POSSIBLE MECHANISM FOR BOULDER CLUSTERING ON THERMAL CONTRACTION POLYGONS. T. C. Orloff, M. A. Kreslavsky, and E. I. Asphaug. Department of Earth and Planetary Sciences, University of California - Santa Cruz, 1156 High St., Santa Cruz, California, 95064, USA

Introduction: Patterned ground dominates the high latitudes of Mars (60-70°) [1]; the same regions found to possess large volumes of ice in the near surface [2, 3]. With High Resolution Imaging Science Experiment (HiRISE) imagery we see individual boulders on patterned ground terrain [4] (also see Fig. 1a). Nearly everywhere, where boulders are present on patterned ground, they appear clustered relative to a random population with respect to the underlying polygonal ground (Fig. 1a). Analysis [5] showed that this clustering should involve actual horizontal movement of the boulders at geologically short time scales (~1.8 Ma, and possibly much shorter), however the particular mechanism of boulder movement is debated [6, 7]. Here we propose a possible mechanism for boulder movement toward polygon exteriors and develop a model to quantify rates of boulder movement.

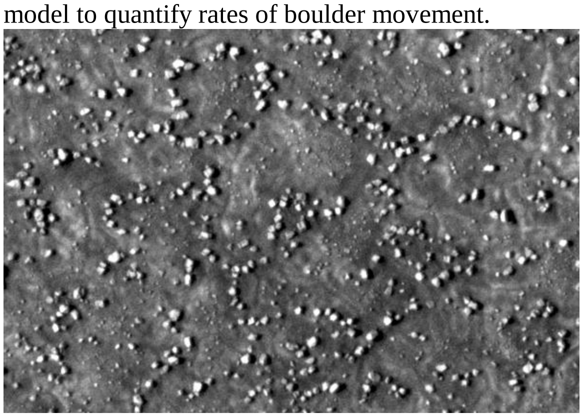

Figure 1: A) Boulders cluster toward polygon margins in patterned ground. HiRISE image PSP_008219_2470 (66.6N, 320.1E) illumination from the left, image width 150 m.

Mechanism: During the winter the surface material contracts (opening cracks) and during the summer it expands (closing cracks). We propose that the carbon dioxide frost layer formed in Martian winters locks boulders in place during the contraction phase of the polygon seasonal contraction / expansion cycle, then, when the seasonal frost disappears in the summer, boulders shift outward with expanding surface material; after many seasonal cycles, this leads to boulder clustering in polygon margins.

When the seasonal CO_2 frost layer covers the surface, the surface temperature is fixed at the CO_2 frost point, which is lower than the year-average temperature. This causes heat flux from beneath to the surface and progressive cooling of the seasonal thermal skin layer. The surface material continues to contract until the seasonal frost disappears in late spring.

The upward heat flux causes sublimation of solid CO_2 at its boundary with soil. Due to this, the CO_2 slab is detached from the soil through the whole winter season, even if initially the CO_2 frost condenses at soil particles. The CO_2 gas produced at the soil - frost boundary migrates through the cold CO_2 slab and condenses in it, at least, partially, which causes pore filling, sintering, and strengthening of the CO_2 frost. Exact degree of sintering is not known, but different lines of observational evidence indicate that this indeed occurs. Transparency of the seasonal frost [8] and its spectral properties [9] suggest that the grain sizes of CO_2 crystals in the frost layer grow through the winter. This produces a seasonal CO_2 layer more similar to a solid slab rather than fluffy snow. The observed venting and formation of plumes by pressurized gas concentrated beneath the frost layer [10] indicates that the slab is impermeable for gas and hence sintered to a high degree. The observed spring-time cracks of a wide spacing (tens of meters) in the frost [11] suggest the slab can support significant stresses.

In the late spring the ice sublimates away, the boulders become unlocked from the ice and rest gently on the surface, which expands as it warms up, and transports boulders outward from the polygon centers. This leads to gradual boulder migration towards polygon margins. Once the boulders reach the polygon margin they become trapped there.

Thermal model: Our simple order of magnitude thermal model of the subsurface (in the fashion of [12]) simulates the temperature $T(z, t)$ with depth z and time t. For the accuracy we need, we can ignore the processes in the thin diurnal thermal skin and solve the linear diffusive heat conduction equation in the thicker seasonal thermal skin modeled as semi-infinite solid bounded by the plane z = 0, with the boundary condition of prescribed model surface temperature $T(z{=}0, t) = T_0(t)$ equal to the actual day-average surface temperature. We take daily average surface temperatures $T_0(t)$ from the Phoenix landing site from the Mars Climate Database (available at http://www-mars.lmd.jussieu.fr/mars/mars.html [13]) to seed the model. We use a cubic spline to interpolate the day-average surface temperatures between the seasons listed in the data base and set the temperature equal to the CO_2 frost point during the period when the seasonal frost is present.

The periodic solution for the linear heat conduction equation with constant thermal diffusivity χ can be obtained by Fourier method as a sum of Fourier series:

$$T(z,t) = T_{ya} + \mathrm{Re}\sum_{n=1}^{\infty} \tilde{T}_{0n} \exp\left(-(1+i)z\sqrt{\frac{\pi n}{\chi\tau}}\right)\exp\left(2\pi i\frac{t}{\tau}\right),$$

where T_{ya} is the year-average temperature, τ is the length of the Martian year, and

$$\tilde{T}_{0n} = \frac{1}{\tau}\int_0^{\tau} T_0(t)\exp\left(-2\pi i n\frac{t}{\tau}\right)dt, \quad n = 1,2,...$$

Practically we used standard implementation of discrete Fourier transform to evaluate the sum and the integral. For χ we used thermal diffusivity of water ice (10^{-4} m^2 s^{-1}), knowing that it makes a dominant part of the material volume in the upper meters. After deriving these temperatures we then use these data as feed for our elastic model described in the next section.

Elastic model: We chose to develop our model using software called Automatic Dynamic Incremental Nonlinear Analysis (ADINA). We model a single polygon as a rotationally symmetric cylinder with a depth of 4 meters (comparable to the seasonal thermal skin thickness) and a radius of 2.5 m. In ADINA we create a grid with 20 cm cell size representing a cross section of the model domain from the cylinder axis to the outer edge. The top and outer boundaries act as free surfaces while the bottom boundary remains fixed at 0 displacement. The unstressed condition corresponds to uniform temperature field of T_{ya}. Then we impose a temperature profile calculated with the thermal model. We apply a constant Young's modulus (7.8×10^{10} Pa), coefficient of thermal expansion $\alpha = 4.5\times10^{-5}$ K^{-1}, and Poisson ratio of 0.33 representative of pure water ice. ADINA computes the displacement, stress, and strain using finite element procedures from [14].

Our interest lies in the comparisons between points in time when frost traps and releases boulders. For our order-of-magnitude estimates we assume that a boulder gets trapped into the frost slab in winter, when its thickness reaches 20 cm, and released in spring, when the slab thins down to 20 cm. We used the evolution of the frost layer thickness through the course of the Martian winter and spring from [15] to find the trapping and release dates. We input the temperatures fields from L_s = 305° (first appearance of 20 cm of frost; Figure 2A) and L_s = 15° (last appearance of 20 cm of frost; Figure 2B) into our elastic model. The change in displacement at the uppermost outer edge between these two states is the maximum amount of boulder movement we predict. In this example we find 0.1 mm of radial displacement. Given this rate of annual movement the time scale of significant boulder clustering is on the order of a hundred thousand years.

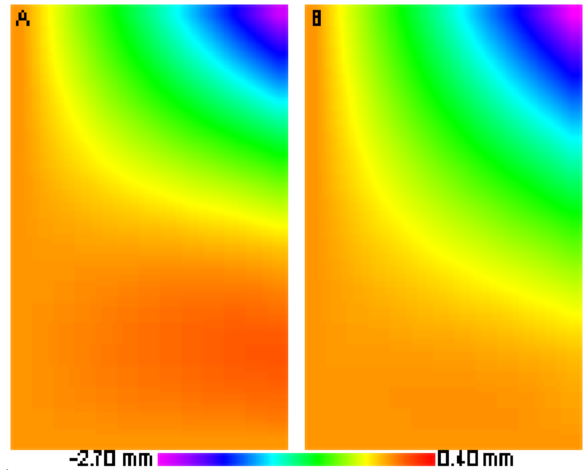

Figure 2: Model results of radial displacement in a polygon for A) L_s = 305° and B) L_s = 15°. The difference in radial displacement between these two at the upper right corner (the outer, surficial edge of the polygon) represents the amount of annual movement we expect. In this case we find the boulder discussed should move 0.1 mm.

Conclusions: We have proposed a mechanism to account for boulder movement on thermal contraction polygons that is driven by the seasonal covering of this terrain by an approximately 1-m thick layer of carbon dioxide frost. CO_2 frost, buffered by the atmosphere, forms an isothermal planar slab that locks boulders in place during the winter contraction of the underlying regolith, preventing them from moving. When the frost sublimates the boulders are free to move with the expansion of ice during warming. This leads to progressive movement of boulders towards polygon edges, which we estimate to be approximately 0.1 mm per year. Our model predicts that stronger or thicker frost would lock in larger boulders so both periods of higher obliquity and higher latitudes are more favorable to boulder movement.

References: [1] Malin M.C. and Edgett K. (2001) *JGR*, *106*, E10, 23429-23570. [2] Feldman W.C., et al. (2002) *Science*, *297*, 75-78. [3] Boynton W. V. et al. (2002) *Science*, *297*, 81-85. [4] Golombek M.P. et al. (2008) *JGR*, *113*, E00A09. [5] Orloff T.C. et al. (2011) *JGR*, *116*, E11006. [6] Mellon M. et al. (2008) *JGR*, *113*, E00A23. [7] Levy J. et al. (2010) *Icarus*, *206*, 229-252. [8] Kiefer H.H. (2007) *JGR*, *112*, E08005. [9] Langevin Y. et al. (2007) *JGR*, *112*, E08S12. [10] Kiefer H.H. et al., (2006) *Nature*, *442*, 793-796. [11] Portyankina G. et al., (2010) *Icarus*, *205*, 311-320. [12] James R. W. (1952) *Pure and Applied Geophys*., *22*, 174-188. [13] Forget F. et al. (1999) *JGR*, *104*, 24155-24175. [14] Bathe K. J. (1996) *Finite Element Procedures*, 1-1037. [15] Kelly N.J. et al. (2007) *JGR*, *111*, E03S07.