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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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3 Tables

9 Figure

1 **Abstract**

2 The work presented here focuses on lobe shapes and clast populations within lobate
3 termini of the 1993 pumice flow deposits at Lascar Volcano, Chile. A new method to
4 analyze a coarse-tail grain size population with field photographs is presented. Using this
5 method, more than 33,000 (>0.5 cm) clasts from the pumice lobes of the 1993 pumice
6 flow deposits were measured at 36 sites, and the resultant grain size distributions were
7 then related to lobe morphology. Lobe margins (i.e., levees, clefts, and snouts) were
8 found to contain significantly larger pumice clasts and be more poorly sorted than lobe
9 central channels (i.e., locations away from the margins). Previous laboratory experiments
10 suggest lobe margins form by the floatation and deflection of larger clasts to the margins
11 of an advancing flow lobe. Results here indicate that the same sorting process efficiently
12 segregates clasts into two flow regimes: 1) a mobile central channel depleted in coarse
13 clasts, and 2) friction-dominated margins enriched in clasts ≥ 15 cm. The lobe margins,
14 60% enriched in larger particles and matrix <20%, slow and frictionally freeze from the
15 base up and before the material in the central channel stops flowing. The advancing
16 pumice lobes finally stop when the margins reach ~ 12 clasts thick and stop flowing and
17 the central channel has insufficient mass flux or momentum to break through or over-top
18 the static margins. These processes form a unique lobe and channel morphology deposit
19 that is diagnostic of granular flow and typical of small to intermediate volume pumice
20 flow emplacement.

21

22 ***1.0 Introduction***

23 Pyroclastic flow deposits range from having a planar sheet-like morphology (e.g., Smith
24 1960), when pumice concentrations of the parent flow are low and velocities are high, to
25 high-relief, lobate morphology (e.g., Wilson and Head, 1981) when flow pumice
26 concentrations are high and velocities are low (Lube et al., 2007 and references therein).
27 Pumice-rich terminal lobes are common in pumice flow deposits and small-volume
28 ignimbrites (e.g., Lascar 1993 [Calder et al., 2000] and Mount St. Helens 1980 deposits
29 [Wilson and Head, 1981 and Kokelaar et al., 2014]), and are also observed in large-scale
30 ignimbrites (e.g., The Bishop and Bandelier Tuffs [Pittari et al., 2005; and references
31 therein], and the Purico Ignimbrite [unpublished observations, 2009]). Pumice-rich lobes
32 are therefore a recognizable and quantifiable feature of both large and small volume
33 pyroclastic deposits, and both their formation and geometry provide information on the
34 parent flow dynamics shortly before deposition.

35

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

45

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

53

54 **2.0 Background**

55 PDCs are produced by the collapse of unstable lava domes (e.g., Soufriere Hills,
56 Montserrat [Calder et al., 1999]), in lateral blasts (e.g., Mount St. Helens, USA [Kieffer,
57 1981; Druitt, 1992]), or by column collapse (e.g., Lascar, Chile [Gardeweg & Medina,
58 1999] and Cotopaxi, Ecuador [Wolf, 1878]). PDCs are gravity currents and during
59 transport segregation occurs that produces a turbulent, diffuse, upper suspended *surge*
60 component and a ground-hugging, dense, particle-rich *granular* traction component
61 (Nairn and Self, 1978; Hoblitt, 1986; Yamamoto, 1993; Boudon et al., 1993; Cole et al.,
62 1998; Valentine and Fisher, 2000). In many cases evidence for a transitional regime also
63 exists. The processes that control flow and deposition in each regime are different. Surge
64 deposits are the subject of numerous field, laboratory and modeling efforts (e.g., Fisher,
65 1979; Wright et al., 1980; Valentine, 1987; Valentine and Fisher, 2000) and are not
66 further addressed here. Instead, the nature of granular flows and their resultant deposits
67 are explored.

68

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

78

79 The geomorphology of landforms is studied to gain insights on both lithologic properties
80 and environmental processes (Ritter et al., 2002). Few studies, however, have addressed
81 ignimbrite geomorphology. Usually, primary, positive-relief flow features are most
82 abundant at the distal margins of ignimbrites, with the remainder of the deposit having a
83 typically planar surface (Smith, 1960). Consequently, ignimbrite aspect ratio (i.e.,
84 thickness divided by extent) is the only geomorphic measure commonly used to describe
85 large-volume ignimbrites (e.g., Walker et al., 1980; Freundt et al., 2000). Bailey et al.
86 (2007) used geomorphology to investigate the relative importance of fluvial and aeolian
87 processes on ignimbrites in the Altiplano region of Chile, but their study concerned
88 climate evolution rather than emplacement mechanisms of the parent flows. Geomorphic
89 investigations of volcanic mass flow deposits have the potential to assess topographic
90 controls on the transport and emplacement of the parent flows. In addition, quantitative
91 geomorphology can be used to analyze deposit characteristics to determine relevant

92 parameters for understanding flow behavior (Thouret, 1999) and as such represent a very
93 rich and, as yet, under utilized source of information.

94

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

102

103 In analog granular flow experiments, a few specific aspects of flow rheology can be
104 inferred from primary deposit features (e.g., Felix and Thomas, 2004; Kokelaar et al.,
105 2014). Specifically, deposit lobe width is directly proportional to clast mass flux
106 (Mangeney et al., 2007). In addition, detailed field studies of the 1975 Ngauruhoe
107 pumice-flow deposits demonstrate that deposit lobe width is inversely correlated with
108 substrate slope, whereas the levee height is positively correlated (Lube et al., 2007). This
109 simple relationship of substrate slope to deposit morphology reinforces the importance of
110 detailed observations of deposit morphology. The interpretations need to concede that
111 there are differences between the rheology of flows that are beginning to frictionally
112 freeze during deposition and the rheology of flows upstream as they are still propagating.
113 However, a quantitative-disconnect remains between field data and experimental or
114 modeling results. Experimental and computational approaches use simple flows with

115 mono- or bi-dispersed particle distributions, whereas natural flows have far more
116 complex constituents and dynamics.

117

118 **2.1. Lobe and levee formation**

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

137

138 Observations suggest that PDC mobility varies systematically with both generation
139 mechanism (i.e., eruption style) *and* particle support mechanisms (e.g., Calder et al.
140 1999; Vallance et al., 2010). This implies that natural granular flows have characteristic
141 thinning properties that relate to either of these parameters or a combination of both.
142 Jessop et al. (2012) suggest a link between deposit thickness and flow h_{stop} , however they
143 did not characterize grain size. By quantifying the granulometry and morphology of
144 lobes, at Lascar, this work explores h_{stop} for polydispersed flows, which constrains the
145 extent that they thin before frictionally freezing. This work identifies parameters in small-
146 volume pumice flows that suggest h_{stop} is useful in natural systems, although it is
147 understood that these systems are far more complex than laboratory analogs.

148

149 **2.2. Lascar pumice lobes**

150 Lascar volcano (23.366° S, 067.733° W; 5590 m) is a stratovolcano in the Andean
151 Central Volcanic Zone (Gardeweg et al., 1998; Fig. 1). In April 1993, Lascar produced a
152 Volcano Explosivity Index (VEI) 4 eruption (Siebert et al., 2010) that culminated with an
153 eruption column as high as 23 km Gardeweg and Medina (1994). Column collapse
154 occurred at least nine times over \sim 30 hours producing pyroclastic flows down the
155 northwestern and southern flanks of the volcano (Calder et al., 2000). For detailed
156 accounts of the chronology of the 1993 eruption see Guarinos and Guarinos (1993),
157 Gardeweg and Medina (1994) and Calder et al. (1999). A map of the distribution of the
158 1993 pyroclastic flow deposits is given in Figure 10 in Calder et al. (2000), and a general
159 interpretation of flow emplacement mechanisms are provided in Sparks et al. (1997),
160 Calder et al. (2000) and Cassidy et al. (2009). The deposits of the 1993 pyroclastic flows

161 include the Tumbres fan that extends 9 km down the northwestern flank and the Lejia fan
162 that reaches 4 km down the southern flank of Lascar (Fig. 1). Together these fans involve
163 approximately $\sim 0.06 \text{ km}^3$ of material (*in situ*) with an estimated maximum thickness of
164 $\sim 30 \text{ m}$ (Calder et al., 2000). In this work we build upon the previous work by explicitly
165 addressing the formation of lobes and levees that are typical of the deposit.

166

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

173

174 **3.0 Methodology**

175 **3.1. Lobe morphology**

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

184 50 cm, were then interpolated using a standard Kriging algorithm in *Surfer* (version 8).
185 To estimate the surface beneath the fans, substrate DEMs were interpolated in *Arc Map*
186 software using elevation points measured adjacent to the fan and a triangular irregular
187 network (TIN) algorithm. The difference between the fan DEMs and the substrate DEMs
188 are the estimated fan thicknesses. Substrate and fan slope maps were calculated, in *Arc*
189 *Map*, by comparing each DEM pixel with its neighbors. These data, slope maps and
190 DEMs, were then used to map the outlines of individual lobes and measure morphologic
191 features.

192

193 Lobe mapping was achieved by comparing slope and thickness maps with image data
194 (air-photos and field photos). Relative lobe stratigraphy was determined by investigating
195 superposition and embayment relationships (Fig. 2 & 3). Topographic profiles were then
196 interpreted based on the lobe contacts determined through deposit mapping (Figs. 2 & 4).
197 The morphology of pumice lobes is represented by variations in key dimensions for each
198 site (Fig. 5): the entire lobe width (W), the width from levee peak to levee peak (w), the
199 central channel thickness ($h_{channel}$), and the thickness of the levee (h_{levee}). The ratio:
200 $\frac{W - w}{2}$ approximates the levee width, and $\frac{w}{W}$ indicates the fraction of a lobe occupied
201 by the channel. Morphologic measurements were extracted directly from lobe maps as
202 well as topographic profiles. Although the locations of lobe contacts at the surface are
203 well constrained, subsurface contacts are estimates. These data quantify the surface
204 morphology of the most distal tens to hundreds of meters of the 1993 pumice flow
205 deposit.

206

207 **3.2. Granulometry**

208 Standard sieving techniques are not particularly practical for characterizing coarse
209 constituents of many natural deposits, as large volumes of material are needed to
210 constitute a statistically valid sample. However, the nature of matrix component of the
211 1993 deposit does not change substantially through the deposit and deposit grain-size
212 variations are largely represented by a varying degree of course-tail grading (Calder et
213 al., 2000). Therefore, the focus here is to quantify the variations of the coarse tail only
214 through an exploratory image analysis technique and relate those variations to lobe
215 morphology.

216

217 During a February 2009 field season, systematic photographs of the Lejia Lobes were
218 taken to analyze the coarse-tail that dominates the pumice-rich facies (Fig. 6a-c). The
219 Tumbres lobes were not visited during this field season, so granulometry data were not
220 taken there. For the Lejia lobes, a 7.1 mega-pixel Kodak digital camera was mounted on a
221 tripod such that the field of view was consistently 1 x 1.33 m. Image locations were
222 determined by using GPS and field sketches. For all images analyzed, masks were drawn
223 over each pumice clast that was larger than 0.5 cm in diameter and completely within the
224 image frame (e.g., Fig. 6d-f) using an oval drawing tool in a vector graphics application
225 (Adobe Illustrator CS2). More than 33,000 pumice clasts were identified by visual
226 inspection in 36 images, from 3 pumice lobes. Pumice masks were then exported as
227 binary images where black pixels represented pumice, and white pixels were background.
228 An assumption of this method is that the background constitutes either ash-rich matrix,
229 pumice clasts <0.5 cm, or void space. A particle-counting routine in *Image-J* (a java
230 based image-processing program) was then used to count the number of pixels in pumice

231 clasts (represented by discrete and continuous black masked regions) in each image.
232 Using the known scale of each image, the number of pixels in each mask was converted
233 to pumice area. To analyze the pumice coarse tail, the following statistics were
234 calculated: the 1st and 99th diameter percentiles (D_1 and D_{99} respectively); the median clast
235 diameter; the abundance of large clasts, determined by calculating the area percent
236 occupied by clasts -7Φ (12.8 cm on the Wentworth scale: Krumbein, 1936) and greater
237 ($A_{7\Phi}$); and clast sorting, determined by diameter standard deviation (σ) where high values
238 indicate poor sorting.

239

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

252

253 **4.0 Results: Pumice lobe measurements**

254 **4.1. Pumice lobe morphology**

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

258 ***4.1.1. Tumbres fan***

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

268

269 ***4.1.2. Lejia fan***

270 The Lejia fan instead comprises long, slender, finger-shaped pumice lobes at the distal
271 end of a 3 km by 1.5 km fan of deposit that is more than 30 m thick at the center (Fig. 1
272 & 2). Individual lobes are narrower (W) at their snouts than they are closer to the vent, as
273 are central channels (w) and levees (Fig. 8a & b). The mean w/W is 0.7 with a standard
274 deviation of 0.12 (Fig. 8d) similar to the w/W ratio observed in the Tumbres fan. The
275 Lejia lobes also generally thin away from the vent (1.5 m mean h_{levee} and 1.1 m mean
276 $h_{channel}$ Fig. 8e & f) but thicken again at their terminal snouts. Levees are thicker (vertical

277 dimension) than central channels except at terminal snouts where channels are again as
278 thick as their adjacent levees (Fig. 8e & f).

279

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

288

289 **4.2. Lejia lobe granulometry**

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

298

299 **5.0 Discussion**

300 **5.1. Granulometry**

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

315

316 **5.2. Considering h_{stop}**

317 Flowing granular material shears and thins as it travels away from the source (Pouliquen
318 et al., 1997). Laboratory experiments suggest that as granular flows progresses and the
319 inundation extent widens, thinning continues until frictional forces halt the flow
320 (Pouliquen, 1999; Felix and Thomas 2004). Furthermore, these experiments indicate that

321 there is a critical thickness, h_{stop} , beyond which internal and basal friction precludes
322 further thinning, which is defined by:

323

324
$$\frac{v}{\sqrt{gh}} = \beta \frac{h}{h_{stop}}$$
 (1)

325

326

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

331

332 The 1993 Lascar pumice lobes thin with distance; this is expected and consistent with
333 experimental results (Pouliquen, 1999; Felix and Thomas 2004. Near their termini,
334 however, the lobes sharply increase in thickness (Fig. 7e & f; 8e & f). This distal
335 thickening is most pronounced in the central channels in the Lejia lobes. Based on field
336 observations, its is clear that lobe termini thickening has resulted from material in the
337 mobile central channel flow becoming dammed or retained by more static or slowly
338 advancing terminal snout. These interactions between different flowing and static parts of
339 the granular flow that vary over small spatial scales (meters) are difficult to reconcile
340 with flow-averaged concepts like h_{stop} . Further, lobe margins are courser-grained than the
341 material represented in the central channel (Table 12 and Fig. 9a) and therefore would
342 have a different (thicker) h_{stop} than the material of central channel. When mass fluxes are
343 low at the advancing flow front, it is the h_{stop} of the margins (levees and snouts) that is

344 important for stopping granular flows, and when the snouts are sufficiently thick to corral
345 the adjacent moving central channel, the flow will stop. Conversely, larger mass fluxes or
346 simply continued fluxes will overtop or push aside levees and pumice dams at the snout
347 recycling the large clasts (Pouliquen et al., 1997) and continue to flow. Therefore, we
348 suggest that levee thickness (h_{levee}) is the deposit dimension that is analogous to the
349 experimental parameter h_{stop} .

350

351 An implication of the h_{stop} model is that there is a characteristic minimum number of
352 clasts (N) that stack upon each other to reach the minimum thickness (Pouliquen, 1999);
353 i.e., the flows, as they are stopping, have a characteristic thickness with regard to their
354 clast size. Pouliquen (1999) defined h_{stop} for monodispersed experimental flows and we
355 will use our observations of natural (polydispersed) deposits to constrain h_{stop} for natural
356 flows. What clast size is the relevant one to consider? For the Lascar deposits, both
357 median clast and D_{99} change systematically with normalized distance from the vent (Fig.
358 9a-c), so either might be appropriate. However, D_{99} is larger than the median and using it
359 ensures N is minimized. N for the Lejia lobes is defined (after Pouliquen, 1999) as:

$$360 \quad N = \frac{h_{levee}}{D_{99}} \quad (2)$$

361 Levee thickness measurements and granulometry observations were collocated at 10
362 locations (Table 3). The mean N for all ten is $N = 12$ clasts with a standard deviation of 5.
363 This suggests that the flow is unable to propagate once the levee thickness decreases to 7-
364 17 D_{99} clasts thick. By comparison, experimental work found that N varies between 5 and
365 15 (depending on substrate slope) in idealized laboratory experiments (Pouliquen, 1999).

366

367 **5.3. Lobe width**

368 Lobe width is observed to narrow with distance, but reaches a minimum just before the
369 lobe snouts (most pronounced in the Lejia lobes: Figs. 2 and 8a &b). Mangeney et al.
370 (2007) suggests that the particle flux in the parent flow controls the lobe width, such that
371 as flux decreases, so does width. Observations here support this interpretation in the
372 following way: a coarse snout is formed at the leading edge of the flowing lobe. If the
373 central flow contains enough material and enough momentum the leading edge snout
374 splits into two levees that are pushed aside. More momentum and material in the central
375 (high flux) channel, pushes the margins farther apart. As the flow progresses, and levees
376 become enriched in larger clasts, central channel flux decreases, eventually leading to a
377 lesser degree of levee spreading. The somewhat uniform lobe width observed in the Lejia
378 fan (Figs. 1 & 2) therefore suggests that the particle flux remained constant for at least
379 the last 60 to 100 m of deposit was being emplaced. The data do not allow for the
380 absolute constraint of flow velocity or particle flux. There does, however, seem to be a
381 characteristic minimum lobe width (~ 10 m) that all three Lejia lobes reached and that the
382 Tumbres lobes approached as they terminated. It seems likely therefore, that this width
383 also relates to a characteristic clast size (or at least grain-size distribution) in a somewhat
384 analogous way that h_{stop} relates to N .

385

386 **5.4. Pumice lobe formation**

387 Our results and interpretations form a conceptual pumice flow emplacement model. A
388 pumice flow begins with a randomly distributed mixture of large and small clasts. As it

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

409

410 **5.5. Implications for planetary geology**

411 Explosive volcanic eruptions are not confined to the Earth (e.g., Greeley and Crown,
412 1990). Modeling suggests that on ancient Mars the lower atmospheric pressure and
413 gravity would have resulted in frequent explosive eruptions (Wilson and Head, 1983).
414 However, confidently identifying pyroclastic deposits on Mars is challenging (De Silva et
415 al., *this issue*). Pyroclastic lobes on Mars are likely dust covered and eroded but granular
416 flow levees, such as those found at Lascar, might be distinct and have sufficient relief to
417 survive. Indeed, lava flow levees have been identified at many large martian shield
418 volcanoes (e.g., Garry et al., 2007). Lobate deposits of a similar scale to those discussed
419 in this paper, and if preserved, would be observable in the newly available High
420 Resolution Imaging Science Experiment (HiRISE) images taken from the currently active
421 Mars Reconnaissance Orbiter. Solving for h_{stop} in equation 1 for a Mars environment
422 where $g = 3.711 \text{ m/s}^2$ and assuming all other variables are equal, the same pyroclastic
423 flow on Mars would produce lobe levees 0.6 times the thickness of the Lascar deposit.
424 This makes potential martian PDC deposits less likely to survive burial or erosion and be
425 observable, and likely why pyroclastic lobes have not been found on Mars to date. If
426 martian granular flow levees can be found, the relationships in this paper, including
427 equation 1, could be used to constrain volcanic clast sizes from levee dimensions and
428 help elucidate PDC dynamics for ancient Mars. Likely candidates for volcanoes that
429 might have pyroclastic flow lobes include the low-relief paterae within the martian
430 highlands (Greeley and Spudis. 1981; Crown and Greeley, 1993; Williams 2008) and
431 plains style caldera complexes within Arabia Terra (Michalski and Bleacher, 2013).

432

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

444

445 **6.0 Concluding remarks**

446 1) The pyroclastic density currents that produced the 1993 Lascar lobes became choked
447 with pumice and frictionally froze when the levees thinned to their h_{stop} (\sim 12 clasts
448 thick) and the interior channelized flows were sufficiently low flux that they did not
449 overwhelm the barriers produced by their static flow margins. This phenomenon was
450 predicted by laboratory and numerical models (Pouliquen, 1999; Felix and Thomas,
451 2004; Mangeney et al., 2007) and is now demonstrated by field observations.

452

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

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

459

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

464

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

469

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

474

475

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485

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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
<i>Deposit Parameters</i>	Lobe: Thickness, Width, Length Levee: Thickness, Width Clast size	Lobe: Thickness, Width, Length Levee: Thickness, Width Clast size Substrate slope	Clast size Substrate slope	Lobe: Thickness, Width, Length Levee: Thickness, Width Clast size Substrate slope Travel distance Clast Density
		Flow: Velocity, Thickness, Width	Flow velocity	
<i>Inferred and Calculated</i>	Deposit Rheology: inferred from shear strength	Clast flux: calculated from laboratory observations Confinement: inferred from topography	Clast flux: modeled Flow velocity: modeled Confinement: inferred from particle paths in model	Flow velocity: calculated from deposit dimensions Confinement: inferred from topography

Table 2: Comparison of Lejia lobe granulometry results.

Category	D_1 : 1 st 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 Deposit¹	0.6	1.2	4.1	0	0.6
Central Channel¹	0.7	2.9	10.7	39.5	2.1
Lobe Margins¹	1.0	4.5	15.2	61.4	3.0
<i>Normalized Distance from vent²</i>	.95	0.5	1.0	5.1	1.0
	.96	0.5	1.7	7.2	1.2
	.97	1.2	4.5	13.5	2.5
	.98	0.5	2.4	8.2	1.8
	.99	0.7	4.7	14.8	3.0
	1	0.7	4.1	14.8	2.9

¹Data from all distances are averaged within each category

²Data 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).