CHARACTERISTICS OF THE CRATERING PROCESS ON ICY BODIES: IMPLICATIONS FOR OUTER PLANET SATELLITES. Mark J. Cintala, E. Marc Parmentier, James W. Head, Dept. of Geological Sciences, Brown Univ., Providence, RI 02912.

While not a familiar occurrence in the context of the "dry" terrestrial planets, impact cratering in frozen volatile targets could be an important process in the evolution of the solid-surface bodies in the outer solar system. Investigations are being carried out into the phenomena and effects associated with the hypervelocity impact of projectiles into H_2O targets. The purpose of this report is to present some preliminary results of largely theoretical studies of impact cratering in H_2O ice, to compare and contrast them with events in more familiar targets, and to consider briefly the implications they might have for cratering on ice-rich bodies.

Crater Scaling: The shear strength of H_2O ice at ~230 K is 1.6×10^7 dynes/cm² (10^6 dynes/cm^2 = 1 bar = 10^5 pascals).[1] Taking 3.6×10^3 dynes/cm^2 for the shear strength of basalt,[2] craters in ice should have diameters ~2.8 times greater than those in basalt for situations in which strength scaling holds (cratering diameter $\propto$ [cratering energy/target strength]$^{1/3}$). On a planetary scale, however, gravitational forces predominate in the formation of kilometer-size craters. Pure gravity-scaling (crater diameter $\propto$ [cratering energy/density x surface gravity]$^{1/4}$) will give craters with diameters only 1.33 times larger in ice than in basalt for identical gravity fields. Actual stiuations will lie somewhere between these two extremes.[3]

Energy Partitioning: Irreversible Heating - The amount of irreversible heat generated during impacts of basalt into H_2O ice has been calculated following the method outlined by Gault and Heitowit[4] with H_2O ice Hugoniot data from Anderson.[5] Preliminary results indicate that a minimum of 2 to 13 projectile masses of target material will be fused or vaporized at impact velocities of 5 km/s and 25 km/s, respectively. Corresponding values for a basalt target are zero and 10 projectile masses. Due to the large density difference (a factor of 3.1) between the two target materials, these values correspond to 7 and 41 times the projectile volume. This density difference will cause less efficient projectile-target coupling and, therefore, lower peak pressures than for the basalt-basalt case.[4] This is illustrated in figure 1, where waste heat and pressure for the impact of an aluminum projectile at 6.25 km/s into basalt, sand, and H_2O ice are plotted as functions of dimensionless radial distance from the point of impact. Comminution - The average surface free energy for quartz - taken here to be 645 ergs/cm^2 (an average from experimental results of surface free energies for three separate crystal faces)[6] - differs from the crushing strength by a factor of ~110.[7] By analogy, the surface free energy of ice-ice grain boundaries of 65 ergs/cm^2 ref. 1 gives a crushing strength for ice of $\sim7.3\times10^3$ ergs/cm^2. It has been found that ~10% of the projectile kinetic energy was utilized in comminuting a basalt target.[3] Scaling crater size for target strength effects, extrapolating a maximum particle size of 4.8 cm, assuming a minimum size of 0.1 µm (by analogy with the basalt case), and using the size distribution model of Gault and Heitowit,[3] the total energy expended in creating free surfaces in the ice target would amount to ~28% of the projectile kinetic energy - almost a factor of 3 higher than that found for the basalt case.[4] Ejecta - In the absence of experimental data, it is difficult to estimate the fraction of projectile kinetic energy partitioned into ejecta kinetic energy. If ejecta velocity were to scale as (target strength/target density)$^{1/2}$,[8] then, accounting for the difference in ejected mass, essentially equal amounts of energy are partitioned into ejecta for the ice and basalt targets (aluminum projectiles at 6.25 km/s, using strength scaling). This implies lower average ejection velocities for small events in

H_2O ice.

Large Scale Cratering: While a larger absolute volume of impact melt should be generated in ice compared to basalt, strength-scaled crater dimensions should keep the ratio of melt volume/crater volume relatively constant in both targets. As the magnitude of the hypothetical cratering event grows, however, the transition to gravity scaling will cause greater melt/crater volume ratios than would occur in basalt targets. The ratio of any measure of strength (or yield stress) to density for H_2O ice is invariably less than corresponding values for basalt. This fact should manifest itself as wall failure and central uplift formation in smaller craters in ice than in basalt, whether driven by gravitational forces or by rebound phenomena. It should be noted, however, that the larger relative volumes of impact melt in ice might obscure the initial appearance of central uplifts in the smaller ice craters. Removal of material from the central region of the crater floor might occur through explosive decompression of the target during the removal of large impact-induced stresses - a mechanism suggested to account for "central pit" craters observed on Mars.[9] Finally, density contrasts and the relative ease with which H_2O ice is melted by impact might combine to create a relatively efficient mechanism by which a net downward migration of suspended silicate particles could occur through settling in impact melt sheets. This process would have been more important in the early history of these bodies, when impact fluxes and crustal temperatures would have been higher during terminal accretion.

References: [1]Hobbs P.V.(1974) Ice Physics, Oxford Univ. Press (London) 837 pp; [2]Jaeger J.C. (1956) Elasticity, Fracture, and Flow, Methuen & Co. (London), 268 pp.; [3]Gault D.E. and J.A. Wedekind (1977) Impact Explos. Cratering, p. 1231; [4]Gault D.E. and E.D. Heitowit (1963) Proc. 6th Hypervel. Impact Symp., p. 419; [5]Anderson G.D. (1968) CRREL Research Report 257, 50 pp.; [6]Spry A. (1969) Metamorphic Textures, Pergamon Press (Oxford), 350 pp.; [7]Zeleny R.A. and E.L. Piret (1959) Colorado School Mines Quarterly 54, 35; [8]Ivanov B.A. (1976) Proc. Lunar Sci. Conf. 7th, p. 2947; [9]Wood C.A. et al. (1978) Lunar Planet. Sci. IX (abs.), p. 1270; [10]Parmentier E.M. and J.W. Head (1978) Submitted to JGR.

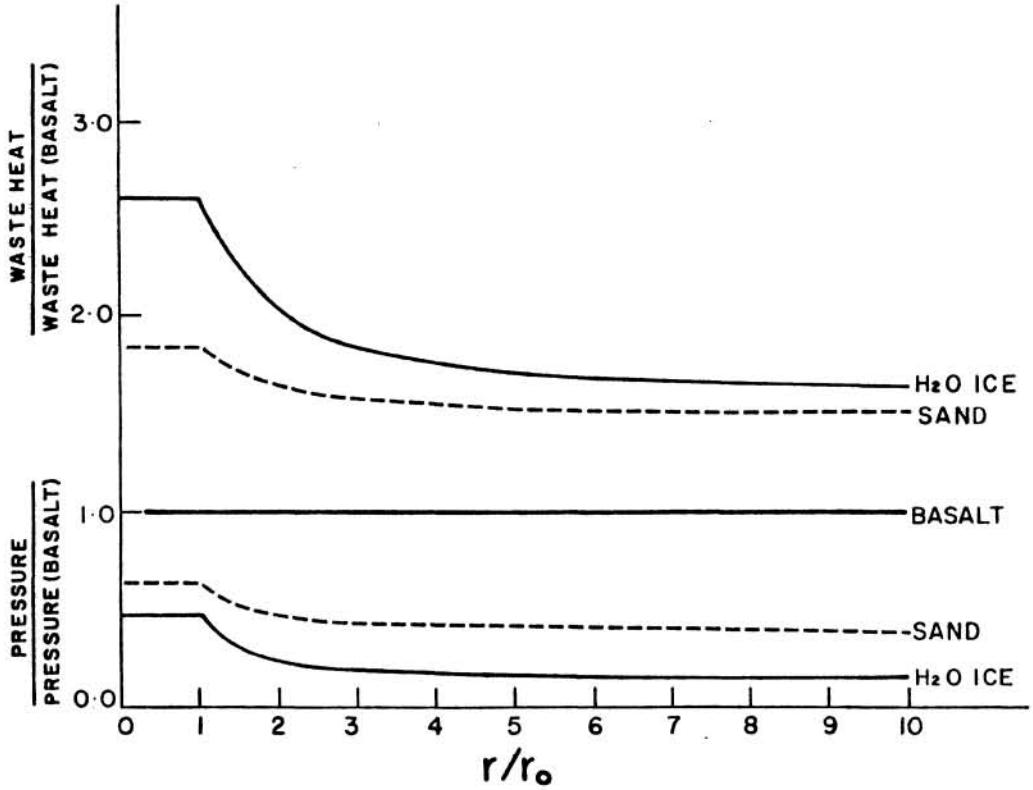

Figure 1. Waste heat and pressure decay in the target as a function of dimensionless radial distance from the point of impact. r_o is the effective radius of the compressed plug of target material after the initial partitioning of energy. See (4). All curves are normalized to those calculated for basalt.