MECHANISM FOR BOULDER CLUSTERING ON THERMAL CONTRACTION POLYGONS . T. C. Orloff[1], M. A. Kreslavsky[1], and E. I. Asphaug[1]. University of California Santa Cruz Department of Earth and Planetary Sciences 1156High St., Santa Cruz, California, 95064

Introduction: Patterned ground covers huge areas on Mars; these terrains dominate the high latitudes of Mars (60-70°) [1]; the same regions found to possess large volumes of ice in the near surface [2, 3, 4]. With current high resolution imagery we see individual boulders on patterned ground terrain [5]. In many cases, these boulders appear clustered relative to a random population with respect to the underlying polygonal ground (Fig. 1). Analysis [6] showed that this clustering should involve actual horizontal movement of the boulders at geologically short time scales (at least ~ 1 Ma, and possibly much shorter), however particular mechanism of boulder movement is unknown. Here we propose a possible mechanism for boulder movement toward polygon exteriors.

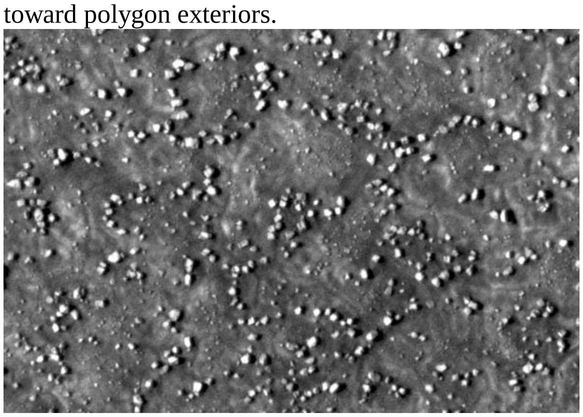

Figure 1: Boulders cluster toward polygon margins in patterned ground. HiRISE image PSP_008219_2470 (66.6N, 320.1E) illumination from the left, image width 150 m.

Mechanism: Thermal contraction/expansion of ground ice causes a polygonal crack network to form [7]. Seasonal shifts in temperature influence the ground ice and change the size of polygons making up the network throughout the year. During the winter the material contracts (forming cracks) and during the summer it expands (closing cracks). We propose that the carbon dioxide frost layer formed in Martian winters at these latitudes lock boulders in place during the contraction phase of polygon seasonal cycle, then, when the ice disappears in the summer, boulders shift outward with expanding surface material; after many seasonal cycles, this leads to boulder clustering in polygon exteriors.

When the seasonal CO_2 frost layer covers the surface, the surface temperature is fixed at the CO_2 frost temperature, which is lower than the year-average temperature. This causes heat flux from beneath and progressive cooling of the seasonal thermal skin layer (~0.3 - 1 m thick for reasonable thermal diffusivities), and the surface material continue 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, strengthening of the CO_2 frost. Exact degree of sintering is not known, but different lines of indirect evidence, namely, inferred CO_2 layer density [8], its transparency [e.g., 9] and spectral properties [e.g., 10], suggest that the seasonal CO_2 layer is more similar to a solid slab rather than to a layer of fluffy snow. Estimates below show that the slab can be strong enough to withstand the frictional forces exerted by the boulder in contact with the ground. If the CO_2 ice is strong enough to lock the boulders, it will be strong enough to withstand the frictional forces exerted by contracting surface; it will not move with the seasonally contracting material and will act as a coherent layer much greater in size than any individual polygon.

As summer returns 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 exteriors. Once the boulders reach the polygon exterior they become trapped there.

Estimations: Here we estimate orders of magnitude for critical quantities for the proposed mechanism. We consider (Fig. 2) a (spherical) boulder of radius r sitting at a distance x from the center of a polygon of a diameter L. Tab. 1 summarizes assumed parameters that we use.

Required strength of the carbon dioxide slab to locks boulders in place: The slab strength should exceed shear stress σ caused by the maximal drag force F applied to the boulder by the moving substrate. The stress is scaled as $\sigma \sim F / A$, where A is a cross-section of the boulder / slab interface; $A \sim 2\, r\, h$, where h is the slab thickness. The drag force is limited by the maximal dry friction force $F = f\, m\, g$, where f is dry friction coefficient, m is boulder mass, g is gravity. Expressing boulder mass through its size, we obtain:

$$\sigma \sim (2\pi / 3)\, (f \rho\, g\, r^2 / h), \qquad (1)$$

where ρ is boulder density.

For values given in Table 1, σ ~ 0.02 MPa. The strength of the CO_2 slab is bracketed between the strength of dry soil layer of thickness *h* and the strength of the solid CO_2. The former is scaled as the layer lithostatic pressure and is obviously below our estimate of σ. However, as we discussed above, we expect at least some degree of sintering of the seasonal frost. Bulk dry ice is significantly weaker than water ice [11], however its strength (0.1 - 1 MPa) well exceed the strength (1) required to lock a boulder. Thus, with some sintering, the CO_2 slab can lock boulders.

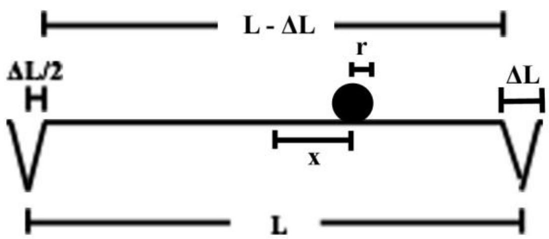

Figure 2: Boulder with radius *r* sits a distance *x* from the center of a polygon with diameter *L* contracting and expanding some distance *ΔL* seasonally.

Seasonal movement and clustering time scale. Seasonal thermal crack opening is scaled as

$$\Delta L \sim \alpha\, \Delta T\, L, \quad (2)$$

where α is the coefficient of thermal expansion and ΔT is the seasonal change in average daily temperature. But because the polygon contracts from both sides, a polygon edge moves a distance $\Delta L/2$ relative to the center of the polygon. A boulder placed some distance *x* from the center of the polygon would then experience a seasonal displacement Δx:

$$\Delta x \sim \alpha\, \Delta T\, x. \quad (3)$$

Using values from Table 1, Δx ranges from 0 at the polygon's center to ~5 mm near the edge of a 5 m diameter polygon.

If we assume that boulders move outward during warm season and do not move inward during cold season, (3) gives an estimate of the net shift during one martian year. Boulders near the centers of polygons migrate slower than boulders near the exteriors. Velocity at the edge of a 5m diameter polygon approach 5mm/yr. A boulder half a polygon radius from the center would take 300 years to reach the polygon edge. A boulder 0.5 m from the polygon center would take 800 years to reach the polygon's edge. Since some cold-season contraction occurs before the seasonal frost is emplaced and sintered, the actual migration rates are slower and migration time scales are longer. Nevertheless, our estimate shows that clustering can occur at time scales of thousands of years and less, fast enough to be consistent with the observations [6].

Discussion and Future Work: Our mechanism assumes that boulders sit at the surface and are not partly buried. Detailed studies of statistics of boulder vertical and horizontal dimensions can check this assumption. Analysis in [12] showed that the boulders, unless they are deeply buried, are not frozen into the ground ice, and thus can be dragged with respect to the surface, if the CO_2 slab is strong enough.

Boulders in clusters can touch each other but never pile on each other (Fig. 1). This observation is perfectly consistent with the proposed clustering mechanism. The mechanism predicts a size threshold for boulder clustering. At the low-latitude edge of the clustering zone, where the seasonal frost is thinner, we would expect clustering of smaller boulders only. We plan to check this prediction.

During periods of higher obliquity (>0.3 Ma ago) the seasonal temperature amplitude is higher, and the seasonal frost is thicker, thus this period is favorable for boulder movement. It is possible that migration actually occurred at high obliquity.

We plan to simulate the clustering of boulders on polygonal terrain with this mechanism under different parameter sets. Doing so allows us to better quantify boulder population evolution on patterned ground terrain and gives a window into the recent Martian past, and allows us to find evidence for the frozen-out atmosphere in the patterning of boulders around thermal contraction polygons.

Table 1: Parameters and values used for estimates

r	Boulder radius	1.5 m
ρ	Boulder density	3000 kg m^{-3}
h	Thickness of CO_2 slab	1 m
g	Gravity	3.7 m s^{-2}
f	Friction coefficient	0.5
ΔT	Seasonal amplitude of day-average temperature	100 K
α	Thermal expansion coefficient of H_2O ice	2×10^{-5} K^{-1} @ 200 K [7]
L	Polygon size	5 m
σ_s	Strength of CO_2 ice	0.1-1 MPa [8]

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