EVOLUTION OF VOLATILE-RICH CRATER INTERIOR DEPOSITS ON MARS.

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Introduction: Many craters on Mars are partially filled by material emplaced by post-impact processes. Populations of such craters include those in the circum-south polar cap region, in Arabia Terra, associated with the Medusae Fossae Formation, and in the northern lowlands proximal to the north polar cap. In this study, crater fill material refers to an interior mound which is generally separated from the interior walls of the crater by a trough that may be continuous along the crater's circumference (i.e. a ring-shaped trough), or which may only partially contact the crater walls (i.e. a crescent-shaped trough). The fill deposit is frequently off-center from the crater center and may be asymmetric, (i.e. not circular) in plan view shape.

Such craters associated with the Medusae Fossae Formation are likely partially exhumed and contain remnants of Medusae Fossae material that may be ignimbrites [1], eolian materials [2, 3], true polar wander deposits [2], volatile-rich deposits [4], or volcanic ash accumulation [5]. In Arabia, such crater fill has also been interpreted as polar layered deposits associated with true polar wander [2] or lacustrine sedimentary deposits [6]. The fill of craters around the south pole is contiguous with south polar layered material, which argues for a similar process of deposition [7] with possible later exhumation of or flow into the crater [8]. Two craters at high northern latitudes contain fill material but are well separated from the north polar layered terrain: Korolev (73°N, 195°W; Fig. 1) and an unnamed crater (77°N, 145°W). This configuration suggests this fill material was also deposited in a similar manner to the polar cap materials [7] and may or may not be remnants of a formerly more extensive polar cap [9].

Motivated by assessment of the martian hydrological cycle, especially the groundwater system, we have previously examined northern lowlands craters for signs that the associated impacts may have interacted with the groundwater system [10,11]. Given the physical and thermal disruption of the ground associated with impact, disruption of the subsurface cryosphere could have allowed effusion of sub-cryosphere confined groundwater into the crater under artesian-like conditions [10,12]. In a globally interconnected hydrosphere-cryosphere system [12], this process would be favored in the northern lowlands due low planetary elevation, where hydraulic pressure head of the groundwater system should be greatest [11]. Such a scenario presents an alternative hypothesis for volatile-rich crater fill in northern lowlands craters. However, the only large craters in the northern lowlands containing significant fill material are most proximal to the north polar cap [11]. Unless these impacts were very recent, such that the volatile fill had not yet sublimated away [13], this non-random clustering near the pole suggests polar-like processes are more likely responsible for their formation. By the same argument of higher hydraulic heads at lower surface elevations in a global groundwater system, impacts into high-elevation circum-south polar terrain would not be expected to have accessed subsurface water. Remaining favored hypotheses of formation of circum-polar crater fill material include preferential deposition by polar-like processes in isolated craters, or deposition contiguous with, or part of, a formerly more extensive polar cap [e.g., 9] by processes identical to those that formed the polar cap. Given these theories of crater fill formation by deposition from above, fill material in the north and south polar regions is almost certainly rich in volatiles, and even the fill of equatorial craters may contain significant volatiles.

Volatile-rich deposits have the property of being modifiable by the local stability of the solid volatile, which is governed by local energy balance. Here we test the hypothesis that asymmetries in volatile fill shape, profile, and center-location within a crater result from asymmetries in local energy balance within the crater, due mainly to variation of solar insolation and radiative effects of the crater walls over the crater interior. We first focus on Korolev crater [14] in the northern lowlands. We then apply this model to other craters in different regions. If asymmetry in morphology and location of crater fill are consistent with radiative-dominated asymmetries in energy budget within the crater, then 1) the volatile-rich composition of the fill is supported (this process should not be effective at shaping volcanic or sedimentary deposits), and 2) the dominant factor determining the observed shape of volatile-rich crater fill is the local radiative energy budget within the crater (and erosive processes such as eolian deflation are not necessary).

We also use a geographic and energy model approach to specifically test the idea that material in partially filled craters around the south pole may once have been contiguous to the cap and may have been sustained and modified by radiative processes specific to the crater environment (as opposed to the surrounding plains) as the cap retreated.

Korolev Crater: Korolev crater (~80 km diameter) is superposed on Amazonian mantle material surrounding north polar terrain [7]. While the crater is circular, rim height is not uniform around its circumference (Figs. 1-3). The rim is highest in the northeast (-3.4 km) and lowest in the west (-4.2 km). The lowest elevation of exposed floor is in the southwest (–6.2 km) (Fig. 1). The smooth-surfaced, roughly circular fill deposit within Korolev does not extend completely to the interior walls of the crater, leaving an intervening ring-shaped trough (Figs. 1-3). Relative to the crater's center, the fill deposit is displaced to the north and east (Fig. 1), where it reaches closer to and higher up the crater walls (Figs. 2, 3). The highest point of the fill deposit (-4.7 km, roughly equivalent to the surrounding plains) is also displaced in the same sense (Figs. 1-3). The rim-to-floor depth expected at a fresh, unfilled crater of Korolev's diameter based on morphometric relations of martian craters is 2.3 km [15] to 2.9 km [16]. This range corresponds well with the observed range of maximum and minimum rim-to-floor depths (2.8 km and 2.0 km) using the floor elevation of the greatest exposed depth and the maximum and minimum rim elevations. This consistency in observed and predicted fresh depths suggests that the actual deepest point of the crater is not much deeper than the observed elevation, -6.2 km. The maximum thickness of the fill mound is then ~1.5 km [16].

Circum-South Polar Craters: There are many craters with fully or partially visible rims within the polar layered terrain of the south polar cap, especially on the half oriented towards 180° (e.g., Fig. 4). Around the fringes of the cap, northern parts of crater rims are fully exposed, while on pole-ward sides crater fill material is still clearly contiguous with polar material (e.g., Fig. 5). Up to ~ 12° of latitude from the edge of the polar layered terrain are craters with fill material isolated from polar material (e.g., Fig. 6). This isolated fill appears to become less circular and symmetric at greater distances, often located in the northern portions of the crater (e.g., Fig. 7). These materials have been mapped as extensions of polar layered material (Apl [7]) or as ice and fine dune material possibly derived from polar layered terrain and possibly covering polar layered terrain material deposited in areas of low wind velocity (Ad [7]).

Based on morphologic and topographic similarity, and in some cases contiguousness, with polar layered deposits, it seems likely that fill material may be of the same composition, possibly deposited by the same process. In this scenario, fill material was either 1) deposited preferentially in craters rather than on surrounding plains, or 2) once present in the plains as well, as part of a larger polar cap, and preferentially remains in the craters as polar material has retreated from the plains. Fill material in craters partially visible around the edges of the polar layered terrain appears to be maintained by the same conditions maintaining the surrounding, extra-crater polar layered terrain, unless both materials are being deflated and the craters are being exhumed. In some cases there is evidence that physical flow of polar layered material contributed to crater fill deposits [8]. Further north, craters not physically connected to the polar layered terrain contain less fill, which is generally in the form of a circular mound. Yet further north, crater fill is significantly less, occurring only locally within craters. The observed trend of decreasing fill amount with increasing northerly latitude suggests that either deposition and equilibrium-amounts of fill are less at more northern latitudes, or erosive, sublimation, or ablation processes have been more sever at more northern latitudes.

To constrain the formation and modification of this fill material, we examine the radiative geometries and properties unique to the crater interior environment that may cause local energy balances to favor the presence of volatile-rich fill material in the craters over the plains. To consider the hypothesis of preferential deposition, we examine the concept of craters as cold traps, noting that this should not be assumed as the shadowing effects of crater walls are minimal at the centers of large craters. To consider the hypothesis of remnant volatile-rich material being left behind by a retreating ice cap, we again compare the stability of ice in the plains with that in a crater, but we also investigate whether geometry and insolation asymmetries expected from modeling energy-driven sublimation processes can account for the observed asymmetries in crater fill shape. As a proxy for evolution of the modification process, we use characteristic fill morphologies at increasing distance from the polar cap terrain. If shape is largely consistent with these modeled processes, then the deposit is likely largely ice-rich, and radiative effects may dominate over wind effects in the size, location, and shape of such crater fill.

Energy Balance Model: Our approach to determine where and how much modification of an assumed existing water-ice crater-fill occurs is to calculate the main energy input and output pathways for a patch of the surface and assume any excess input energy is available for sublimation. The main processes involved are as follows: 1) solar insolation, incremented by 5 minute intervals over a martian year, including the slope and slope direction of the surface and the shadowing effects of the crater walls, 2) temperature-dependent re-radiation from the surface, including the geometric effects of the crater walls on reducing emittance to the sky, 3) diffusion of heat into or out of the body of ice below the surface, and 4) energy, if any, available for phase change and sublimation [17]. By iteratively calculating the energy balance of these processes at different points within the crater, we can determine the relative amount of sublimation at each point.

In this investigation, we are interested in timescales less than those of eccentricity and obliquity variations, given the rapid rates of sublimation expected on Mars [13], so we hold orbital parameters constant. The sensitivity of the model and resulting crater-fill morphology and asymmetry is assessed with respect to physical and geometric parameters such as albedo, emissivity, slope angle, atmospheric scattering (based on [18]), proximity to the crater wall, crater wall height, subsurface percent ice (and associated dependence on conductivity, heat capacity, and density).

The relative role of incident solar radiation on differently-facing slopes is dramatic. As expected at the high northern latitude of Korolev, south facing slopes receive more total yearly insolation, yet the maximum daily insolation occurs on north-facing slopes due to obliquity effects. With a nominal, non-dust storm, atmospheric optical depth of 0.5, incident insolation is reduced by 10-30% when the sun is more than 10° above the horizon [18]. Albedo can vary by a factor of 4 [17], which directly effects absorbed insolation. The latter two effects affect the total amount of insolation, while the first, and the geometry of the crater, affect the relative distribution of insolation. Asymmetry in insolation is clearly a candidate for being the major control on volatile fill asymmetry. This is supported by observation in a north-south profile across Korolev (Fig. 2) showing a strong asymmetry in which fill is concentrated to the north, consistent with more yearly energy input from southerly insolation.

However, because insolation from the west and east are similar, it is evident from the asymmetry in an east-west profile of Korolev fill (Fig. 3) that other factors are influencing fill morphology. In this case, a strong east-west asymmetry in rim height (Fig. 3) suggests that shadowing by a high rim may be a secondary, or possibly locally primary, influence on volatile fill stability.

A nearby high rim, however, will also decrease radiative heat loss by reducing the angle of sky seen by a surface [17]. Due to a thin atmosphere that is ineffective at convecting heat, the sky on Mars is very cold relative to these crater walls. Thus, the greater the visible angle of sky, the more energy can be radiated away, and the more the crater wall fills the field of view, the less the effective emissivity [17]. This concept of effective emissivity is summarized in the following equation: *radiated energy* = :

$$(E\sigma T_{surf}^4 - \sigma T_{sky}^4) * skyfraction +$$

$$(E\sigma T_{surf}^4 - \sigma T_{cwall}^4) * cwallfraction \quad (1)$$

where *E* is emissivity of the surface, σ is the Stephan-Boltzman constant, and *T* is the temperature of the surface, sky, and crater wall, respectively. The hemisphere centered on the normal to the surface is divided into that fraction which is open to the sky and that which is filled, or "blocked" by the crater wall.

Conduction of energy into the subsurface is represented very simply by a one-layer slab the thickness of the skin depth. It is assumed that, at each iteration of time, this slab changes temperature based on its heat capacity and the difference between its temperature at the previous time iteration and the temperature at the surface.

Future Application: While absolute amounts of sublimation may be attainable in the future, we are currently mainly interested in what factors control the asymmetry of the deposits, for which relative differences around the crater are sufficient. By modeling Korolev with both a uniform rim and a more realistic approximation of varying rim height, the role of rim height in combination with azimuth orientation of fill material slope will be assessed. By applying the model to circum-south polar craters, we will test the hypothesis that observed latitudinal trends in fill material morphology result from modification by radiative processes of remnants of a retreated polar cap.

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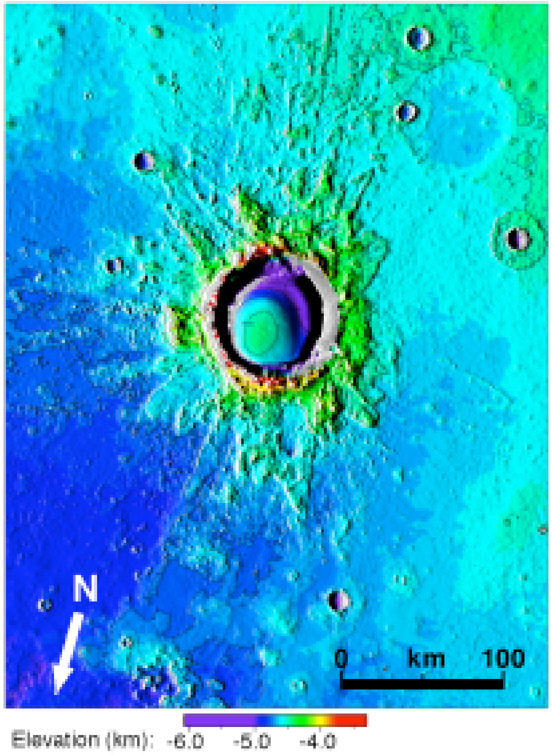

Figure 1. Gridded MOLA topography of Korolev Crater.

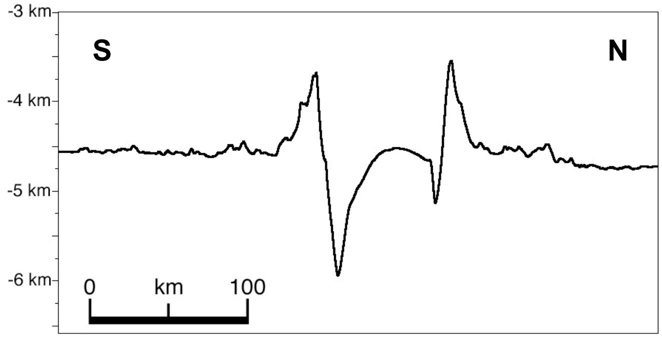

Figure 2. South-north altimetric profile of Korolev Crater.

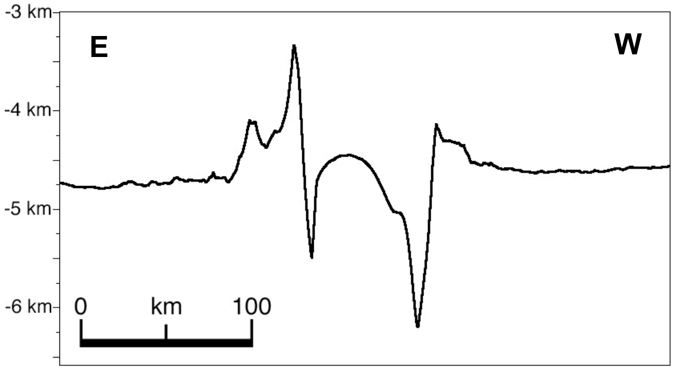

Figure 3. East-west altimetric profile of Korolev Crater.

Figure 4. Crater rims visible, or partially visible, through the south polar layered terrain. Main crater is 100 km wide, at 75°S, 120°W. All images at roughly the same scale.

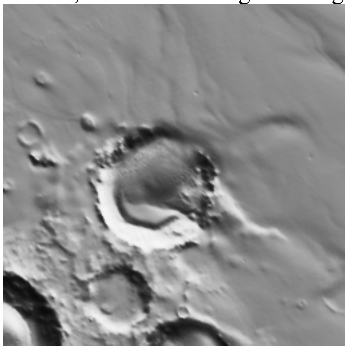

Figure 5. Crater mostly exposed, but still half surrounded with south polar layered terrain. Fill material is still contiguous with polar terrain. Crater is 55 km wide, at 80°S, 124°W.

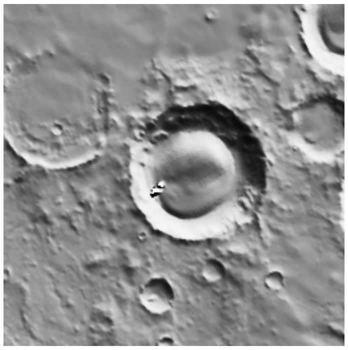

Figure 6. Crater isolated from south polar layered terrain, with circular fill material. Nearby fringes of polar layered terrain visible at top. Crater is 70 km wide, at 78°S, 126°W.

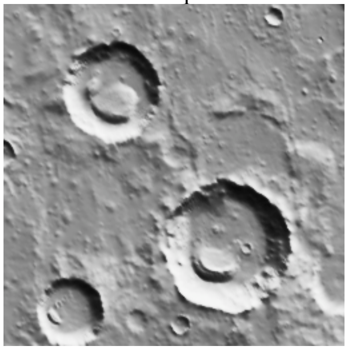

Figure 7. Craters with local, isolated, irregularly-shaped fill material. These craters are furthest from the polar layered terrain. Large crater is 50 km wide, at 74°S, 131°W.