TYCHO CRATER LUNAR IMPACT MELT EMPLACEMENT: COMSOL MODELING OF FLOW, FOLDING, AND COOLING S. E. H. Sakimoto[1,2], T. K. P. Gregg[2], [1]Space Science Institute, 4765 Walnut St. Suite B, Boulder, CO 80301; ssakimoto@spacescience.org; [2]Department of Geology, 126 Cooke Hall, University at Buffalo, Buffalo NY 14260; tgregg@buffalo.edu.

Introduction: Folded lava flow surfaces have been observed on most of the rocky planets in the solar system, and they are enticing because fold amplitudes and wavelengths are features that can be readily measured. Fink and Fletcher [1] presented a model wherein surface fold dimensions could be related to the ratio between the surface folding layer and the molten flow interior. Subsequent investigations have built on this work, but have not significantly advanced our understanding of the folding processes.

Recently, Sakimoto and Gregg [2] demonstrated that multiphysics modeling can be used to help explain how multiple scales of folding occurs on flowing, viscous fluids. Here, we apply COMSOL multiphysics software to provide insight into the emplacement and formation of folded flow surfaces observed on isolated impact melt deposits on the southwest rim of Tycho crater (43.31°S, 11.36°W) on the Moon (Fig. 1). Tycho crater is 85 km across and is one of the freshest impact craters on the lunar surface. A lobate deposit, interpreted to be impact melt [e.g. 3] cascades down the outer southeast crater rim. Arcuate ridges along portions of the deposit are interpreted to be folds.

Methods: *Image Analysis:* High-resolution (~1 m/px) Lunar Reconnaissance Orbiter-Narrow Angle Camera (LROC-NAC) images [4] were obtained using the "search" tool on the LROC::QuickMap website. We divided the flow into 5 folded segments (A–E) and investigated each segment independently.

We used LROC-NAC image meta data with, shadow measurements to calculate ridge height. We obtained minimum estimates of flow thickness at each segment using flow-margin shadows. Maximum estimates were obtained by assuming the impact melt flow occupied a valley with a V-shaped cross-section, and extrapolating the observed slope on the adjacent valley walls to continue beneath the flow. The underlying slope over which the flow advanced was estimated from the QuickMap profile "Terrain Height."

Computational Approach: Using COMSOL Multiphysics, we model each flow segment as a cooling laminar 2-D gravity driven flow with a temperature-dependent viscosity and a deformable free surface; all flows are firmly within the laminar flow regime. We use the current flow top elevation as a proxy for the flow base topography, and constrain the thicknesses with the image analysis data. The flow cools through radiative cooling from the flow surface and conductive cooling

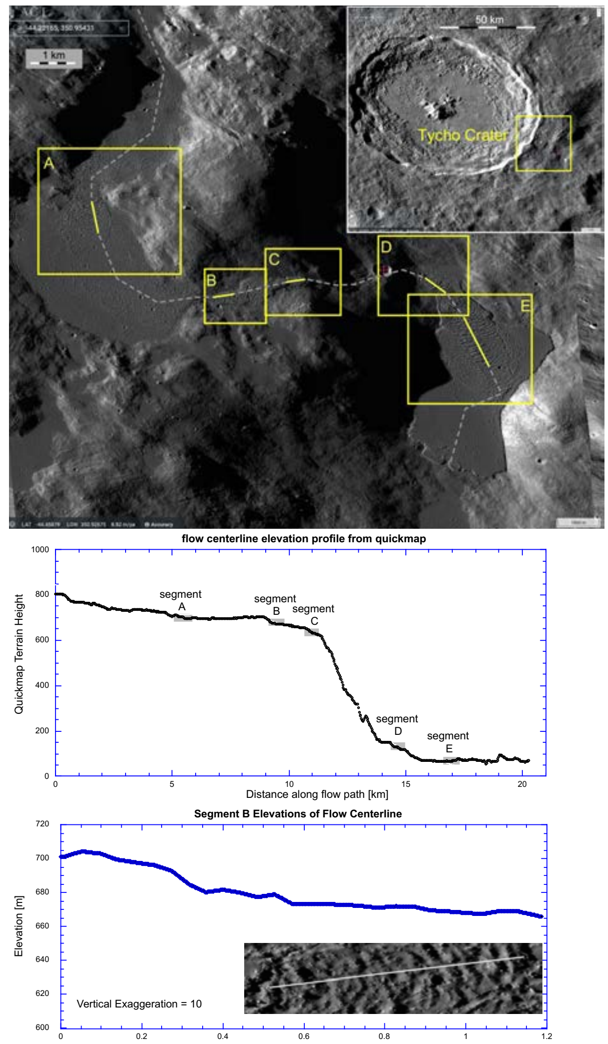


Figure 1 (Top) LROC QuickMap image centered at 43.31°S, 11.36°W showing Tycho (inset) and impact melt flow used in this study. Flow surface is divided into segments for modeling (yellow boxes); dashed line is flow centerline. (Middle) Topographic profile (obtained from QuickMap). (Bottom) Topographic profile of segment "B", and (inset) the ridges interpreted as folds. White line is profile location.

through the base, and the temperature-dependent viscosity evolves as the flow cools (with an initial viscosity of 80 Pa s [5]) and a viscosity function of $\mu = 4.1817^{27}$*exp(-0441T, where T is temperature). In all cases, we used lunar gravity (1.67 m s^{-2}), a constant melt density (2700 kg m^{-3}), thermal conductivity (0.9 J m^{-1} s^{-1} K^{-1}), heat capacity (1150 J kg^{-1} K^{-1}) and emissivity (0.9) for the impact melt.

Table 1 shows the measured parameters used in modeling. Fold height was used as a proxy for the deforming surface crust thickness [cf. 1]; measured fold wavelength was used as a check for model results.

Results: Initiating surface folding at submeter scales and hundred-meter scales (too small and too big, respectively, compared with observations) is a readily obtained model result. Submeter folds tend to originate at topographic breaks and propagate back up the flow (as seen in natural flows [6]). Long-wavelength surface deformations (>100 m) reflect a smoothed version of subsurface topography. Neither of these wavelengths is likely to be observed with available lunar data, although they can be found in terrestrial flows. Incorporating underlying slope breaks, as is observed between the Tycho crater flow segments, does not create folds at the observed wavelengths (tens of meters).

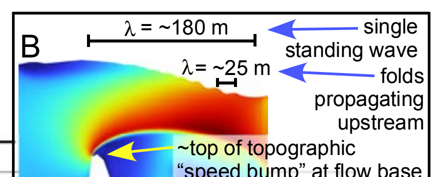
For COMSOL to generate surface folds at the scales observed on the impact melt flow, topographic irregularities on the flow base (i.e., "speed bumps" on the topography at the bottom of the flow) are required. In prior work modeling thinner flows, similar wavelength folds are readily generated with a depth-dependent viscosity like that used in Fink and Fletcher [1], and commonly instigated in numerical solutions by a slope break or modest flow-base topographic irregularity. In these Tycho flow models, the flow basal topography plays a significant role and generates free surface deformations sufficient to cause problems with a depth-dependent viscosity approach. Accordingly, we applied a temperature-dependent viscosity, and solve for the temperature field of the flow as well.

A relatively thin, cool crust over a thick hotter flow core only generates observed fold wavelengths if significant (>30% of flow depth) basal topographic obstacles ("speed bumps") are encountered. A variety of rheologies and slope breaks were tested, but none generated the observed folds until the basal obstacles were significant.

Discussion and Conclusions: Folds on lunar impact melt surfaces are rare: a preliminary search of cataloged impact melt deposits on the Moon [7] reveals few flows with well organized fold trains. In contrast, folded lava surfaces on Earth are common [cf. 1]. Impact melt flows are gravity-driven: the melt is dropped onto the surface during the impact process, and then flows downhill. The low lunar gravity results in a low velocity.

Furthermore, impact melt compositions are mixtures of the target material and are likely emplaced at superliquidous temperatures [5]. Impact melt therefore is likely to have rheologies and behaviors distinct from terrestrial lava flows. Low gravity, high emplacement temperatures and distinct melt rheologies apparently act to impede surface folding. The presence of underlying "speed bumps" may play an important role in fold generation on the lunar surface.

References: [1] Fink, J.H. and R.C. Fletcher. (1978) *JVGR, 4,* 151-170. [2] Sakimoto, S.E.H. and T.K.P. Gregg (2022) *Fall GSA Meeting,* 188-5. [3] Krüger et al. (2016) *Icarus, 273*, 164-181. [4] Robinson, M.S. et al. (2010), *SSR, 150*, 81-124. [5] Lev., E. et al. (2021) *Icarus 369*, 114578. [6] Gregg, T.K.P. et al. (1998) *JVGR, 3-4*, 281-292. [7] Neish, C.D. et al. (2014) *Icarus 239*, 105-117.



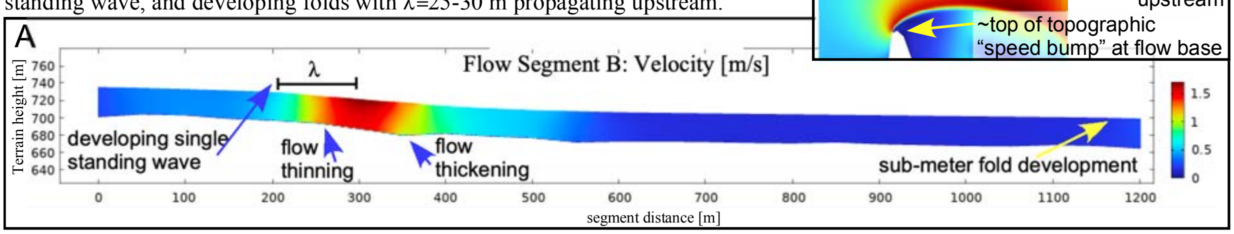


Figure 2. Colors represent velocity (scale lower right [m/s]. A) Velocity field for flow segment B without underlying "speed bump" shows develoment of a single standing wave as well as sub-meter folds. B) Inset shows a portion of segment B with an underlying "speed bump" and a more fully developed, large (λ~180 m) standing wave, and developing folds with λ=25-30 m propagating upstream.

Table 1. Parameters used in COMSOL modeling.

Flow Segment	Measured flow thickness (m)	Modeled flow thickness (m)	Slope (°)	Measured average fold wavelength (m)	Max measured fold height (m)
A	120	120	0 – 3	21	33
B	35	35	0 – 15	33	5.5
C	19 – 49	49	3 – 10	33	4.1
D	15 – 50	50	0.8 – 4	38	6.6
E	7 - 60	60	0.5 - 3	81	6.1