CIRCUM-POLAR CRATERS WITH INTERIOR DEPOSITS ON MARS: POLAR REGION GEOLOGIC, VOLATILE, AND CLIMATE HISTORY WITH IMPLICATIONS FOR GROUND ICE SIGNATURE IN ARABIA TERRA.

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Introduction. Ice-rich crater-interior fill deposits at subpolar latitudes (here, between 65° and 80°) represent an important class of feature on Mars that may hold clues as to 1) the stability of ice in local topographic settings, 2) the geologic and climate history of the polar regions, and 3) the large-scale transport patterns of volatiles in the past.

The most prominent case of a crater with interior deposits as studied here is Korolev, (73°N, 165°E, 80 km across) which contains a deposit of ice-rich material with a maximum height above the crater floor of ~1.5 km [1,2]. The interior ice-rich deposit is a smooth-surfaced dome with relatively steep sides descending into a surrounding annular trough along the interior of the crater wall. This dome and trough morphology is asymmetric in that the trough is deeper and broader on the equatorwards side of the crater than on the polewards side. Other craters around both poles contain similar ice deposits with variable morphologies.

Here we document the distribution and full morphological range of crater-interior deposits around both poles and then group the craters into general types based on variation in fill morphology, using MOLA, MOC, and THEMIS data. These groupings are explored for trends in size, location (latitude, longitude, relative distance from the pole), orientation, and associated features, and are interpreted in light of our modeling study of ice stability within a crater [3]. We seek a model of emplacement and evolution of this peculiar class of volatile-related martian feature that explains their occurrence, location, variability, and history. Special attention will be paid to any implications for polar region history and a formerly more extensive cap. Finally, we speculate on possible implications of crater interior deposits in Arabia Terra and the heightened detection of hydrogen there by the neutron spectrometers on Mars Odyssey [4].

Energy Balance Model. In a previous study [3], we developed a numeric energy balance model to determine spatial and temporal variation of sublimation rate from an ice surface within a crater interior, giving special attention to the effects of topography on energy balance. Geometry-dependent sublimation results in the initiation and evolution of an interior domed surface with an annular trough around the periphery adjacent to the inner crater walls, qualitatively similar in form to deposits in circum-polar craters such as Korolev. Because of the prevailing north-south asymmetry in insolation, a feed-back cycle develops that increases trough size more quickly on the equatorward side of the crater than on the poleward side.

Crater Deposit Morphology and Distribution. Four main morphological types of crater fill are distinguished from amongst 37 craters in the south and 15 in the north. "*Embedded*" type craters are mostly occupied by a smooth, flat-topped fill material that abuts against, or even covers entirely, the crater rim for 50% to >75% of its circumference. This configuration results in a well-defined, slightly curved trough between the deposit and the opposing walls around the remaining circumference. "*Lobe*" type craters contain a tongue-shaped lobe of smooth fill material that extends from, and may cover, the crater rim on one side of the crater, resulting in a crescent-shaped trough interior to the other three sides. The lobe's top surface is flat to gently sloping downwards from the rim-adjacent side. Lobe termination is generally abrupt and may be in more of a flat snout than a protruding shape in plan view. THEMIS data reveals that some of the crater-interior deposits are layered and may also be contiguous with surrounding polar layered deposits (PLD). "*Center*" type craters contain a smooth fill material that is roughly centered within the crater, round to oval in shape, and may or may not extend completely to the interior base of the crater wall. Fill material in "*Remnant*" type craters is displaced significantly from the crater center, does not extend completely to the base of the wall in any direction, may be oval, arcuate, or irregular in plan-view shape, usually slopes more steeply on one side than the other, and often has a relatively rough surface.

Within each type some range of morphology exists. The existence of fill deposits that appear to have characteristics of more than one fill type suggests they may be transitional morphologies.

Because there are more and larger craters in the south, with more clearly developed fill morphologies, the southern data set provides more opportunity to examine trends in latitude, longitude, orientation, and morphology of deposits. Plotted on a grid of latitude and longitude, the above morphologies of crater fill in the south fall into zones that are remarkably exclusive and show a clear general trend with latitude: Embedded types are found at high latitudes with a band of Lobe types, a scattering of Center types, and a zone of Remnant types at successively lower latitudes. Zone boundaries vary in latitude with longitude but parallel the spatial extent of the regional PLD. Embedded type craters are completely surrounded by PLD, Lobe types are partially surrounded, and Center and Remnant types are completely isolated, or detached, from PLD (Fig.1).

Crater Deposit Emplacement Model. The spatial relationship and the number of apparent transitional morphologies among fill types suggests that the types 1) represent a sequence of evolution in time, with more distal deposits representing the equivalent of a longer or more intense cumulative period of sublimation, and 2) were once more completely surrounded and/or filled with PLD-like material and have since been exhumed as stated in 1). Thus, the fill types may have been emplaced as part of a more extensive south polar cap, which has since retreated, exhuming the craters to various degrees, rather than being deposited as independent outliers, for example. The proposed emplacement mechanism is consistent with current understanding of global-scale volatile transport resulting from large scale variations in Mars' orbital parameters.

At Mars' current orbital configuration, water ice is most stable at the surface in polar regions, is stable slightly below the surface in mid latitudes, and is not stable at all at low latitudes [e.g., 5,6]. During the last 10-20 Myr, however, an obliquity of ~45° was not uncommon, and obliquities up to ~60° may not be unusual over the last 250 Myr [7]. Under conditions of high obliquity, the stability zone of ice extends to lower latitudes [e.g., 8,9]. At very high obliquity (~60°), ice is actually predicted to be unstable at the pole and stable at certain locations near the equator [10,11].

The proposed mechanism of crater fill emplacement is a consequence of volatile mobilization and redistribution as a result of changing obliquity. At low obliquity, water ice is concentrated at the surface only at high latitudes, as we see the polar caps today. As obliquity gradually increases, the modeled climatic response is for ice to become stable at lower latitudes as well. Thus, the polar cap has the potential to lose ice to the regolith and surface of progressively lower latitudes. At very high obliquity, there may be more volatiles accumulated at low latitudes than at high latitudes. This sequence leads to a shift in the mass balance of ice from the poles to equatorial regions. As obliquity, and hence ice, migrates from one extreme to the other, the ice stability at intermediate latitudes fluctuates. We propose that the volatile-rich fill material in circum-polar craters was deposited at an intermediate obliquity as ice was either 1) retreating towards the polar cap due to decreasing obliquity, or 2) moving equatorwards due to increasing obliquity. The present situation is that obiquity is low, ice is concentrated at the poles, and these crater interior deposits exist with morphologies that vary with distance from the PLD as in Fig. 1. The simplest scenario of formation of crater interior deposits is thus the former of the above: that crater interior deposits are remnants of more extensive ice deposits in the subpolar region that have since sublimated and been redeposited on the relatively thick polar cap itself as obliquity decreased. During this process, surrounding terrain was exhumed and the deposits in craters remained because of their greater initial thickness due accumulation in a depression. From the present back to 4 or 5 Ma, obliquity is predicted to have ranged from ~15° to ~35°; prior to 5 Ma, obliquity ranged from ~25° to ~45° [7]. Thus, sublimation of previously more extensive ice deposits at subpolar latitudes and exhumation of underlying terrain due to migration of ice stability *polewards* with *decreasing* obliquity is consistent with Mars' orbital history. Furthermore, the simplest estimate for the time at which current sublimation conditions may have onset is the point at which obliquity variation underwent a major shift, from oscillating about ~35° to oscillating about ~25°, or between 4 and 5 Ma [7].

Discussion. A similar scenario is consistent with the population of filled craters in the north subpolar region as well, although trends are not as clearly developed. The fewer and smaller craters, as well as the more regularly boundary of PLD, in the north is likely tied to the more regular underlying topography due to its younger geologic age.

Center and Remnant type crater fill would be expected to persist long after complete sublimation of the surrounding PLD if they develop significant surface lag deposits. The low albedo in MOC data and dune cover in THEMIS data corresponding to most interior fill deposits in the north and south, especially those further from the PLD and Remnants, suggests many interior deposits are a preferential location for accumulation of non-ice material. The possibility that Center and Remnant type deposits could have high ice-content cores protected from sublimation by dune surfaces is supported by their gradual integration into the latitudinal variation in fill morphology observed here and by their location in the center of the crater away from the walls where sublimation rates are expected to be lowest according to physical modeling [3].

Possible Implications in Arabia Terra. Arabia Terra is peculiar in two ways of interest to this study: 1) there is a population of *equatorial* craters with fill deposits that fall within the range of morphologies observed in circum-polar regions [12,13], and 2) the region is one in which hydrogen detection by neutron spectrometers on Mars Odyssey is intriguingly high, possibly as much as ~7-11% by mass of water equivalent [4]. As ice is not predicted to be stable under current martian conditions at such low latitudes [e.g., 8], one interpretation is that this hydrogen is chemically or physically bound in minerals [4]. Given what we expect for the evolution of ice-rich interior deposits from modeling [3] and the concept of migrating ice stability applied to emplacement of these deposits in this study, we find it plausible that layers of ice and dust, similar to some craters in this study and the PLD, were deposited in Arabia at times of high obliquity, as is argued for low latitude mountain glaciers [10,11,14]. If a lag deposit developed, as is evidenced in outlying circum-polar Remnant type craters in this study, ice at depth could remain present for a long time even under current conditions. Qualitatively, given the large size of the neutron detector footprint relative to crater size, a high water content subsurface in the craters could manifest itself as a low regional water content subsurface in neutron data. We note, however, that there is a paradox in the need for a lag deposit to maintain ice presence during low obliquity and the hindrance that such a lag creates in the detection of subsurface neutrons.

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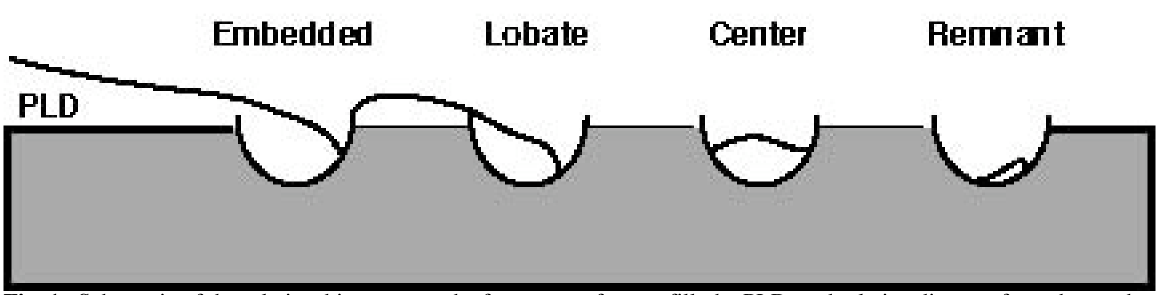

Fig. 1. Schematic of the relationship amongst the four types of crater fill, the PLD, and relative distance from the south pole.