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PROPERTIES OF THE DUNE SANDS OF TITAN: KNOWN AND UNKNOWN. Jani Radebaugh¹, Jason W. Barnes², Alice Le Gall³, Xinting Yu⁴, Elizabeth P. Turtle⁵, R. Aileen Yingst⁶, Shannon Mackenzie⁵, Sarah Horst⁴, Jonathan Lunine⁷, Jeff Johnson⁵, Mike Malaska⁸, Catherine Neish⁹, Sebastien Rodriguez¹⁰. ¹Department of Geological Sciences, Brigham Young University, Provo, UT (janirad@byu.edu), ²University of Idaho, Moscow, ID, ³LATMOS/IPSL, Paris, France, ⁴Johns Hopkins University, MD, ⁵Johns Hopkins University Applied Physics Laboratory, Laurel, MD, ⁶Planetary Science Institute, Tucson, AZ, ⁷Cornell University, Ithaca, NY, ⁸Jet Propulsion Laboratory, Pasadena, CA, ⁹University of Western Ontario, London, ON, ¹⁰University of Paris Diderot, Paris, France.

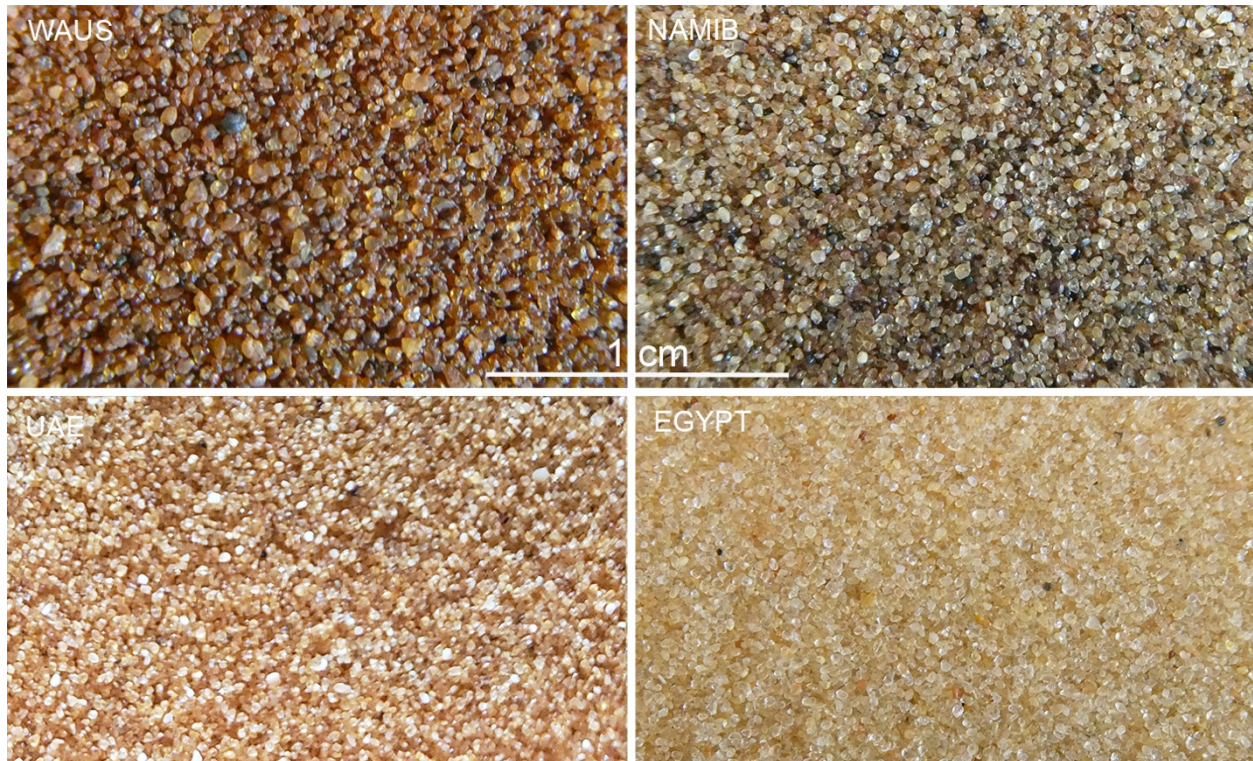


Fig. 1. Sands in linear dunes on Earth. WAUS: Great Sandy Desert, Western Australia. NAMIB: Dead Vlie in the Namib Sand Sea. UAE: United Arab Emirates south of Al Ain. EGYPT: Great Sand Sea in western Egypt.

Introduction: Titan is a sedimentary world, with large cobbles filling river channels [1, 2] and fans [3, 4] and with small dust observed in the atmosphere [5] and as evaporites and other deposits on the surface [6]. But intermediate-sized sedimentary particles, i.e. sands, make up a significant proportion of the sedimentary surface cover of Titan. They form dunes and sandy regions that span large areas near the equator, up to 18% of Titan's surface area [7, 8]. They also fill channels and shorelines and form some high-latitude dunes. Many aspects of these sands are still unknown [9], but there are certain properties that are required, based on what has been observed by Cassini and by what is known from morphologically identical, large, linear dunes on Earth (Fig. 1). We discuss these knowns and the needed work to continue to predict the nature of the sands of Titan.

Titan Sand Particle Size: Materials on planetary bodies can organize into sand dunes if they fall into a specific size category (appropriate for their body's gravity and atmospheric density; [10]). Based on

atmospheric density, gravity, and particle density, the sands of Titan are constrained to be similar in size to those of Earth, $\sim 0.18\text{-}0.25$ mm [7] (Fig. 1). Furthermore, the sandy regions of Titan are dark to Cassini Synthetic Aperture Radar (SAR) at a wavelength of 2.17 cm, indicating the particles are small and/or the surface is smooth at that scale [7, 11]. The consistency observed in terrestrial dune sand sizes and the narrow size distributions of linear dune sands (Fig. 1) reveal that saltation and dune formation is strongly effective at sorting.

Titan Sand Cohesion: Sand particles must be free to saltate, that is to move by the action of wind knocking particles into one another in a chain reaction of collisions, in order to form into dunes [12]. In Titan's current environment, cohesive, relatively immobile, sands would erode fluvially and fill in the interdune regions. This is not seen in Cassini SAR and Visual and Infrared Mapping Spectrometer (VIMS) images; rather, dunes are frequently distinct from interdunes [13, 14].

Dune sands can occasionally be cohesive, such as in the clay dunes found in western China [15], but these features are lee dunes, and are thus not morphologically analogous to the large, linear dunes on Earth and Titan [7]. Sand made of quartz can charge frictionally, as happens in volcanic ash clouds, and become temporarily cohesive. Studies of Titan sand analogues show electrical charging and other factors can increase cohesiveness [16, 17], but given the dune morphologies and lack of sand in the interdunes, this condition cannot be widespread or long-lived.

Titan Sand Hardness: Sands in sand seas on Earth can move large distances over long periods of time [18]. Sand particles move in discrete saltation events, covering ~10-50 cm: to move from the middle of one interdune to the nearest dune (~0.5 km) would require ~1000 individual jumps. It is likely that particles within a sand sea move much greater distances in their lifetime, and thus survive hundreds of thousands of saltation events. If Titan sand broke down easily, then it would not be able to persist over long time periods in dunes, as we see the mature quartz sands on Earth do (Fig. 1). Sand hardness is measured as peak load over area and also scales linearly with the elastic modulus [19]. Quartz is of a generally high hardness and breaks down by chipping or spalling until it reaches a round shape (Fig. 1) [20, 19].

Titan Sand Composition: Titan's sands are known to have a high proportion of organics. In Cassini VIMS and Imaging Science Subsystem (ISS) observations they are dark in color, consistent with organic material [21]. Furthermore, VIMS spectra and RADAR radiometry properties are consistent with a high proportion of organics [13, 14, 22, 23]. Experiments on organic materials that are analogues for Titan sand, e.g. tholins, reveal an order of magnitude lower hardness (0.5-0.8 vs. 15 GPa), meaning they break down more readily.

Titan's bedrock is composed of water ice with a sedimentary veneer of organics, and on Earth, the sand in large sand seas is derived from such preexisting rocks. It has been suggested that Titan's sand could consist of water ice coated in organics [9], which would be consistent with Cassini radiometry observations (effective permittivity of 1.6, high emissivity, and low volume scattering) [23]. This scenario is analogous to quartz sand being coated with iron oxide, which is common in any red dune sands on Earth. Water ice at Titan's temperatures is modeled to have the same (or lower) hardness as tholins [19]; however, it has an order of magnitude higher fracture toughness, or ability of cracked material to resist fracture, at 0.89 vs. 0.036 MPa*m^{1/2} (though organics are 0.6-5.0 and quartz only 0.89 MPa*m^{1/2}) [19]. Thus, water ice as a component of Titan's dune sands, or perhaps of fluvial/alluvial sands in other regions [24], should not be ruled out.

The gypsum sands of White Sands, NM have an order of magnitude lower hardness (1-2 GPa) than quartz (Fig. 2). These sands have traveled up to 15 km and been formed into dunes. These sands break down into dust and leave the dune system, and must be replenished by new sand, which is created in a playa upwind [6].



Fig. 2. White Sands in New Mexico, US. gypsum sands.

While the gypsum sands are several times harder than tholins [19], they are a possible analogue for Titan sands [9]. Under this scenario, a persistent source of new sand would be needed to accommodate the constant breakdown [25]. However, the formation of large, mature dunes, suggests the sands move great distances over long periods of time, requiring robustness.

Conclusions: In the analogous sand seas of Earth, sand-sized particles are loose and hard. To understand Titan's dunes, it is important to identify materials with properties that could make up the sands of Titan. Potentially, the sand could be sampled directly by future missions, e.g. *Dragonfly* [26]. Experiments at Titan temperatures with all kinds of organics, in addition to tholins [19], and organic-covered water ice, will prove fruitful.

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