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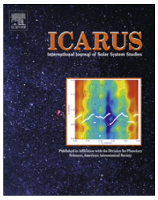

Elevation distribution of Titan's craters suggests extensive wetlands

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ABSTRACT

Using a new global topographic map of Titan, we find that craters on Titan preferentially lie at higher than average elevations. We explore several explanations for this observed behavior, and judge the most reasonable explanation to be the presence of widespread wetlands of liquid hydrocarbons at low elevations over much of geologic time. Impacts into a shallow marine environment or a saturated layer of sediments more than several hundred meters thick would produce crater morphologies similar to terrestrial submarine impacts. These are known to lack significant topographic expression, and would thus be difficult to observe with the Cassini spacecraft. Since Titan's near-surface methane inventory likely fluctuated over geologic time, with episodic delivery and continuous depletion, a few craters at low elevations can nonetheless be expected.

1. Introduction

The distribution of craters on Titan is not uniform. There is a noticeable lack of craters near Titan's volatile-rich poles and in some sand seas, and a slight enhancement of craters in Titan's Xanadu region (Wood et al., 2010). The reason for this asymmetric distribution is not clear, although it may be related to differing ages of the surface or different depositional environments. For example, a recent survey of Titan's crater topography found that its craters are hundreds of meters shallower than similarly sized craters on Ganymede, and this difference may be related to gradual infill by aeolian sediments (Neish et al., 2013a).

There is, however, another possibility that has not yet been explored: it is possible that the regions deficient in craters may simply be saturated by liquid hydrocarbons. The presence of liquids on the surface and in the near subsurface of a planetary body can cause extensive modification to crater shape, as is observed on Earth (Dypvik and Jansa, 2003; Collins and Wünnemann, 2005; Ormö et al., 2006) and possibly Mars (Ormö et al., 2004), and was anticipated for Titan (Lorenz, 2004). In the case of Titan, the liquids consist of hydrocarbons, either in wet unconsolidated sediments (such as the damp ground observed at the Huygens landing site [Niemann et al., 2005; Lorenz et al., 2006; Karkoschka and Tomasko, 2009]) or in shallow marine environments (such as the lakes observed at the north and south poles [Stofan et al., 2007]). Craters formed in similar environments on the Earth lack any significant surface topography, including the absence of a raised rim, as poorly consolidated, water-saturated sediments slump into the crater soon after impact (Collins and Wünnemann, 2005). On Earth, such craters are typically identified through seismic profiling and drilling (e.g., Poag et al., 1994), and would be difficult to detect with an orbital spacecraft like Cassini (see Fig. 1).

It is reasonable to assume that saturated soils will preferentially lie in regions of low elevation, possibly fed by a global 'aquifer' composed of liquid methane and/or ethane. Titan's surface is thought to be composed of a mixture of fractured water ice and organic materials, and fractured water ice is known to be extremely permeable to liquid methane and ethane (Sotin et al., 2009). There is also evidence for small lakes fed by subsurface liquid flow in the polar regions of Titan (Hayes et al., 2008; Cornet et al., 2012), and globally, Titan's regolith is likely porous enough to conceal a layer of at least several hundred meters equivalent of liquid in the top few kilometers of its crust (Kossacki and Lorenz, 1996). Indeed, the global shape of Titan may be explained by the circulation of 1.5 to 6 × 10^{18} kg of ethane in the top three kilometers of the crust over the last 300–1200 Myr, causing ethane substitution in methane clathrates (Choukroun and Sotin, 2012).

If such 'wetlands' were present, we would expect Titan's craters to be preferentially observed in the drier highlands, and remain unobserved in the wetter lowlands (somewhat like the Earth, where no craters are observed in the oceans). A new global topographic map recently published by Lorenz et al. (2013) allows us to test this hypothesis for the first time. In this work, we compare the elevations of Titan's craters to its overall topography, to determine if a correlation with elevation can explain the distribution of craters on Titan.

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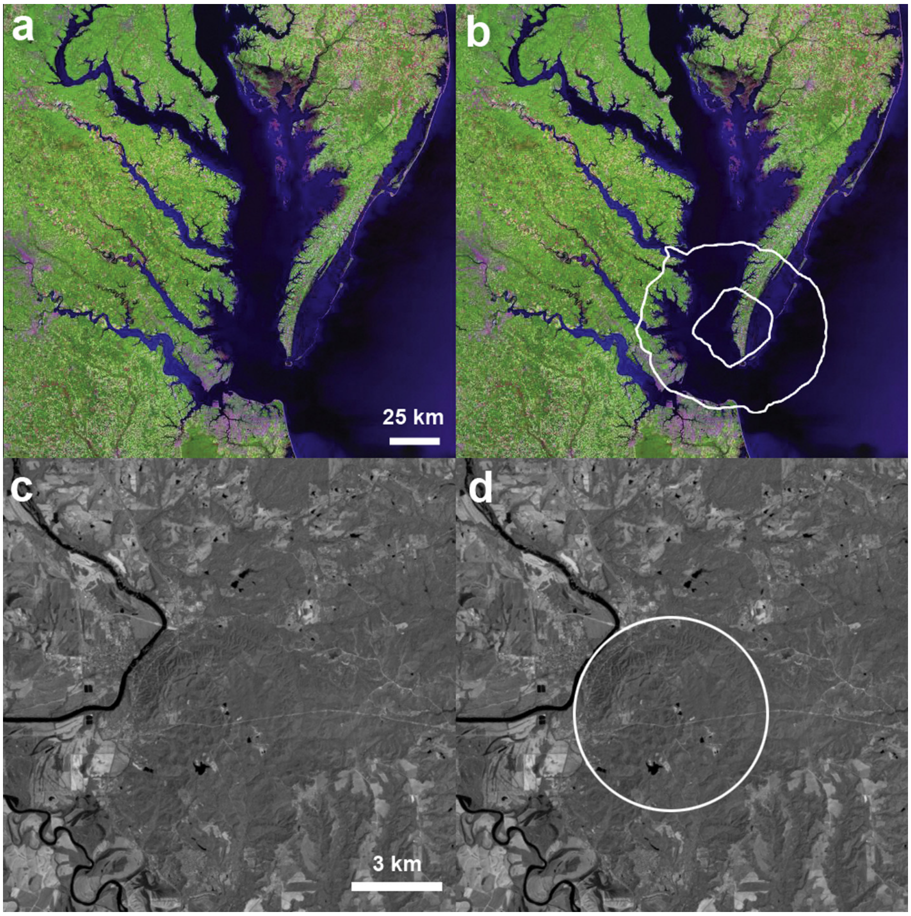

Fig. 1. (a) Landsat image of Chesapeake Bay on the coast of Maryland and Virginia. (b) The same image, with the inner and outer rim of the Chesapeake Bay impact crater outlined in white (crater outline adapted from Powars (2000)). This crater formed 35 myr ago in a shallow sea several hundred meters deep (Dypvik and Jansa, 2003). (c) Landsat 4 TM image of the Wetumpka impact crater in Alabama. (d) The same image, with the outer edge of the crater outlined in white. This crater formed 80 myr ago in a shallow sea < 100 m deep (Dypvik and Jansa, 2003). These examples demonstrate the difficulty in identifying marine impacts from orbital imagery alone. Landsat images obtained from the U.S. Geological Survey, Department of the Interior/USGS.

2. The elevation of Titan's craters

A growing body of radar topography data allowed Lorenz et al. (2013) to produce a global gridded topographic map of Titan. They constructed the map by interpolating all available topography data for Titan, in the form of elevation tracks obtained through altimetry (Zebker et al., 2009) and a technique known as SARTopo (Stiles et al., 2009). This product is binned in 1 × 1 latitude–longitude space (of which 11% of the bins contain data).

Through Titan flyby T77 (acquired June 20, 2011), sixty-one craters have been identified on Titan with varying certainty (Lorenz et al., 2007; Wood et al., 2010; Soderblom et al., 2010; Neish and Lorenz, 2012; Buratti et al., 2012; Neish et al., 2013a). The central latitude and longitude of these craters were plotted on the global topographic map to give an initial indication of whether there is any correlation with elevation (Fig. 2a). The visual correlation was encouraging, so we proceeded to sort the craters into elevation bins 100 m in size, from −1500 m to 500 m (which broadly covers the range of elevations observed on Titan, where the zero elevation represents a 2575 km radius sphere), and compared it to a histogram of Titan's global topography (Fig. 3a).

If Titan's lowlands are preferentially wet due to a subsurface hydrocarbon table, we may expect the craters to correlate not with simple elevation, but with the geopotential surface. Titan is slightly oblate, consistent with a hydrostatically relaxed body shaped by tidal and rotational effects (Iess et al., 2010), so it is necessary to subtract this spheroid from the topography to extract the geopotential (Fig. 2b). After subtracting the spheroid defined in Iess et al. (2010), we again sorted the craters into elevation bins 100 m in size (Fig. 3b).

In both cases (global topography and geoid subtracted topography), the distribution of the craters is skewed towards higher elevations. The median of the crater distribution is ∼200 m higher than the median elevation on Titan (3d), and ∼100 m higher than the median geoid subtracted elevation (Fig. 3e). As we demonstrate in Fig. 3c, this is not simply a selection effect based on the incomplete SAR coverage of Titan. The elevations of the SAR imaged portions of Titan are in fact remarkably similar to its overall topography, with 56% of SAR imaged Titan lying below the median elevation of −377 m, and 44% lying above that elevation. If anything, the bias in the SAR data set is towards lower elevations.

To investigate the hypothesis that the elevations of Titan's craters do not come from the same distribution as its global topography, we used the Anderson–Darling goodness-of-fit technique. This technique evaluates the statistic A2, which quantifies the difference between the cumulative probability function for the observed crater elevations, $F_n(x)$, and the cumulative probability function for Titan's topography, $F(x)$, at elevation x:

$$A^2 = n \int \left[(F_n(x) - F(x))^2 / (F(x)(1 - F(x))) \right] dx \qquad (1)$$

The greater the difference between the data and model probability distribution, the larger A^2 becomes, increasing the probability of observing a given A^2 value by chance. In the case where the model