VOLATILE-RICH CRATER INTERIOR DEPOSITS IN THE POLAR REGIONS OF MARS: EVIDENCE FOR ICE CAP ADVANCE AND RETREAT

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Introduction: Many craters on Mars are partially filled by distinctive material emplaced by post-impact processes. This crater fill material is an interior mound which is generally separated from the walls of the crater by a trough that may be continuous along the crater 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 offset from the crater center and may be asymmetric in plan view. 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. We focus on those craters in circum-polar regions and assess their relationship to polar cap advance and retreat, especially the possibility that fill material represents remnants of a formerly larger contiguous cap.

Motivated by assessment of the martian hydrological cycle, especially the groundwater system, we have previously examined northern lowlands craters for signs that the impacts may have interacted with the groundwater system [4]. 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 [4,5]. In a globally interconnected hydrosphere-cryosphere system [5], this process would be favored in the northern lowlands, where hydraulic pressure head of groundwater should be greatest [4]. Such a scenario presents an alternative hypothesis for volatile-rich crater fill in northern lowlands craters, but impacts into high-elevation circum-south polar terrain would not be expected to have accessed subsurface water. In addition, the only large craters in the northern lowlands containing significant fill material (e.g., Korolev) are those closest to, but isolated from, the north polar cap [6]. Unless these impacts were very recent, such that the volatile fill had not yet sublimated away [7], this non-random clustering near the north pole suggests that there has been either preferential deposition by polar-like processes in isolated craters, or deposition contiguous to, or part of, a formerly more extensive polar cap [e.g., 3] and subsequent preferential removal of material in intercrater plains. Fill deposits in some craters around the south pole are contiguous with south polar layered material [1], which argues for a similar process of deposition with possible later exhumation or flow into the crater [2].

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. Model profiles of crater fill are compared with MOLA topographic profiles to assess this hypothesis. 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 (and erosive processes such as eolian deflation are secondary or unnecessary).

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; [6,8]) is superposed on Amazonian mantle material surrounding north polar terrain [1]. While the crater is circular, rim height is not uniform around its circumference. 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. Relative to the crater's center, the fill deposit is displaced to the north and east, where it reaches closer to and higher up the crater walls. The highest point of the fill deposit is also displaced in the same sense. Based on rim-to-floor depths expected at a fresh, unfilled crater of Korolev's diameter [8,9] the actual deepest point of the crater is not much deeper than the observed elevation. The maximum thickness of the fill mound is then ~1.5 km [8].

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. 1). 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. 2; [10]). 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. 3). 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. 4). These materials have been mapped as extensions of polar layered material (Apl; [1]) 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; [1]).

Based on morphologic and topographic similarity, and in some cases contiguousness, of crater fill with polar layered deposits, we hypothesize that fill material either 1) was deposited preferentially in craters rather than on surrounding plains, or 2) was once present in the plains as well, as part of a larger continuous polar cap, and preferentially remains in the craters today 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 as 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 [2,10]. Further north, craters not physically connected to the polar layered terrain contain less fill, and this 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 severe at more northern latitudes.

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, including 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 of CO_2 and H_2O [11]. By iteratively calculating the energy balance of these processes at different points within the crater, we determine the relative amount of sublimation at each point. The same is done for a point in the plains, outside a crater environment. As an observed proxy for evolution of the modification process, we use characteristic fill morphologies at increasing distance from the south polar cap terrain. If actual fill shape is largely consistent with these modeled processes, then 1) the deposit is likely largely ice-rich, 2) radiative effects likely dominate over wind effects, for example, in the size, location, and shape of such fill, and 3) the retreat (in the plains) of a formerly larger polar cap is supported.

We are interested in timescales less than those of eccentricity and obliquity variations, given the rapid rates of sublimation expected on Mars [7], so we hold orbital parameters constant during each trial. However, the stability of ice changes drastically at different orbital configurations [e.g., 12], so we test several combinations of obliquity and eccentricity. 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 [13]), proximity to the crater wall, and crater wall height.

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 [13]. Albedo can vary by a factor of 4 [11], 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, which is supported by observation in a north-south profile across Korolev showing a strong asymmetry in which fill is concentrated to the north, consistent with more yearly energy input from southerly insolation [6].

A nearby high rim, however, will also decrease radiative heat loss by reducing the angle of sky seen by a surface [11]. 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 [11]. This concept of effective emissivity is summarized in the following equation: *radiated energy* = :

$$(E\sigma T_{surf}^4 - \sigma T_{sky}^4) * skyfraction + (E\sigma T_{surf}^4 - \sigma T_{cwall}^4) * cwallfraction \qquad (1)$$

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 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.

The amount of CO_2 deposited and sublimated each season, which we take to be a relatively thin cover over the H_2O ice-rich fill material, is tracked over the interior of the crater based on the latent heat available and assuming the surface temperature never drops below the CO_2 frost point of 148K.

At current orbital configuration, significant energy for sublimation of water ice is not available, thus evolution of deposits may not be currently active. If outlier fill material between ~150° and 240° W longitude was once part of a larger contiguous southern cap, we estimate that on the order of 0.5-2 x 10^6 km^3 of material has since been removed. We are further testing a variety of orbital configurations which will reveal under what conditions, when, and for how long, evolution of ice-rich crater deposits will occur. This will help constrain the relationship of fill material to polar cap material over geological history.

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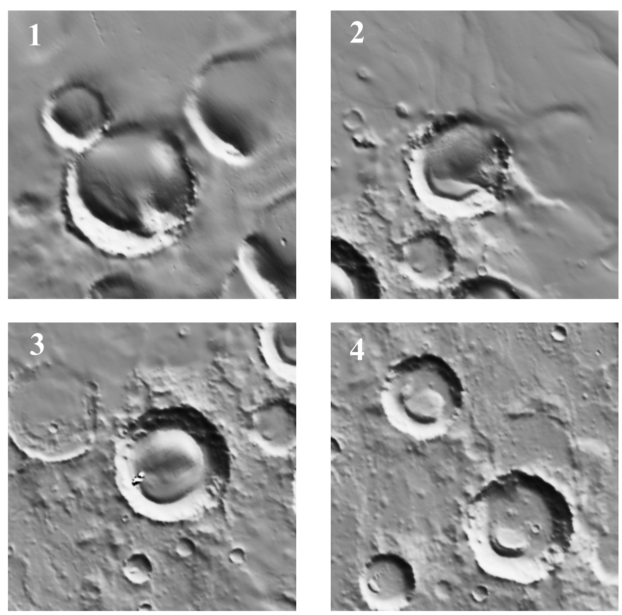

Figure 1. Crater rims visible, or partially visible, through the south polar layered terrain. 75°S, 120°W. All figures at roughly same scale: ~200 km wide. **Figure 2.** Crater mostly exposed, but still half surrounded with south polar layered terrain. Fill material is still contiguous with polar terrain. 80°S, 124°W. **Figure 3.** Crater isolated from south polar layered terrain, with circular fill material. Nearby fringes of polar layered terrain visible at top. 78°S, 126°W. **Figure 4.** Craters with local, isolated, irregularly-shaped fill material. These craters are furthest from the polar layered terrain. 74°S, 131°W.