ICE-ASSOCIATED IMPACT CRATERS ON MARS: IMPLICATIONS FROM MOLA OBSERVATIONS.

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Introduction: Impact features adjacent to the permanent North Polar Cap on Mars provide a unique perspective on the crater formation and modification process. Little attention has been previously paid to the dozen's of ice-associated or "frost-filled" craters north of 70N on Mars. We have examined Mars Orbiter Laser Altimeter (MOLA) cross-sections of 13 of these features between 70N and 82N in an effort to understand cavity modification processes potentially associated with the advance and retreat of the North Polar ice cap. Here we treat the general geometric properties of these impact features and focus attention on one almost entirely filled example (i.e., 32 km diameter, located at 77N, 89E) for which high resolution Viking Orbiter images (50 m per pixel) provide key constraints for interpreting MOLA's meter-precision topographic measurements (Fig. 1).

MOLA Observations: As part of MGS Science Phasing Orbit operations, MOLA acquired 188 topographic transects across the Northern Hemisphere of Mars. Zuber and others have described these observations as they apply to the North Polar region in general [1]. Here we address what the geometrical properties of those impact craters adjacent to the permanent cap indicate about the effects of target properties and subsequent modification processes in the polar latitudes of Mars. Our previous work with martian impact craters [2] has provided us with a frame of reference for the basic geometrical characteristics of Northern Hemisphere craters. The properties displayed by the well-sampled population of ice-associated craters vary considerably from the trends described in [2]. Figure 1 illustrates one of the best examples of an ice/frost filled crater in the northern polar latitudes of Mars. The 32 km crater is traversed by 2 independent MOLA profiles, both of which sample the cavity and parts of the ejecta. A centerline pass acquired on MGS Orbit 415 provides key geometric constraints. It suggests the total cavity depth should be ~ 1.4 km, instead of the observed 0.66-0.72 km. Thus, this example indicates an effective infill thickness of ~ 600m for a 32 km diameter cavity. In contrast, the 43 km diameter ice-fill crater located at 77N, 215E, is 2.13 km deep, more than 0.6 km deeper than would be predicted for non-polar impact features on Mars. These observations indicate that crater growth and modification in this unique region of Mars does not follow the basic trends defined for impact features in the Northern Hemisphere [2].

Examples: There are 13 ice-associated craters that were adequately sampled by MOLA to facilitate geometric property estimation. Of these, 6 display high albedo deposits within the crater cavity, indicating either a frost-mantle, or infilling deposits enriched in ice. We have examined all of these using the highest resolution Viking Orbiter images in association with MOLA cross-sections. In at least one case, crossing MOLA ground-tracks bisect the crater cavity, providing excellent azimuthal sampling of this 20 km feature. The largest of the putative ice-filled craters is Korolev, an 81 km diameter complex feature located at 73N, 163E. Only one MOLA ground-track samples the cavity of this structure, the largest in the polar cap region on Mars. It suggests a depth of 2.4 km, which is consistent with other regions of Mars [2]. For 3 of these ice-fill craters, near centerline MOLA cross-sections are available. The best-sampled is a 20 km crater located at 78.6N, 331E; an ice bench or tilted central deposit is observed in MOLA transects of this relatively deep feature (0.73 km). The crater illustrated in Fig. 1 is also sampled by a centerline pass, as is the 19 km crater located at 81.6N, 189E (within the Olympia Planitia dune field). Complex impact features 20 km in diameter should be ~ 1.06 km in depth, and MOLA measurements indicate a total depth of 0.912 km, suggesting very minor amounts of cavity floor infill. Most of the ice-fill craters display cavity deposits that are topologically unlike typical martian central uplift features. There are marginal lows surrounding irregularly positioned interior deposits that often display a tilted appearance. We conclude that these cavity interior features are not primary central uplift structures, but instead are related to the pattern of cavity infill and subsequent erosion experienced by each crater. MOLA measurements of the cavity cross-sectional shape indicate a strong tendency toward "U-shaped" cavities for these ice-filled varieties, independent of diameter. The 19 km crater in the Olympia Planitia dune field has a power-law shape exponent n of 4.7, where the cavity is modeled using a function of the form $z = kx^n$, with z as the MOLA topography and x as a radial position relative to the cavity center [2]. The crater at 78.6N, 29E (20 km diameter) has a cavity shape parameter n = 4.23 (i.e., also very U-shaped). In order to examine the processes responsible for modifying the cavities of these near-polar impact craters, we will consider the infilled cavity of the crater illustrated in Fig. 1.

Case Study of an Ice-Filled Crater: The 32 km crater shown in Fig. 1 is noteworthy in several respects. The cavity volume associated with a 32 km crater with a cross-sectional shape parameter n of 2.3 (paraboloidal), and a reconstructed depth of 1.4 km should be ~ 750 km^3. The apparent volume of the crater cavity plus that of the topographically defined ejecta blanket is 766 km^3. Allowing for the rim height assymetry of 273 m, this suggests that ~ 60% of the original cavity is filled. If we consider an off-center cavity-crossing MOLA cross-section that appears to have sampled the deepest part of the present-day crater floor (60 m deeper than the centerline pass), there is further evidence of extreme infill, with an average depth of fill in excess of 600m. The tilted and textured appearance of the upper surface of the cavity fill deposit is suggestive. The centerline MOLA cross-section (Fig. 1) indicates that terrace-like features on the order of 8 – 20 m in relief characterize a 15 km long section of cavity interior. These "staircase" features are reminiscent of certain layers in the polar layered terrain. The high-resolution Viking image illustrated in Fig. 1 suggests these scarps are curvilinear, and they could mark areas of relatively rapid erosion, perhaps caused by rapid defrosting, ablation, or other processes [3]. Their appearance within this apparently fresh rim impact crater could provide a constraint on layer thickness properties throughout the North Polar region. We speculate that these exposed layers may be similar to the 10-50 m thick bands that are widespread in the polar layered deposits [3].

Discussion: If the impact crater cavity infill deposits are similar in composition to the polar layered deposits, then their formation or existence inside craters tens to hundreds of km from the permanent cap edge has several implications. One possibility is that episodic advance of the terminus of the permanent cap permits burial of 1-2 km deep impact features, which are later exhumed as the cap retreats during warmer climatic epochs. This would require that the exhumation process preserves the freshness (in high resolution images) of crater rims such as that shown in Fig. 1. Alternately, deep impact crater cavities could slowly accumulate polar deposits over periods of tens to hundreds of millions of years, building infill deposits whose geometry may reflect such factors as solar incidence angle, regional winds, and original cavity floor topology. Additional MOLA transects through the several dozen ice-associated impact features observable in Viking image mosaics, coupled with carefully targeted MOC images could resolve many of the key issues.

Summary: We have examined ice-filled impact features adjacent to the martian North Polar cap using MOLA topographic cross-sections. We observe that most of those that were sampled suggest cavity infill levels in the 30 to 60 % range. Analysis of one key example (Fig. 1) supports the hypothesis that deep craters within 100 km of the permanent cap may have been buried by ice during a former time of cap advance, and are now exhumed. This has implications for the time-variable ice volume of the North Polar Cap of Mars [1].

References: [1] Zuber M. T. et al. (1998) *Science 282*, 2053-2060. [2] Garvin J. B and J. J. Frawley (1998) *GRL 25*, 4405-4408. [3] Thomas P. et al., in *Mars*, H. Kieffer and others (Eds.), Univ. Arizona Press, Tucson, pp. 767-795.