# EXAMINING SCENARIOS FOR GLACIAL FLOW OF VOLATILE ICES ONTO PLUTO'S SPUTNIK PLANUM.

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**Introduction:** Of the many intriguing features uncovered by New Horizon's observations of Pluto, the indication of past and (possibly) present-day glacial flow raises many interesting questions regarding the origins, transport and cycling of Pluto's volatiles. Spectroscopic analysis of Sputnik Planum (SP) and its immediate highlands show that the surface volatiles found are mainly $N_2$, CO and $CH_4$ and while their relative proportions are not yet certain, it is likely that the surface on and around SP is dominated by $N_2$ ice [2] (All Pluto-system place names are informal). The conspicuous absence of any craters on SP itself suggests that the plain is geologically young, being no older than 1 Myr [3]. The center of SP shows polygonal patterns indicated by darkened lanes that have been interpreted as evidence for $N_2$ solid-state buoyant convection [3], suggesting further that SP is a volatile ice rich basin. These polygons disappear as one approaches the shoreline of SP suggesting the basin is relatively shallow there because buoyant ice convection will cease to operate for sufficiently shallow layers.

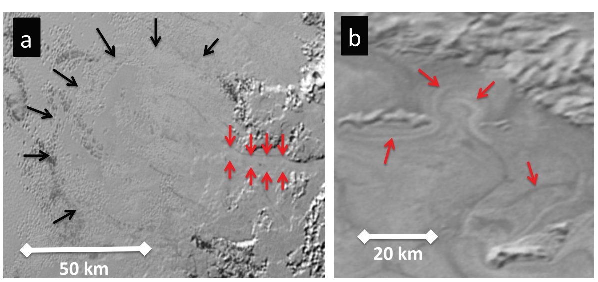


Fig. 1 (a) Eastern SP flow lobes (black arrows). Channel shown (red arrows) (b) Northern SP near CR. Possible flow around obstacles.

Two additional visual observations of SP are of particular interest: (1) The landscape on the eastern side of SP bordering the highlands of Tombaugh Regio show features indicative of glacial flow [3,4]. Uplands descend and open out onto SP's open plains, where high albedo material (presumably $N_2$) appears to carpet the two regions (**Fig. 1a**). The high albedo material appears to emerge from narrow channels and throats (red arrows) and appear bounded with a lobate pattern (black arrows) indicated by dark features on the ice – strongly suggesting an analogy to terrestrial glacial moraines. (2) The northern end of SP bounded by Cousteau Rupes (CR) similarly shows what appears to be smooth glacial ice embaying the base of the CR range. The ice shows albedo variations indicating material forming a gently swirling pattern suggesting that this feature is evidence for viscous flow around an obstactle (**Fig. 1b**, red arrows).

Alpine ranges and fluted valleys seen in the uplands surrounding SP show patterning consistent with glaciation [4] suggesting that the surface flow processes like scouring may be shaping the underlying bedrock, presumably made of $H_2O$ ice (see next section). Given that the annual sublimation/deposition budget of $N_2$ is anywhere between 1-5cm/yr [5] (assuming there are negligible losses to space on the timescales of interest), the aforementioned observations present an interesting puzzle as to (i) the nature of volatile dynamics on Pluto and (ii) assessing viable scenarios explaining the historical development of SP and the conditions leading to what appear to be glacier outflow events. Our initial aims are to setup a modeling framework to assess hypotheses regarding the development of the various features seen on SP and, in turn, (longer term goals) determine what it may mean for the origin and history of SP and the ices it holds.

**Some Physics and Hypotheses:** Based on available laboratory evidence $N_2$ ice at conditions characterstic of Pluto's surface flows quickly where, e.g., a 50 km long drainage channel at an angle $\theta = 10^o$ (with respect to the horizontal) filled with a hectometer thick layer of pure $N_2$ ice will drain in approximately 15 years [3]. Given the relatively low viscous nature of the these volatile ices, it is unlikely that the mountainous uplands immediately surrounding SP, with high grades $(\theta \sim 10^o - 20^o)$ and relief of nearly 2-3km, is made entirely of these materials for they would smooth out on short timescales. It is more likely that these high relief scale features are primarily made of highly rigid $H_2O$ ice, acting as a bedrock, and the volatiles form a thin veneer over its surface. We adopt this assumption in all of our subsequent hypotheses

Some of the questions we initially consider are the following: (A) Are the swirly flow-like patterns seen on the margins of SP a result of $N_2$ ice flowing over shallow topography and, if so, on what timescales does this occur and how does this conform with the volume and timescales associated with global atmosphereic transport of $N_2$? What might this say about Pluto's 1-2 Myr superseasons and the role it may be playing in these dynamics? (B) Are the outflowing glacier features, like those seen on the eastern shore of SP, indicative of a seasonal process involving the sublimation/deposition of $N_2$ ice from SP onto the highlands resulting in a net build-up of highland $N_2$ ice over thousands of orbits? Or, could it be that these glacier outflow features might be the result of sudden dam-break like events of higher elevation catchments of $N_2$ ice, resulting in its rapid drainage?

**Model and Methods:** We have recently adapted the landform evolution model MARSSIM [6] to represent the viscous flow of non-Newtonian materials. We adopt a vertically integrated model (Glen law) representation and model the evolution of the thickness of $N_2$ ice, given as $h_N$ over a bedrock substrate at elevation $h_b$. The net-seasonal deposition of $N_2$ ice is given by the expression $\dot{h}_a$. The governing equations are

$$\begin{aligned} \partial_t h_N &= \nabla\cdot\mathbf{q} + \dot{h}_a + \dot{h}_b, \\ \partial_t h_b &= -\dot{h}_b = -\tau_0 \Phi(|\mathbf{q}|), \end{aligned} \tag{1.1}$$

where the mass flux rate $\mathbf{q}$ is given by

$$\begin{aligned} &\mathbf{q} \equiv q_0 h_N^{\,n+2} F(S)\nabla H; \;\; H \equiv h_N + h_b, \\ &S \equiv |\nabla H|; \;\; F(S) = S^{n-1}/(1+S^2)^{n/2}. \end{aligned} \tag{1.2}$$

A surface scouring functional form $\Phi(|\mathbf{q}|)$ is chosen as guided by those used in the glacier literature. The time scale $\tau_0$, is a freely chosen parameter while $q_0$ depends on the stress-strain properties of $N_2$ ice.

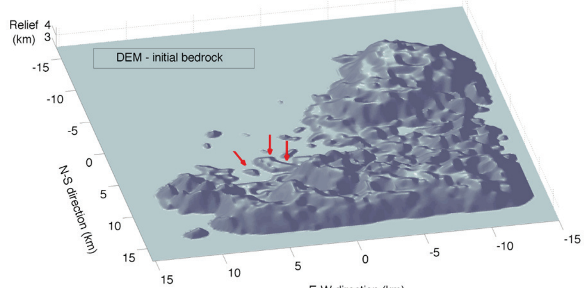


**Fig. 2.** A hilly section on the eastern SP border. The edges and SP plain has been artificially flattened.

We initiate our simulations with actual digital elevation models (DEM) of highland sections bordering SP (**Fig. 2).** To these landscapes, which we input as the bedrock $h_b$, we add volatile ice with varying amounts and distributions and follow its response to make several qualitative assessments.

**Results thus far.** We have considered a series of artificial testruns to test basic feasibility of the aforementioned scenarios. In **Fig. 3** we begin with a large amount of $N_2$ ice deposited in the mid section of the landscape which is then allowed to flow out. This run also has a net seasonal-deposition of material. No glacial scouring added. **Fig. 4** shows the resulting viscous readjustment of the initial condition. Flow lobes have clearly developed after 20 years. An interesting observation is the appearance of shallow ridgelines in the lower left quadrant of the simulation as indicated by the red arrow. The ridgelines are imprints of the corresponding bedrock features indicated by red arrows in **Fig. 2**. This bears qualitative resemblance to similarly appearing ridgelines in **Fig. 1b**.

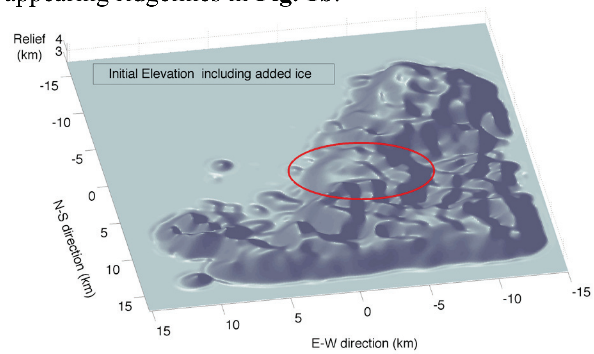


**Fig. 3** Initial elevation plus added glacial ice (about 400 m), indicated by red oval. Artificially large amount of seasonal ice deposited (50 m/year).

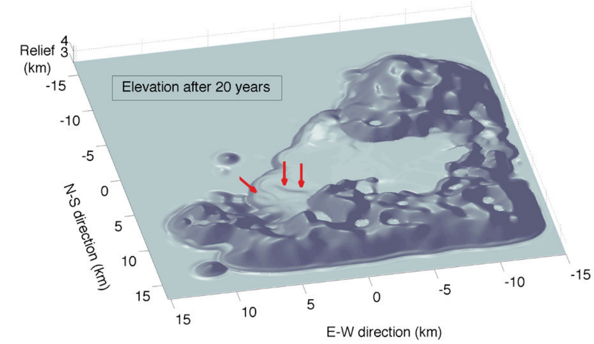


**Fig. 4** Final landscape after glacial ice relaxes -- 20 years later. Flow lobes are apparent. Imprint of low-lying bedrock topography is also apparent (shown by red arrows, cf. **Fig. 2**). Deposited ice flows down nearby craters to form $N_2$ ice pools.

**References and Notes:**. [1] All place names of the Pluto system are informal. [2] Grundy, W.M. et al. (2015) *Science*, submitted. [3] Moore, J.M. et al. (2015) *Science*, submitted. [4] Howard, A.D. et al (2016), LPSC-XLVII (this conference). [5] Young, L.A. et al. (2016) LPSC-XLVII (this conference). [6] Howard, A.D. (2007) *Geomorph. 91,* 332-363.