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Crater relaxation on Titan aided by low thermal conductivity sand infill

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ABSTRACT

Titan's few impact craters are currently many hundreds of meters shallower than the depths expected. Assuming these craters initially had depths equal to that of similar-size fresh craters on Ganymede and Callisto (moons of similar size, composition, and target lithology), then some process has shallowed them over time. Since nearly all of Titan's recognized craters are located within the arid equatorial sand seas of organic-rich dunes, where rain is infrequent, and atmospheric sedimentation is expected to be low, it has been suggested that aeolian infill plays a major role in shallowing the craters. Topographic relaxation at Titan's current heat flow was previously assumed to be an unimportant process on Titan due to its low surface temperature (94 K). However, our estimate of the thermal conductivity of Titan's organic-rich sand is remarkably low (0.025 W m^{-1} K^{-1}), and when in thick deposits, will result in a thermal blanketing effect that can aid relaxation. Here, we simulate the relaxation of Titan's craters Afekan, Soi, and Sinlap including thermal effects of various amounts of sand inside and around Titan's craters. We find that the combination of aeolian infill and subsequent relaxation can produce the current crater depths in a geologically reasonable period of time using Titan's current heat flow. Instead of needing to fill completely the missing volume with 100% sand, only ~62%, ~71%, and ~97%, of the volume need be sand at the current basal heat flux for Afekan, Soi, and Sinlap, respectively. We conclude that both processes are likely at work shallowing these craters, and this finding contributes to why Titan overall lacks impact craters in the arid equatorial regions.

1. Introduction

Unlike most moons in our solar system, Saturn's moon Titan has very few impact craters identified on its surface. Only a few hundred crater candidates have been identified on Titan, of which only 11 have been officially recognized and named as craters (Buratti et al., 2012; Lorenz et al., 2007; Neish et al., 2013; Neish and Lorenz, 2012; Wood et al., 2010). Since impact cratering is among the most common geologic processes in the solar system, the number of impact craters on a planetary body can be used to indicate the relative extent of surface modification that it experienced. Surfaces dominated by impact craters are likely little modified, ancient surfaces, while low crater counts, such as on Titan, suggest that significant modification has occurred to remove craters. Indeed, Titan has many signs of surface modification processes: fluvial features with various morphologies are found across the globe (Burr et al., 2013; Langhans et al., 2012), there are hundreds of lakes and a few large seas that are constrained to the polar-regions (Stofan et al., 2007; Lorenz et al., 2014), many mountains and mountain chains have been identified (Liu et al., 2016; Radebaugh et al., 2007), the photochemically produced atmospheric haze of organic molecules continually snows to the surface (Tomasko et al., 2005), and there are vast sand seas of thousands of kilometer-long linear dunes in the equatorial region (Lorenz et al., 2006; Radebaugh, 2013; Savage et al., 2014).

Aside from being surprisingly crater-poor, Titan's surface is also abnormal in that the identified craters are hundreds of meters shallower than expected. Neish et al. (2013) used SARTopo (Synthetic Aperture RADAR-derived Topography; see Stiles et al., 2009) data to create topographic profiles of the named craters Ksa, Momoy, Sinlap, Soi, Hano, Afekan, Menrva, and two "probable" unnamed craters identified by Wood et al. (2010). Soi and the two probable craters did not have topographic profiles that resembled impact craters despite their morphological similarity to impact craters in SAR imagery. They might not be craters or may have had their topographies completely obliterated by some process or combination of processes (see Section 1.1). For the rest, Neish et al. (2013) measured the crater depths using the SARTopo topographic profiles for all of the craters except for Momoy, for which they used autostereo where the depths are estimated by comparing the

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Table 1
Crater rim height, actual depth, and total depth are average values measured from the two sides of the SARTopo crater profiles. *Momoy's current total depth and diameter were determined by Neish et al. (2013) using autostereo, but the apparent depth and rim heights could not be measured. **Soi's current topographic profile is so unclear that we could not measure the rim height and apparent diameter with confidence. We choose to use the same rim height as Sinlap, and choose the final apparent depth to be zero because it is essentially at the level of the background topography. The expected depth is the average of the depths expected for similar-size craters on Ganymede and Callisto using depth-diameter relationships for fresh craters over 25 km in diameter from Schenk (2002). Relative total depth is defined as $R(D) = 1 - d_t(D)/d_e(D)$, where $d_t(D)$ is the current total depth of the Titan crater and $d_e(D)$ is the expected depth.

Crater	Latitude (°N), longitude (°W)	Diameter measured (km)	Diameter modeled (km)	Current rim height (m)	Current actual depth (m)	Current total depth (m)	Expected initial total depth (m)	Total depth difference (m)	Relative total depth
Ksa	14, 65.4	39 ± 2	NA	180	470	650	1200	550	0.46
Momoy	11.6, 44.6	40 ± 1*	NA	–	–	680*	1200	520	0.43
Soi	4.3, 140.9	78 ± 2	80	340**	0**	340**	1100	760	0.69
Sinlap	11.3, 16	82 ± 2	80	340	300	640	1100	460	0.42
Hano	40.3, 345.1	100 ± 5	NA	250	290	540	1060	520	0.50
Afekan	25.8, 200.3	115 ± 5	110	270	200	470	1060	590	0.55

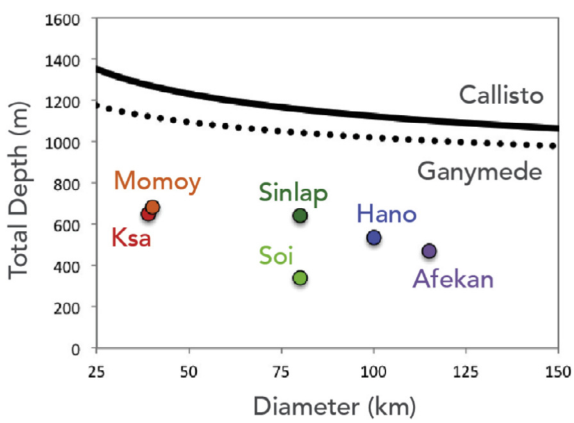

Fig. 1. Depth/diameter plot of fresh craters with diameters over 25 km on Callisto and Ganymede from Schenk (2002). Titan's craters are the labeled circles.

foreshortening of the near and far walls, assuming a perfectly symmetric profile across the crater.

The depths of these craters (Fig. 1) are significantly shallower when compared to similar-sized fresh craters on Ganymede and Callisto (Schenk, 2002). This observation is surprising because Ganymede and Callisto have a similar target rock (water ice) and gravitational acceleration (T: 1.35 m s^{-2}, G: 1.4 m s^{-2}, C: 1.3 m s^{-2}), and reasonably similar average impact velocities to Titan (T: 10.5 km s^{-1}, G: 20 km s^{-1}, C: 15 km s^{-1}), so impact crater morphology on all three bodies is expected to be very similar. Instead, Titan's craters are shallowed by many hundreds of meters compared to their expected depths, which we define as the average of the depths expected for similar-size craters on Ganymede and Callisto (Schenk, 2002) (see Table 1).

We use the topographic profiles of the craters Ksa, Momoy, Soi, Sinlap, Hano, and Afekan from Neish et al. (2013) to measure the total crater depth (top of rim to bottom of crater), apparent crater depth (depth referenced to background terrain), and rim height at each side of the crater profiles, and found the average values. In general, these topographic profiles do not cross the center of the craters; however morphologically, sand infill suggests a relatively flat crater floor (see below). We cannot currently confirm that these craters have completely flat floors because each crater only has one topographic profile; however, it would appear that this one profile is likely representative. In one case (Sinlap), Neish et al. (2013) found that the SARTopo depth estimates agreed well with the estimated depth from another technique, "autostereo" (which uses differences in the foreshortening of the near and far crater walls to estimate depths), implying that Sinlap has a relatively flat floor. In comparison with their expected depths, Titan's craters are shallowed by 460–760 m, and have relative total depths of between 0.42 and 0.69. The smallest craters, Ksa (diameter 39 ± 2 km) and Momoy (40 ± 1 km) fall short of the expected depth by similar amounts, 550 m and 510 m, respectively. Soi (78 ± 2 km) and Sinlap (82 ± 2 km) have nearly the same diameter within error, but they have experienced very different amounts of shallowing. Sinlap is shallowed by only 460 m, a relative total depth of 0.42, while Soi on the other hand has nearly lost all of its apparent depth, 760 m and has a relative total depth of 0.69. The largest craters Hano (100 ± 5 km) and Afekan (115 ± 5) currently fall short by comparable amounts, 520 m (relative total depth of 0.50) and 590 m (0.55), respectively. Surprisingly, all of the craters are currently at least 460 m shallower than expected.

1.1. What could make Titan's craters shallow?

Titan's craters initially should have had a similar depth to fresh craters on Ganymede and Callisto, and over time, one or more unknown processes has shallowed them. What could be responsible for hundreds of meters of shallowing? Initially suggested by Neish et al. (2013), the four most plausible mechanisms include: erosion and deposition by rain and rivers, direct atmospheric sedimentation of haze particles, aeolian infill of dune material, and topographic relaxation.

Erosion and deposition by rain and rivers is thought to be a less significant process for these craters specifically, simply because of where the craters are located (Fig. 2). They are all (except Hano) located within Titan's equatorial region (±30° latitude) where global circulation models, Huygens lander data, and cloud observations predict it to be more arid and rainstorms to be infrequent (Mitchell, 2008; Rannou et al., 2006; Tokano, 2011; Tomasko et al., 2005; Turtle et al., 2011). Crater degradation through fluvial processes was modeled for some of Titan's craters through the use of a landscape evolution model (Neish et al., 2016). They found that it can modify craters to the point where they would be unrecognizable by an orbiting spacecraft given enough time and a large enough erosion rate. However, the rate of erosion depends on the latitude of the crater. Erosion by rain may not be as important in the arid dune regions near the equator (where these craters are), but could perhaps be much more important at higher latitudes where rainfall is more prevalent. While rivers are seen at all latitudes, including near the Huygens landing site at 10° S, they are notably scarce in the dune fields where most of these craters are located (Langhans et al., 2012). In general, dunes appear to cross-cut rivers, suggesting that dune movement is more recent than fluvial activity. With the exception of Menrva (which we are not studying), none of these craters are incised in SAR imagery, but smaller-scale (and therefore unrecognizable in SAR imagery) fluvial erosion may exist. Altogether, these observations suggest that fluvial erosion may only contribute to crater shallowing during