SPECTRAL PROPERTIES OF TITAN'S IMPACT CRATERS IMPLY CHEMICAL WEATHERING OF ITS SURFACE.

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Introduction: The Visual and Infrared Mapping Spectrometer (VIMS) on the Cassini spacecraft has shown that the surface of Titan is spectrally diverse [1]. Some regions on Titan appear enriched in water-ice, other regions are highly correlated with regions of organic sand particles [2], and still other regions are interpreted to be areas of evaporites [3]. There is also a widespread spectral unit known as the equatorial bright terrains composed of an as yet unidentified substance less enriched in water ice. The spectral units tend to have a strong latitudinal dependence, with most dune units within 30° of the equator, and many evaporitic units found around lakes near the poles.

The observed variations in composition are somewhat surprising, given that Titan's atmosphere supports an active photochemistry. These reactions produce an organic haze that eventually settles to the surface, and a few micron layer of such aerosols could obscure the composition of any underlying material. The spectral variety indicates that Titan has a surface actively shaped by exogenic and possibly endogenic processes (e.g., [4]). To determine the composition of Titan's upper crustal layer, one must therefore look at features that have been exposed in the recent past. Impact craters are capable of probing the subsurface, so the rims, ejecta blankets, and central uplifts of the freshest craters should represent the composition of Titan's upper crust. A crater's excavation depth is roughly 1/10 the transient diameter, so for Titan's craters (which typically have final diameters > 20 km), this translates to a depth of several kilometers [5].

Most models of Titan's origin and evolution suggest that its crust is ice rich, and recent atmospherically corrected images of Titan's surface support this notion [6]. However, the material exposed in the rims of fresh impact craters does not appear to be the most ice-rich material found on Titan. Sinlap is one of the freshest craters on Titan, with a depth comparable to similarly sized craters on Ganymede [7], but its rim, ejecta blanket, and central uplift are not composed of the spectral unit thought to represent ice-rich material [8]. Rather, they are characterized by an unidentified spectral unit that appears less enriched in water ice. Soderblom et al. [2] proposed that this material represents a deposit of bright, fine precipitating aerosols, but that fails to explain why Sinlap – a feature known to be relatively young – looks spectrally similar to the equatorial bright terrains that are presumably much older. It also fails to explain why Sinlap shows any spectral diversity at all, and is not uniformly coated in aerosols.

In this work, we analyze the spectral properties of a sample of Titan's impact craters, to infer their evolution over time. We use the depth of the crater as a proxy for the degradation state, and observe how craters change as exogenic processes modify them. The results will help to constrain the composition of Titan's upper crust, as well as the primary processes working to degrade its surface.

Observations: VIMS uses spectral image mapping to obtain images in 352 colors simultaneously [9]. VIMS's wavelength range, 0.3 – 5.2 μm, includes windows at 0.92, 1.06, 1.26, 1.57, 2.0, 2.7, 2.8, and 5.0 μm, where neither haze nor atmospheric absorption completely obscures Titan's surface. Combinations of these windows enable the production of color images of the surface of Titan. In this work, we will use a color scheme (R: 4.8–5.2 μm, G: 2.00 μm, B: 1.28 μm), such that 'blue' indicates regions enriched in water-ice, 'brown' indicates regions of organic sand particles, 'red' indicates regions of hydrocarbon-rich evaporites, and 'green' indicates an unidentified substance less enriched in water ice.

We examined three craters in a range of degradation states (Fig. 1). All three craters have overlapping Cassini RADAR and VIMS images, as well as a depth estimate from either SARTopo profiles or stereo topography [7]. We use the relative depth of the crater, R(D), as a proxy for degradation state. Relative depth is defined as $R(D) = 1 - d_t(D)/d_g(D)$, where $d_t(D)$ is the depth of a crater with diameter D on Titan, and $d_g(D)$ is the depth of a crater with diameter D on Ganymede. A relative depth of zero indicates the crater is as deep as a similarly sized crater on Ganymede, while a relative depth of one indicates the crater is completely flat [7]. Craters with small relative depths are therefore less degraded than craters with large relative depths.

The least degraded crater examined here is Sinlap, with a relative depth of 0.4 ± 0.2. It is characterized by a spectrally 'blue' interior and a spectrally 'green' rim and ejecta blanket [8]. The rim of Sinlap is presumably some of the freshest material exposed on the surface of Titan, yet it is less enriched in water ice than many other areas on Titan, including its own crater floor. Le Mouélic et al. [8] also observe the remnants of a central uplift on Sinlap's crater floor, with a spectral signature similar to its ejecta blanket. This suggests that the impact target site was vertically homogeneous.

Craters that are more degraded than Sinlap, such as the crater in Santorini Facula (R = 0.65 ± 0.12), are characterized by a spectrally 'brown' interior and a spectrally 'green' rim. In the case of the crater Paxsi, Buratti et al. [10] attribute this to infilling by dune material. This interpretation is strongly supported in the case of Santorini, where there are dune forms observed in the crater interior in the high resolution RADAR image. As in the case of Sinlap, the rim and ejecta blanket are spectrally similar to the nearby equatorial bright terrain.

Finally, Soi, the shallowest known crater on Titan (R = 0.8 ± 0.1), is characterized by a spectrally 'green' interior and a spectrally 'blue' rim. Soi is an extremely degraded crater, and may have been subject to both fluvial erosion and infilling by sand. However, if Soi was ever filled in by sand, sediments of a different composition have since coated it.

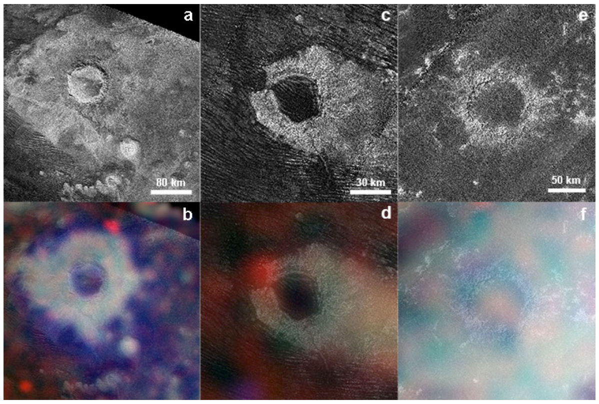

Figure 1: Cassini RADAR and VIMS images of three craters on Titan in a range of degradation states: (a-b) Sinlap, (c-d) Santorini, and (e-f) Soi. Colors are mapped with 4.8–5.2 µm as red, 2.00 µm as green, and 1.28 µm as blue.

Discussion: These observations suggest an evolutionary sequence for Titan's impact craters, which includes both mechanical and chemical weathering (Fig. 2). We propose that the rims, ejecta blankets, and central uplifts of Titan's impact craters are composed of a water ice matrix whose cracks and pores are filled with concretions of an unknown organic substance. The craters undergo rapid erosion by fluvial processes and mass wasting, forming steep crater walls, removing evidence of central peaks or central pits, and filling the crater with water-ice rich sediments. During this process, mechanical weathering reduces the crater's depth while the chemical weathering removes the organic concretions, leaving the water ice matrix intact. Water ice is incredibly resistant to chemical weathering by organic solvents, but theoretical estimates of the equilibrium solubilities of many of Titan's organic materials suggest they may be as soluble as common cave forming materials on Earth, such as limestone [11]. The crater interior may then be filled with wind blown sand, and eventually, organic sediments washed off the crater walls. This last stage results in an ice-rich rim surrounding an organic rich interior.

Since the central uplifts and rims of Titan's craters are sourced from the top few kilometers of its crust, one interpretation of this evolutionary sequence is that Titan's upper crust is not composed of pure water ice. If Titan had a haze-producing atmosphere during the Late Heavy Bombardment, it is possible that the organics could be intimately mixed with water ice in a deep megaregolith. Alternatively, the ejecta blanket and central uplift could become intimately mixed with hydrocarbons on Titan's surface during or shortly after crater formation. In either case, it appears Titan's craters expose an intimate mixture of water ice and hydrocarbons from depth, and chemical weathering by methane rainfall removes the soluble organic materials, leaving the insoluble water ice behind.

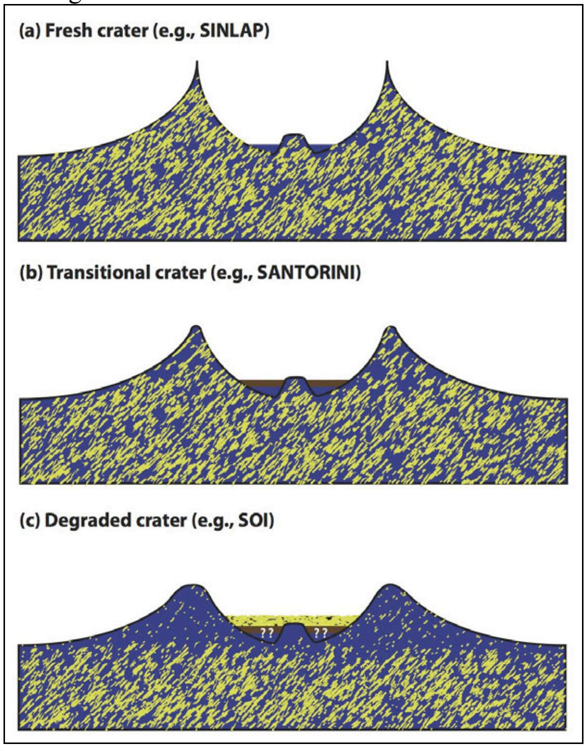

Figure 2: A proposed progression of impact crater degradation on Titan. Blue materials are water-ice rich, brown materials are correlated with regions of sand dunes, and yellowish-green materials represent an as-yet unknown material, presumably more enriched in organic material.

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