. By comparison, experimental work found that N varies between 5 and 15 (depending on substrate slope) in idealized laboratory experiments (Pouliquen, 1999).

5.3. Lobe width

Lobe width is observed to narrow with distance, but reaches a minimum just before the lobe snouts (most pronounced in the Lejia lobes: Figs. 2 and 8a &b). Mangeney et al. (2007) suggests that the particle flux in the parent flow controls the lobe width, such that as flux decreases, so does width. Observations here support this interpretation in the following way: a course snout is formed at the leading edge of the flowing lobe. If the central flow contains enough material and enough momentum the leading edge snout splits into two levees that are pushed aside. More momentum and material in the central (high flux) channel, pushes the margins farther apart. As the flow progresses, and levees become enriched in larger clasts, central channel flux decreases, eventually leading to a lesser degree of levee spreading. The somewhat uniform lobe width observed in the Lejia fan (Figs. 1 & 2) therefore suggests that the particle flux remained constant for at least the last 60 to 100 m of deposit was being emplaced. The data do not allow for the absolute constraint of flow velocity or particle flux. There does, however, seem to be a characteristic minimum lobe width (~10 m) that all three Lejia lobes reached and that the Tumbres lobes approached as they terminated. It seems likely therefore, that this width also relates to a characteristic cast size (or at least grain-size distribution) in a somewhat analogous way that h_{stop} relates to N.

5.4. Pumice lobe formation

Our results and interpretations form a conceptual pumice flow emplacement model. A pumice flow begins with a randomly distributed mixture of large and small clasts. As it progresses, large clasts are preferentially brought to the surface by granular interactions (Felix and Thomas, 2004; Baker et al., 2016) and buoyancy forces when in a fluidized mixture of ash and gas (Sparks and Wilson 1982). Because of boundary layer effects, velocities are faster at the surface; therefore, large clasts (already segregated to the flow surface) are preferentially brought to the flow front. When flow regions accumulate sufficient concentrations of large clasts that they approach their local h_{stop} they begin to frictionally lock-up. At high mass flux rates, adjacent portions of the flow that remain sufficiently thick, or contain sufficiently small clasts, can continue propagating past stalled regions. The flow adjacent to the obstruction can accelerate (analogous to water accelerating around a bridge support in a river) splitting the flow into lobes joined by a cleft. At lower velocities, the flow is unable to change direction to move past the obstruction and so the leading edge is split into two flanking levees. The current continues to concentrate large clasts near the upper surface and front of the flow, and deflect the surface clasts, along flow lines, to the margins (Lube et al., 2007) where the velocity is lower, and levee-h_{stop} is reached. The result is a concentration of large clasts in the levees and depletion of large clasts in the central channel. Lobes will continue to form, and will be progressively smaller and narrower as the flow continues. Mass flux decreases until h_{stop} is achieved (where $N \approx 12$) in the levees and snout by a large enough fraction of the leading edge such that the flow does not have enough momentum to further cleave the snout into levees or overtop its margins.

5.5. Implications for planetary geology

Explosive volcanic eruptions are not confined to the Earth (e.g., Greeley and Crown, 1990). Modeling suggests that on ancient Mars the lower atmospheric pressure and gravity would have resulted in frequent explosive eruptions (Wilson and Head, 1983). However, confidently identifying pyroclastic deposits on Mars is challenging (De Silva et al., *this issue*). Pyroclastic lobes on Mars are likely dust covered and eroded but granular flow levees, such as those found at Lascar, might be distinct and have sufficient relief to survive. Indeed, lava flow levees have been identified at many large martian shield volcanoes (e.g., Garry et al., 2007). Lobate deposits of a similar scale to those discussed in this paper, and if preserved, would be observable in the newly available High Resolution Imaging Science Experiment (HiRISE) images taken from the currently active Mars Reconnaissance Orbiter. Solving for h_{stop} in equation 1 for a Mars environment where g = 3.711 m/s^2 and assuming all other variables are equal, the same pyroclastic flow on Mars would produce lobe levees 0.6 times the thickness of the Lascar deposit. This makes potential martian PDC deposits less likely to survive burial or erosion and be observable, and likely why pyroclastic lobes have not been found on Mars to date. If martian granular flow levees can be found, the relationships in this paper, including equation 1, could be used to constrain volcanic clast sizes from levee dimensions and help elucidate PDC dynamics for ancient Mars. Likely candidates for volcanoes that might have pyroclastic flow lobes include the low-relief paterae within the martian highlands (Greeley and Spudis. 1981; Crown and Greeley, 1993; Williams 2008) and plains style caldera complexes within Arabia Terra (Michalski and Bleacher, 2013).

Recent missions to the surface of Mars have sent back in-situ images (sub-centimeter resolution) of granular deposits (Grotzinger et al., 2014). Most are hypothesized to have aeolian, alluvial or fluvial origins [e.g., Milliken et al., 2014; Grant et al., 2014; Grotzinger et al., 2014]. A volcanic origin for coarse-grained deposits could be tested using the clast size to lobe height relationships identified in this paper. In cross section, deposits found to have reverse grading (i.e., larger clasts above smaller clasts) and contain regularly spaced vertical lenses enriched in coarse clasts (i.e., levees in cross section) would be consistent with emplacement by granular flow and, therefore a PDC. Such deposits could be tens or hundreds of kilometers from the source vent, as this diagnostic morphology of pyroclastic flow lobes is typical of the distal margins of the deposit.

6.0 Concluding remarks

1) The pyroclastic density currents that produced the 1993 Lascar lobes became choked with pumice and frictionally froze when the levees thinned to their h_{stop} (~12 clasts thick) and the interior channelized flows were sufficiently low flux that they did not overwhelm the barriers produced by their static flow margins. This phenomenon was predicted by laboratory and numerical models (Pouliquen, 1999; Felix and Thomas, 2004; Mangeney et al., 2007) and is now demonstrated by field observations.

2) In this work, we link field measurements of grain size and deposit morphology to experimental and numerical modeling based predictions of granular flow dynamics. By studying the largest clasts in the deposit and relating their characteristics directly

to lobe morphology, it is found that measuring the deposit coarse-tail can elucidate differences in flow characteristics between the margins and the central channel of granular portions of PDCs.

3) Existing flow models are based on single rheological laws, which govern flow spreading and emplacement. Field observations demonstrate the intricacies of how progressive segregation, affects material properties and resultant rheology in parts of the static and moving flow juxtaposed to each other.

4) Although these observations are of a small-volume pumice flow, pumice-rich distal facies are also commonly observed on large-volume ignimbrites. We postulate that similar sorting and segregation processes take place in the distal reaches of even the largest volume PDCs.

5) The relationships between morphology and clast size demonstrated in this paper suggest granular flow lobes should be somewhat thinner on Mars than on Earth. Furthermore, these quantitative relationships can be used to test for the volcanic origin hypotheses for granular deposits on Mars.

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Tables

Table 1: A summary of observations and objectives of small-volume PDC deposit morphology investigations.

Paper		***Wilson and Head, 1981***	***Felix and Thomas, 2004***	***Mangeney et al., 2007***	***Lube et al., 2007***
Goal		Infer flow behavior from field observations	Infer flow behavior from laboratory simulations	Infer flow behavior from numerical simulations	Infer flow behavior from field observations
Deposit Parameters	***Direct observations or model inputs***	Lobe: Thickness, Width, Length	Lobe: Thickness, Width, Length		Lobe: Thickness, Width, Length
		Levee: Thickness, Width	Levee: Thickness, Width		Levee: Thickness, Width
		Clast size	Clast size	Clast size	Clast size
			Substrate slope	Substrate slope	Substrate slope
					Travel distance
					Clast Density
			Flow: Velocity, Thickness, Width	Flow velocity	
	Inferred and Calculated	Deposit Rheology: inferred from shear strength			
			Clast flux: calculated from laboratory observations	Clast flux: modeled	
				Flow velocity: modeled	Flow velocity: calculated from deposit dimensions
			Confinement: inferred from topography	Confinement: inferred from particle paths in model	Confinement: inferred from topography

Table 2: Comparison of Lejia lobe granulometry results.

Category		*D_1: 1st percentile of measured clasts (cm)*	*Mean measured clast (cm)*	*D_{99}: 99th Percentile of measured clasts (cm)*	*$A_{7\Phi}$: Area percent occupied by clasts >-7Φ*	*σ: Standard Deviation of measured clasts*
Bulk Deposit[1]		0.6	1.2	4.1	0	0.6
Central Channel[1]		0.7	2.9	10.7	39.5	2.1
Lobe Margins[1]		1.0	4.5	15.2	61.4	3.0
Normalized Distance from vent[2]	**.95**	0.5	1.0	5.1	11.2	1.0
	.96	0.5	1.7	7.2	12.2	1.2
	.97	1.2	4.5	13.5	55.7	2.5
	.98	0.5	2.4	8.2	27.5	1.8
	.99	0.7	4.7	14.8	65.2	3.0
	1	0.7	4.1	14.8	55.8	2.9

[1] Data from all distances are averaged within each category

[2] Data from all categories (channels and margins) are averaged within each distance

Table 3: Co-located margin granulometry and morphology measurements on the Lejia fan.

Normalized Distance	*h_{levee} (m)*	*D_{99} (cm)*	*N*
0.969	1.80	18.12	10
0.970	1.83	10.82	17
0.974	0.42	23.10	2
0.977	2.03	13.89	15
0.981	1.04	7.04	15
0.991	1.59	16.05	10
0.994	2.26	15.88	14
0.997	1.46	18.67	8
1.000	2.22	11.25	20
1.000	2.23	16.90	13
		Mean *N*:	**12**
		Standard Deviation *N*:	**5**

Figure captions

Figure 1: The location of deposits (bright fans outlined in dashed lines) from the 1993 eruption at Lascar volcano. Tumbres lobes are to the north of Lascar volcano, and the Lejia lobes are to the south. Boxes indicate locations of both study areas. The base image is a portion of GEOTEC air photo #14603 taken in 1996.

Figure 2: The Lejia lobes and context for detailed observations. (Right) Topographic profiles of the Lejia lobes; the locations are shown on the lobe map (Left). Numbered dots represent locations of photographs taken of the lobe surfaces from which granulometry is derived that are discussed in section 3.2. Images from boxed locations are included in fig. 6. The base image is a portion of GEOTEC air photo #14603 taken in 1998.

Figure 3: Tumbres lobes and locations of the profiles (A-F). White contours represent deposit thickness. Lobe map is draped over a shaded relief map produced from the GPS surveys.

Figure 4: Tumbres topographic profiles. Locations of profiles A through F are shown in figure **3**. Lobe colors represent the emplacement generation where cool colored lobes are the oldest and are partially covered by progressively warmer colored (younger) lobes.

Figure 5: A simplified section through a pumice lobe with key morphologic parameters labeled.

Figure 6: Example pumice images (a-c) with corresponding masks (d-f). Each image is 1 x 1.33 m and the locations are marked with boxes in figure 2. Notice that the clasts in the margin images (a & c) are much coarser than the central channel image (b).

Figure 7: Morphology results from the Tumbres lobes (Fig. 3). Vertical axes are lobe measurements defined in Figure (5). Lobes generally thin away from the vent then abruptly thicken forming terminal snouts.

Figure 8: Morphology results for the Lejia lobes (Fig. 2). Vertical axes are lobe measurements defined in Figure (5). Lobes generally thin away from the vent then abruptly thicken forming terminal snouts.

Figure 9: Granulometry results from the Lejia lobes. Each point represents one image. Vertical axes represent clast population statistics calculated for measured pumices in each image. The vertical axes are: **a&b)** the 99% pumice clast; **c)** the median of measured pumices; **d)** the smallest 1%; **e)** standard deviation (σ), a measurement of particle sorting; **f)** $A_{7\Phi}$ a measure of the abundance of large (over 128 mm) clasts; and **g)** the ratio of standard deviation over $A_{7\Phi}$.

Electronic Supplementary Material: Included in the ESM files are granulometry observations for the Lejia lobes. The first numbers of the file names are the locations given in Figure 2. The numbers after the underscore are the image camera number. Within each file, the tab-delineated columns are: pumice number, pumice mask area (in cm^2), apparent pumice diameter (in cm) and the corresponding Phi designation on the Wentworth scale (Krumbein, 1936).