IMPACT CRATER GEOMETRIES PROVIDE EVIDENCE FOR ICE-RICH LAYERS AT LOW LATITUDES ON MARS. B. A. Black and S. T. Stewart, Harvard University (Department of Earth and Planetary Sciences, 20 Oxford St., Cambridge, MA 02138, bblack@fas.harvard.edu, sstewart@eps.harvard.edu).

Introduction. The impact cratering record documents the history of resurfacing events on Mars. The morphology and distribution of layered (rampart) ejecta blankets provide insights into the presence of volatiles in the upper crust [1-4]. The physical properties of the crust and history of water have been revealed through recent quantitative studies of the geometry of Martian craters [5-9]. Here, we present the results from a study focused on impact craters in Utopia Planitia and the Elysium Mons province to infer the history and properties of resurfacing episodes.

Crater Measurements. Using the HMars program, an interactive toolkit for measuring crater geometries based on the Mars Orbiter Laser Altimeter (MOLA) data [5, 7], we measured 384 craters in Utopia, Isidis, Elysium, the Vastitas Borealis Formation (VBF), Acidalia, Solis Planum, and Lunae Planum. Of these, 208 well-resolved craters (all fresh and intermediately degraded craters greater than 4 km diameter) in the Utopia region were studied in detail.

The MOLA PEDR altimetry profiles are gridded using Delaunay triangulation at a resolution of 0.6 km/pixel. Rim height, cavity depth, and diameter measurements are conducted on the PEDR data and volume measurements are based on the gridded data. The accuracy of measurements with the HMars program are ~10% for rim height and <30% for ejecta volumes based on measurements of simulated craters on realistic background terrains [5, 7].

Results. Our results (Fig. 1) expand previous studies of crater geometries using the HMars program and demonstrate significant differences in crater geometries with region on Mars. For example, VBF craters (□) are distinctly softened compared to Utopia, with in-filled cavities and degraded rims. In the Utopia-Elysium region, we found a set of fresh craters with apparent ejecta volumes in excess of expected excavation volumes (identified by + and ◻ in Fig. 1). Fresh craters are defined by cavity depths, rim heights, and visual inspection of THEMIS imagery. These "excess-ejecta" (EE) craters have volumes above the apparent pre-impact surfaces (V_{above}) several times larger than their cavity volumes (V_{cavity}). We defined two classes of these excess-ejecta craters for illustrative purposes. Class one (EE-I) contains the freshest craters with the highest proportions of excess ejecta: $d_S/D_R>0.08$, $H_R/D_R>0.03$, $V_{above}/V_{cavity}>1.5$. Class two (EE-II) contains craters have slightly lower criteria for freshness and excess ejecta, defined as craters with $d_S/D_R>0.06$, $H_R/D_R>0.023$, $V_{above}/V_{cavity}>1.25$ that do not fall in class EE-I.

We investigated the geologic setting of EE craters and found a spatial correlation with certain flows from Elysium (Fig. 2). Seventy percent of the craters were located on lava and sediment units associated with Amazonian flows extending from the northwest of the Elysium rise [10]. No EE craters were found in Isidis Planitia, Acidalia Planitia, Solis Planum, or Lunae Planum, although surveys of the last three regions were not complete.

In our survey, we identified eight EE-I craters in Utopia-Elysium. The amount of excess ejecta is calculated using two independent methods (Table 1). First, the volume above the apparent pre-impact surface, V_{above}, is compared to the crater cavity volume, V_{cavity}. Second, the observed ejecta, V_{obs_ejecta}, is calculated by subtracting a conservative model for the uplifted surface (defined at a radius r by $H_R(r/R_R)^{-5.5}$), where H_R and R_R are the rim height and radius of the crater), from V_{above}. The observed ejecta volume, V_{obs_ejecta}, is compared to the expected ejecta volume, $V_{expected\_ejecta}$, for the crater diameter [11]. The excess volume ratios from the independent methods are in very good agreement, confirming that the excess volume is robust.

Discussion. Several scenarios were examined to explain the apparent excess ejecta. Based on the geological history of the region, the locations of the EE craters, and the crater geometries, we interpret the excess material in the ejecta blanket as evidence for removal of a volatile-rich layer surrounding the craters. The two volume ratios (Table 1) imply that the apparent excess ejecta is a result of deflation of the pre-impact surface level producing *perched ejecta.* Among the eight EE-I craters, the average apparent ejecta thickness is ~45 m larger than expected.

We rejected scenarios involving removal of material by scouring events (e.g., debris or lahar flows) because of the symmetric preservation of ejecta around most of the craters. Our preferred model is sublimation of one or more water ice-rich surface deposits emplaced before the impact events under a different climate. After the impact events, the ejecta blanket covers and insulates a portion of the layer. As the climate changed, the unprotected icy layer surrounding the ejecta blanket sublimates more quickly, leaving an apparently lower pre-impact surface. The inner ejecta blanket of most EE-I craters appear softened (Fig. 3), suggesting partial sublimation or relaxation.

Such an ice-rich layer may have been emplaced during a glacial period on Mars. Climate simulations suggest that the flank of Elysium Mons may accumulate ice deposits during high obliquity periods [12]. Alternatively, the clustering of EE craters on Elysium flow deposits may indicate that many of these flows were fluidized with liquid water.

We estimate the time scale for sublimation of an icy layer [following methods of 13, 14]. Longevity depends strongly on the thickness of the layer, ice fraction, burial depth, porosity of the insulating ejecta, and temperature. At an average temperature of 210 K, a 45-m thick pure ice layer, buried under 20 m of ejecta (10% porous, 10-μm pores), would sublimate in ~55 Ma. A 45-m thick partial ice layer would sublimate in a few 10's Ma in the present climate.

Conclusions. Craters with perched ejecta in the region of Utopia Planitia provide evidence for an ice-rich layer preserved by overlying ejecta blankets. These observations support climate models and geomorphologic observations that suggest Martian obliquity cycles produced recent glacial periods and deposition of low- and mid-latitude ice [8, 12, 15-17]. The inference of ice-rich layers, residing below the penetration depth of the Neutron Spectrometer [18], is testable with ground-penetrating radar or drilling.

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References. [1] Cave, J.A. (1993) *JGR* **98**, 11079. [2] Cintala, M.J. and P.J. Mouginis-Mark (1980) *GRL* **7**, 329. [3] Barlow, N.G. and T.L. Bradley (1990) *Icarus* **87**, 156. [4] Stewart, S.T., et al. (2004) *Shock Compression of Condensed Matter -- 2003*, AIP, 1484. [5] Valiant, G.J. and S.T. Stewart (2004) *LPSC* **34**, 1293. [6] Boyce, J.M., et al. (2005) *JGR* **110**, E03008. [7] Stewart, S.T. and G.J. Valiant (2004) *7th Mars Crater Consortium Meeting*. [8] Meresse, S., et al. (2005) *LPSC* **36**, 1748. [9] Black, B.A. (2005), B.A. thesis, Harvard. [10] Russell, P.S. and J.W. Head (2003) *JGR* **108**, 5064. [11] Kring, D.A. (1995) *JGR* **100**, 16979. [12] Mischna, M.A., et al. (2003) *JGR* **108**, 5062. [13] Stewart, S.T. and F. Nimmo (2002) *JGR* **107**, 5069. [14] Moore, J.M., et al. (1996) *Icarus* **122**, 63. [15] Hauber, E., et al. (2005) *Nature* **434**, 356. [16] Head, J.W., et al. (2005) *Nature* **434**, 346. [17] Laskar, J., et al. (2004) *Icarus* **170**, 343. [18] Feldman, W.C., et al. (2002) *Science* **297**, 75.

Table 1. Excess Ejecta Volume. Ratios of observed apparent ejecta volume to expected ejecta volume and ratios of volume above apparent pre-impact surface to cavity volume for EE-I craters.

Crater #	1	2	3	4
$\frac{V_{above} - V_{uplift}}{V_{expected\ ejecta}}$	2.79	1.31	1.43	5.45
V_{above}/V_{cavity}	2.07	1.77	1.61	7.36
Crater #	**5**	**6**	**7**	**8**
$\frac{V_{above} - V_{uplift}}{V_{expected\ ejecta}}$	2.76	9.9	1.77	4.47
V_{above}/V_{cavity}	2.03	7.3	1.64	4.17

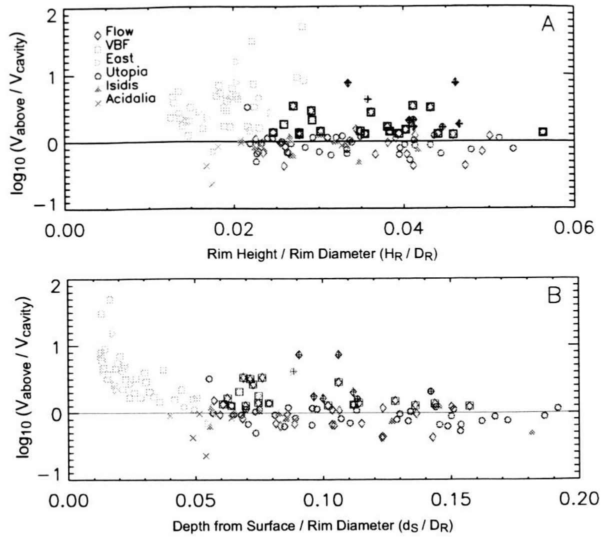

Fig. 1. Log of ratio of volume above apparent pre-impact surface to cavity volume as a function of **A.** rim height / rim diameter and **B.** depth from surface / rim diameter. Craters on the right are considered the freshest. +: class one excess-ejecta craters; □: class two excess-ejecta craters. Log ratio of zero indicates $V_{above} = V_{cavity}$.

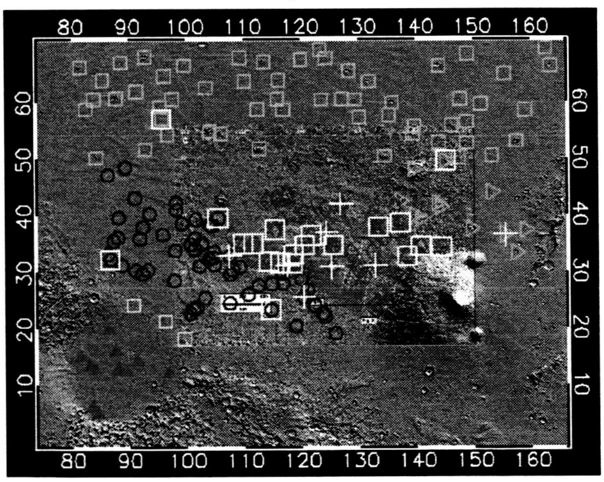

Fig. 2. Locations of excess ejecta craters, overlaid on shaded relief topography and map of Elysium flow units [from 10]. Symbols identify different crater groups (defined in Fig. 1). White +: EE-I craters; white □: EE-II craters.

Fig. 3. Daytime THEMIS IR image of crater no. 4 from Table 1 (6.2-km diameter, 124.3 E, 36.9 N). Note softened appearance of inner ejecta blanket. [THEMIS I10232013, north up].