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Crater topography on Titan: Implications for landscape evolution

C.D. Neish [a,*], R.L. Kirk [b], R.D. Lorenz [c], V.J. Bray [d], P. Schenk [e], B.W. Stiles [f], E. Turtle [c], K. Mitchell [f], A. Hayes [g], Cassini RADAR Team

[a] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[b] United States Geological Survey, Astrogeology Science Center, Flagstaff, AZ 86001, USA
[c] The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA
[d] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA
[e] Lunar and Planetary Institute, Houston, TX 77058, USA
[f] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[g] University of California Berkeley, Berkeley, CA 94720, USA

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ABSTRACT

We present a comprehensive review of available crater topography measurements for Saturn's moon Titan. In general, the depths 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 vs. diameter trend. Depth-to-diameter ratios are between 0.0012 ± 0.0003 (for the largest crater studied, Menrva, $D \sim 425$ km) and 0.017 ± 0.004 (for the smallest crater studied, Ksa, $D \sim 39$ km). When we evaluate the Anderson–Darling goodness-of-fit parameter, we find that there is less than a 10% probability that Titan's craters have a current depth distribution that is consistent with the depth distribution of fresh craters on Ganymede. There is, however, a much higher probability that the relative depths are uniformly distributed between 0 (fresh) and 1 (completely infilled). This distribution is consistent with an infilling process that is relatively constant with time, such as aeolian deposition. Assuming that Ganymede represents a close 'airless' analogue to Titan, the difference in depths represents the first quantitative measure of the amount of modification that has shaped Titan's surface, the only body in the outer Solar System with extensive surface–atmosphere exchange.

1. Introduction

Unique among the icy satellites, Titan's surface shows evidence for extensive modification by fluvial and aeolian processes (Tomasko et al., 2005; Lorenz et al., 2006, 2008; Stofan et al., 2007). These processes act to change the topography of its surface over time, through fluvial erosion, mass wasting, burial by dunes and submergence in seas. 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, which have been determined from extensive studies of the airless worlds of the outer Solar System (e.g., Schenk et al., 2004). By comparing the topography of craters on Titan to similarly sized, relatively pristine analogues on airless bodies, we can obtain one of the few direct measures of the amount of modification that has occurred on Titan.

The best analogues for comparison to Titan are Jupiter's moons Ganymede and Callisto. For large craters (formed in the gravity regime), crater size is dependent on gravity, impact velocity, projectile size, and target and projectile density (Holsapple and Housen, 2007). Ganymede and Titan have similar gravity ($g \sim 1.4$ m/s^2), target density ($\rho \sim 1$ g/cm^3), and likely projectile density ($\rho \sim 1$ g/cm^3), and the average impact velocity at Ganymede is twice that at Titan (20 km/s vs. 10.5 km/s, Zahnle et al., 2003). The gravity on Callisto is also similar to that of Titan ($g = 1.25$ m/s^2), and its average impact velocity is somewhat lower than that on Ganymede ($\langle v \rangle \sim 15$ km/s). However, given that the depths of craters on Callisto are almost indistinguishable from those of Ganymede (Schenk, 2002), and the topographic data set that exists for Callisto is somewhat sparser than that for Ganymede, we focus in this paper solely on comparisons to Ganymede.

In addition to target and projectile properties, the subsurface structure of an icy satellite is important to the shape and morphology of craters, since rheological changes at depth influence the depth-to-diameter ratio of large craters ($D > 26$ km) (Schenk, 2002). This range of diameters coincides with those most likely to be observed on Titan, as models predict that craters with $D > 20$ km were formed by projectiles large enough to be only minimally disrupted by Titan's extended, thick atmosphere (Korycansky and Zahnle, 2005). In the case of Ganymede and Titan, it appears that their outermost layers (∼100 km) are both

* Corresponding author.
E-mail address: catherine.d.neish@nasa.gov (C.D. Neish).

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dominated by cold water ice. Titan's long-wavelength topography (Nimmo and Bills, 2010) and Cassini Radio Science Subsystem (RSS) gravity measurements (Iess et al., 2010) both suggest that Titan has a floating, isostatically compensated ice shell with a mean thickness of ∼100 km overlying a subsurface ocean. Ganymede is also thought to possess an H_2O-NH_3 ocean at ∼100 km depth (Spohn and Schubert, 2003).

Cassini RADAR has imaged ∼50% of the surface of Titan at resolutions as good as 350 m (e.g., Elachi et al., 2005; Hayes et al., 2011), and in this data set, more than 60 potential craters have been identified (Wood et al., 2010; Neish and Lorenz, 2012). Topographic information for these craters has thus far been difficult to obtain. There is only a limited amount of topographic data on Titan in the form of altimetry (Zebker et al., 2009) and stereo (∼2% areal coverage, Kirk et al., 2012). Additionally, altimetry requires nadir pointing, and thus is incompatible with simultaneous synthetic aperture radar (SAR) imaging of the surface. Fortunately, a technique known as 'SARTopo' (Stiles et al., 2009) has been developed that estimates surface heights by comparing the calibration of overlapping SAR beams. The Cassini RADAR instrument has five different antenna feeds (or beams), and data from overlapping beams are acquired nearly simultaneously. Surface height can be computed by maximizing the correlation between the received power and the antenna gain pattern at each point along track in the overlap region. This technique is capable of estimating surface heights for most of the SAR-imaged surface of Titan with ∼10 km horizontal resolution and a vertical resolution of tens of meters. It has extended the area over which co-located topography and SAR imagery is available on Titan by at least an order of magnitude.

In this work, we present topography data for several craters on Titan using the SARTopo data set. We compare this topography to similarly sized craters on Ganymede, for which topography has been extracted from shadow length measurements and stereo-derived digital elevation models (Schenk, 2002; Bray et al., 2008, 2012). Finally, we make inferences regarding the relative amount of landscape degradation that has occurred on Titan due to erosion and infill.

2. Observations

We plotted the position of the SARTopo data over SAR images of every known crater on Titan with $D > 20$ km. There are roughly 30 such craters (Wood et al., 2010; Neish and Lorenz, 2012), with eight interpreted as 'certain' impact structures. Of these, six 'certain' or 'nearly certain' craters (Table 1) and two 'probable' craters had corresponding SARTopo coverage (Fig. 1). Of the six 'certain' craters, five had topographic profiles broadly consistent with craters of their size on other icy worlds, including a central peak in the 39 km diameter crater Ksa (Kirk et al., 2012; see also Figs. 1b and 2), a central uplift in the 100 km diameter crater Hano (Figs. 1g and 3), and a near-flat profile for the 425 km diameter crater Menrva (Figs. 1i and 3). Only Soi lacked any recognizable topography (Fig. 4), as did the two 'probable' craters (craters #43 and #49 from Wood et al. (2010); Fig. 5). Both of the 'probable' craters are located in Titan's expansive sand seas, so these features are either not impact craters or have been completely infilled with aeolian deposits. Since we cannot unambiguously determine whether these features are craters, we exclude them from the remainder of the depth analysis.

The diameter of each crater was determined from the SAR imagery, and the errors reported in Table 1 represent the natural variations of the craters away from circularity. Height measurements were determined from a 10-km long (along-track) by w-km wide (across-track) region of SAR pixels, where w is the width of overlap between the two antenna beams that contribute to a SARTopo profile. The value of w varies depending upon the spacecraft altitude and instrument pointing angles, but is generally on the order of several kilometers. All of the pixels in the 10-by-w km region were then used together with knowledge of the viewing geometry and radar antenna gain patterns to estimate the heights. The along-track translation between consecutive measurements is significantly smaller than the 10 km region of interest (typically 200 m), however, making it necessary to subsample tracks to a 10 km separation distance (∼50 data points) to ensure independent height measurements. This was possible for all depth measurements reported here. Note that this method of height derivation tends to reduce the calculated crater depths, since crater rims are averaged with adjacent, lower topography and crater floors are averaged with adjacent, higher topography (see Fig. 6). These measurements could therefore be considered lower limits.

For the six 'certain' craters, we then calculated depth, $d = h_1 - h_2$, by taking the difference between the highest point on the crater rim and the lowest point on the crater floor, on both sides of the crater, d_1 and d_2 (Fig. 6). Systematic errors in height, δh_i, were propagated throughout the analysis. These errors were determined from radar instrument noise and viewing geometry, and are summarized in Table 1 of Stiles et al. (2009). For the depth measurements, we used the topographic profile closest to the midpoint of the crater. However, in several cases, only profiles near the edge of the crater were available (e.g., Sinlap, Afekan). The depth measurements therefore assume that the depth is constant across the crater floor. If this assumption is incorrect, these values represent lower limits for the depth of the craters.

Table 1
Depth-to-diameter ratio for seven 'certain' or 'nearly certain' craters on Titan.

Crater	Diameter, D (km)	Depth, d (m)	d/D	Technique	Relative depth, R[b,c]	Relative depth, R[e]
Ksa	39 ± 2	660^{+170}_{-170}	$0.017^{+0.004}_{-0.004}$	SARTopo	$0.24^{+0.20}_{-0.20}$	$0.42^{+0.15}_{-0.15}$
		750 ± 175	0.019 ± 0.005	Stereo[a]	$0.13^{+0.20}_{-0.20}$	$0.34^{+0.15}_{-0.15}$
Momoy	40 ± 1	680 ± 100	0.017 ± 0.003	Autostereo	$0.22^{+0.11}_{-0.11}$	$0.40^{+0.09}_{-0.09}$
Soi	78 ± 2	110 ± 100	0.001 ± 0.001	SARTopo	$0.90^{+0.09}_{-0.09}$	$0.89^{+0.10}_{-0.10}$
Sinlap	82 ± 2	640^{+160}_{-150}	$0.008^{+0.002}_{-0.002}$	SARTopo	$0.43^{+0.14}_{-0.13}$	$0.36^{+0.16}_{-0.15}$
		700 ± 100	0.009 ± 0.001	Autostereo	$0.38^{+0.09}_{-0.09}$	$0.30^{+0.10}_{-0.10}$
Hano	100 ± 5	525^{+105}_{-95}	$0.005^{+0.001}_{-0.001}$	SARTopo	$0.56^{+0.09}_{-0.08}$	$0.46^{+0.11}_{-0.10}$
Afekan	115 ± 5	455^{+175}_{-180}	$0.004^{+0.002}_{-0.002}$	SARTopo	$0.62^{+0.15}_{-0.15}$[d]	$0.52^{+0.19}_{-0.19}$
Menrva	425 ± 25	490^{+110}_{-120}	$0.0012^{+0.0003}_{-0.0003}$	SARTopo	N/A	N/A

[a] See Kirk et al. (2012).
[b] 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.
[c] Ganymede crater depths from Table 4 in Bray et al. (2012).
[d] Assumed to have the same depth as a $D = 100$ km crater.
[e] Ganymede crater depths from Fig. 2b in Schenk (2002).