ABRASION SUSCEPTIBLITY OF ULTRA-COLD WATER ICE: PRELIMINARY MEASUREMENTS OF ABRASION RATE, TENSILE STRENGTH AND ELASTIC MODULUS.

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Introduction: Images of the surface of Titan obtained by the Cassini mission have revealed a remarkably earth-like surface morphology, with branching channel networks, meandering river valleys, and finely-dissected ridge and valley topography [1-3]. Fluvial erosional processes likely play a major role in modifying Titan's surface, raising the question of whether we can apply process models developed for fluvial bedrock incision on earth to ultra-cold conditions on Titan, where liquid methane is cutting into water ice.

The saltation-abrasion bedrock incision model, developed by *Sklar and Dietrich* [4] is sufficiently explicit in its representation of the physics of rock detachment by low-velocity sediment impacts to be scaled to Titan considitions [5]. The model treats erosion as proportional to the flux of kinetic impact energy delivered to the river bed by saltating bedload sediments. Wear of brittle-elastic materials by repeated low-veocity impacts occurs by the growth and intersection of a network of fractures. The energy required to detach a unit volume of rock (ε_v) is proportional to the material strain energy, which depends on tensile strength (σ_T) and the modulus of elasticity (E)

$$\varepsilon_v = K_v \frac{\sigma_T^2}{2E} \qquad (1)$$

where the constant of proportionality (K_v) is a dimensionless abrasion susceptibility coefficient. *Sklar and Dietrich* [6] established experimentally that for a wide variety of terrestrial rock, K_v is a constant $\sim 10^6$ to first order, but varies somewhat depending on the relative strength and surface geometry of the bedrock and impacting sediment particles.

Impact tests on sea ice [7] have shown that the erosion rate of water ice is also proportional to impact energy, suggesting that ultra-cold water ice can be modeled with equation 1. To estimate the value of K_v for water ice under Titan conditions, *Collins* [5] conducted simple drop tests with ice samples cooled with liquid nitrogen, and found K_v to be $\sim 10^4$, suggesting that water ice is roughly 100 times more erodible than rock of similar strength. However, these tests were not conclusive, in part because we lack measurements of σ_T and E measured at ultra-cold temperatures, far from the melting point of ice.

Here we report preliminary results of an experimental program to measure rates of water-ice erosion by ice sediment impacts, as well as water-ice material properties, from near melting point down to the ~90 °K conditions that prevail on Titan.

Making and testing water-ice "bedrock": To create consistent, poly-crystalline ice, we freeze clear blocks from boiled-distilled water, which we then crush and sieve to obtain uniform-sized seed crystals ranging from 1 to 4 mm. The seed crystals are packed into cylindrical and disk-shaped molds, which are then filled with near-freezing water. The molds have copper bottoms and insulated sides and tops, to force the water to freeze from the bottom up, preventing any bubbles and large fractures from forming.

We use the 50mm-diameter cylinders for "Brazilian" tensile-splitting strength tests [6], in which samples are loaded on a line parallel to the cylinder axis to cause tensile failure. Ice cylinders are also loaded in axial compression for measurements of elastic modulus. We use dry ice and liquid nitrogen to control sample temperature, and have conducted tests both in air and submerged in ethanol; we will submerge samples in liquid nitrogen to reach the coldest temperatures.

To reproduce the sediment particle impacts that drive fluvial incision, we have constructed an apparatus for repeatedly dropping an ice clast from a known height onto an ice disk target. The 20cm-diameter, 10cm-thick disks are placed in the bottom of a cylinder, which is encased in a larger cylinder that can hold dry ice or liquid nitrogen (figure 1). We use balloons as molds to make spheroidal ice sediment clasts, and position lead weights suspended from Kevlar strings in the balloon center before adding ice seed crystals and water in a freezer. In the test apparatus, the string is used to raise the clasts to a known height before releasing, while the lead weights allow control of the buoyant density of the ice clasts for submerged drop tests. We will conduct drop tests in air and submerged in ethanol and liquid nitrogen. After a sequence of drops from a fixed height, any liquid is drained off, eroded fragments are vacuumed from the disk surface, and the disk is weighed from a suspended balance. Volume eroded per impact energy can be calculated from the change in disk mass and the clast mass, and impact velocity.

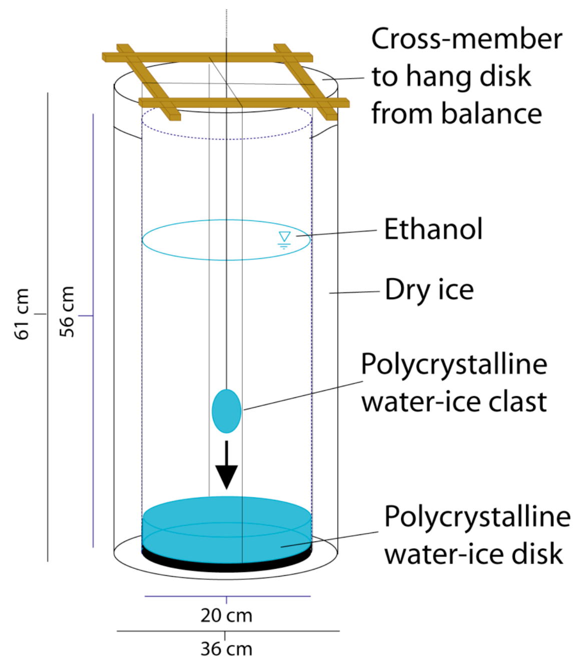

Figure 1. Schematic of drop test apparatus for measuring erosion of ice disks due to multiple impacts of water ice sediment clasts.

Preliminary experimental results: To date we have obtained measurements of ice tensile strength over temperatures ranging from -5 to -75 °C, for two grain-size ranges, in both air and submerged in ethanol (figure 2). These preliminary data suggest a linear increase in tensile strength down to about -50 °C, below which strength may become insensitive to further reductions in temperature.

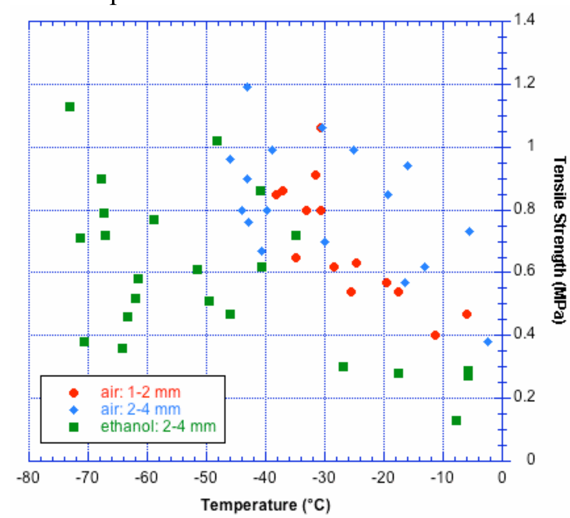

Figure 2: Preliminary measurements of variation in ice tensile strength with temperature.

Applications to planetary geomorphology: Understanding the controls on ice strength and abrasion susceptibility will not only help parameterize the saltation-abrasion fluvial incision model for application to Titan, but will be useful for interpreting many other geomorphic processes and features on Titan as well as on Mars. For example, the efficiency of fluvial erosion by suspended particles, and erosion by aeolian processes, should depend on abrasion susceptibility. The width and sinuosity of bedrock channels on earth are sensitive to rock strength, as is the rate of knickpoint propagation [8]. Strength also plays a role in the debate over the importance of sapping in creating amphitheater headed valleys [9].

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