WARM-COLD CLIMATE CYCLES ON PLUTO AS INFERRED FROM A NEW GRAVITY-SCALED VISCO-ELASTO-PLASTIC POLYGON FORMATION MODEL. A. Yin, Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA 90095-1567, USA (ayin54@gmail.com; yin@epss.ucla.edu).

Introduction: Polygon terrains have been documented on surfaces of several solar-system bodies (e.g., Earth, Mars, Triton, and Pluto). Their horizontal dimension appears to increase with surface gravity: <10s m on Earth (e.g., ice-wedge polygons, [1]) but are 20-80 km on Pluto [2, 3] that has a surface gravity of 0.62 m/s^2. Attributing thermal contraction as the formation mechanism, the small aspect ratios (2-5) of polygon dimension vs. host-layer thickness on Earth is thought to be independent of gravity [4]. Based on this argument, a thermal-contraction origin of large (>25 km) Pluto polygons was ruled out as the polygon hosting layer (= thermal skin) appears to be too thin (<500 m) to create the observed polygon dimensions [5]. As such, Pluto polygon dimension has been best explained by bottom-heating Rayleigh–Bénard convection in two-dimensional models [5, 6]. Attempts using three-dimensional simulations, however, have failed to produce the observed geometry (e.g., Y intersections) and high surface relief of the Pluto polygons [7].

Model: The classic polygon model [3] considers only thermal stress, neglecting gravity-dependent frictional shear stress at the base of a thermally contracting layer [4]). Here, I consider an elastic layer with a thickness h overlying a visco-elasto-plastic shear zone that has a thickness Δz. The overlying layer contracts radially relative to the basal shear zone towards a point, set here as the origin of a polar coordinate in the model. In response to the horizontal thermal contraction in a radial direction x_θ, a horizontal shear stress τ_θ must be induced at the base of the contracting layer. The combined effect of thermal contraction, self-gravitation, and basal shear yields an elastic solution in the contracting layer: $\sigma_{x_\theta x_\theta} = (\tau_\theta/h)x_\theta$, $\sigma_{zz} = -\rho g z$, $\sigma_{x_\theta z} = -(\tau_\theta/h)z$ (e.g., [8]), where z is the vertical axis. The horizontal stressing rate due to cooling is $\dot{\sigma}_{x_\theta x_\theta} = E\dot{\varepsilon}_{x_\theta x_\theta} = E(-\alpha\dot{c})$, where $\dot{\varepsilon}_{x_\theta x_\theta} = (-\alpha\dot{c})$ is the horizontal strain rate, E Young's modulus, α coefficient of thermal expansion, and averaged $\dot{c}$ cooling rate of the contracting layer. The shear strain rate $\dot{\varepsilon}_\theta$ relates to the horizontal strain rate by $\dot{\varepsilon}_\theta = \frac{x_\theta}{\Delta z}\dot{\varepsilon}_{x_\theta x_\theta}$ which leads to $\dot{c} = -\frac{\Delta z \dot{\varepsilon}_\theta}{x_\theta \alpha}$. The total shear strain rate is:

$$\dot{\varepsilon}_\theta(t) = \dot{\varepsilon}_\theta^V(t) + \dot{\varepsilon}_\theta^E(t) + \dot{\varepsilon}_\theta^P(t) \quad (1)$$

where $\dot{\varepsilon}_\theta(t) = \dot{\varepsilon}_0$ is total strain considered to be constant in the model, and $\dot{\varepsilon}_\theta^V$, $\dot{\varepsilon}_\theta^E$, and $\dot{\varepsilon}_\theta^P$ are viscous, elastic, and plastic strain rates. The elastic and viscous stress components are $\dot{\tau}_\theta^E(t) = 2G\dot{\varepsilon}_\theta^E(t)$ and $\dot{\tau}_\theta^V(t) = 2\eta\dot{\varepsilon}_\theta^V(t)$, with G and η as shear rigidity and viscosity. When the shear zone undergoes progressive strain hardening, its plastic strain relates to the total shear stress $\dot{\tau}_\theta(t)$ by

$$\dot{\varepsilon}_\theta^P(t) = \frac{\dot{\tau}_\theta(t)}{H} \quad (2)$$

where H is the coefficient of hardening determined by

$$\frac{1}{H} = \frac{1}{G_t} - \frac{1}{2G} \quad (3)$$

Here G_t is the *tangent* modulus

$$G_t = \frac{(Y_f - Y_i)}{(\varepsilon_0 - \varepsilon_\theta^E)} = \frac{(Y_f - Y_i)}{(\dot{\varepsilon}_0 t_f - Y_i/2G)} \quad (4)$$

where $Y_i = Y_E = \mu'_i \rho g h$ and $Y_f = \mu'_f \rho g h$ are the initial (= elastic limit Y_E) and final frictional strengths of the shear zone, $\Delta\mu' = \left(\mu'_f - \mu'_i\right) > 0$ with μ_f and μ_i as effective friction coefficients, h and ρ are thickness and density of the overlying layer, t_i is the time taken to reach the elastic limit of the shear zone from the onset of thermal contraction, and t_f is the duration of tensile-fracture formation in the contracting layer since the onset of thermal contraction, and g is surface gravity. Assuming $\tau_\theta(t=0) = 0$ (i.e., no pre-stress) we have the solution for shear stress in the shear zone at $t = t_f$ as

$$\tau_\theta(t_f) = 2\eta\dot{\varepsilon}_0\left[1 - e^{-\frac{\Delta\mu'\rho g h}{2\eta((\dot{\varepsilon}_0 t_f - Y_i/2G)}t_f}\right] \quad (5)$$

As the total strain ε_0 is likely much greater than the elastic strain ε_θ^E, the above equation becomes

$$\tau_\theta(t_f) = 2\eta\dot{\varepsilon}_0\left[1 - e^{-\frac{\Delta\mu'\rho g h}{2\eta\dot{\varepsilon}_0}}\right] \quad (6)$$

As $\sigma_{x_\theta x_\theta}(x_\theta = L_\theta) = (\tau_\theta/h)L_\theta = T$ (T, tensile strength), the polygon dimension $2L_\theta$ can be expressed as

$$2L_\theta = \frac{Th}{\eta\dot{\varepsilon}_0} / \left[1 - e^{-\frac{\Delta\mu'\rho g h}{2\eta\dot{\varepsilon}_0}}\right] \quad (7)$$

Here $2L_\theta$ is independent of the duration of crack formation when the shear zone is assumed to be visco-plastic. Note $2L_\theta(g \to \infty \; or \; \Delta\mu' \to \infty) = 2Th/\eta\dot{\varepsilon}_0$ and $2L_\theta(g = 0 \; or \; \Delta\mu' = 0) = \infty$. Using the full solution in (5) we find the total duration leading to tensile fracturing as:

$$t_f = \frac{(2\eta Y_i/2G)\ln\left(\frac{2L_\theta\eta\dot{\varepsilon}_0}{2L_\theta\eta\dot{\varepsilon}_0 - Th}\right)}{\left[2\eta\dot{\varepsilon}_0\ln\left(\frac{2L_\theta\eta\dot{\varepsilon}_0}{2L_\theta\eta\dot{\varepsilon}_0 - Th}\right) - \Delta\mu'\rho g h\right]} \quad (8)$$

As Pluto model parameters are highly uncertain, t_f is estimated from a few seconds to about 10 Pluto years.

Model Results: Fig. 1 shows that polygon dimension decreases exponentially with surface gravity, shear-zone viscosity, and shear strain rate. **Fig. 1c** indicates that at g = 10 m/s^2 a 30-m thick layer yields an aspect ratio of ~40 whereas at g = 0.5 m/s^2 the aspect ratio increases to ~700! As shown in **Fig. 2**, a thermal skin of 10s-100s m thick can produce polygon dimensions of L_θ ~ 20-50 km using parameters relevant to Pluto. For $h \leq$ 300 m and $\dot{\varepsilon}_0$ = 10^{-6}, we have $\dot{c} = \sim 10^{-9}$ K s^{-1} (~10 K per Pluto year) during polygon formation if α = 2x10^{-3} K^{-1} [6] and $\frac{\Delta z}{L_\theta} \sim 1$.

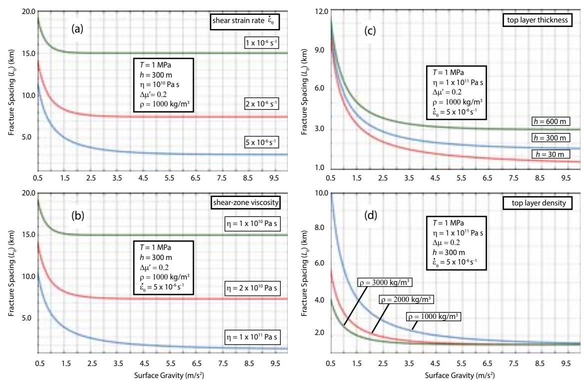

Figure 1. Polygon spacing as a function of gravity and variable shear strain rate (a), shear-zone viscosity (b), top-layer thickness (c), and top-layer density.

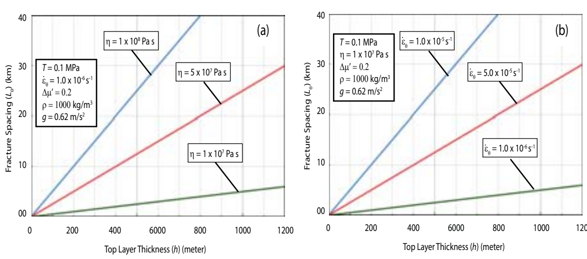

Figure 2. Polygon spacing as a function of top layer thickness with variable viscosity (a) and shear strain rate (b).

Pluto Polygons by Layer-parallel Contraction: Evidence for a tensile-fracture origin of Pluto polygons includes free-ending cell-bounding troughs interpreted as propagating fractures (**Fig. 3a**) and radial fractures around water-ice blocks interpreted as stress concentration at pre-existing flaws during thermal-skin contraction (**Fig. 3b**). As polygon boundaries are truncated by nitrogen ice glaciers (**Fig. 3a**), the polygon formation must have ceased across the entire Sputnik basin. Otherwise, newly formed polygons should have cut the inactive ones, a relation not present across Sputnik Planitia. Water-ice debris along polygon boundaries may have resulted from buoyancy-driven upward emplacement, which also explains radial fractures as shown in **Fig. 3b**.

Discussion: Thermal contraction requires climate cycles on Pluto: warmer conditions relax polygon morphology and may also allow warm glaciers to flood Sputnik Planitia, while cool climates contract the warm nitrogen ice leading to polygons formation. Repeated polygon formation due to recent climate cycles (< 4 Ma) [9] explain the youthfulness of the Sputnik surface. On Earth the model explains increasing polygon size with latitude [4], as cold/wet conditions favor slow contraction and larger polygons. For Mars, the model explains the giant polygon dimensions (10-20 km) [10] and may be used to the time scales of climate cycles.

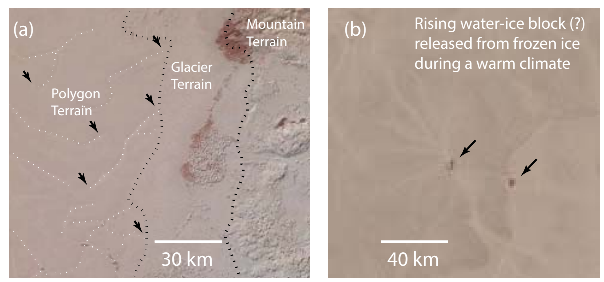

Figure 3. (a) Free-ending polygon boundaries and truncational relationships between polygon boundaries and glacier flow/flow deposits. (b) Polygon boundaries radiating from water-ice inclusions in Sputnik basin filled by a mixture of dominantly nitrogen ice and a minor component of buoyant water-ice blocks of various sizes. The rising of the water ice block may have caused the radiating pattern of polygon boundaries interpreted here as brittle tensile fractures.

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