

DOWNHILL SLEDDING AT 40 AU: MOBILIZING PLUTO'S CHAOTIC MOUNTAIN BLOCKS.

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Introduction: The western rim of Pluto's informally named Sputnik Planitia is notable for its collection of tall, angular, and chaotically oriented mountain block chains, designated as the al-Idrisi, Zheng-He, Baré, Hillary, and Norgay Montes. Their fragmental appearance and clustering suggest an origin as tectonically disrupted and transported pieces of Pluto's water ice crust, with a potential source region identified near the basin's northwestern rim [1]. The transport mechanism is not yet clear. Water ice is buoyant in solid nitrogen, and this may be how isolated hills of water ice within the basin are transported. However, the largest blocks reach up to 5 km above the plains and are up to 40 km in diameter, far too large for buoyant support in a basin of reasonable depth [1].

We present an analysis of the forces acting on a block of water ice that is partially immersed in solid nitrogen and on a slope. We find that, for reasonable slopes and friction coefficients, the largest blocks can be transported from their source over very short (at short as ~ 100 yr) timescales, and that the forces acting on the blocks are consistent with their observed size distribution and position on the basin rim.

Methodology: Figure 2 summarizes the forces considered: the weight of the block oriented downslope (F_D) is opposed by the basal friction force (F_F) and modified by any net lateral forces from convection in the nitrogen ice that fills the basin (F_C). In cases where net downhill force exists ($F_T > 0$), it will be balanced by the viscous drag force of the low viscosity nitrogen ice (F_V), effectively Stokes flow. In order to calculate these forces, we require estimates of the coefficient of friction μ , the net lateral forces of convection acting on a block, the effects of partial buoyancy, and a Stokes law derivation of the viscous drag forces.

Modeling convection. In order to model the lateral convective forces acting on the block, we implement a material model for solid nitrogen in the finite element code ASPECT (Advanced Solver for Problems in Earth's ConvecTion) [2]. We model the effective viscosity of nitrogen as a temperature-dependent fluid after the Newtonian formulation in Umurhan et al. [3]. Convection is modeled in a wide ($\sim 1:20$ aspect ratio) 2D box with depths varying from 500 m to 2 km. The surface temperature was fixed at 37 K, and the bottom temperature was adjusted until it provided a convective heat flux equal to Pluto's estimated radiogenic



Figure 1: New Horizons LORRI mosaic depicting the southern portion of the informally named al-Idrisi Montes. The large block on the right side of the image is ~ 40 km across.

production ($\sim 3 \text{ mW m}^{-2}$). No-slip boundary conditions are specified at the base, representing nitrogen in contact with bedrock ice. The mountain block is represented by a no-slip side boundary with a temperature profile fixed to that of conductive water ice. Convective systems similar to those described by McKinnon et al. [4] are observed to develop, with surface velocities of approximately tens of centimeters per year and wide aspect-ratio convection cells. Deviatoric stresses experienced on the no-slip side boundary are then measured to determine the net stress on the boundary.

Over the range of depths studied, the forces felt on the boundary are net compressive, with magnitudes increasing with depth. This suggests a net uphill force on the block. However, the magnitude of force is in the low kN per unit width range. This is 3-4 orders of magnitude lower than the other lateral forces considered here. We thus conclude that lateral convective forces are not an important component in the transport of large, grounded mountain blocks.

Modeling force balance. To model the downhill force on a partially submerged mountain block, we consider a cylindrical block with height above nitrogen H , depth below nitrogen T , and radius R . Because slopes are shallow ($< 3^\circ$), we neglect downhill variances in H and T . The total weight of the grounded block (F_W) is:

$$F_W = (\rho_l g H - \Delta \rho T) g \pi R^2, \quad (1)$$

where ρ_l is the water ice density (920 kg m^{-3}), $\Delta \rho$ is the density difference between water ice and solid nitrogen ($\sim 60 \text{ kg m}^{-3}$), and g is Pluto's gravity (0.617

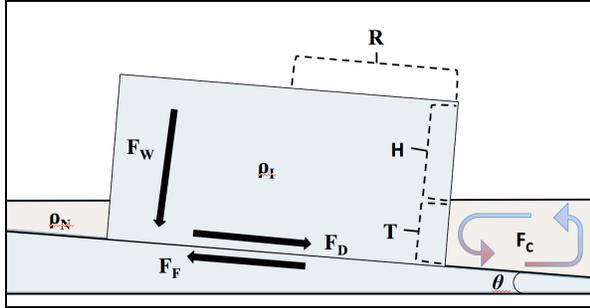


Figure 2: Summary of the forces acting on a water ice block with density ρ_i partially immersed in solid nitrogen of density ρ_N . Convecting nitrogen on the side provides a net upslope force F_C , but the driving force is dominated by the downslope F_D ($F_W \cdot \sin \theta$) and frictional F_F ($\mu \cdot F_W \cdot \cos \theta$) forces.

m s^{-2}). In the limit of a floating block, F_W goes to zero.

From elementary analysis of forces acting on a slope, the total force felt is the difference between the downslope and frictional forces ($F_D - F_F$):

$$F_T = F_W (\sin \theta - \mu \cos \theta), \quad (2)$$

where θ is the angle of slope of the basin (again neglecting convective forces). We can estimate the coefficient of friction μ required for a given slope by noting that for F_T to be positive, $\mu < \tan \theta$ since F_W is by definition positive. A topographic slope of $\sim 2^\circ$, a reasonable value given the slopes near the rims of other large basins in the Solar System such as South Polar Aitken and Hellas [5, 6], results in a maximum μ for movement of ≈ 0.04 . We consider this a reasonable value given studies of μ values for glacial beds [7], along with the possibility of basal infiltration by liquid or solid nitrogen between the rough surfaces of the basin and block, which would serve to reduce friction [8]. Basal nitrogen melt may also play a role in reducing friction during periods of higher atmospheric pressures and temperatures [3].

Modeling viscous drag. If there is a net downhill force, it will be balanced by the viscous flow of the nitrogen glacier. Stokes' law defines the drag force felt by a sphere descending into a viscous fluid as:

$$F_V = 6\pi\eta Rv, \quad (3)$$

where η is the viscosity and v is the sphere's descent velocity. While this law does not technically apply to a cylinder, we can use Oseen's approximation [9] to show that the solution only differs by $1 + (\frac{3}{8}) \cdot Re$, where Re is the Reynolds number. For the slow, laminar flow we are modeling, $Re \approx 10^{-9}$, so Oseen's approximation is valid.

Equating the total downhill force felt by the block F_T to the viscous drag force F_V , we can rearrange the equation to find the block's downhill velocity v :

$$v = \frac{(\rho_i H - \Delta \rho T) g R}{6\eta} (\sin \theta - \mu \cos \theta). \quad (4)$$

For a large block ($H + T = 6$ km, $R = 20$ km) and reasonable values of the other parameters ($\theta = 2.5^\circ$, $\mu = 0.04$, $\eta = 10^{12}$ Pa*s [determined from our convection calculations]), we find a velocity $\approx 10^{-5}$ m s $^{-1}$. This is sufficient to move a block a distance of 100 km on the timescale of ~ 100 yrs. Smaller block sizes, conversely, move slower because of the increased drag effect.

Discussion: While our calculated translation time for the largest blocks is very short by geologic standards, it is consistent with observations. The angular nature of even the smallest observed blocks and the preservation of primary crustal features [1] indicate that, aside from fracturing, the blocks have not experienced much erosional weathering from a long period of mobile processing. We also note that even increasing the viscosity of nitrogen ice by several orders of magnitude still results in geologically short translation times. The strong dependence on slope means that the blocks would come to a natural stop as the basin flattens away from its rim [5, 6]. Finally, the influence of viscous drag would create a size-filtering effect on the blocks, with the largest blocks migrating farthest. This prediction is supported by the qualitative observation that the largest mountain blocks are typically located radially inward relative to the smaller fragments.

Conclusions: We conclude that Pluto's chaotic mountain blocks can be mobilized via downhill sliding in the presence of partial buoyancy, and without the aid of lateral convective forces. Their present locations can be adequately explained by a change in slope with basin depth and the size filtering effects of viscous drag on blocks of differing size. Once separated from the crust, the largest blocks probably reached their current location in a timescale of the order of a hundred years, where the balance of forces has kept them relatively stable since.

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