SUBLIMATION AS A LANDFORM-SHAPING PROCESS ON PLUTO. J.M. Moore[1], A.D. Howard[2], O.L. White[1], O.M. Umurhan[1], P.M. Schenk[3], R.A. Beyer[1], W.B. McKinnon[4], K.N. Singer[5], J.R. Spencer[5], S.A. Stern[5], L.A. Young[5], H. Weaver[6], C.B. Olkin[5], K. Ennico[1], and the New Horizons Geology and Geophysics Imaging Team. [1]NASA Ames Research Center, MS 245-3, Moffett Field, CA, 94035, [2]Dept. Environ. Sci., Univ. of Virginia, Charlottesville, VA 22904, [3]Lunar & Planetary Inst., 3600 Bay Area Blvd., Houston, TX 77058, [4]Dept. Earth & Planetary Sci., Washington Univ., St. Louis, MO 63130, [5]Southwest Research Inst., 1050 Walnut St., Suite 300, Boulder, CO 80302, [6]JHU Applied Physics Laboratory, Laurel, MD 20723 (jeff.moore@nasa.gov)

Introduction: Several icy-world surfaces in the solar system exhibit sublimation-driven landform modification erosion, condensation, and mass wasting [1]. In addition to the obvious role of gravity, mass wasting can work in conjunction with internal disaggregation of a landform's relief-supporting material through the loss (or deteriorating alteration) of its cohesive matrix. To give a conspicuous example, Callisto's landscape exhibits widespread erosion from sublimation erosion of slopes, which results in smooth, undulating, low albedo plains composed of lag deposits, with isolated high albedo pinnacles perched on remnants of crater rims due to the re-precipitation of ice on local cold traps [2, 3, 4]. Sublimation-driven mass wasting was anticipated on Pluto prior to the encounter (see refs in [5]). Here we report on several landscapes on Pluto we interpret to be formed, or at least heavily modified, by sublimation erosion.

Some Properties of Ices at Pluto: Nitrogen, CH_4, CO, and H_2O ice are all observed spectroscopically on Pluto [6]. Nitrogen, CH_4 and CO are solid at Pluto's surface temperatures of ~40K. N_2 and CO are much less viscous than water ice at ~270K, and thus flow readily under the low stresses on Pluto. CH_4 is relatively less volatile and may be significantly more rigid than N_2 and CO. Nitrogen ice is denser than water ice at 40K. Methane ice is the least dense of all these ices. Water ice probably forms the crustal "bedrock" on Pluto, supporting steep mountains up to 4 km high.

Observations: Several terrains within the cratered uplands are probably shaped by sublimation erosion and/or volatile redistribution. Perhaps the easiest to recognize is *scarp retreat*. The cratered plateau uplands of Vega Terra are separated from the nearly uncratered plains unit of Piri Planitia by a generally N-facing crenulated scarp centered at ~ 25°N, 100°E. (All place names used here are informal.) The scarp breaks up into isolated mesas in several places. The terrain just above the scarp shows a strong CH_4 signature while the plains unit below does not. It shows exposed H_2O instead. We speculate that CH_4 sublimation may be driving the scarp retreat.

Pitted Uplands (Fig. 1) comprise much of eastern Tombaugh Regio. This unit may be the remnants of a formerly continuous deposit degraded either by sublimation (analogous to terrestrial sun cups but on a much larger scale), or the growth of ridges through preferential deposition of volatiles on ridge crests, analogous to pinnacle formation on Callisto. Undermining and collapse may also play a role.

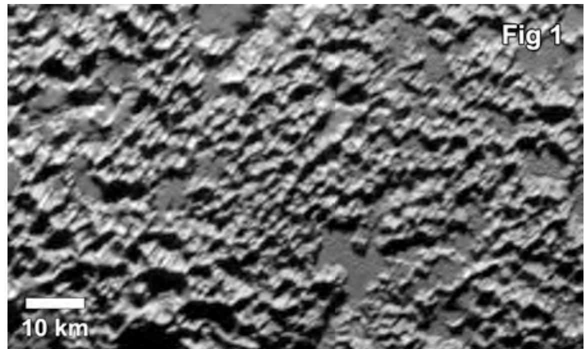
Bladed Terrain covers the flanks and crests of Tartarus Dorsa with numerous roughly aligned blade-like ridges oriented ~N-S. Individual ridges are typically several hundred meters high, and are spaced 5 to 10 km crest to crest, separated by V-shaped valleys. Many ridges merge at acute angles to form Y-shape junctions in plan view. Perhaps they form from the sublimation-driven widening and deepening of pre-existing parallel tectonic fractures, and/or the consequence of pinnacle accumulation like on Callisto. If so insolation could control orientation. N_2 is probably too soft to retain their topography so a possible alternative is CH_4. Intimate mixtures of volatile and non-volatile ices may also provide a degrading but relief supporting "bedrock," perhaps analogous to Callisto [2, 3]

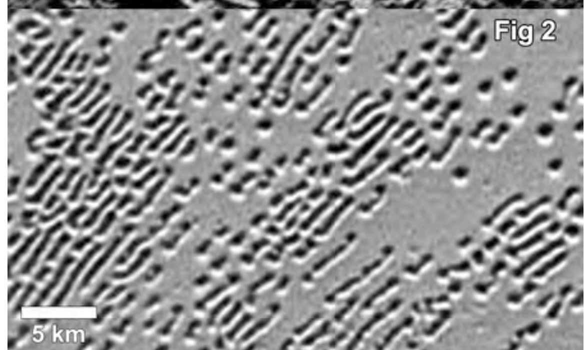
Fields of often aligned pits are especially well developed where seen in high resolution images of southern Sputnik Planum (Fig. 2) informally referred to as *Sputnik Bacilli*. They exhibit variations in size, width/depth ratio, and density (varying from isolated to shoulder-to-shoulder). Some have dark floors. We suspect much of this variability can be explained by simple models of sublimation erosion (below).

Initial Landform Evolution Modeling: Utilizing the Landform Evolution Model developed by Howard [7], particularly as it has been applied to Callisto and Hyperion [3, 8], we begin with an initial assumption that sublimation is enhanced in depressions due to inward scattering of solar radiation. Within a given depression, sublimation from one spot relative to any other spot is proportional to the product of cosine of 2φ, where φ is the angle formed between the two (locally planar) spots, and the inverse of their separation distance squared. Total sublimation is the sum of radiation from all visible locations and for simplicity of the initial modeling; sublimation from direct radiation is ignored. The model is heuristic as was our initial Callisto model [3]. We begin with a high-frequency fractal surface with low relief with 257x257 cell periodic boundaries and cell size of 100 m. Initial gradients on the surface are > 0.01. We chose this initial surface to assure there is no intrinsic scale in the initial conditions and to test that sublimation as modeled intrinsically produces a pitted surface from arbitrary initial conditions (Fig. 3A). Next we coupled the sublimation model with a diffusive (mass wasting) model. We chose the non-linear diffusive creep model of Roering et al. [9, 10]. Our runs clearly show that intrinsic scale of pitting and pit spacing is controlled by our varying the ratio of diffusivity to sublimation rate. The models also indicate that the temporal evolution of pitted surfaces was such that initially lots of time passes with little happening, then very rapid development of relief and rapid sublimation.

Initial Conclusions: Pluto exhibits many examples of eroded terrains and landforms probably substantially aided by sublimation. Pluto's sublimation modified landforms appear to require a significant role for (diffusive) mass wasting as suggested by initial modeling (Figs. 3B & 3C). Spectacularly outstanding unknowns are the mechanical properties of N_2 and CH_4 ice at Pluto conditions. For instance N_2 is thought to be too weak to support more than a few 10s of m of steep relief. However, pre-encounter studies give disparate answers as to whether CH_4 can hold up a few 100s of m of steep relief [11], or perhaps not [12].

References: [1] Moore, J.M. et al. (1996) *Icarus 122,* 63-78. [2] Moore, J.M. et al. (1999) *Icarus 140,* 294-312. [3] Howard, A.D. & Moore, J.M. (2008) *Geophys. Res. Lett. 35,* L03203. [4] White, O.L. et al. (2016) *JGR Planets 120 in press*. [5] Moore, J.M. et al. (2015) *Icarus 246,* 65-81. [6] Grundy, W.M. et al. (2016) *Science,* submitted. [7] Howard, A.D. (2007) *Geomorph. 91,* 332-363. [8] Howard, A.D. et al. (2012) *Icarus 220,* 268-276. [9] Roering, J.J. et al. (1999) *Water Resour. Res. 35,* 853-870. [10] Roering, J.J. et al. (2001) *Geology 29* (2)*,* 143-146. [11] Eluszkiewicz, J. & Stevenson, D.J. (1990) *Geophys. Res. Lett. 17,* 1753-1756. [12] Yamashita, Y. et al. (2010) *Icarus 207* (2), 972-977.





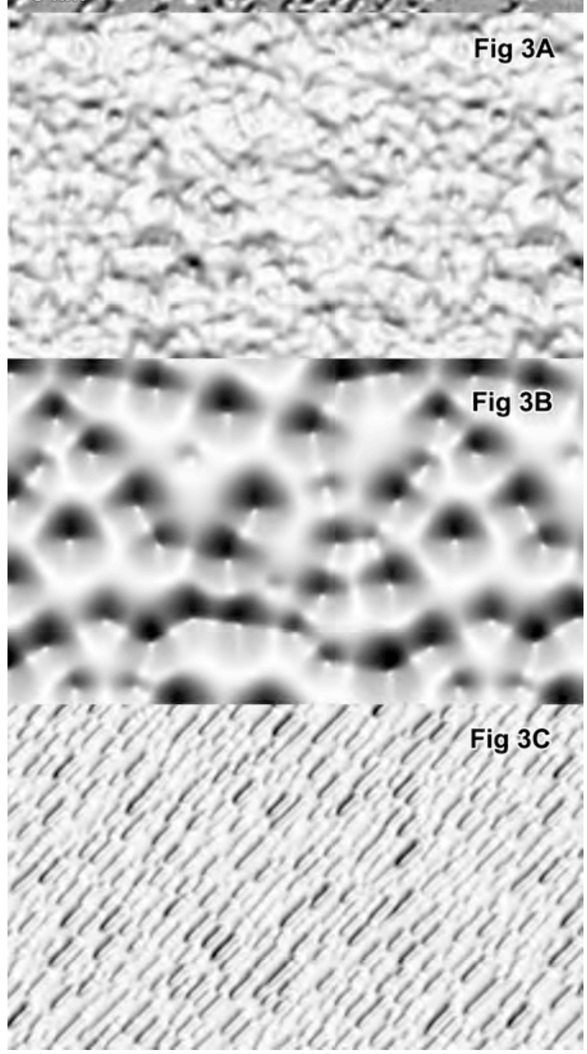


Fig. 1: Pitted Uplands Terrain. (~10°N, 210°E)

Fig. 2: Fields of often aligned pits in southern Sputnik Planum informally referred to as *Sputnik Bacilli*. (~15°S, 185°E). North up in both images.

Fig. 3: **(A)** High-frequency fractal surface with low relief and gradients used as initial model surface. **(B)** Model simulating a pitted landscape somewhat similar to that in Fig. 1. This run clearly manifest that the intrinsic scale of pitting and pit spacing is controlled by the ratio of diffusivity to sublimation rate. **(C)** Model simulating a landscape somewhat similar to *Sputnik Bacilli* shown in Fig. 2, created by changing the bias so that NE facing slopes erode 3x faster than other orientations.