Resistance of water ice to fluvial abrasion and implications for erosion on Titan G. C. Collins[1], P. J. Polito[2,3], K. L. Litwin[2,4], and L. S. Sklar[2], [1]Physics and Astronomy Dept., Wheaton College, Norton MA 02766, gcollins@wheatonma.edu; [2]Dept. of Geosciences, San Francisco State University; [3]Jackson School of Geosciences, University of Texas at Austin; [4]Dept. of Earth and Environmental Science, University of Pennsylvania.

Introduction:

The surface of Titan appears to be extensively modified by fluvial erosion processes, creating branching valley networks [e.g. 1]. Topography on Titan is mostly subdued with a few mountain peaks [2], and fluvial erosion may be a major factor in decreasing the overall relief. In areas where the surface of Titan is already broken down into sediment particles (especially lowlands and basins), the rate of fluvial erosion will be controlled by the amount of time that the flow in a channel exceeds the critical threshold for sediment transport [3]. Other areas of Titan (especially at higher elevations) may have a smaller supply of transportable sediment available on the surface than channels can theoretically carry. For these supply-limited stream channels, the rate of erosion will be controlled by the process of bedrock incision.

While several different types of loose material may exist in Titan's regolith, the material that composes solid bedrock near the surface of Titan could be (a) the water ice that is likely to form the bulk of Titan's crust, (b) solid organic materials derived from Titan's atmosphere, or (c) some mixture of water ice with contaminants such as ammonia, organics, or exogenic rock particles. Here we present an investigation of possibilities (a) and (c), as possibility (b) is too unconstrained at this point. Our investigation covers the strength and erodibility of simulated Titan bedrock at cryogenic temperatures, and we conclude with some implications for fluvial erosion on Titan.

Tensile strength of ice at low temperatures:

The resistance of terrestrial bedrock to wear by sediment impacts during fluvial erosion appears to be related to the tensile strength of the bedrock material. To measure tensile strength, we used the Brazil splitting test, a standard engineering test that was used on previous work relating tensile strength to terrestrial bedrock erodibility [4]. To make polycrystalline water ice samples, we crushed pure ice, optionally sieved the ice grains, packed these seed grains into a mold, and then slowly poured water into the mold while freezing from the bottom up. The crushed ice seed grains varied from 0.4 to 10 mm in size -- some experiments used this wide grain size distribution for seeds, while others were sieved between 2 to 4 mm before freezing. We also made impure ice samples by mixing the mixed size seed grains with urea (a simple organic contaminant), ammonium sulfate (an easier to work with ammonia substitute), or crushed 1-2 mm basalt particles (as a generic silicate contaminant). Experiments were run at various temperatures using a walk-in freezer, dry ice, or liquid nitrogen to chill the sample and its holding apparatus.

All types of ice samples exhibited increasing tensile strength with decreasing temperature. For pure ice (*Figure 1*), we expect a tensile strength between 1.5 and 2 MPa at Titan's 94K surface temperature. Adding impurities to the ice increased the tensile strength, regardless of the type of impurity. *Figure 2* shows an example of varying amounts of urea added within the polycrystalline ice samples, with increasing concentra-

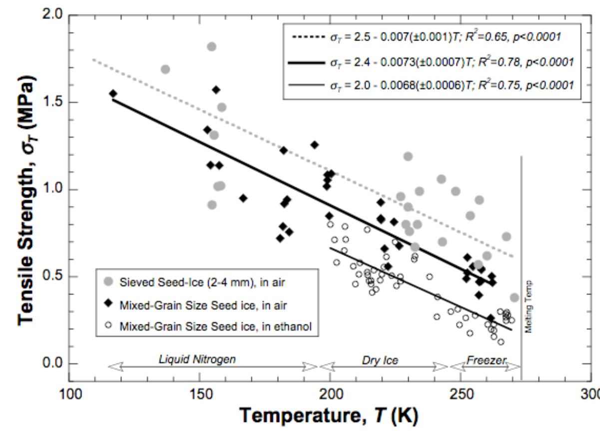

Figure 1: Results of brazil splitting tests on polycrystalline water ice samples. The top trend line is sieved seed particles, while the middle trend represents mixed grain size seed particles. The bottom trend shows data collected with the ice submerged in ethanol.

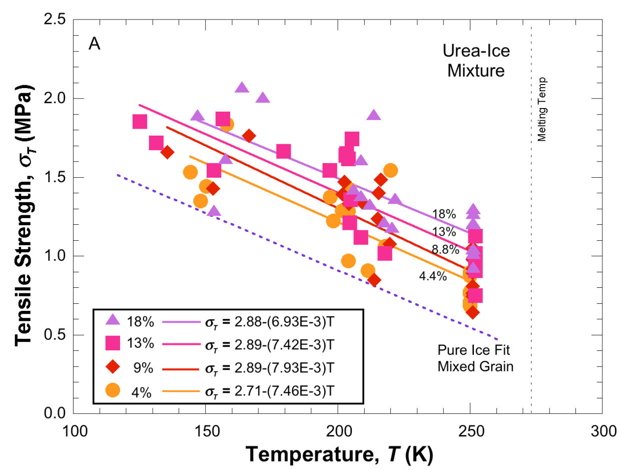

Figure 2: Results of brazil splitting tests on samples of polycrystalline water ice mixed with varying concentrations of urea, as a simple organic contaminant. Concentrations varied from 4 % on the bottom line to 18% on the top line.

tions leading to increasing tensile strength measured. The effect of impurities did not produce any strength increases larger than a factor of 2.

Abrasion resistance of ice at low temperatures: The resistance of a bedrock material to abrasion by moving sediment particles is related to its ability to elastically store the energy from the impacts. The amount of energy required to erode a certain volume ε_v, is related to the tensile strength σ_T and the Young's modulus Y as $\varepsilon_v = k_v\, \sigma_T^2 / 2Y$ where k_v is a nondimensional constant for the material known as the abrasion resistance coefficient [4]. We have measured σ_T in the previous section, and previous workers have constrained Y for polycrystalline water ice [5]. To constrain the value of k_v, we measure ε_v directly by dropping sediment particles onto an ice target and measuring the relationship between input kinetic energy and the volume of material detached by the impacts.

An initial estimate of k_v was made by repeatedly dropping a sediment clast onto a small monocrystalline water ice disk [6], but this procedure suffered from catastrophic cracking through the disk after many impacts. To simulate more realistic bedrock, we prepared large (55-gallon drum) sized polycrystalline ice targets for our sediment drop tests, and ran them through hundreds of small sediment impacts at a given temperature before scanning them with a laser system to determine the volume of bedrock eroded. Two targets were prepared of low porosity pure polycrystalline ice, one of pure ice with higher porosity, and one each of polycrystalline ice contaminated with urea and ammonium sulfate. The results of these tests (*Figure 3*) show that the energy required to detach a given volume of bedrock increases with decreasing temperature, with a power-law fit of exponent 2 (except for ammonium sulfate which fits with exponent 1). Using these results to calculate values of k_v (*Figure 4*), we find that k_v appears to be change with temperature, rather than staying constant. However, this may be influenced by uncertainties in the Young's modulus of polycrystalline ice with decreasing temperature. The value of k_v for all ice samples is about an order of magnitude less than typical terrestrial rocks.

Application to Titan: The resistance of Titan's bedrock to fluvial erosion is an important factor in understanding the rate at which landforms on Titan are eroded. Our new data does not significantly modify previous conclusions that Titan bedrock will erode similarly to terrestrial bedrock [6]. Ideas about endogenic vs. exogenic activity on Titan [7] need to be constrained by the rate at which topographic features on Titan's surface will be removed. The crater population on Titan exhibits a lack of small craters and an excess of large craters [8], perhaps indicating erosive and depositional processes wiping out topographic features. The question is whether the current rate and distribution of rainfall can produce enough erosion to explain the crater population on Titan without appealing to other endogenic and exogenic influences.

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References: [1] Lorenz et al., *PSS* 56, 1132-1144, 2008; [2] Radebaugh et al., *Icarus* 192, 77-91, 2007; [3] Burr et al., *Icarus* 181, 235-242, 2006; [4] Sklar and Dietrich, *Geology* 29, 1087-1090, 2001; [5] Dantl, *Physics of Ice*, 223-230, 1969; [6] Collins, *GRL* 32, 10.1029/2005GL024551, 2005; [7] Moore et al., *LPSC* 41, #1167; [8] Wood et al., *Icarus* 206, 334-344, 2010.

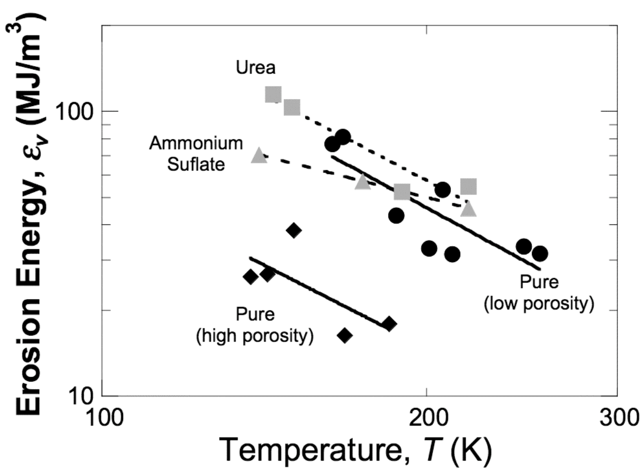

Figure 3: The energy required to detach a volume of ice bedrock by small sediment impacts increases with decreasing temperature. Results for 2 pure ice and 2 impure ice drums were similar, while one high porosity pure ice drum showed much lower energy required for detachment.

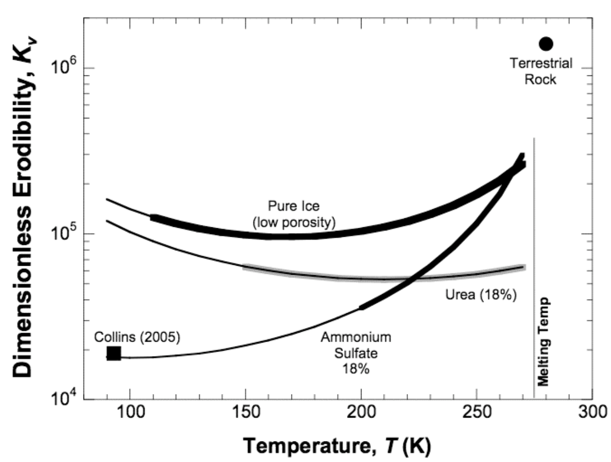

Figure 4: The abrasion resistance coefficient calculated for pure ice samples from the drum tests in Figure 3, compared to typical terrestrial sandstone and previous ice results [6].