INVESTIGATING THE EFFECTS OF SUBSTRATE ROUGHNESS ON LAVA FLOW EMPLACEMENT THROUGH ANALOG EXPERIMENTS. M. E. Rumpf and E. Lev, Lamont-Doherty Earth Observatory, Columbia University (61 Route 9W, Palisades, NY 10964, erumpf@ldeo.columbia.edu),

Introduction: Lava flows are the most abundant volcanic deposit throughout the Solar System. All rocky bodies display evidence for ancient volcanism, and evidence for active volcanism has been observed on Io, Triton, Enceladas, and possibly Venus [1-4]. However, the influence of substrate type on flow emplacement has not been studied thoroughly. Numerical models have shown that physical properties (including composition, porosity, and cohesion) of lava and substrate can affect system temperatures and behavior [e.g. 5-7]. Observations of terrestrial flows show that even topographic features on the order of flow height can affect lava emplacement [e.g. 8].

We describe a series of experiments to investigate the influence of substrate grain size on flow dynamics using analog materials, including corn syrup, PEG, and molten basalt. For each material, the surface of the slope was systematically varied to explore a range of substrate roughnesses. Laboratory experiments using analog materials are a well-used method for studying lava flow dynamics. This method allows for adjustment of exp. parameters in a safe and predictable environment. Previous studies using polyethylene glycol (PEG), a commercially available wax, have revealed that substrate roughness does affect PEG emplacement [9-14]. Our results will improve interpretations of planetary and historical lava emplacement conditions and environments and can be integrated into terrestrial flow hazard assessment models for increased accuracy.

Laboratory Setup:

Analog fluids experiments. Analog-material experiments were designed and completed at the new Fluid Mechanics Laboratory at the Lamont-Doherty Earth Observatory (LDEO) at Columbia University. Both corn syrup and PEG were tested on substrates of three different sand paper grades (0.0115, 0.0265, and 1 mm grain size) and one gravel substrate (1 cm average grain size) at a slope of 7°. Both analog materials were extruded at room temperature (~24 °C). Corn syrup was poured into open air with a constant flux of 3 to 4 $cm^3\ s^{-1}$ and PEG was extruded into water chilled to ~ 5 to 7 °C at 7 to 8 $cm^3\ s^{-1}$. Experiments were recorded with a high-definition video camera and still cameras. Still images extracted from overhead video of two PEG experiments are shown in Figure 1a & b.

Molten basalt experiments. Experiments with molten basalt were performed at the Syracuse University Lava Project facility, which is capable of melting >350 kg of basalt to >1200 °C. We completed a series of six experiments in which molten basalt was poured onto beds of gravel of various sizes (~0.5, 1.0, 1.5, 2.0, 3.0 to 6.3 cm average grain size) at 9 - 10° slope. Basalt was poured at a flux of 100 to 140 $cm^3\ s^{-1}$ for 1 to 2 minutes for each bed type. Still cameras, a high-definition video camera, and a thermographic camera monitored experiments, along with thermocouples embedded in the substrate and placed at the lava-substrate boundary. Still images of two basalt pour experiments are shown in Figure 2a & 2b.

Results: We analyze experiments in terms of flow morphology, flow shape, and flow front advance rate.

Corn Syrup. Flows over each sand paper substrate had similar symmetric, oval outlines advancing downslope at a central flow front while flows over gravel had irregular outlines and advanced from several spatially variable flow lobes as gravel pieces locally diverted the flow. Average flow thicknesses were scattered between 0.35 and 0.50 cm and maximum flow widths increased from 0.20 to 0.45 m with increasing grain size. Initial flow front velocity decreased from ~0.8 to ~0.5 cm/s with increasing grain size. This effect continues but diminishes with time after initial onset of the experiment.

PEG. All flows were ovaloid with increasing minor axis radius downslope and each developed lobate margins and central levéed channels (Figure 1). Flows tended to advance downslope from one central flow front, however, multiple flow fronts advancing at similar rates were common. Average flow thicknesses varied between 0.7 and 1.0 cm and maximum flow widths ranged from 0.29 to 0.36, however no systematic relationships could be found between flow thickness or width and grain size. Flow front velocity decreased from 1.5 to 1.0 cm/s from smallest to largest grain size. This relationship continued but decreased with time after flow start.

Basalt. Most of the basalt flows maintained oval outlines and sometimes produced breakouts near the flow front. Coarser substrates produced scalloped edges around flow margins as compared to smooth edges with finer substrates (Figure 2a). The coarsest substrate produced an irregular flow with several random breakouts (Figure 2b). Average flow thicknesses were scattered between 3.0 and 5.0 cm and maximum flow widths varied between 54 and 69 cm with no correlations with grain size. As with the analog-materials, flow front velocity decreased with increasing grain size, from a maximum of ~7 cm/s with a 1 cm grain size to a minimum of ~2.5 cm/s with a 6.3 cm grain size (Figure 3). This effect decreased with time after flow start.

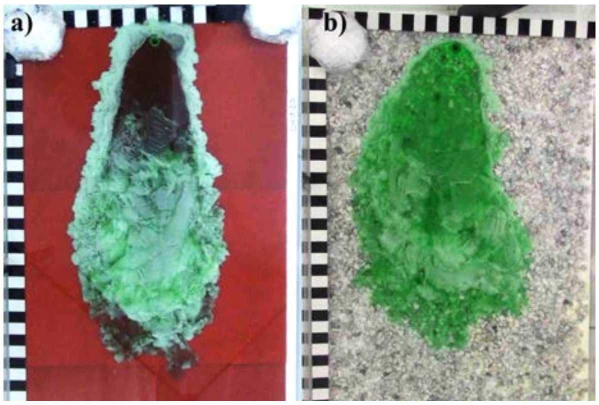

Figure 1. a) PEG flow on sand paper with 1 mm grains. b) PEG flow on 1 cm gravel substrate. Both images are taken 200 seconds after flow began. Black and white scale marks are 2 cm wide. Substrate plane slopes 7° towards the bottom.

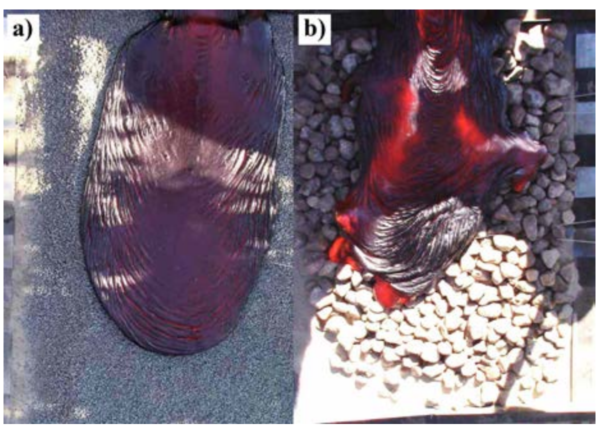

Figure 2. a) Basalt flow on pebbles with 0.5 cm average grain. b) Basalt flow on ~6 cm rock substrate. Both images are taken 120 seconds after flow began. Scale bars are 10 cm wide. Substrate sloped at 9°, downslope to the bottom.

Implications: Our experiments show that substrate grain size has an effect on fluid flow front velocity. This trend diminishes with time within the scale of experiments. When obstacles are of a height on the order of flow height they become significant topographical barriers that can affect flow movement. With a substrate of large grain sizes, the fluid must fill in the pore spaces between the grains as it moves forward. At later times, the fluid is advancing over a basal boundary layer that has developed at the fluid-substrate interface and decreases the influence of substrate type. This layer may be thermal, keeping the flow warm and mobile; mechanical, creating a no slip condition at the base allowing for a free-surface channel flow above; or both. Additionally, a more viscous flow front (cooler, older) may not fill in voids as efficiently.

The above effects likely influence flows in terrestrial and planetary environments. Large grain sizes in our experiments correspond to blocky, boulder, or irregularly eroded terrains seen in imagery of planetary surfaces (e.g. boulder fields revealed in Mars by HiRISE [15] sand dunes visited by Curiosity [16]). Similar terrains likely existed during periods of active volcanism and may have affected flow emplacement dynamics. Numerical modeling or *in situ* observations of natural lava flows may reveal if these trends hold at natural scales.

Flow volume estimates may be underestimated in areas of rough terrain, as downward penetration of fluid is not accounted for. Further, continued understanding of the scales at which roughness affects lava flows through our experiments and the analysis of natural flows can drive recommendations for sampling resolutions of future missions. We recommend the inclusion of substrate terrain characteristics in forward models in order to determine how best to use roughness in planetary and terrestrial contexts.

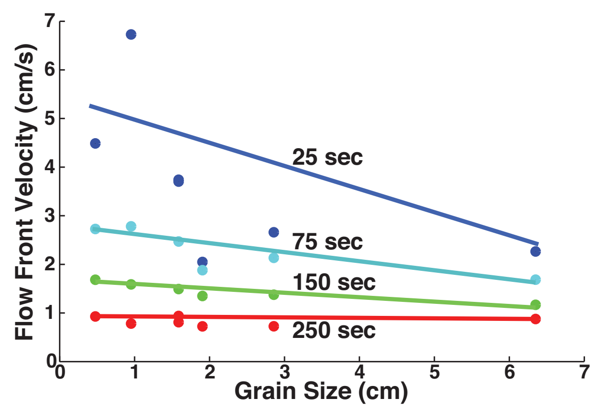

Figure 3. Flow front velocity versus grain size with time for 6 molten basalt experiments.

References: [1] Morabito, L.A. et al. (1979) *Science, 204*, 972. [2] Soderblom, L.A. et al. (1990) *Science, 250* 410–5. [3] Porco, C.C. et al. (2006) *Science, 311*, 1393-1401. [4] Shalygin, E.V. et al. (2015) *GRL, 42*,4762-9. [5] Fagents, S.A. & Greeley, R. (2001) *Bull, Volc., 62,* 519-532. [6] Fagents, S.A. et al. (2010) *Icarus, 207*, 595–604. [7] Rumpf, M.E. et al., (2013) *JGR-P 118*, 382–397. [8] Dietterich, H.R. & Cashman, K.V.J. (2014) *GRES*, 1704–1724. [9] Fink, J.H. and Griffiths, R.W. (1990) *J. Fluid Mech., 221*, 485–509. [10] Griffiths, R.W. and Fink, J.H., (1992) *JGR,* 19,739-19,748. [11] Gregg, T.K.P. and Fink, J.H., (1996) *JGR, 101(E7)*, 16,891-16,900. [12] Gregg, T.K.P. and Fink, J.H., (2000) *JVGR, 96*, 145-159. [13] Bridges, N.T. (1990) MS Thesis, ASU. [14] Kerr, R.C. et al (2006) *JGR, 111(B10)*:B10206, [15] McEwen, A.S. et al. (2007), *JGR, 112*, E05S02. [16] NASA/JPL-Caltech/MSSS.