THE UNUSUAL CRATER SOI ON TITAN: POSSIBLE FORMATION SCENARIOS. C. D. Neish[1], R. D. Lorenz[2], J. L. Molaro[3], J. Lora[3], A. D. Howard[4], R. L. Kirk[5], J. W. Barnes[6], J. Radebaugh[7], E. P. Turtle[2], V. J. Bray[3], and P. Schenk[8]. [1]NASA Goddard Space Flight Center, Greenbelt, MD, 20771 (catherine.d.neish@nasa.gov), [2]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, 20723, [3]The University of Arizona, Tucson, AZ, 85721, [4]The University of Virginia, Charlottesville, VA, 22908, [5]Astrogeology Science Center, U.S. Geological Survey, Flagstaff, AZ, 86001, [6]The University of Idaho, Moscow, ID, 83844, [7]Brigham Young University, Provo, UT, 84602, [8]Lunar and Planetary Institute, Houston, TX, 77058.

Introduction: Unique among the icy satellites, Titan's surface shows evidence for extensive modification by fluvial and aeolian processes. Quantifying the extent of this modification is difficult, since the original, un-eroded surface topography is generally unknown. However, fresh craters on icy satellites have well-known shapes and morphologies, so by comparing the topography of craters on Titan to similarly sized, pristine analogues on airless bodies, we can obtain one of the few direct measures of the amount of modification that has occurred on Titan.

A recent study of crater topography on Titan found that most of Titan's craters are within the range of depths observed for similarly sized fresh craters on Ganymede, but several hundreds of meters shallower than Ganymede's average depth versus diameter trend [1]. One notable exception is Soi crater (24°N, 141°W), a 78-km-diameter crater with a stereo-derived depth of only 242 ± 115 m [2] (Figure 1). This makes Soi ~800 m shallower than a typical Ganymede crater of its size (a relative difference of ~80%) and the 'flattest' known crater on Titan. In this work, we investigate several formation scenarios that may explain Soi's unusual topography, including viscous relaxation, impact into a shallow marine environment, infill by cryolava, infill by sand, and infill by fluvial sediments. We judge infill by fluvial sediments to be most consistent with the currently available observations, although we cannot rule out the possibility that some combination of multiple processes has worked to modify this crater's morphology.

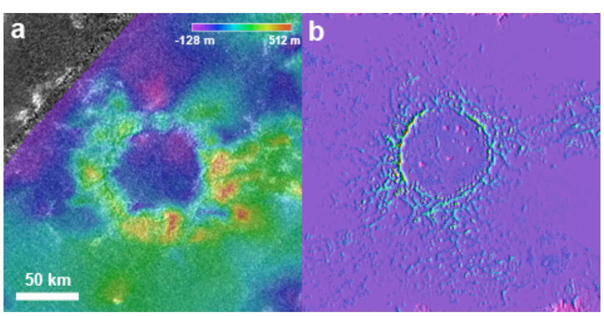

Figure 1: (a) DTM of Soi on Titan (D ~ 78 km), overlaid on a Cassini RADAR image of the same region. (b) Simulated DTM of Isis crater on Ganymede (D ~ 75 km), degraded by fluvial erosion so that it has the same approximate depth as Soi (see *Infill by Fluvial Sediments.)*

Formation Scenarios: There are several geologic processes that could account for Soi's unusually flat topographic profile. Using Cassini RADAR and Visual and Infrared Mapping Spectrometer (VIMS) data, along with stereo-derived topography and comparisons to planetary analogues, we investigate five of the most likely processes below.

Viscous Relaxation. One mechanism known to alter crater topography and reduce crater depths on icy satellites is viscous relaxation [e.g., 3]. Craters > 10 km in diameter on Ganymede show a range of relaxation states, from fresh craters to craters with more subdued topography and upbowed floors. However, given Titan's lower surface temperature (95 K vs. 120 K), viscous relaxation is predicted to cause less than a 3% change in topography for craters with D < 125 km on Titan [4]. Furthermore, craters on Titan do not appear to have a depth distribution typical of viscous relaxation [1], and Soi in particular shows no evidence of an upbowed floor (the floor topography varies by only ~40 m). Still, it is difficult to completely rule out viscous relaxation as a modification process for any single crater on Titan.

Marine Impact. The presence of liquids on the surface and in the near subsurface of a planetary body can also cause extensive modification to crater shape [5]. Craters formed in marine environments on Earth lack any significant surface topography, as poorly consolidated, water-saturated sediments slump into the crater shortly after its formation [5]. One particularly intriguing analogue is Lawn Hill crater in Queensland, Australia [6]. Like Soi, it has a radar-bright ring and radar dark interior, but only ~20 - 40 m in topographic relief. There is, however, a noticeable compositional difference between the limestone precipitate that makes up the radar-bright ring and the shale basement rock found in the interior. If a similar process occurred on Titan, we might expect a similar compositional contrast, with an organic-rich precipitate forming the ring and ice-rich basement rock in the interior. VIMS observations reveal the opposite trend – an ice-rich ring with an organic-rich interior (Figure 2). We thus rule that a marine impact into a simple organic-over-ice target is unable to explain the observed structure of Soi.

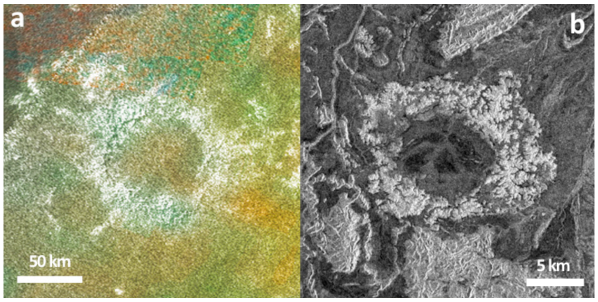

Figure 2: (a) VIMS tri-band color image of Soi, overlaid on a Cassini RADAR backscatter image of the same region. The spectra are most consistent with an ice-rich rim, and an organic coating in the crater interior. (b) European Remote Sensing satellite image of Lawn Hill crater in Australia. The radar-bright crater annulus is composed of limestone that may have slumped into the crater during a marine impact [6].

Infill by Cryolavas. Morphologically, Soi resembles some Venusian craters, with rough, radar-bright rims filled with smooth, radar-dark lava [7]. If areas of the surface of Titan were flooded by nearly a kilometer of lava, one might expect other nearby craters to be similarly infilled. The closest crater with measured topography, Afekan, is ~2500 km away and ~500-700 m shallower than a typical Ganymede crater of its size (a relative difference of ~50-60%). Although cryolavas would likely be icy in composition, organic precipitates washing off from the crater rim could have later coated the interior of the crater. Thus, we cannot rule out infill by cryolavas as a possible modification mechanism.

Infill by Sand. An initial survey of Titan's craters found that the depth distribution is consistent with a modification process whose rate is constant with time, such as aeolian infilling [1]. Simple aeolian infilling tends to leave the crater rim largely clear of deposits, while the crater center becomes filled with a deposit roughly parabolic in cross-section [8]. From the relationship between crater rim height and crater diameter given in Bray et al. [9], we expect the unmodified rim of Soi to be between 0.3 and 1.2 km in height, which exceeds the observed depth of 0.24 ± 0.11 km. The VIMS spectra of the crater interior are also not consistent with infill by 'brown' sand, unless the sand was later coated by atmospheric sediments. Thus, active aeolian infill cannot account for the topographic profile of Soi, but we cannot rule it out as an important process in the past.

Infill by Fluvial Sediments. Fluvial erosion is clearly an important process on Titan, as images from the Cassini spacecraft reveal a world with extensive networks of riverbeds and valleys. Simulations of Martian crater evolution suggest that fluvial modification infills crater floors while the crater rim gradually backwastes [8]. To determine the extent to which fluvial modification can alter the depths of craters on Titan, we used a landscape simulation model similar to that presented in [8] and applied it to a Ganymede crater similar in size to Soi (Figure 1b). We monitored the change in the relative depth of the crater, $R = 1 - d(t=t_i)/d(t=0)$, over time, and found an infilling rate that diminishes with time, leveling out at R ~ 0.8 as crater slopes decrease and the area of deposition on the crater floor increases (Figure 3). Thus, fluvial modification alone can account for the topography of Soi. The organic coating observed in the crater interior could be explained by organic precipitates washing off from the surrounding water-ice crater rim.

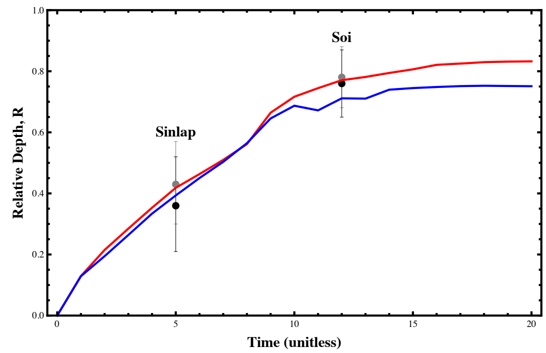

Figure 3: The relative depth, R, of Isis crater as a function of relative time during simulations of fluvial erosion for a sand substrate (red) or a gravel substrate (blue). Data points show the relative depths of Soi and Sinlap compared to the average depths of craters of similar size on Ganymede, as reported by Bray et al. [9] (gray) and Schenk [10] (black).

Summary: Soi is the flattest known crater on Titan. Our simulations show that fluvial modification can account for the relatively subdued topography of this feature, although we cannot rule out the possibility that some combination of multiple processes (e.g. infill by cryolavas or sand) has worked to modify the crater's morphology. If this is the correct interpretation (and the rates of fluvial erosion do not vary dramatically between their locations), it indicates that Soi must be at least twice as old as the much fresher crater Sinlap (D ~ 82 km). This is the first quantitative estimate of relative crater ages on Titan.

References: [1] Neish C.D. et al. (2013) *Icarus, in press*. [2] Kirk R.L. (2012) *AGU, Abstract #P22B-02*. [3] Dombard A.J. and McKinnon W.B. (2006) *JGR, 111*, E01001. [4] Baugh N. and Brown R.H. (2006) *BAAS, 38*, 587. [5] Collins G.S. and Wunnemann K. (2005) *Geology, 33*, 925-928. [6] Salisbury J.A. et al. (2008) *Aust. J. Earth Sci., 55*, 587-603. [7] Herrick R.R. and Rumpf M.E. (2011) *JGR, 116*, E02004. [8] Forsberg-Taylor N.K. et al. (2004) *JGR, 109*, E05002. [9] Bray V.J. et al. (2012) *Icarus, 217*, 115-129. [10] Schenk P.M. (2002) *Nature, 417*, 419-421.