Where does Titan Sand Come From: Insight from Mechanical Properties of Titan Organic Analogs.
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Introduction: Across the Solar System, many planetary worlds have aeolian processes despite the wide spread environmental conditions on these bodies: Venus, Earth, Mars, Titan, Neptune's moon Triton, possibly Pluto and comet 67P. Other than environmental conditions, what makes the aeolian processes on icy bodies (Titan, Triton, and Pluto) different from on terrestrial bodies (Venus, Earth, and Mars) is the transporting materials. On icy bodies, the transporting material is mainly organics produced photochemically in the atmosphere, while it is mainly silicate sand (weathering and erosion products of silicate rocks) transporting on terrestrial bodies. Silicate sand is known to have high resistance to abrasion due to its hardness, and it might be the reason that it can transport long distances, eventually spreading across the whole planet, without being abraded to dust [1]. While for icy bodies like Titan, we do not know the basic mechanical properties of the organic sand on the surface, so we cannot infer its transport capabilities.

Another puzzle is that the mechanism for how small aerosol particles produced in Titan's atmosphere (up to 1 μm [2]) are transformed into large, sand-sized particles on Titan's surface (100—300 μm). Barnes et al. [3] proposed four mechanisms for the transformation: sintering, lithification and erosion, flocculation, and evaporation. The sintering and lithification and erosion mechanisms could happen in subaerial conditions while the flocculation and evaporation need subaqueous environments. However, current lakes and seas on Titan are mainly at high latitudes while the longitudinal dunes are thousands kilometers away in the equatorial region. Thus, if sand particles on Titan are still actively produced in the current lakes and sea, they need to be mechanically strong enough to travel long distances to the equator. If that is not the case, then either the sand on Titan is produced by paleo-seas like Tui Regio or the subaqueous mechanism is not how Titan sand particles form.

Therefore, it is important to quantify the mechanical behaviors of Titan sand analog materials so that we can understand the origin of Titan's sand particles and their transportation behaviors better. The lab produced “tholin” is compositionally similar to Titan sand [4], but is usually produced in low yields and thus is hard to quantify mechanically using macroscopic approaches. This makes nanoindentation an ideal method to quantify the mechanical behaviors of the thin tholin films.

Kuenen [5] found that various mechanical properties are involved in mechanical abrasion in Aeolian transport. For relatively soft materials, the dominant abrasion mechanism is “grinding” (where hardness of the material dominates). While for relatively hard materials like quartz, its brittleness makes “chipping” (or “spalling”) the dominate mechanical abrasion mechanism under aeolian transport. ‘Chipping’ of quartz sand slow down with increasing roundness and decreasing size of grains. Thus it is important to characterize both the mechanical hardness and brittleness (fracture toughness) of the Titan sand analog, so that we can better assess the aeolian transportation capability of organic sediments on Titan.

Methods: *Materials and preparation.* Materials used in our study include: 1) analog organic materials for Titan sand, including laboratory produced tholin [6], naphthalene, biphenyl, and two polycyclic aromatic hydrocarbons (PAHs) (phenanthrene and coronene); 2) natural sand on Earth (silicate beach sand, basalt, and white gypsum sand); 3) materials used in planetary wind tunnels, including walnut shells, instant coffee, activated charcoal, etc. [7].

Laboratory produced tholin film (thickness ~1.3 μm) is used directly for the measurements. While other materials in particle are prepared before measurement. The preparation procedure is as follows: the particles were embedded in an epoxy matrix using a vacuum mounting system in cylinder sample stubs (1.25” diameter). The samples were cured overnight resulting in a composite of particles in a hardened epoxy matrix. The samples were then polished using either a Tegramin-20 Sample polisher (for non-water soluable materials, finest polishing size is 40 nm) or hand polishing (for water soluable materials, finest polishing size is 6.5 μm).

Nanoindentation and tips. An iNano Nanoindenter was used for elastic modulus, hardness and fracture toughness measurements. We used a Berkovich tip for elastic modulus and hardness measurements. A set of load-displacement curves were taken on each material. To obtain a higher accuracy of measurement, we performed dynamic indentation through each load-displacement cycle so the instrument could continuously measure hardness as a function of displacement.

We used a much sharper cube-corner tip to measure fracture toughness, which can significantly reduce the cracking thresholds of brittle materials [8]. When brittle materials are indented with the sharp cube-corner tip, radial cracks are generated. We used an atomic force microscope to image the indents and the associated cracks. Fracture toughness (K) can be calculated through: $K=\alpha(E/H)^{0.5}(P_{max}/c^{3/2})$ [9], where α is an empirical constant that depends on the geometry of the tip, for a cube-corner tip, $\alpha=0.036$ [8]. P_{max} is the maximum load on the sample, and the c is the crack length determined in AFM images.

Results: *Hardness and elastic modulus.* Table 1 shows the elastic moduli and hardness of all materials. Tholin has a Young's modulus of around 10 GPa and hardness around 0.5 GPa. In terms of amorphous organics, which usually have moduli in the range of 1-10 GPa, tholin is very stiff. This may be caused by cross-linking between molecule chains in tholin similar to network polymers [10]; so stretching or breaking of covalent bonds are necessary to deform tholin.

Even though tholin is very stiff as an organic material, its stiffness and hardness is an order of magnitude lower than silicate sand (modulus ~100 GPa, hardness ~14 GPa) and basalt (modulus ~100 GPa or ~200 GPa, hardness ~9 GPa or ~14 GPa). As a mechanically weak sand on Earth, white gypsum is an example of a material that is not able to transport long distances because of its mechanical weakness and also its high solubility to water [11]. However, white sand is stiffer (37 GPa) and harder (1.5 GPa) than tholin.

It is interesting to note that lots of low density wind tunnel materials have similar hardness and modulus to tholin, including walnut shells (hardness 0.3 GPa, modulus 7 GPa), instant coffee (hardness 0.4 GPa, modulus 8 GPa) and activated charcoal (hardness 0.8 GPa, modulus 9 GPa), even though those materials have very different interparticle forces compared to tholin [4, 7].

The simple solid organics (naphthalene, biphenyl, coronene, and phenanthrene) we tested, could be good analogs to evaporites on Titan, which may be mainly made of acetylene, ethylene or butane [12, 13]. However, they all have lower stiffness and hardness than tholin. This indicates that evaporites may be poor candidates for Titan's equatorial sand since they are mechanically weaker than tholin.

Table 1: Measured Hardness and elastic modulus of materials.

Material	*Hardness (GPa)*	*Std. Dev. (GPa)*	*Modulus (GPa)*	*Std. Dev. (GPa)*
Tholin	0.528	0.026	10.38	0.52
Quartz Sand	13.583	0.347	107.50	1.49
Basalt	9.104	1.024	92.31	8.75
	13.865	1.009	184.35	6.61
White Gypsum Sand	1.531	0.402	37.44	7.19
Walnut Shells	0.258	0.054	6.02	1.14
Instant Coffee	0.421	0.090	7.99	1.18
Activated Charcoal	0.802	0.310	8.78	1.34
Napthalene	0.083	0.014	8.41	1.16
Biphenyl	0.056	0.023	2.38	0.59
Phenathrene	0.143	0.038	5.90	0.89
Coronene	0.057	0.026	2.27	0.85

Fracture Toughness. Table 2 shows the fracture toughness of several selected materials. Material with lower fracture toughness is more brittle. Tholin has a fracture toughness of 0.036 $MPa \cdot m^{0.5}$, which is a magnitude lower than quartz sand (0.89 $MPa \cdot m^{0.5}$) and basalt (0.55 $MPa \cdot m^{0.5}$). Thus, tholin is very brittle and is easy to break apart during transportation.

Table 2: Measured fracture toughness of various materials.

Material	*Fracture Toughness ($MPa \cdot m^{0.5}$)*	*Std. Dev. (GPa)*
Tholin	0.036	0.007
Quartz Sand	0.89	0.03
Basalt	0.55	0.05

Discussion: The low hardness and high brittleness of tholin indicates that it may not be able to transport long distances as the prevalent quartz sand on Earth. Thus, Titan sand may not not originate from the current lakes and seas because it is not mechanically strong enough to transport from the poles to the equator. Another possible mechanism is that Titan sand is cyclically broken apart and then electrostaticly aggregated together during transport. The lower hardness and stiffness of several simple organics and PAHs compared to tholin also indicate that evaporites may be even worse candidates for Titan sand because of their mechanical weaknesses.

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