

# How shear helps lava to flow

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## 1 How shear helps lava to flow

A. Harris<sup>1</sup>, S. Mannini<sup>1\*</sup>, S. Thivet<sup>1</sup>, M.O. Chevrel<sup>1</sup>, L. Gurioli<sup>1</sup>, N. Villeneuve<sup>2</sup>, A. di
Muro<sup>2</sup>, A. Peltier<sup>2</sup>

<sup>1</sup>Université Clermont Auvergne, CNRS, IRD, OPGC, LMV, F-63000 Clermont-Ferrand,
5 France

6 <sup>2</sup>OVPF, Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Univ. Paris Diderot,

7 CNRS, F-97418, La Plaine des Cafres, La Réunion, France

8 \*Now at: University of Geneva

### 9 ABSTRACT

10 Understanding the thermo-rheological regime and physical character of lava while it is 11 flowing is crucial if we are to adequately model lava flow emplacement dynamics. We present 12 measurements from simultaneous sampling and thermal imaging across the full width of an active channel at Piton de la Fournaise (La Réunion, France). Our data set involves 13 14 measurements of flow dynamics at three sites down-channel from the vent. Quantification of 15 flow velocities, cooling rates, sample texture and rheology allows all thermo-rheological 16 parameters to be linked, and down- as well as cross-channel variations to be examined. 17 Within 150 m from the vent we recorded an unexpected velocity increase (from 0.07 to 0.1 m/s), in spite of cooling rates of 0.19 to 0.29 °C/m and constant slope. This change requires a 18 19 switch from a Newtonian-dominated regime to a Bingham plug-dominated regime. Sample 20 analysis reveals that the plug comprises foam-like lava and the shear zones involve vesicle-21 poor (low viscosity) lava. With distance from the vent, shear zones develop carrying the 22 vesicular plug between them. This causes flow to initially accelerate, helped by bubble 23 shearing in narrow lateral shear zones, until cooling takes over as the main driver for viscosity 24 increase and, hence, velocity decrease.

25 Key words: Lava channel; Velocity; Cooling; Vesicles; Viscosity; Shearing.

26

#### 27 INTRODUCTION

Understanding the thermo-rheological regime of an active lava is fundamental if we are to 28 29 adequately model its emplacement behavior (e.g., Harris and Rowland 2001; Hidaka et al. 30 2005; Del Negro et al. 2005). The interrelation between flow physical properties and 31 dynamics is a crucial link for which we are rich in heat-loss-driven models (e.g., Keszthelyi 32 and Self 1998), but lacking in data to allow validation of models and theory. Traditionally, 33 lava flow rheology has been modeled as a cooling-dominated process, so that the lava steadily 34 cools, degasses and crystallizes down flow, increasing in viscosity from the vent to the flow 35 front (e.g., Harris and Rowland 2001). However, to date only a few measurements have been performed to assess whether this assumption is valid, and these measurements have all been 36 37 for active channels in Hawaii, with the first measurements being made more than a kilometer 38 or two from the vent (Lipman and Banks 1987; Moore 1987; Crisp et al. 1994; Cashman et al. 39 1999). While such a down-channel thermal and rheological regime has been borne out by 40 analysis of inactive channels (Soule et al. 2004; Riker et al. 2009; Chevrel et al. 2014, Robert 41 et al. 2014; Rhéty et al. 2017), thermal measurements and modeling have also indicated that 42 down flow cooling is inevitable and progressive, the rate depending on degree of insulation, 43 flow velocity and channel dimensions (Harris and Rowland 2009). Other work has 44 highlighted the importance of the crystallization sequence on lava viscosity and strain rate on 45 influencing crystallization behavior and, hence, emplacement dynamics (e.g., Chevrel et al. 46 2014; Kolzenburg et al. 2018). The role of bubbles on lava transport properties is, however, 47 very poorly constrained, and detailed measurements down near-vent segments of active 48 channels are scarce, with Lipman and Banks (1987) remaining a precious resource.

49 Down-flow degassing will likely cause loss of volatiles and undercooling of the melt
 50 to trigger micro-crystallization, both of which will increase the viscosity of the lava mixture

51 (Sparks and Pinkerton 1978). Down-flow evolution of bubble quantity and shape may also 52 affect rheology, where the mixture viscosity will decrease or increase depending on whether bubbles are deformed or not (Llewellin and Manga 2005). Down-flow degassing and loss of 53 54 bubbles has also been documented in lava tubes (Cashman et al. 1994) and from the structure of inflated pahoehoe flows (Cashman and Kauahikaua 1997), as well as from measurements 55 56 along active (Cashman et al. 1999) and solidified (Riker et al. 2009) systems. The effect of 57 vesicles on rheology has also been inferred from in-situ viscosity measurements on pahoehoe 58 lobes (Chevrel et al. 2018). However, no direct field measurements exist to constrain and link 59 changing bubble states with flow dynamics down a lava channel.

60 Here, we present unique data from thermal imaging and sampling down the near-vent 61 reach of an active lava channel at Piton de la Fournaise (Réunion Island, France) during July-62 August 2015. This allows simultaneous constraint and linking of down and across flow 63 velocity, temperature and rheology. Surprisingly, we measure an acceleration within 150 m of 64 the vent. At constant slope, this implies a down-flow evolution of the rheological regime 65 (from Newtonian to Bingham) which is caused by strain localization on the margin of a 66 central plug. This can be supported by the difference in bubble content between lava sampled 67 in the plug and shear zones. Our current understanding of lava flow is that it can evolve from 68 Newtonian to Bingham rheology, but bubbles are rarely taken into consideration to explain 69 such evolution. Here, we provide a unique data set that documents this evolution and attempt 70 to model this with available rheological models (as detailed in the supplements), showing that 71 bubbles play a fundamental role in determining rheology and evolving flow dynamics.

#### 72 MEASUREMENTS IN AN ACTIVE LAVA CHANNEL

#### 73 Channel dimensions and surface velocity

Piton de la Fournaise's July–August 2015 eruption lasted two days (31 July–1 August) and
fed a single master channel which extended 1 km (Supplement 1). Down this stable channel

76 system thermal image sequences were collected at four stations (30, 110, 220 and 440 m from 77 the vent, Fig. 1) on the same day (1 August) and within 20 minutes of each other (Supplement 2). Using manual particle tracking (Supplement 2) surface velocities were measured at 78 79 0.03±0.01 m/s at the channel margins and 0.07±0.04 m/s at the center. The horizontal and 80 vertical velocity profiles were best-fit with a parabolic equation (Supplement 2), indicating horizontal velocity gradients of 0.07 s<sup>-1</sup> (Fig. 2) and suggesting that flow was laminar and 81 Newtonian. Further down flow (at stations 2 and 3, Fig 1), the channel was wider (4-5 m, 82 83 instead of 2 m) and shallower (0.8 m instead of 1.8 m, Supplement 2). A constant surface 84 velocity was measured across a central, 3 m-wide, plug at an average of 0.1 m/s at both 85 stations, which was faster than at station 1 (Fig. 2). The central plug was flanked by two 86 narrow, 0.5 m-wide, shear zones where velocity declined to zero (Fig. 2a). These profiles 87 revealed a plug-dominated Bingham behavior, with a velocity gradient across the shear zones of 0.2 s<sup>-1</sup>; a rate three times higher than at station 1. Assuming that the plug comprises 75% of 88 89 the flow by thickness (as it does by width), then the plug height was 0.47 m, for a basal shear zone height of 0.16 m, across which the velocity vertical gradient was 0.45 s<sup>-1</sup> (Fig. 2b). 90

#### 91 Heat loss and cooling rate

92 Eruption temperature at the vent (1146 °C) was obtained from thermal images of bubbles 93 bursting at the vent. At station 1 flow was poorly crusted, with a mean surface temperature of 94 704±107 °C (Supplement 3). At stations 2 and 3, while the surface of the central plug was 95 partially covered by a crust of fragmenting slabs of spiny pāhoehoe and nascent 'a'ā, the shear 96 zones had a cover of down-flow thickening 'a'ā. Due to the crust cover of the shear zones, 97 surface temperatures at the channel margins were cooler than at the center, where average 98 surface temperatures of the plug was 558±38 °C, but 300 °C at the margin (Fig. 3). These surface temperature ranges converted to heat losses of  $87\pm2$  kW/m<sup>2</sup> at station 1, and  $31\pm24$ 99 and  $45\pm23$  kW/m<sup>2</sup> at stations 2 and 3. Cooling was then estimated between the vent and at 100

station 1 at 0.21±0.07 °C/m. Lower heat losses and higher velocities at stations 2–3 resulted in
cooling of 0.13±0.10 and 0.12±0.10 °C/m, at the two stations, respectively (Supplement 3).
Such cooling per unit distance is high in comparison to previously reported values for flow
down a lava channel (typically 0.005–0.007 °C/m, Crisp et al. 1994; Cashman et al., 1999;
Soule et al. 2004; Riker et al. 2009; Robert et al. 2014; Rhéty et al. 2017). This is because, for
our channel, lava was poorly insulated and velocities were low.

107

#### 108 Sampling, sample characteristics and lava viscosity

Lava was sampled on the first day near the vent and on the second day at Station 2 coincident with thermal imaging (Supplement 4). The station 2 sample was collected by inserting a metal rod laterally 50 cm into the channel resulting in two distinct, simultaneously collected, fragments: one from the shear zone and one from the plug. Mass flux was steady during field work of day 2, during which this key (shear zone and plug) sample was collected coincident with the thermal imagery.

115 Lava bulk composition was basaltic with a porphyritic texture (<3 vol.% phenocrysts; 116 15-34 vol. % microlites of plagioclase and pyroxene; Supplement 4). Near-vent samples had a 117 bulk density of 1370±280 kg/m<sup>3</sup>, resulting in a vesicularity of 53±10 vol.%. Vesicles were 118 rounded with equivalent diameters of 1 mm (Fig. 4). Temperature estimated from the glass 119 MgO content was 1138±2°C (Supplement 4). The two station 2 sample fragments had 120 contrasting textural characteristics. The shear zone part was dense (2020 kg/m<sup>3</sup>) with a 121 vesicularity of 30 vol.%, including rounded and small (0.5 mm) vesicles and a few larger (>2 122 mm) vesicles. Crystals showed alignment and the calculated melt temperature was 1119±1 123 °C. The difference between melt temperature near the vent and of the sample from the shear 124 zone resulted in a cooling per unit distance of 0.17 °C/m which agrees with the theoretical 125 calculations obtained from heat loss (Supplement 3). Conversely, the central plug fragment had an extremely low density (500 kg/m<sup>3</sup>), a very-high vesicularity (83 vol.%) and crystals were the less abundant (17 vol.%). The vesicle population was heterogeneous being a mixture of small-rounded (10–100  $\mu$ m), larger-rounded (< 0.5 mm) and irregularly-shaped vesicles.

At station 1, the strain rates were relatively low  $(0.07 \text{ s}^{-1})$  and the bubble capillary 129 130 number (Ca) was around 0.7 (Supplement 4). Given a threshold Ca of 0.5, above which bubbles are able to deform (Manga et al. 1998), i.e. bubble internal forces are weaker than the 131 132 surrounding fluid forces (viscosity×strain-rate), the apparent viscosity of the three-phase lava 133 (i.e. melt+crystal+bubbles) was estimated at  $1.5 \times 10^3$  Pa s (Supplement 4). At station 2 within the shear zones the vesicle-free (melt+crystal) viscosity was higher at  $8.4 \times 10^3$  Pa s due to 134 lower temperature. However, because strain rates were 0.2 s<sup>-1</sup> in the plug and 0.45 s<sup>-1</sup> in the 135 136 shear zones, we obtained Ca>>0.5 in these locations-meaning that bubbles were highly deformable. The effect of the bubbles therefore decreased the effective viscosity to  $4.7 \times 10^3$ 137 138 Pa s. Conversely, within the plug, although crystallinity was lower, the very high bubble concentration (>80 vol. %) and very low strain rates (near 0 s<sup>-1</sup>) prevented bubbles 139 140 deformation.

#### 141 **DISCUSSION**

142 Given the interior flow temperature difference of 19 °C between stations 1 and 2, an average 143 surface velocity of 0.05 m/s at station 1 and a distance between the two stations of 80 m, the 144 time to travel to station 2 was around 1600 s. This gives cooling along the shear zones at a 145 rate of ~0.012°C/s, which is in line with cooling rates obtained for active flows in Hawaii 146 (Cashman et al., 1999). Given such a decrease in temperature we would expect a viscosity 147 increase, and hence velocity decrease, down this vent-proximal channel length. However, the 148 measured velocities revealed an acceleration between stations 1 and 2, after which velocity 149 was constant until station 3. Given a constant slope between the three stations and stable 150 effusion rate at the time of measurements, we explain this as a change in rheological behavior by strain localization on either side of a down-flow-developing central plug (i.e., within theshear zones).

153 We therefore propose a scenario whereby lava emitted at the vent flowed under a 154 Newtonian regime, as supported by the parabolic velocity profile. After 110 m (by station 2), 155 narrow shear zones had appeared either side of a central plug, suggesting that flow had 156 become Bingham. In the central plug, high bubble concentration and low strain rates resulted 157 in bubble growth and increasing capillary forces resulting in a polyhedral foam with internal 158 yield strength and stabile bubble walls so that the plug was not flowing. Instead it behaved as 159 a solid, being carried between the two marginal shear zones. At the channel margins, although 160 temperature was lower than near the vent, strain rates were so high that bubbles were sheared. 161 The effect of this sheared-bubble population on flow bulk rheological properties outweighed 162 the effect of cooling, resulting in a lower viscosity. The non-sheared and bubble-rich plug was 163 thus carried between two lateral zones of sheared lava, highlighting the effect of bubbles 164 which either acted as a lubricant in the shear zones or as a retardant to deformation in the 165 plug. We note, also, that that the shear zone had lower MgO than the plug (Supplement 4). 166 This could be due to preferential settling of larger olivine crystals in the slower moving shear 167 zones, further supporting the fact that the shear and plug zones were independent identities.

The lower bubble content within the shear zones could be due to more outgassing than in the plug, or shear pressing of bubbles out of the marginal shear zones and into the central plug. However, due to relaxation effects during the time between sampling and quenching (Moitra et al. 2013; Lindoo et al. 2017), the evidence of the shearing effect is lost from the vesicle signature, but is visible from microlite alignment (Fig. 4b).

The change in flow regime over the proximal reach of the flow, from shear dominated with a parabolic velocity profile at the vent to plug dominated after 110 m is reflected in the temperature profiles (Fig. 3). Temperatures are high across the entire channel near-vent

because of a highly disrupted, young crust. At stations 2 and 3, temperatures become low in the marginal shear zones where an increasingly thick carapace of mature 'a'ā is built (cf. Rowland and Walker, 1987), and higher across the central plug where slabs of crust can form, which then broke-up to expose hotter interior lava. The lower velocities of the shear zone lava also meant that lava at the channel margins had more time to cool and develop a more mature crust than at the center, as well as giving time for larger olivines to preferentially settle and gas to escape.

#### **183 CONCLUSION**

184 An unexpected velocity increase and apparent viscosity decrease was recorded down a lava 185 channel over the first 110 m of flow, in spite of stable slope, constant mass flux and high 186 cooling rates. This peculiar change was caused by the down-flow development of a central 187 plug flanked by narrow shear zones in which bubbles were highly deformed; and hence where 188 the effective viscosity is low. As in a volcanic conduit (e.g., Wright and Weinberg 2009), the 189 lateral shear zones lubricate the central plug. This causes the flow to initially accelerate over 190 the proximal reach of the channel until cooling and crystallization can take over as the main 191 drivers for viscosity increase and, hence, velocity decrease.

Our measurements represent a unique (and difficult to obtain) near-vent data set (given here in the data repository and fully described in the supplement) in which, for the first time, we can identify and quantify a velocity increase over a relatively short distance close to the vent. Future measurements will need to focus on this near-vent part of the channel system so as to properly define and explain the complete down-channel evolution of flow dynamics, and add to this repository.

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#### 203 **REFERENCES CITED**

- 204 Cashman, K V, C Thornber, and J P Kauahikaua. 1999. "Cooling and Crystallization of Lava
- in Open Channels, and the Transition of Pāhoehoe Lava to 'a'Ā." Bulletin of
   Volcanology 61: 306–23. doi:https://doi.org/10.1007/s004450050299.
- 207 Crisp, J, K v. Cashman, J A Bonini, S B Hougen, and D C Pieri. 1994. "Crystallization
  208 History of the 1984 Mauna Loa Lava Flow." *Journal of Geophysical Research* 99 (B4):
  209 7177–98. doi:10.1029/93JB02973.
- 210 Harris, A. J. L., John Bailey, Sonia Calvari, and Jon Dehn. 2005. "Heat Loss Measured at a 211 Lava Channel and Its Implications for Down-Channel Cooling and Rheology." 212 396 (09): Geological Society America *Special* Papers 125-46. of 213 doi:10.1130/2005.2396(09).
- Harris, A J L, and S K Rowland. 2001. "FLOWGO: A Kinematic Thermo-Rheological Model
  for Lava Flowing in a Channel." *Bulletin of Volcanology* 63: 20–44.
  doi:10.1007/s004450000120.
- 217 . 2009. "Effusion Rate Controls on Lava Flow Length and the Role of Heat Loss: A
- 218 Review." The Legacy of George P.L. Walker, Special Publications of IAVCEI. Eds
- Hoskuldsson A, Thordarson T, Larsen G, Self S, Rowland S. Geological Society, London.
  2: 33–51.
- Hidaka, M, A Goto, S Umino, and E Fujita. 2005. "VTFS Project: Development of the Lava
  Flow Simulation Code LavaSIM with a Model for Three-Dimensional Convection,
  Spreading, and Solidification." *Geochemistry, Geophysics, Geosystems* 6: Q07008.
- Keszthelyi, L, and S Self. 1998. "Some Physical Requirements for the Emplacement of Long
  Basaltic Lava Flows." *J. Geophys. Res.* B11: 27,447-27,464.
  - 9

- Kolzenburg, S., D. Giordano, K-U. Hess, and D.B. Dingwell. 2018. "Shear-rate Dependent
   Disequilibrium Rheology and Dynamics of Basalt Solidification." *Geophysical Research Letters*. doi:doi.org/10.1029/2018GL077799.
- Lipman, P W, and N G Banks. 1987. "Aa Flow Dynamics, Mauna Loa 1984." U.S. Geol.
  Surv. Prof. Pap 1350, 1527–67.
- Llewellin, E W, and M Manga. 2005. "Bubble Suspension Rheology and Implications for
  Conduit Flow." *Journal of Volcanology and Geothermal Research* 143: 205–17.
- Moore, H J. 1987. "Preliminary Estimates of the Rheological Properties of 1984 Mauna Loa
  Lava." U.S. Geological Survey Professional Paper 1350 99: 1569–88.
- Negro, C Del, L Fortuna, A Vicari, C Del Negro, L Fortuna, A Vicari Modelling, and
  Nonlinear Networks. 2005. "Modelling Lava Flows by Cellular Nonlinear Networks
  (CNN): Preliminary Results." *Nonlinear Processes in Geophysics* 12: 505–13.
- Rhéty, M., A. J. L. Harris, N. Villeneuve, L. Gurioli, E. Médard, M.O. Chevrel, and P.
  Bachèlery. 2017. "A Comparison of Cooling-Limited and Volume-Limited Flow
- 240 Systems: Examples from Channels in the Piton de La Fournaise April 2007 Lava-Flow
- 241 Field." Geochemistry, Geophysics, Geosystems 18 (9): 3270–91.
  242 doi:10.1002/2017GC006839.
- Riker, J M, K V Cashman, J P Kauahikaua, and C M Montierth. 2009. "The Length of
  Channelised Lava Flows: Insight from the 1859 Eruption of Mauna Loa Volcano,
  Hawaii." *Journal of Volcanology and Geothermal Research* 183: 139–56.
- Robert, B, A Harris, G Gurioli, E Medard, A Sehlke, and A Whittington. 2014. "Textural and
  Rheological Evolution of Basalt Flowing down a Lava Channel." *Bulletin of Volcanology* 76: 824.
- Robertson, J. C., and R. C. Kerr. 2012. "Solidification Dynamics in Channeled Viscoplastic
  Lava Flows." *Journal of Geophysical Research: Solid Earth* 117 (7): 1–18.

- doi:10.1029/2012JB009163.
- Rowland, S.K., and G.P.L. Walker. 1987. "Toothpaste lava: characteristics and origin of a
  lava structural type transition between pahoehoe and 'a'a." *Bulletin of Volcanology* 49:
  631-641
- 255 Soule, S. A., K.V. Cashman, and J. P. Kauahikaua. 2004. "Examining Flow Emplacement
- through the Surface Morphology of Three Rapidly Emplaced, Solidified Lava Flows,
- 257 Kīlauea Volcano, Hawai'i." *Bulletin of Volcanology* 66 (1): 1–14. doi:10.1007/s00445258 003-0291-0.
- Sparks, R S J, and H Pinkerton. 1978. "Effect of Degassing on Rheology of Basaltic Lava." *Nature* 276: 385–86.
- Wright, Heather M N, and Robert F. Weinberg. 2009. "Strain Localization in Vesicular
  Magma: Implications for Rheology and Fragmentation." *Geology* 37 (11): 1023–26.
  doi:10.1130/G30199A.1.
- 264

#### 266 FIGURE CAPTIONS

Figure 1. Map of the lava flow field (yellow outline), fissures (green outline), main vent (red outline) and stable channel (pink outline) of the July-August 2015 eruption of Piton de la Fournaise.

270

271 Figure 2. a) Mean (squares) and standard deviation (given as error bars) for all velocity 272 measurements made. Lines are best-fit velocity profiles across the channel width at stations 1 273 (red), 2 (orange) and 3 (blue) using the approach of Supplement 2. b) Modeled vertical 274 velocity profiles at stations 1 (red) and 3 (blue). For clarity, the mean and standard deviation 275 of the total data set at the three stations is plotted and fitted here. Results are the same if we fit 276 through individual measurement sample sets that make up the population that the mean 277 describes, where (for any one measurement set) there is always a lower velocity at station 1 278 than at stations 2 and 3. The full data set, for each station, is described and plotted in 279 Supplement 2. Note that the asymmetry of the measurements at stations 2 (S2) and 3 (S3) is 280 due to the missing far bank shear zone, which we could not resolve from our low oblique 281 viewing angle (see Supplement 2).

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Figure 3. Surface temperature across the channel at stations 1 (red) and 3 (orange).

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Figure 4. Binary images of the thin sections and back scattered electron images for (a) the near-vent sample of day 1, plus (b) the shear zone and (c) plug zone of the sample taken on day 2 (in the binary images white = matrix, grey = phenocrysts and black = vesicles).

288



# 200 m







#### a) Example of sample near the vent



#### b) Shear zone s ample at Station 2



#### c) Sample from plug at Station 2

