Paradox of Enceladus' Craters at the Poles: Northern Scars vs. Southern Erasure

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Abstract

This presentation discusses research on the morphologies of Enceladus' craters in its polar regions. In this preliminary investigation of the latitudes between 80°N and 90°N, hundreds of craters ranging in diameters from as small as 1 km to over 25 km have been counted, measured, and analyzed, with continued studies being performed down to lower latitudes and the south pole. There is a stark contrast between the cratering record in the north pole as compared to the south pole of Enceladus. The north pole is heavily cratered and shows possible indication of recent geological activity. Conversely, the south pole's crater history has been extensively erased by geologic and tectonic processes as well as active geysers emanating from four "Tiger Stripes". Across both poles, crater features tend to be significantly influenced by viscous relaxation. Additionally, craters on Enceladus share more similarities with other icy worlds of the Galilean satellites and sister moons within the Saturnian system, than rocky bodies such as Mercury, the Moon, and Mars. However, even among the icy bodies in the solar system, Enceladus' crater morphologies are unique. Enceladus' miniscule gravity, icy composition, shell thickness variations, freezing surface temperature, tidal stresses, and heat flux from its subsurface ocean, are all contributing factors of the distinctive crater morphologies observed. The goal of this analysis is to establish a deeper understanding of the geologic history of Enceladus' surface, its composition, and how craters are formed and evolve over time on icy bodies, particularly those with subsurface oceans.

Keywords: Enceladus, Impact Craters, Crater Morphology, Viscous Relaxation, Heat Flux, Tidal Stress

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La paradoja de los cráteres de Encélado en los polos: cicatrices del norte vs. borrado del sur

Resumen

Esta presentación aborda la investigación sobre la morfología de los cráteres de Encélado en sus regiones polares. En esta investigación preliminar de las latitudes entre 80°N y 90°N, se han contabilizado, medido y analizado cientos de cráteres con diámetros que van desde tan solo 1 km hasta más de 25 km, y se continúan realizando estudios en latitudes más bajas y en el polo sur. Existe un marcado contraste entre el registro de cráteres en el polo norte y el del polo sur de Encélado. El polo norte presenta una gran cantidad de cráteres y muestra posibles indicios de actividad geológica reciente. Por el contrario, el historial de cráteres del polo sur ha sido ampliamente borrado por procesos geológicos y tectónicos, así como por géiseres activos que emanan de cuatro "Franjas de Tigre". En ambos polos, las características de los cráteres tienden a estar significativamente influenciadas por la relajación viscosa. Además, los cráteres de Encélado comparten más similitudes con otros mundos helados de los satélites galileanos y lunas hermanas del sistema saturnino que cuerpos rocosos como Mercurio, la Luna y Marte. Sin embargo, incluso entre los cuerpos helados del sistema solar, las morfologías de los cráteres de Encélado son únicas. La minúscula gravedad de Encélado, la composición helada, las variaciones en el espesor de su capa, la temperatura superficial de congelación, las tensiones de marea y el flujo de calor de su océano subsuperficial son factores que contribuyen a las distintivas morfologías de los cráteres observadas. El objetivo de este análisis es profundizar en la comprensión de la historia geológica de la superficie de Encélado, su composición y cómo se forman y evolucionan los cráteres con el tiempo en cuerpos helados, en particular aquellos con océanos subsuperficiales.

Palabras clave: Encélado, Cráteres de impacto, Morfología de cráteres, Relajación viscosa, Flujo de calor, Tensión de marea

土卫二两极陨石坑悖论：北极陨石坑的痕迹与南极陨石坑的抹除

摘要

本篇报告探讨了关于土卫二两极地区陨石坑形态的研究。在对北纬80°至90°之间地区的初步调查中，统计、测量并分析了数百个直径从1公里到25公里以上的陨石坑，并正在对更低纬度和南极地区进行持续研究。土卫二北极和南极的陨石坑记录存在显著差异。北极陨石坑密集，显示出近期地质活动的可能迹象。相反，南极的陨石坑历史已被地质构造过程以及从四条“虎纹”喷发的活跃间歇泉大量抹去。在南北两极，陨石坑特征往往都明显受到粘性松弛的影响。此外，土卫二上的撞击坑与伽利略卫星和土星系统卫星的其他冰冷天体的相似度更高，而不是与多岩石天体（如水星、月球和火星）相似。然而，即使在太阳系的冰冷天体中，土卫二的撞击坑形态也独一无二。土卫二极小的重力、冰质成分、壳层厚度变化、极低的表面温度、潮汐应力以及来自其地下海洋的热通量，都是造成其独特撞击坑形态的因素。本篇分析旨在深入了解土卫二表面的地质历史、成分，以及冰冷天体（尤其是拥有地下海洋的天体）上撞击坑的形成和演化过程。

关键词：土卫二，撞击坑，撞击坑形态，粘性松弛，热通量，潮汐应力

Background

Enceladus might be a tiny 504 km in diameter, tidally locked moon of Saturn, but it is one of the most fascinating and geologically active bodies in the solar system. It undergoes tidal heating from resonance with Dione (Porco et al., 2006). Cassini is the only spacecraft to study Enceladus in detail and performed 23 flybys of Enceladus between 2005 and 2015 (Krupp et al., 2018). Enceladus has a composition of an icy shell encapsulating a briny, subsurface ocean that surrounds a porous, rocky core (McKinnon, 2013). From the southern pole of Enceladus are active geysers erupting water-ice material from the surface (Porco et al., 2006), with some of the particles that escape becoming Saturn's E-ring (Kirchoff et al., 2009), and what falls back to the surface, fills in impact craters (Bland et al., 2012). These geysers emanate from four sulci, or "tiger stripes," cutting across the South Polar Terrain (SPT) (Porco et al., 2014). In addition, viscous relaxation plays a crucial role in the modification of craters (Schenk et al., 2018) that contributes to their erasure (Bland et al., 2012).

Akin to Mars' hemispherical dichotomy of its northern lowlands and southern highlands terrains (Carr, 2018), Enceladus exhibits a polar dichotomy of its crater population. The north pole is heavily cratered, and its terrain is significantly older than the south pole (Kirchoff et al., 2009), and not as dynamic as the tiger stripes in the south pole. There is a lack of craters in the south pole than the north (Blanco-Rojas et al., 2024) and a major difference between morphologies (Bray et al., 2007). While the north pole has mostly retained its cratering record, the south pole is almost completely erased. Some of these differences can be identified by examining the crater depth to diameter ratio. The depth-diameter ratio (d/D) is a fundamental metric for crater morphometry used to identify the simple-to-complex transition point and infer a target's composition and strength, influenced by gravity and potential atmosphere (Baldwin, 1949; Pike, 1977).

Method

Data were collected using the Java Mission-planning and Analysis for Remote Sensing (JMARS) desktop application (Gorelick et al., 2003; Christensen et al., 2009), leveraging the Enceladus Cassini Global Mosaic 100m Schenk layer for the visual source and the Enceladus Cassini Global 200m Schenk Digital Elevation Model (DEM) for numerical source for measurements (Schenk et al., 2024). For each crater identified, the three-point circle method was employed to draw a best-fit circle. The resulting circle calculates the crater's central coordinates and diameter (Wren et al., 2017). Twenty topographic elevation profiles per crater were plotted and averaged using JMARS' Profiler Viewer (Christensen et al., 2009) extending to two crater radii beyond the rim to generate a cross-section graph. Key measurements taken from the averaged profile were the maximum elevation of the crater rim, maximum depth, and the elevation of the surrounding topography beyond the crater rim (Melosh, 1989). The d/D ratio was also calculated. Multiple morphologies including central peaks, central mounds, summit and central pits, ejecta blankets, and wall terraces were documented. Polygonal craters identified were triangles, squares, pentagons, hexagons, baseball diamonds, and irregular in shape.

A five-point preservation scale, ranging from 0.0 to 4.0, was used to group craters based on qualitative visual observations of the crater rim, crater modifications, interior and rim impacts, ejecta blanket, and state of viscous relaxation. On this scale, 0.0 represents a ghost crater (barely discernible), and 4.0 represents a pristine crater (fresh and geologically recent). It is modeled after Barlow's (2004) eight-point preservation scale for Mars, ranging from 0.0 to 7.0, and Zeilnhofer and Barlow's (2021) six-point scale, ranging from 0.0 to 5.0.

Preliminary Results and Analysis

To date, 414 craters have been counted and measured between 80.013°N and 89.516°N and 48 between -80.349°S and -87.516°S, across all longitudes as seen in Figure 1. An additional 54 craters have been counted and measured in lower southern latitudes as well as almost 2,800 craters counted in lower northern latitudes. Crater diameters ranged from 1.0 km up to 38.01 km in the north and from 1.0 km up to 35.8 km in the south.

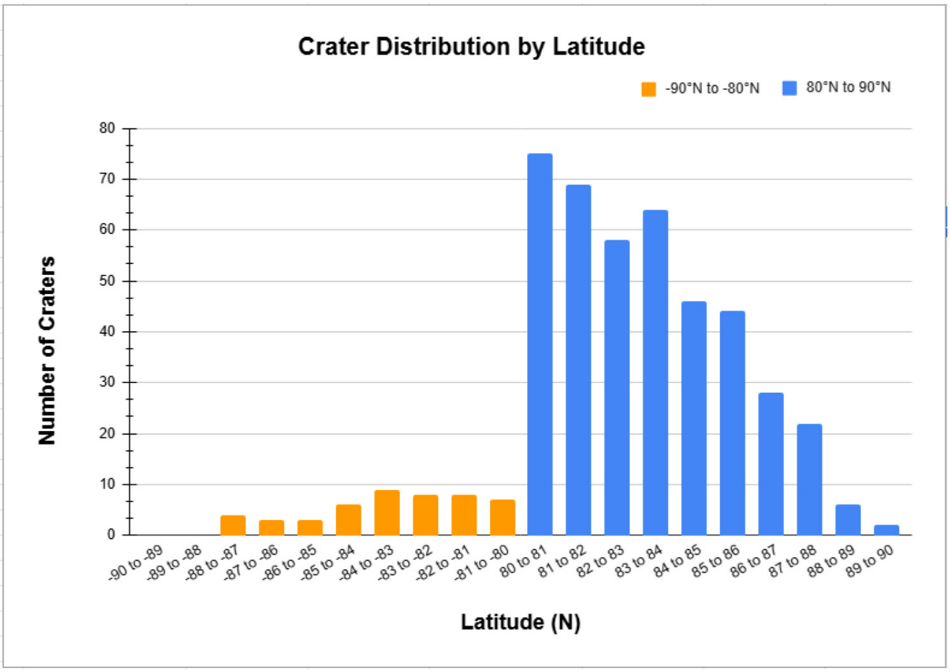

Figure 1. *Crater distribution by latitude across all longitudes (0° to 360°)*

Eight ghost craters were found in total, five in the north and three in the south. In the north, 61.12% are class 1.0 and 25.12% are class 2.0, whereas in the south 89.58% are class 1.0 and 4.17% are class 2.0. Only 12.32% of the craters in the north were identified as class 3.0; there were no class 3.0 craters found in the south (Table 1). With only a single class 4.0, Gharib (81.12°N 118.85°E, D = 26.0 km) Crater, there is not enough data to calculate d/D for only pristine craters.

Unlike Gharib Crater which is complex, Bahman (14.703°N 298.627°E, D = 10.564 km) Crater is a pristine class 4.0 crater, but is outside the current scope of this study and only mentioned to provide a comparative example of a simple crater. Analysis of the larger northern sample suggests a simple-to-complex transition point between 8 and 13 kilometers as seen in Figure 2.

The average d/D ratio for all preservation classes in the north polar

Table 1. *Crater Preservation Scale*

Class	80°N to 90°N	80°S to 90°S
0.0	5	3
1.0	253	43
2.0	104	2
3.0	51	0
4.0	1	0
Total	**414**	**48**

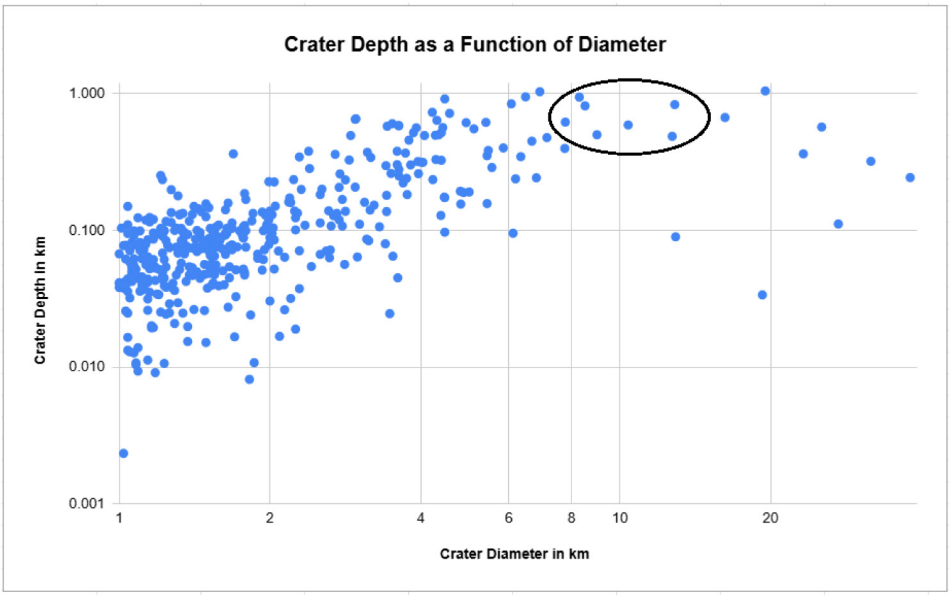

Figure 2. *Crater Depth-To-Diameter.*
Note: Plotted for the 414 craters measured between 80°N and 90°N.

region was 0.069. In contrast, the south polar region average was 0.026. A d/D ranging between 0.1 and 0.15 was found for the Jovian, Saturnian, and Uranian satellites (Croft, 1988). For the Saturnian satellites Mimas, Dione, Tethys, and Rhea the approximate d/D ratio was found to be 0.13 (Schenk, 1989). Data obtained from Bland et al. (2012) and Robbins et al. (2017) determined a d/D ratio of 0.11 for Enceladus. A d/D ratio between 0.06 to 0.37 in the equatorial region of Enceladus was identified (Blanco-Rojas et al., 2024). These d/D ratios, including those found in this study, are below the 0.2 found throughout the solar system for pristine, terrestrial craters (Melosh, 1989).

Initial Conclusion and Future Work

Initial observations demonstrate that the north pole resembles other heavily cratered bodies, with an abundance of craters in comparison to the paucity in the south. The north has better-preserved, morphologically diverse craters than the south. There is a greater prevalence of fractures that cut across the northern topography, crater rims, and interiors, whereas the south is dominated by flow features. While in the south, there is extensive erasure due to active geological processes resurfacing the local topography. A larger d/D ratio in the north than the south further indicates that craters in the north are deeper. In comparison to terrestrial craters, the d/D ratios found on Enceladus suggest that they are shallower overall than their terrestrial counterparts.

The ongoing research for this study will extend into lower latitudes and continue to examine the various morphologies and morphometries discussed. Ejecta blankets will be examined in more detail. Comparisons, across all metrics, with other icy bodies such as Dione and Ganymede will be performed. With a larger data set, additional analysis of key metrics such as d/D ratio and the simple-to-complex transition point will be analyzed. Further work is required to understand how Enceladus' ice shell dynamics and heat sources influence crater evolution across its body.

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