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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

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.

45

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.

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

6

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 ~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 ~0.06 km^3 of material (*in situ*) with an estimated maximum thickness of

164 ~30 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 $\dfrac{W - w}{2}$ approximates the levee width, and $\dfrac{w}{W}$ 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

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

11

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**

12

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_{leve} 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: $\dfrac{\sigma}{A_{7\phi}}$ (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

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.

315

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

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

16

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

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

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

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 $g = 3.711$ 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} (~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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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 $>-7\Phi$	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).