USING MOLASSES, A LAVA FLOW SIMULATION CODE, TO INTERPRET THE MORPHOLOGY OF VOLCANOES: EXAMPLE OF OLYMPUS MONS (MARS)

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Introduction: Lava flow simulators are used to model the distribution of lava flows [1, 2]. Our lava flow simulator, MOLASSES, is a modular computer code written in C [3]. Inputs to MOLASSES include the location of the vent (easting and northing coordinate, m), the volume of the lava flow to be simulated (m^3), the modal thickness of the lava flow (m) and the volume of lava erupted per iteration (the pulse volume, m^3). A digital elevation model (DEM) of sufficient extent to contain the entire lava flow is also specified by the user. The DEM may have any format recognized by GDAL (Geospatial Data Abstraction Library).

Outputs of MOLASSES are the map area of the lava flow and the variation in thickness of the lava flow over this map area (Figure 1) in text file or raster format. MOLASSES can simulate many successive lava flows to model the development of a lava flow field or volcano edifice (Figure 2).

We use MOLASSES to model eruption of hundreds of lava flows to simulate the morphology of volcanoes, like Olympus Mons (Mars). We use probability density functions (PDFs) to describe the range of potential lava flow volumes and modal lava flow thicknesses. We have found that the morphology of effusive volcanoes is dominated by the PDF of lava volumes, with secondary control from the PDF of lava flow thickness and the spatial distribution of vents. Thus, using MOLASSES one can infer eruption processes from volcano morphology, potentially a powerful method for interpreting volcanic landforms on other planets.

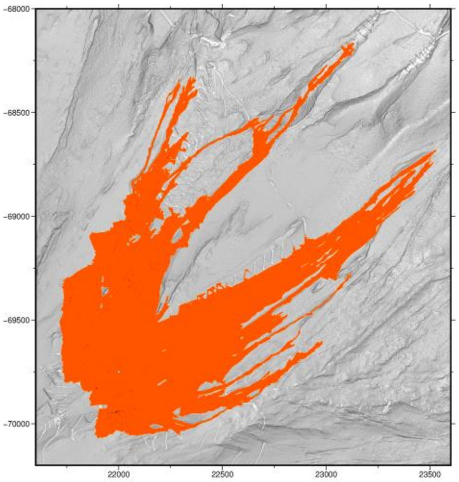

Figure 1. A simulated lava flow on a 1-m-DEM of Mt. Fuji (Japan). DEM provided by K. Mannen.

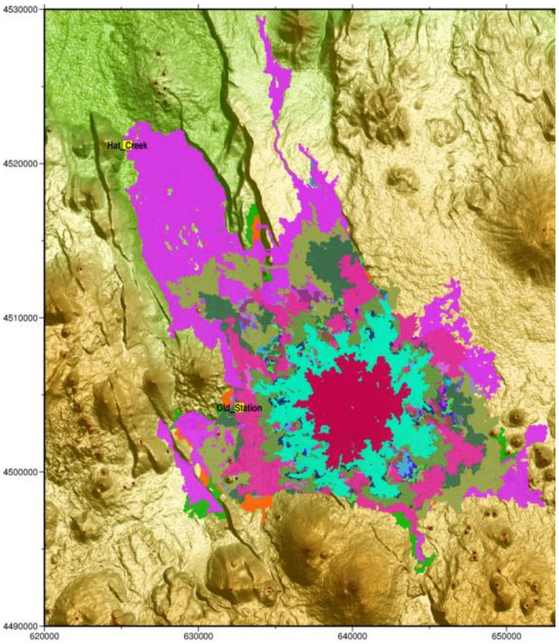

Figure 2. MOLASSES can be used to simulate construction of entire volcano edifices, as shown by this simulated geologic map based on eruption of 500 lava flows from a central vent, within a distributed volcanic field. 30-m-DEM provided by P. L. Whelley.

Model Framework: MOLASSES uses a model framework to simplify the simulation workflow. Each pixel of the entire DEM is specified as part of the *grid data structure*. The grid data structure stores the original elevation of the grid cell, and the amount of lava that accumulates in each grid cell as the simulation progresses. A second data structure is created during execution to speed the simulation. We call this the *active list*, enumerating all cells in each iteration that contain lava. Initially, the active list only contains the vent cell, where lava is added at the beginning of each iteration. As lava flows from one grid cell to another, the active list grows. Since lava can only be distributed to cells on the active list, or to their adjoining neighboring cells, only a small subset of the grid data structure must be evaluated in a given iteration. Each cell on the active list tracks its parent cells. These are the cells that gave lava to the cell, and therefore it is assumed that lava will not flow from the active cell to its parent cell(s). Active cells also have neighbors. Neighbor cells are those adjoining cells that are not parents and that have sufficiently low elevation to receive lava from the active cell. As the simulation proceeds, more grid cells are added to the active list. On each iteration (each time lava is added to the vent cell), cells on the active list distribute lava to adjoining cells, and neighboring cells are added to the active list as lava is distributed to them.

This model framework exists independently of how lava is divided among neighboring cells. An active cell will give lava to its neighbors when lava has accumulated in excess of the residual lava thickness specified by the user. We have attempted to simplify the structure of the code so that users can use the distribute algorithms we have developed, or create their own algorithms. MOLASSES has been benchmarked by comparison with other lava flow simulators [4] and by comparison to observed lava flows [5].

Simulating Volcano Edifices: We use MOLASSES to simulate the formation of an entire volcano edifice, say a shield volcano. In our first example simulation, we erupt 100 lava flows from a single vent. The vent location does not change during the simulation. The 100 lava flows are sampled from a log-normal distribution, with log mean 7 and log standard deviation 1. The distribution is truncated. The minimum lava flow volume is 10^6 m^3 and the maximum is 10^8 m^3. The residual lava flow thickness is sampled from a U[5m, 10m] distribution.

The simulated edifice is approximately 2 km in radius and approximately 750 m in relief. The sample mean corresponds to a lava flow that covers approximately 1.75 km^2 (Figure 3, black curve). Approximately 90% of the lava flows cover areas of 6.5 km^2 or less, and one lava flow covers an area of approximately 11 km^2. In our second simulation, the lava flow volume PDF is the same, but different samples are drawn from the PDF (Figure 3, red curve), resulting in a different form to the volcano edifice, and different topographic profile. Overall, we have found that it is possible to construct a wide range of volcano morphologies, from low-sloped shield volcanoes to classic composite volcano edifices, by varying the PDF of lava flow volume.

Modeling the topographic profile of Olympus Mons (Mars) suggests this massive edifice comprises ~500 lava flows drawn from a lognormal distribution of volume, with mean ~10^{12} m^3, and truncated at ~10^{13} m^3. The truncated upper limit on lava volume explains the characteristic break in slope low on the flanks of the volcano. This model suggests a relatively large number of eruptions occurred with volumes near this upper volume limit. Unlike smaller Martian shield volcanoes, the Olympus Mons magmatic system appears to have reached this upper limit of eruptible lava volume during individual eruptions, building a scarp and rendering the edifice susceptible to later mass wasting [6].

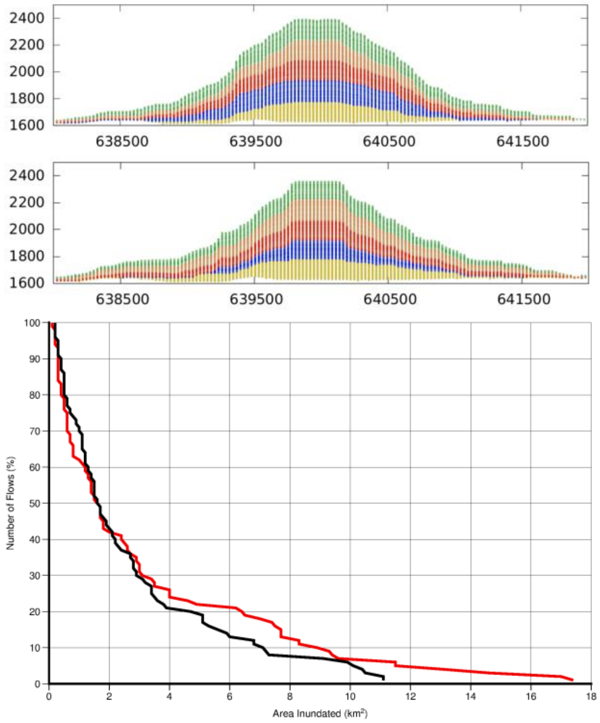

Figure 3. Topographic profiles of simulated volcano edifices constructed from 100 lava flow each, with different PDFs of lava flow volume. The shorter-tailed distribution (black curve) produces a more rounded edifice (upper panel), the longer-tailed distribution (red curve) produces a classic, concave topographic profile (middle panel). On the topographic profiles, each color represents a package of 20 lava flows simulated using MOLASSES.

Discussion: MOLASSES provides a means of inferring eruptive processes from the topography of remotely observed volcano landforms. The diameter, relief, topographic profile of a volcano edifice is explained in terms of the number of lava flows erupted, the thicknesses of the lava flows, and most importantly by the variation in eruption volume. Since most of the eruption history of any volcano is obscured by subsequent lava flows, the modeling framework provided by MOLASSES can potentially remove bias from the interpretation of a volcanic system that naturally arises from limited observations of its most recent products.

References: [1] Miyamoto, H. and S. Sasaki (1997) *Comp & Geosci* 23:283-292. [2] Costa, A. and G. Macedonio (2005) *GRL* 32(5). [3] Richardson, J.A. (2016) PhD thesis, University of South Florida. [4] Dietterich, H. R., et al. (2017) *J Appl Volcanol* 6: 9. [5] Kubanek, J. et al. (2015) *Bull Volcanol* 77: 106. [6] McGovern et al. (2004) *JGR* 109: E8.

Additional Information: MOLASSES is open-source and freely available from GitHub.