MODELING HELENE'S MASS FLOWS. A. D. Howard[1], O. M. Umurhan[2], and J. M. Moore[3], [1]Planetary Science Institute, 1700 E. Fort Lowell, Suite 106, Tucson, AZ 85719 (ahoward@psi.edu), [2]SETI Institute at NASA Ames Research Center, Moffett Field, CA 94035. [3]NASA Ames Research Center, Moffett Field, CA, 94035.

Introduction: Helene is a small (43.4 x 38.2 x 26 km) Lagrangian satellite of Dione that exhibits extensive mass flows up to 20 km in length (Fig. 1a) [*1, 2*]. Similar mass flows occur on the two small Lagrangian satellites of Tethys (Telesto and Calypso). Explaining the composition and flow mechanisms of these flows occurring in microgravity and over gradients of ~15° is challenging. Our approach is to quantitatively model these flows to examine possible rheologies and evolutionary histories.

Helene's Surface Features: The leading hemisphere of Helene (Fig. 1a) features sharply-defined, rough-textured ridges surrounding broad, relatively smooth basins interpreted to be strongly modified impact basins. Broad smooth plains in basins contrast with sharp-edged ridges and mesas elevated 10-30 m above the plains and oriented down-gradient (white arrows, Fig. 1a) [*2*]. In some locations the mesas narrow downgradient, producing long tails. The mesas appear to be eroded remnants of a formerly continuous surface and nearly parallel to the surface defined by the basin deposits. The steep sideslopes of the slot incision indicate that the mesa-forming materials are somewhat cohesive. Those deposits appear relatively darkened, possibly having reddened through time. The basin deposits are smooth at 42 m/pixel resolution except for a scattering of <500 m diameter impacts. Under oblique illumination flows reveal lobate morphology (blue arrows, Fig. 1a) such that opposing flows meet at sharp concavities, or seams (red arrow, Fig.1a). The evolution of Helene is interpreted to involve 1) accretion dominated by H_2O ice forming a cratered surface; 2) Accumulation of a mantle up to 100+ m deep through weathering of crater walls and deposition of exogenous fine H_2O ice, accompanied by mass flow; 3) an interval in which the surface materials became modestly cohesive; and 4) remobilization of parts of the mantle except for the mesa remnants.

Models of Landscape Evolution: We evaluate the explanatory sufficiency of both shallow and deep-seated mass wasting to produce landforms similar to those observed on Helene and the other Lagrangian satellites using the spatially explicit MARSSIM simulation model [*3-5*]. All simulations utilize 20m/pixel resolution with a saturation-cratered surface as initial conditions. We use the term *regolith* to refer to the mobile layers involved in mass-wasting.

Models involving shallow mass wasting. Mass-wasting is shallow if it affects the subsurface to a depth that is small compared to total relief. We consider generation of regolith to occur via either *weathering* of the substrate or through exogenous *accretion* from space. Mass wasting is assumed to be driven by the slope gradient, $\boldsymbol{S}$. A widely used model [6] for mass wasting assumes flux, $\boldsymbol{q}$, involves both a diffusive component and accelerated motion for gradients close to a failure gradient, S_c: $\boldsymbol{q} = K_s \boldsymbol{S} / \left[1 - \left(S / S_c\right)^2\right]$. Fig. 1b shows the results of weathering plus mass wasting. These assumptions result in smoothly concave basin floors, unlike the sharp seams on the Lagrangian satellites. If the assumption is made that mass movement only occurs near threshold (replacing the numerator $\boldsymbol{S}$, above, by unity) seams are formed on the basin floors and slopes hover near threshold values (Fig 1c). By assuming that a thin resistant crust - perhaps driven by H_2O ice grain sintering - forms after an initial period of mass wasting (Fig. 1d), followed by additional weathering and erosion by avalanching of weathered debris, a pattern of mesas similar to those on Helene can be produced (Figs. 1a,e).

Models involving deep-seated mass wasting. A very low value for the threshold slope S_c (tan15°) must be assumed for shallow mass wasting, much lower than the angle of repose for most granular materials. We have therefore explored deep-seated mass wasting using Bingham flow rheology such that there is a critical threshold shear stress, τ_c, with flow occurring only where the shear stress, $\rho g h \cdot \sin\theta$, exceeds the critical value (ρ is regolith density, g is gravity, h is depth of overlying regolith, and θ is the slope angle). We also assume there is a maximum mobile regolith depth, h_m, to immobile substrate. We have conducted simulations using regolith generation either by weathering or by accretion. Fig 1f shows basin infilling by Bingham flow with regolith produced by weathering. Note flow convexity and sharp seams. Fig 1g shows further evolution of Fig 1h when the threshold stress is increased as is maximum flow depth. This produces mesas (arrows) possibly analogous to those on Helene. The most rapid fluxes occur in narrow downgradient flows as on Helene (Fig. 1h), which shift in location and intensity through time.

Conclusions: Modeling indicates mass wasting features of Helene, Telesto, and Calypso can be explained by either shallow or deep mass wasting, although the low slope gradients are more consistent with deep Bingham flow. Either substrate weathering or exogenous accretion may produce the mobile regolith. Flow rejuvenation produces Helene's mesas. We are at present cannot conclude whether the flows were relatively rapid or slow.

References: [1] Thomas, P., Helfenstein, P., (2019), *Icarus*, doi:10.1016/j.icarus.2019.06.016. [2] Thomas, P. C. *et al.*, (2013), *Icarus* **226**, 999-1019. [3].Howard, A. D., (2007), *Geomorphology* **91**, 332-63. [4].Howard, A. D. *et al.*, (2012), *Icarus* **220**, 268-76. [5].Matsubara, Y. *et al.*, (2018), *JGR Planets* **123**, 2958-79. [6].Roering, J. J. *et al.*, (2001), *Geology* **29**, 143-46.

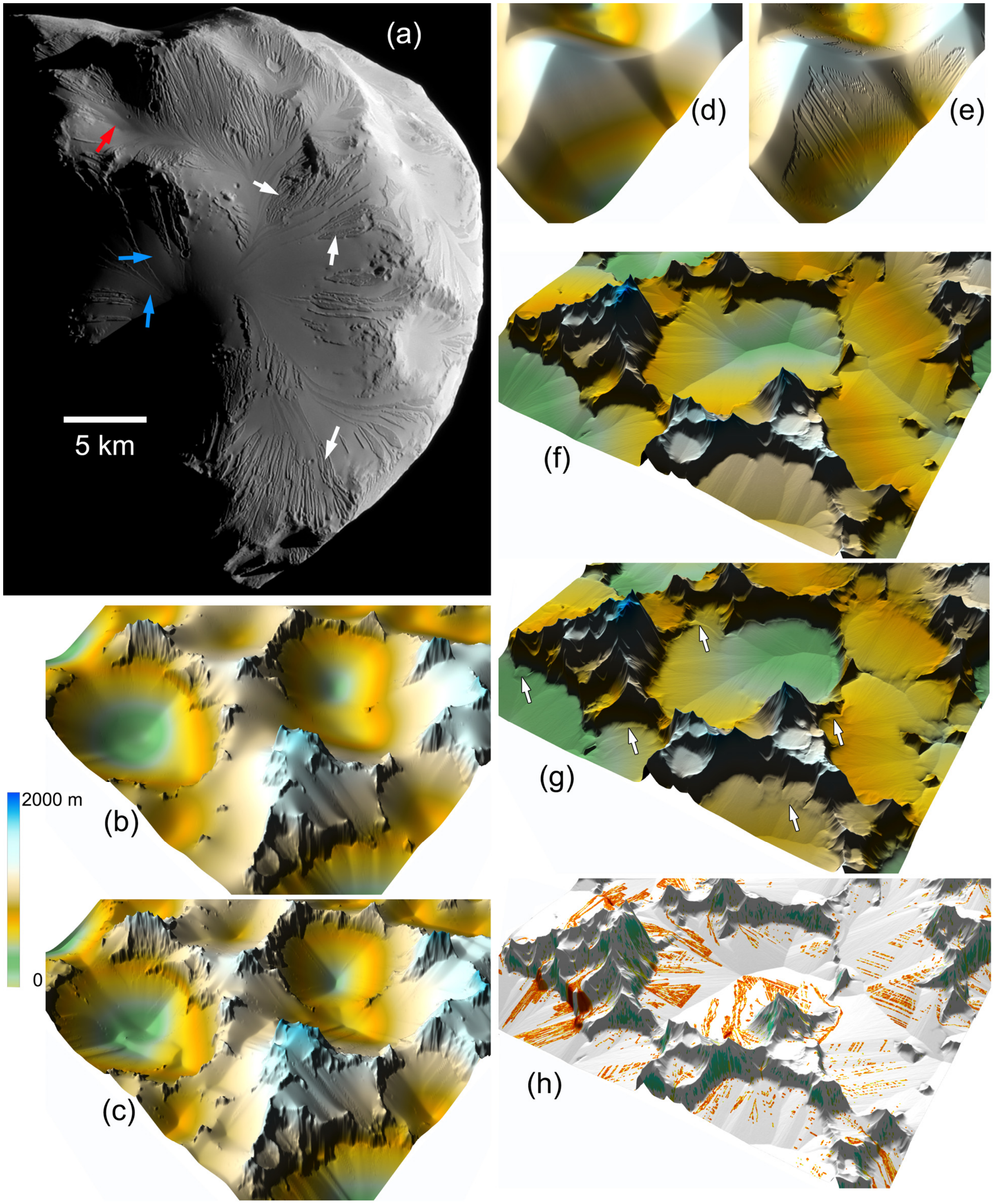

Figure 1. (a) Helene, white arrows point to mesas, red arrow points to seams, blue arrows point to flow convexities. (b) Simulation with weathering and dissuasive mass wasting. See elevation scale. (c) Simulation with threshold mass wasting. (d) Initial conditions for mesa simulation. (e) Formation and erosion of crust, forming mesas. (f) Bingham flow simulation with regolith produced by weathering. (g) Rejuvenated flow with greater threshold stress and deeper flows. Arrows point to scarps. (h) Bingham flow rate superimposed on topography for simulation in (f). Uncolored regions very slow, blue areas intermediate rate, reds and yellows fast. (b) to (h) are perspective views.