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# Impact craters on Titan

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ABSTRACT

Five certain impact craters and 44 additional nearly certain and probable ones have been identified on the 22% of Titan's surface imaged by Cassini's high-resolution radar through December 2007. The certain craters have morphologies similar to impact craters on rocky planets, as well as two with radar bright, jagged rims. The less certain craters often appear to be eroded versions of the certain ones. Titan's craters are modified by a variety of processes including fluvial erosion, mass wasting, burial by dunes and submergence in seas, but there is no compelling evidence of isostatic adjustments as on other icy moons, nor draping by thick atmospheric deposits. The paucity of craters implies that Titan's surface is quite young, but the modeled age depends on which published crater production rate is assumed. Using the model of Artemieva and Lunine (2005) suggests that craters with diameters smaller than about 35 km are younger than 200 million years old, and larger craters are older. Craters are not distributed uniformly; Xanadu has a crater density 2–9 times greater than the rest of Titan, and the density on equatorial dune areas is much lower than average. There is a small excess of craters on the leading hemisphere, and craters are deficient in the north polar region compared to the rest of the world. The youthful age of Titan overall, and the various erosional states of its likely impact craters, demonstrate that dynamic processes have destroyed most of the early history of the moon, and that multiple processes continue to strongly modify its surface. The existence of 24 possible impact craters with diameters less than 20 km appears consistent with the Ivanov, Basilevsky and Neukum (1997) model of the effectiveness of Titan's atmosphere in destroying most but not all small projectiles.

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## 1. Introduction

Solid bodies in the Solar System have surfaces scarred by impact craters unless active geologic processes erase them. Large numbers of impact craters – as in the lunar highlands – attest to an ancient, little changing surface, and a paucity of craters – as for Jupiter's moons Io and Europa – implies a very young and geologically active crust. Surfaces with intermediate numbers of craters provide opportunities to investigate both processes and ages of modification. The very first Cassini radar image of Saturn's moon Titan showed no impact craters, providing strong evidence for a youthful surface and a dynamically active world (Elachi et al., 2005). By December 2007, as radar coverage of the surface increased to ~22%, the original conclusion stands: Titan has very few impact craters. In this paper we describe five certain impact craters, and another 44 nearly certain and probable ones which appear to be older, eroded craters (Table 1). The number, distribution and modification of these craters provide clues to the history and dynamic processes that transform the surface of Titan.

The images analyzed come from the Radar Mapper instrument on the Cassini spacecraft. In its synthetic-aperture radar (SAR) mode the 13.78 GHz radar typically covers a swath 4000–5000 km long and 200–300 km wide. Resolution varies from about 350 m near closest approach to 1.7 km at the ends of swaths. Similarly, look angles change across swaths, typically between 25° and 45°. Images presented here vary in sharpness because of resolution and degree of enlargement. In interpreting radar images we speak of bright and dark regions. There can be multiple reasons for these reflectivities, including roughness at the scale of the instrument's wavelength (2.2 cm).

## 2. Recognizing impact craters

Planetary scientists have become familiar with impact craters because they occur throughout the Solar System, having formed on

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**Table 1**
Catalog of Titan impact craters Ta through T39.

| Number | Certainty[a] | Cat. no. | Longitudinal-W | Latitudinal | N or S | Diameter | Radar swath | Description |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | N006154 | 65.4 | 14 | N | 30 | T17 | *Ksa* – raised rim with drk fl and brt circular central pk, radial ejecta |
| 2 | 1 | N001161 | 16.1 | 11.3 | N | 79 | T03 | *Sinlap* – brt morph rim with massive brt ejecta blanket, on brt area |
| 3 | 1 | N008179 | 87 | 19.6 | N | 445 | T03 | *Menerva* – 2 ring basin with dk moat |
| 4 | 1 | N103292 | 139.6 | 22.7 | N | 75 | T16 | Bright jagged rim and ejecta, definite crater |
| 5 | 1 | N001205 | 10.5 | 25.7 | N | 139 | T23 | brt jagged mtous rim, dk fl, possible cp |
| 6 | 2 | S003187 | 38.4 | 17.1 | S | 3 | T25 | On brt relic hill |
| 7 | 2 | S003199 | 39.3 | 19.4 | S | 3 | T25 | On brt relic hill |
| 8 | 2 | N001174 | 17.2 | 14.1 | N | 4 | T03 | brt rim, dk fl |
| 9 | 2 | N205348 | 254.2 | 38.7 | N | 4 | T21 | 1/2 bt rim, gray floor and area |
| 10 | 2 | N004138 | 43.4 | 18.3 | N | 5 | T03 | brt rim on mountain range |
| 11 | 2 | N304235 | 343.1 | 25.1 | N | 5 | T16 | brt ejecta, drk fl w/brt raised rim |
| 12 | 2 | S001524 | 12.9 | 54.5 | S | 7 | T07 | brt elevated rim on dark area |
| 13 | 2 | N300893 | 309.9 | 83.3 | N | 7 | T29 | Gray rim sticking above gray area, on edge of lake; possible central peak, floor darker |
| 14 | 2 | N304494 | 349.1 | 44 | N | 7 | T18 | brt rim, dk fl in gray area |
| 15 | 2 | N205309 | 250.9 | 39.3 | N | 8 | T21 | Raised, fragmentary rim, gray area |
| 16 | 2 | N203892 | 239 | 82.5 | N | 10 | T29 | 270° brt rim sticking out of lake |
| 17 | 2 | S007152 | 75.5 | 12.9 | S | 14 | T13 | On brt area, brt rim, brt fl |
| 18 | 2 | N205308 | 250.1 | 38.7 | N | 16 | T21 | 12 × 16 km, raised rim, fl and exterior gray |
| 19 | 2 | S007143 | 74.9 | 13 | S | 17 | T13 | In mt area, dk fl |
| 20 | 2 | S007077 | 77.9 | 7.7 | S | 17 | T13 | brt rim, gray fl |
| 21 | 2 | S008140 | 84.3 | 10.4 | S | 20 | T13 | In mts, brt rim, dk/mottled fl |
| 22 | 2 | N002191 | 29.8 | 11.2 | N | 26 | T29 | Beautiful, raised rim crater embayed by dunes. |
| 23 | 2 | N004497 | 49.8 | 47.6 | N | 33 | Ta | Sharp half rim, flat fl |
| 24 | 2 | S106058 | 165.1 | 8.1 | S | 35 | T13 | On Shikoku, dk floor, bright ejecta? |
| 25 | 2 | S008181 | 88.6 | 11.2 | S | 45 | T13 | Thin brt mtous rim, dk inner third, brt talus |
| 26 | 2 | S008058 | 85.9 | 8 | S | 63 | T13 | mtous brt rim, big cp,dk fl, cut by stream |
| 27 | 2 | S105111 | 151.5 | 11.4 | S | 68 | T13 | *Guabonito*-massive brt rim, dk floor (dunes), surrounded by dunes |
| 28 | 2 | N304440 | 344.7 | 40.2 | N | 110 | T16 | mtnous brt jagged rim w/drk fl, oval |
| 29 | 3 | N206310 | 261.8 | 30.5 | N | 3 | T21 | dk floor on sm brt area |
| 30 | 3 | S004138 | 43.4 | 18.8 | S | 3 | T25 | On edge brt mt |
| 31 | 3 | S004258 | 45.9 | 28.6 | S | 3 | T25 | brt rim, dk fl in gray area |
| 32 | 3 | N202893 | 229 | 83 | N | 6 | T25 | brt rim, dk fl, central peak |
| 33 | 3 | N302843 | 324.5 | 83.9 | N | 8 | T25 | Gray rim, dk fl |
| 34 | 3 | N202386 | 228.2 | 36.4 | N | 8 | T30 | brt rim in gray area |
| 35 | 3 | N206273 | 267 | 23.6 | N | 8 | T21 | brt halo, dk floor, on dk area |
| 36 | 3 | N100654 | 105.2 | 64.4 | N | 9 | T18 | Gray bland area, bright remnants |
| 37 | 3 | N304491 | 349.4 | 41.8 | N | 10 | T18 | Circular depression in dk area |
| 38 | 3 | S002547 | 24.2 | 57.4 | S | 10 | T39 | brt rim emerging above gray plain |
| 39 | 3 | N102392 | 129.7 | 33.4 | N | 14 | Ta | bt elevated rim, flat floor, central peak, on bt mtn |
| 40 | 3 | S006172 | 67.3 | 12.2 | S | 18 | T13 | brt rim on brt area, cp? |
| 41 | 3 | N206209 | 260.2 | 29.6 | N | 18 | T21 | dk floor, bt rim in dk area |
| 42 | 3 | S106160 | 166.8 | 10.8 | S | 21 | T13 | On Shikoku, dk floor, brt |
| 43 | 3 | N005100 | 50.2 | 10.8 | N | 26 | T17 | Missing bright area in dune-crossed brt area |
| 44 | 3 | N006122 | 62 | 12.7 | N | 31 | T17 | Circle of darkness, brt, fragmentary rim, dune-crossed |
| 45 | 3 | N001088 | 18.5 | 8.1 | N | 34 | T03 | Totally dune covered, half rim exists |
| 46 | 3 | S004500 | 40.2 | 50 | S | 34 | T36 | Elevated rounded rim, 1/4 missing, rim exits |
| 47 | 3 | S108047 | 184.4 | 7.2 | S | 35 | T08 | Half, brt rim, covered by dunes |
| 48 | 3 | N200408 | 200 | 48.1 | N | 37 | T21 | bt rim, gray area |
| 49 | 3 | S108180 | 188.9 | 10.7 | S | 60 | T08 | brt mtn rim, surrounded and interior dunes |

[a] Certainty: 1 = certain, 2 = nearly certain, 3 = probable.

many types of target rocks, and being modified by very many processes. In most places in the Solar System fresh impact craters larger than about 15 km in diameter are immediately recognized by their near-circular outlines, low rims, deep interiors, flat floors, central peaks, terraced walls, and ejecta deposits. For a planet with active geological processes – volcanism, aeolian and fluvial activity, or tectonism – the ejecta are quickly eroded or covered, the crater becomes shallowed, with central peaks often buried by sediments or volcanic materials, and the inner walls are smoothed by downslope movement, perhaps enhanced by seismic shaking. Subsequent impacts also cut, churn and obliterate pre-existing craters. All of these processes are well documented, with variations such as isostatic shallowing and transformation of central peaks to central pits for worlds with ice in their crusts (Wood et al., 1978). The recognition of the impact origin of specific features is usually not in doubt on most planets and moons because there are few competing processes that form similar circular landforms. In radar images (e.g. Harman et al., 2007), impact crater rims and peaks are usually bright because of their rough-textured surfaces. Crater floors often appear radar dark, being smoothed by infill of sediments or lava flows.

Volcanism also creates circular depressions that in some cases look similar to impact craters. The debate over the volcanic versus impact origin of lunar craters was not resolved by individual details of specific craters, however, but by Baldwin's (1949) statistical studies of crater dimensions, and later by the return of impact-brecciated rocks during the Apollo missions. The similar morphology of craters on small moons and asteroids, as well as on icy satellites and silicate planets, demonstrates that impact cratering yields distinctive morphologies, and has been a pervasive process throughout the Solar System.

For the handful of fresh craters on Titan, similarities in morphology with impact features on other worlds makes an impact

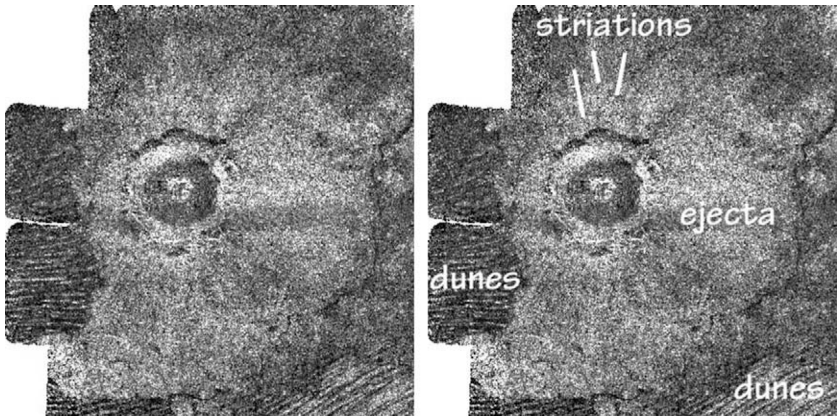


**Fig. 1.** Ksa (diameter, $D$ = 30 km) is the most certain impact crater yet identified on Titan. On this and all other figures north is at the top.

interpretation compelling. It is more difficult to determine the mode of origin for other circular features on Titan that do not have the canonical fresh morphologic signature. We do not know what styles of volcanism exist on Titan, or if other processes make circular landforms. Evidence that mitigates against an impact origin for specific features include clustering of craters (as in the north polar lakes area) and association with apparent lava flows (in the Ta radar swath; Elachi et al., 2005; Lopes et al., 2007). For the circular features described here there are no obvious volcanic signatures so we assume that impact is the most likely origin, but cannot rigorously exclude that other under-appreciated processes may be important. Each of the craters is classed on a 1–3 scale, representing our evaluation of the likelihood of an impact origin. Class 1 craters are considered to be of certain impact origin; Class 2 features are nearly certain; and Class 3 objects are probable. We conclude that the most likely origin for all 49 structures listed here is impact, but erosional state or unusual morphology mean we have less certainty for classes 2 and 3. However, since fresh examples of potential non-impact landforms have not been identified, impact origin is the most likely origin for all the craters discussed here.

## 3. Certain impact craters

Ksa (Fig. 1) is the most familiar-looking impact crater yet seen on Titan. Ksa is 29 km in diameter and has all the characteristics of an inner planet fresh impact crater, including a circular outline, raised rim, flat floor with central peak and a radially striated (on north side of crater) continuous ejecta deposit. SARtop (Stiles et al., 2009) crosses the center of Ksa, revealing that the rim rises 300–500 m above the surrounding terrain and that the crater is about 800 m deep. Its floor is radar dark, which implies that it is smooth at Cassini's 2.2 cm wavelength. On Mars and the Moon, smooth floors are often due to lava flows, basin ejecta, mass wasting, and uniquely for Mars, windblown sediments. The observation that such dark material does not drape Ksa's ejecta mitigates against significant infill from external sources, suggesting that the radar-dark floor material is volcanic lavas or impact melt. The existence of a central mountain demonstrates that peaks do form in the ice-rich crust of Titan, rather than central pits as on Jupiter's icy moon, Ganymede (Schenk, 1993). The ejecta from Ksa is superposed on the adjacent dunes, but other dunes appear to encroach on the northern ejecta deposit.

Sinlap (Fig. 2) is an 80 km diameter crater with a morphology that strongly indicates that it too is of impact origin. Its outline is circular with some short linear wall segments, and its inner walls is cut by radial gullies. The floor is relatively flat and appears to be crossed by a few dark dunes. There is no apparent central peak in radar data, but infrared imaging from the Cassini Imaging Science Subsystem (ISS) camera (Le Mouelic et al., 2008) shows a dark off-center spot that could be a small peak. Sinlap is surrounded by two radar distinct patches of probable ejecta. The inner, ~40 km wide annulus is slightly darker than the more distant material and has radial lineations, especially visible to the north. The outer bright deposit is very unequal in radial extent; to the west it is roughly concentric with the crater and extends about 70–110 beyond the rim. On infrared images this outer unit opens up like a parabola to the east, where it appears to extend 600 km. The ejecta deposits of Ksa and Sinlap indicate that despite Titan's dense atmosphere ejecta was emplaced over distances up to 100 km beyond the craters' rims, and in the case of Sinlap may have been blown hundreds of kilometers further by wind (Le Mouelic et al., 2008). Sinlap has a

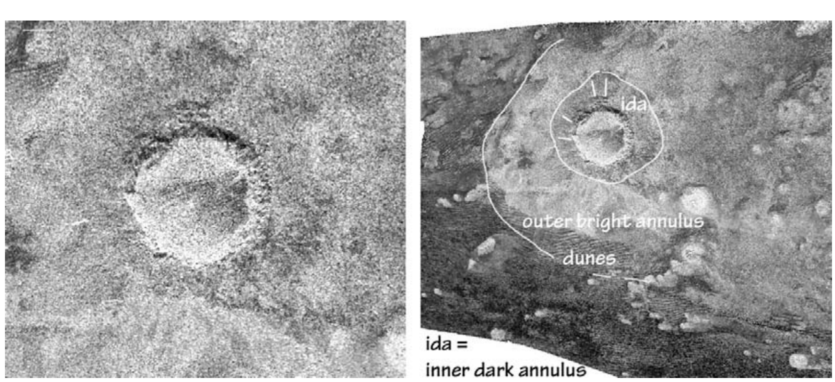


**Fig. 2.** Sinlap ($D$ = 79 km) is apparently a somewhat eroded impact crater, but faint radial lineations appear on its ejecta deposit.

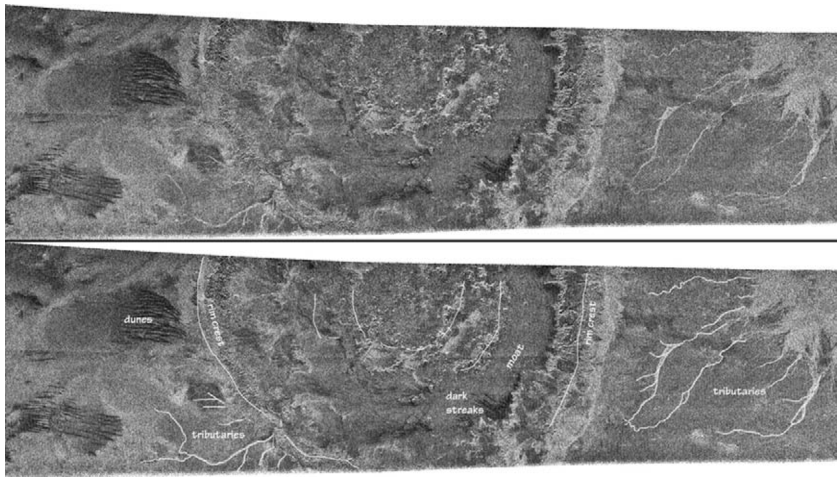


**Fig. 3.** The 444 km wide multi-ring basin Menrva is the only impact basin yet discerned on Titan.

more rounded rim, a broader flat floor, and a less distinct ejecta blanket than Ksa, and thus appears morphologically older. Its ejecta is clearly covered by dunes to the south and west.

The largest landform of impact origin is the 440 km wide Menrva (Fig. 3). This is a two ring impact basin, as is common on Mars and Mercury for impact structures of this diameter (Wood and Head, 1976). The outer ring is well-defined on the east, where a sharp boundary separates a gray plain from a bright scarp dropping down to a more ambiguous boundary of bright and dark material near the bottom of the inner wall. A number of bright river tributaries start near the inferred rim crest and flow eastward away from the crater, debouching into a large bright area of probable deposited sediments. The inner wall exhibits numerous radial grooves and chutes.

The western rim of Menrva is arcuate with the same radius of curvature as the eastern rim, and is marked by a narrow band of roughness. West of the rim there is one major river system and a few smaller ones that flow eastward toward the apparent high point of the crater rim. The rivers appear to be stopped by the rim, suggesting that it is a local high in an area with an eastward regional slope.

Within Menrva bright knobby material defines a broad elevated inner ring about 100 km in diameter. A lower outer ring has a diameter of roughly 170 km. Menrva may be like the Moon's Orientale impact basin, with two closely spaced rings – the Inner and Outer Rook rings. The central area within this ring is darker because it has fewer bright knobs. The moat between Menrva's main wall and the knobby inner ring is dark (smooth at radar wavelength) and contains two sets of darker streaks. In the middle of the southern part of the moat are short clumps of dunes that extend approximately E–W. East of these is another exposure of linear dark material almost at right angles to the dunes. This material does not look like it has blown in and appears to be coming from the very bottom of Menrva's rim, which is also dark.

Menrva is so large that only about half is visible in the radar swath, but its circular structure is confirmed on infrared ISS images (Porco et al., 2005) where the moat appears as a continuous dark ring surrounded by a bright rim.

A new technique for recovering topographic traverses from SAR imagery (Stiles et al., 2009) shows that the eastern rim of Menrva rises about 300 m above the nearby plain, the moat is $\sim$500 m below the eastern rim, and the central area is up to 450 m higher than the moat. The highest point of the central region is about as high as the basin rim, and higher than the terrain east of the basin. This is possible evidence that this large basin has been deformed by viscous relaxation as is common on Ganymede, Callisto, Enceladus and Dione (Schenk et al., 2004). But channels both east and west of the basin have tributaries that flowed to the east, indicating that Menrva formed on sloping terrain, where the surrounding terrain to the west is somewhat higher than that to the east, suggesting that the inner region may not be elevated above its poorly known average surroundings, reducing support for possible viscous relaxation.

Two other undisputed impact craters (Fig. 4) recently have been discovered in areas not covered by this survey. Afekan (26°N, 200°W) was imaged by radar in May 2008, and is about 115 km in diameter. The crater has a small central peak complex and a rim whose inner and outer slopes are cut by valleys. Portions of a radially striated eject blanket are visible in an arc from the south to east to north. Selk (198°W, 7°N) was first seen on VIMS near-infrared imagery, and later was imaged by radar. Selk is 80 km wide and possesses a broad flat floor and a small central peak.

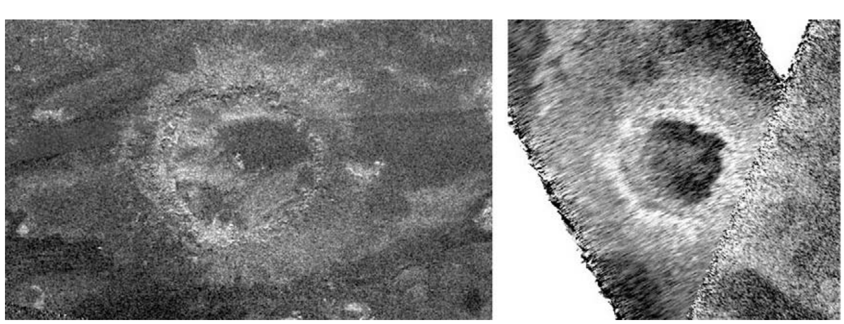

**Fig. 4.** Afekan and Selk are two impact craters discovered outside the area of the present survey.

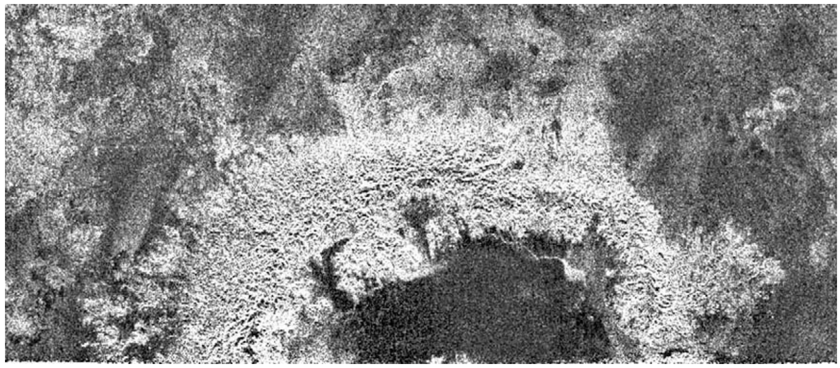

**Fig. 5.** Only half of crater #5 ($D$ = 139 km) is visible, but its bright jagged rim and dark floor reveal it to be a certain impact crater.

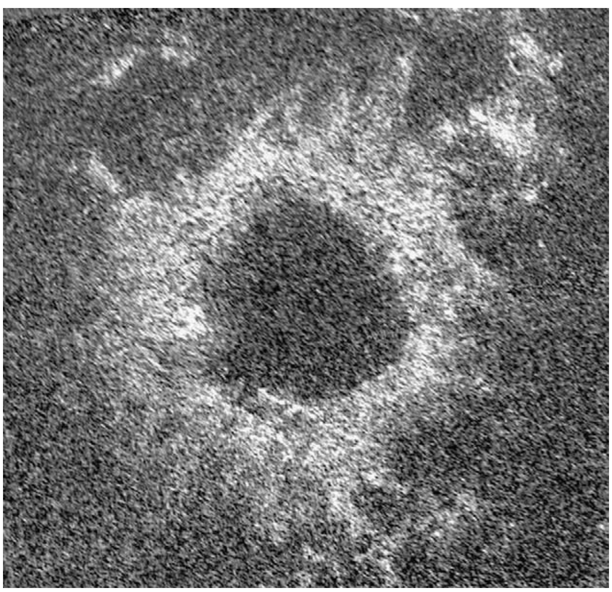

**Fig. 6.** Crater #4 ($D$ = 75 km) appears to be a very fresh impact crater with bright ejecta extending out over adjacent terrain.

Ksa, Sinlap, Afekan, Selk and Menrva demonstrate that impact craters have formed on Titan and can be preserved. No other circular structures on Titan have as many familiar impact crater characteristics. However, another morphological class of crateriform structures is also considered to be of certain (Class 1) impact origin. Three craters, including Selk, have bright, rough and very jagged rims, looking as if an explosion from below fractured and upturned the crust. The best seen of these (Fig. 5) is the half of an unnamed 139 km diameter crater on the edge of radar swath T23. Its rim is very bright and rugged and has a well-defined narrow central mountainous core with less rugged material (talus?) both interior and exterior to it. The floor is smooth (radar dark) and there is a hint of a bright central peak just at the image edge.

A 75 km wide crater at 140°W, 23°N (Fig. 6) has a similar crisp rim crest, and short streamers of bright material/ejecta lead away from the rim. The floor is very dark/smooth and there is no hint of a central peak. This crater is about the same diameter as Sinlap and its jagged rim suggests that it is younger, but it has no significant ejecta blanket. Both this crater and the 139 km wide one described above have morphologies very similar to radar imaged impact craters on Venus (Herrick et al., 1997), and are interpreted to be of impact origin, but with considerably different morphologies than Sinlap and Ksa.

## 4. Nearly certain impact craters

Twenty-three other features seen on Titan are interpreted to be of impact origin but their lack of multiple diagnostic morphologies make their classification *nearly certain* (Class 2), rather than *certain* (Class 1). Figs. 7 and 8 illustrate these likely impact craters. They are arranged by diameters ($D$) so that variations can be clearly seen within craters that would be expected to have had initially similar morphologies. The 11 craters with diameters between 3 and 10 km have four different morphologies. The smallest ones tend to be

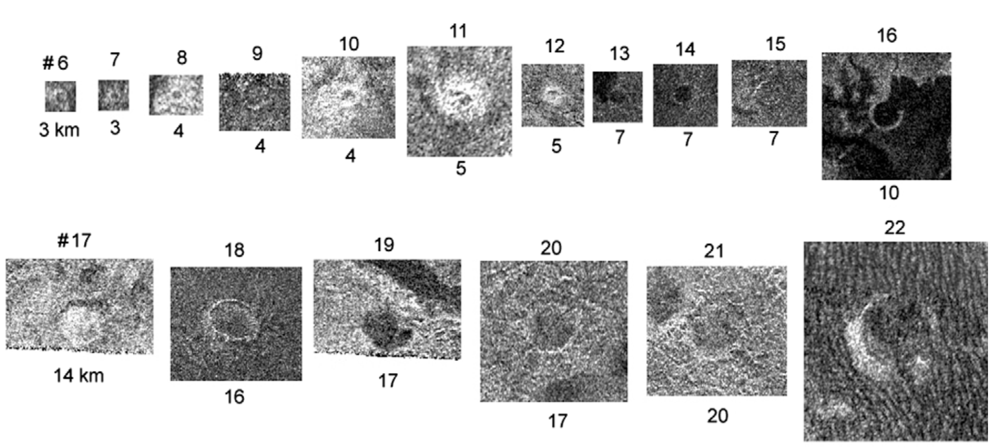


**Fig. 7.** Nearly certain impact craters (Class 2) with diameters of 3–26 km.

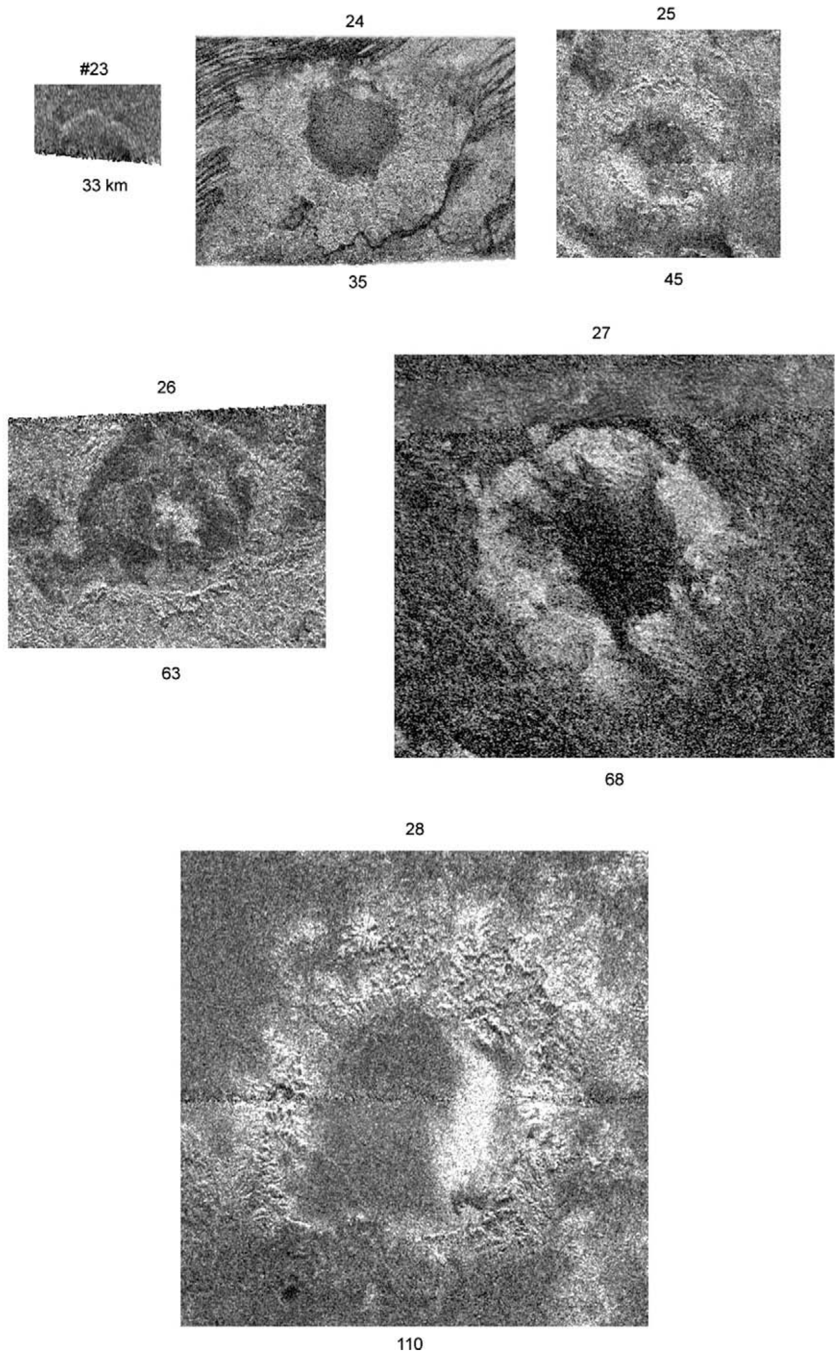


**Fig. 8.** Nearly certain impact craters (Class 2) with diameters of 33–110 km.

small bright-rimmed circles with dark floors. Numbers 10, 11 and 12 are surrounded by bright halos that may be blocky ejecta; they look very much like radar images of Earth's Meteor Crater. Craters 9, 13–15 have broad flat floors and parts of their rims appear broken – these look like older features than the smaller craters. Number 16 is a nearly complete bright rim, clearly elevated since it rises above the dark lake liquid; a hint of a central peak exists right in the crater's center. The six craters with diameters between 14 and 26 km all appear to be eroded and modified. They have wide flat and relatively smooth floors and no central peaks. Number 18 has a rim that rises above its surroundings, as does #22, which also has a broken rim with dark dunes passing through and around it.

Many other crater-like features exist with diameters between 2 and 10 km. There are hundreds of "ink-spots" whose occurrence largely in just one region of Titan (Adiri), and in concentrated groups, suggest that they are not primary impact craters (Wood et al., 2006). It is also unlikely that they are secondary craters because there are no obvious nearby large craters that could be their sources. The features included in our survey are not within the ink-spot areas, but a few of our craters with diameters smaller than 10 km have dark interiors and bright rims and do look similar to ink spots.

There are six nearly certain craters larger than 30 km in diameter (Fig. 8) and each is morphologically distinct from the others. Number 23 is a well-defined raised rim structure that is bisected by the edge of the radar swath. The floor is flat. It is relatively convincing as a crater. Nearly the same diameter is crater #24 on Shikoku Facula which has a mostly round outline with only a hint of a raised rim. The interior is filled with radar dark (smooth) material that may be the same dune material that is to the north. The crater appears to have a thick bright ejecta apron and there are hints of radial features, but the apron may be an illusion caused by a dark channel that arcs around the southern half of the feature, for the bright material continues to the east.

Craters 25 and 26 are heavily eroded circular structures that occur in eastern Xanadu. Number 25 is defined by a perfectly circular ridge about 270° of arc and 45 km in diameter. Part of its rim is missing but the remaining hilly parts convincingly argue that it is a remnant crater. Bright talus covers about half the floor, which is dark in the center. Number 26 also appears to be severely eroded. The hilly 63 km wide rim is broken and a bright stream traverses the crater floor. The floor is mostly dark, except near the rim where talus may occur, and there is a bright central hilly area. Both the 45 km and 63 km rings have morphologies consistent with heavily eroded impact craters.

Guabonito, a 68 km wide bright ring, was first spotted on ISS imagery (Porco et al., 2005) and was one of the early suspiciously circular features. When imaged at high resolution by radar the details of the structure became clear, but its morphology is different than certain impact craters. Unlike the large craters in Fig. 4 this feature does not have a jagged rim, but rather a massive and wide, relatively smooth one. The rim has been penetrated and dark dune material surrounds and fills the crater. There are no nearby lava flows or other features to suggest that Guabonito is volcanic, and even though its morphology is different than other structures likely to be of impact origin, that remains the most likely interpretation.

The final Class 2 crater is an 110 km wide, slightly oval feature with a bright and rough rim very similar to craters #4 and 5. Its rim is more mountainous and wider and appears to be very low or missing on the south. This may be an older, eroded version of the two jagged rimmed craters. SARtopo profiles (Stiles et al., 2009) show that its rim is elevated ~200 m above the floor, and perhaps 100 m above adjacent terrain.

## 5. Probable impact craters

Twenty-one structures are considered Class 3 – *probable* impact craters. In general, these are morphologically similar to Class 2 craters but are more degraded or are seen on radar swathes with lower resolution than normal. There are 10 probable impact craters 10 km and smaller in diameter (Fig. 9). These have morphologies that are similar to small Class 2 craters, but existing radar images do not show them in as much detail so there is more uncertainty of their origins. But the most reasonable interpretation is that they formed by impact processes.

Crater #43 has a different morphology than previously described craters – its circularity is defined by bright material that has been crossed by dunes. The 26 km wide center is dark, presumably where bright material was removed by the impact, or dune material is thick enough to cover it. Dunes play a role in most of the larger Class 3 craters (Fig. 10). Numbers 44, 47 and 49 are bright-rimmed circular structures whose floors are partially cut by dunes. Their crater rims are broken and cannot be very tall because the dunes are not deflected by them. Number 45 is a hardly visible 34 km wide half rim that is very similar in morphology to crater #23, but obscured by closely spaced dunes.

## 6. Are they really impacts?

These 49 features are the best candidates for impact craters yet seen on Titan. Ksa has a morphology that is very similar to fresh craters formed on Mars, Mercury, the Moon and even Earth. In this case the classic morphology of an impact crater has not been significantly altered by its formation in extremely cold ice target rocks. Sinlap and Menrva also look familiar from our inner Solar System experience as somewhat more eroded impacts. Others of the 49 craters look substantially different from these three, but are deemed to be of impact origin. In particular, the bright and apparently jagged rimmed features (#4 and 5) appear not to be severely modified and one even has possible ejecta. But the morphology and brightness of their rims are very different from the more normal looking rims of Ksa and Sinlap, suggesting that relatively youthful craters on Titan may have different rim appearances. Similarly, Guabonito has a fundamentally different rim morphology. This may imply that target rocks across Titan have different physical characteristics; in some cases they deform like silicates, in others they appear much more fractured and jagged, and in others they produce bulkier rims than seen anywhere else in the Solar System.

The images of these 49 circular features demonstrate that they have consistent patterns – round outlines, bright rims and dark floors. While the origins of the majority are not completely certain, the main two known options are impact, a process we know occurs in the Saturn system, or volcanism, a process that has produced on Titan only a handful of circular structures with associated flows (Lopes et al., 2007). Accepting the majority of these 49 structures as impact craters is geologically reasonable and consistent with what we see across the Solar System; accepting them as volcanoes is possible, but less likely, since none has associated volcanic

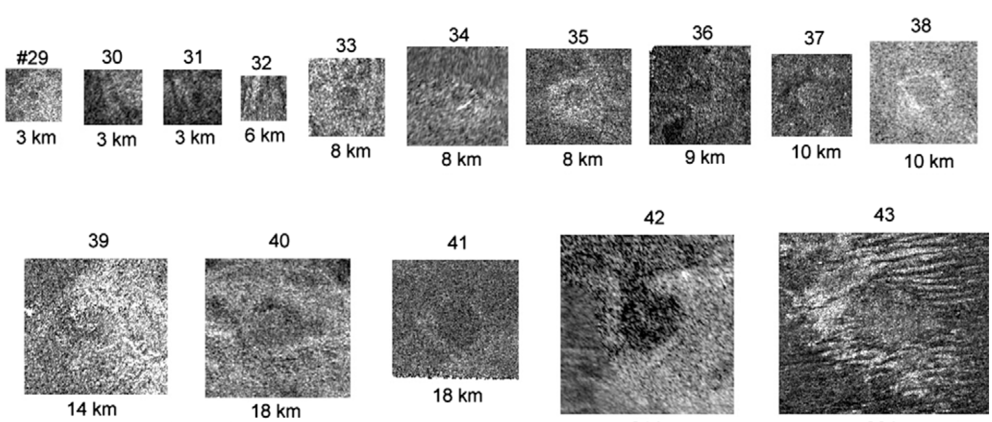


**Fig. 9.** Probable impact craters (Class 3) with diameters of 3–26 km.

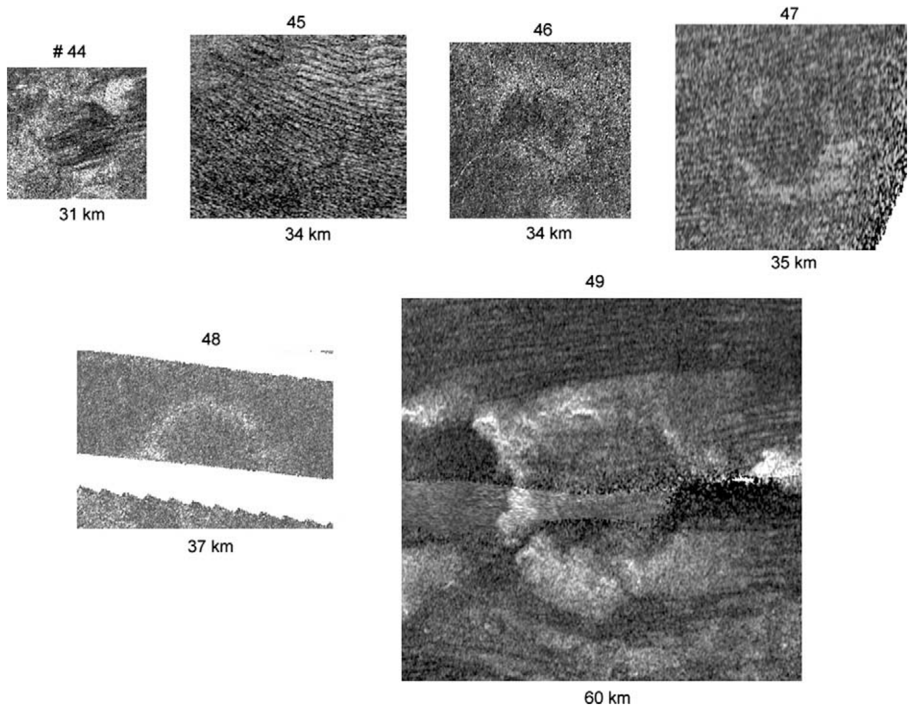


**Fig. 10.** Probable impact craters (Class 3) with diameters of 31–60 km.

features. If many of these 49 features are not of impact origin then Titan's surface is even younger than estimated below.

## 7. Modification processes

All observed craters on Titan have been modified. Even fresh-looking Ksa has dunes on part of its ejecta blanket and a river channel may cut the ejecta. Apparently a variety of modification processes has acted on Titan. Ksa, Sinlap, Menrva, Guabonito and others have been encroached upon and some nearly concealed by dunes. And in the far north, one crater is nearly submerged by lake liquids.

Another type of modification is suggested by the observation that the majority of craters have dark floors and no evidence for central peaks; the dark material is a smooth-surfaced material that may have filled craters sufficiently to bury peaks. On the Moon, lavas do that, as do fluidized impact ejecta from distant basins, and material mass-wasted from crater walls. Craters on Mars often have smooth floors due to lavas, lake deposits and windborne dust. On Titan, the radar-dark floors are unlikely to be due to mass wasting, for where apparent talus is observed around mountains it is radar bright/rough. And presumably, the distribution of any ballistically deposited ejecta is extremely limited by the atmosphere. It is possible that the smooth floors are material from the atmosphere, either wind-carried dust, or hydrocarbons that have been predicted to fall from the sky (Khare et al., 1978). But delicate radial lineations on the ejecta deposits of Ksa and Sinlap suggest that little atmospheric material has been deposited since those craters formed. And abrupt boundaries between bright crater rims and dark floors suggest that most features cannot be covered by homogenizing deposits thicker than a few radar wavelengths (2.2 cm). A final possible mechanism to smooth crater floors (and bury peaks) is the lunar example of the dark/smooth material being lavas erupted within the crater floors.

Nineteen of the 23 Classes 2 and 3 craters on Titan larger than 10 km have incomplete or broken rims. Some processes have breached them and removed significant amounts of rim material. The craters on Xanadu appear to be eroded significantly, as if hundreds of meters of rim material have been removed. Bright talus extending from some of these crater rims suggests that mass movement has occurred. Rivers are also common on Titan, and a few craters are traversed by them. Rivers can erode and carry away debris. The existence of rivers systems with dendritic patterns (Lorenz et al., 2008a) and the observation of storm clouds (Porco et al., 2005) argue that rainfall may be a continuing erosional force degrading impact craters.

There is no compelling evidence of very shallow large craters, uplifted crater centers, or palimpsests, and hence for viscoelastic relaxation. Thus, Titan differs from other icy satellites where this process strongly modifies large craters (Schenk et al., 2004).

Although all the processes of crater modification cannot be identified, the fact that so few craters are found on Titan and that all of them have been altered testifies to vigorous erosion, which is currently acting. Burial by dunes is well documented, and other processes are lowering and cutting crater rims, smoothing floors, and eliminating central peaks.

## 8. Crater distributions

The distribution of Cassini radar swaths is uneven (Fig. 11), with little coverage south of 30°S, and more over the leading hemisphere (0–180°) than for the trailing. Presently, cartographic mapping (and accurate calculations of areas) is complete only through the December 2007 data take, which includes the 49 craters described here. To investigate the spatial distribution of these craters Titan's surface has been divided first into leading and trailing hemispheres (Table 2), and then into six equal area latitude zones (Table 3). The percent of Titan's surface area sampled by radar's swaths in these various subdivisions is compared with the percent of the total number of craters in those subdivisions.

Longitudinally, there is a slight excess of craters on the leading hemisphere compared to the trailing. Based on radar swath

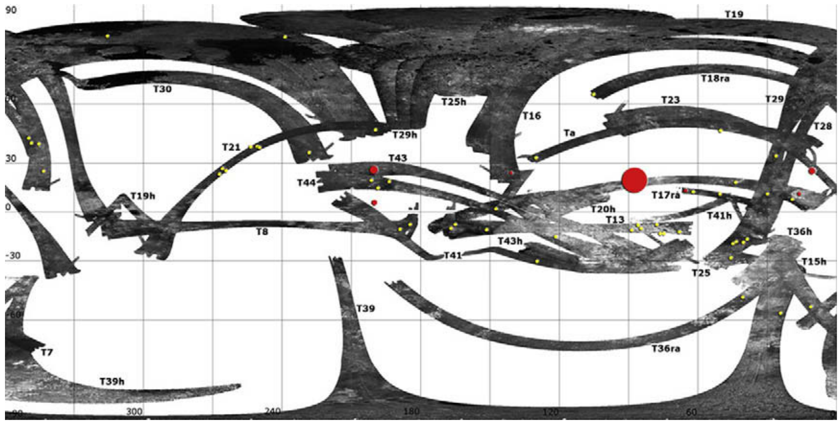


**Fig. 11.** This map shows all the impact crater identified on Titan thus far as red dots for certain impact craters (and the dot size is proportional to crater diameter) and yellow for nearly certain and probable craters. The area covered by all radar swaths through January 2009 (T44) is shown but craters were only counted for swaths Ta through T39. The two leftmost red dots are Afekan (top) and Selk (below).

**Table 2**
Longitudinal distribution of Titan's impact craters.

| Longitude | Areal coverage (%) | Expected # of craters | Observed # of craters | Percentage *O–E* (%) |
|---|---|---|---|---|
| 0–180° | 57 | 27.9 | 31 | 111 |
| 180–360° | 43 | 21.1 | 18 | 85 |

**Table 3**
Latitudinal distribution of Titan's impact craters.

| Latitude | Areal coverage (%) | Expected # of craters | Observed # of craters | Percentage *O–E* (%) |
|---|---|---|---|---|
| 90–42°N | 29 | 14.2 | 8 | 56 |
| 42–19.5°N | 14 | 6.7 | 14 | 204 |
| 19.5–0°N | 16 | 7.8 | 8 | 102 |
| 0–19.5°S | 24 | 11.8 | 15 | 128 |
| 19.5–42°S | 10 | 4.9 | 1 | 20 |
| 42–90°S | 7 | 3.4 | 3 | 87 |

coverage, 57% of the craters would be expected to occur on the leading hemisphere, but 63% are observed on that half of Titan. Based on the areal coverage there should be a leading/trailing hemisphere ratio of 132%, but the observed value is 170%, meaning that there is a ~40% excess of craters on the leading hemisphere. Binomial probability statistics suggests that this result is significant only at the 1-sigma standard deviation because of the small number of craters. If later studies confirm it, this small excess of impact craters on the leading compared to the trailing hemisphere will make Titan only the second satellite (after Triton – Schenk and Zahnle, 2007) with a leading/trailing asymmetry.

Korycansky and Zahnle (2005) analyzed the difference in expected crater density on the leading and trailing sides of Titan, assuming Titan has been in a synchronous rotation over billion year periods (a seasonally-varying rotation rate that has a long-term synchronous average does not affect this apex–antapex asymmetry). They model that the leading hemisphere cratering rate is some four times higher than that of the trailing side, a result considerably higher than our finding of an enhancement of only 40%. Accepting their model as correct suggests the speculation that the recently discovered (Lorenz et al., 2008b) movement of the crust over an underlying ocean has largely erased the leading and trailing hemisphere differences.

Table 3 compares expected and observed numbers of craters (based on percentages of swath areas and craters, respectively) in equal area latitude zones. Craters are found approximately in proportion to the areas of coverage, except there is a 46% deficiency of craters between 42°N and 90°N, and a 204% excess between 42°N and 19.5°N. There is also a strong deficiency between 19.5°S and 42°S, but the number of expected (5) and observed (1) craters is too small to be significant.

The paucity of impact craters in the northern polar region may be due to the abundance of lakes and seas that may submerge craters; indeed, a 10 km diameter crater is revealed by its circular rim rising above a lake surface. A large area of the surface north of 60° is also composed of circular and irregular depressions that may be of karstic or volcanic origin (Mitchell et al., 2007). The factor of two excess of craters between 42° and 19.5°N is harder to explain for the landscape does not appear old in any way. Finally, the slight excess (128%) of craters in the 0–19.5°S latitude belt is partially due to seven craters in eastern Xanadu. The excess for the zone is not very large, however, because the Belet dune field takes up a considerable portion of the radar coverage and there are no craters on these dunes. Further statistical testing is required at the end of the mission when presumably more craters will have been discovered and we will have determined the areal coverage of all data takes.

## 9. Crater densities and surface ages

Accepting all 49 of these circular features as impact craters permits estimation of the crater retention age of the surface. Table 4 presents the statistics for seven diameter intervals. The surface area

**Table 4**
Crater densities/$10^6$ km$^2$.

| Diameter | 1–8 km | 8–16 | 16–32 | 32–64 | 64–128 | 128–256 | 256–512 | 1–512 |
|---|---|---|---|---|---|---|---|---|
| # Craters | 17 | 7 | 10 | 9 | 4 | 1 | 1 | 49 |
| All Titan density | 0.93 | 0.38 | 0.55 | 0.49 | 0.22 | 0.05 | 0.05 | 2.68 |
| Xanadu density | 0 | 0.81 | 3.25 | 1.63 | 0 | 0 | 0 | 5.69 |
| Non-Xanadu density | 1.02 | 0.36 | 0.36 | 0.42 | 0.24 | 0.06 | 0.06 | 2.53 |
| Xanadu/non-Xanadu density | 0 | 2.25 | 9.01 | 3.86 | 0 | 0 | 0 | 2.25 |

for the radar data included here is 18.3 million km$^2$, and the area of Xanadu for this analysis is 1.2 million km$^2$. In Fig. 12 the crater frequency curves or crater densities are plotted for: (1) all of the areas of Titan imaged by radar through December 2007, (2) the area of Xanadu shown on radar swath T13, (3) the non-Xanadu areas of Titan, and (4) a theoretical crater production curve. The All Titan line includes all 49 craters seen on the 22% of Titan observed. An almost identical curve maps the crater densities for All Titan minus Xanadu, and the strongly arced curve is for the seven craters observed on Xanadu – this curve represents a crater density 3–9 times higher than the non-Titan curve for diameters ($D$) from 8 to 64 km. These results document what is clear from examining the distribution map of craters: different surfaces have different relative ages, with Xanadu having a crater density significantly greater than the rest of Titan. Because it has no craters, the Belet dune field must have a lower crater density than any plotted.

Converting these crater frequency curves into estimated surface ages is difficult because the cratering history of the Saturn system and the outer Solar System in general is poorly known. The line in Fig. 12 labeled A&L 2005 is the crater production model from Artemieva and Lunine (2005, hereafter AL05). The line is essentially identical to an independent model by Korycansky and Zahnle (2005, hereafter KZ05). As noted in Lorenz et al. (2007) these two models yield ages for a given crater distribution that differ by a factor of 5. For AL05 the line represents and age of 200 Ma, but for KZ05 it is 1 Ga. Although we are unable to resolve that discrepancy here, we can at least consider some of the different model assumptions.

Both papers adopt as a starting point the Zahnle et al. (2003) impactor population, due to long-period comets. KZ05 assume that the cratering rate is constant with time, whereas AL05 discuss how the impact rate probably has decreased with time, and use a $1/t$ dependence. Thus, the number of impacts over 4.5 Ga in AL05 in fact is presumed to be about 15 times the present-day rate of impacts/Ga, as shown in the number of impacts vs *projectile* diameter for 1 and 4.5 Ga retention ages (AL05, Fig. 8) and also in a cumulative impact plot in an abstract that reports further results of that modeling effort (Lunine et al., 2005). However, the effect of this assumed dependence is not large for ages of 1–2 Ga.

AL05 then report (their Fig. 10) a differential crater size distribution (i.e. number of craters over all of Titan's surface in root-2 size bins), the text indicating that this corresponds to 4.5 Ga of accumulated impactors. If we integrate this curve, we find the cumulative size distribution (i.e. total number of craters greater than a given size) and then divide by 15 to obtain the present-day cratering rate per Ga, and divide by 82 to obtain the flux in impacts/Ga/million km$^2$. Distressingly, the cumulative crater curve for 1 Ga in (Lunine et al., 2005) seems to give a density about half as large – 200 craters > 20 km, ~2 craters > 100 km – as the procedure above.

KZ05 report differential size distributions (again in root-2 bins) per 1 Ga over Titan's surface, for both A and B models. We integrate the A curve (the B curve is indistinguishable from A) and divide by 82 to obtain the flux in impacts/Ga/million km$^2$. The rate is a factor of ~5 lower than for AL05, as noted in Lorenz et al. (2007). There is insufficient detail in the KZ05 and AL05 papers to isolate the reasons for this difference: a plot of impactor diameter against resultant crater size (as shown in Artemieva and Lunine, 2003) for the KZ05 model is one missing item that might help. Another missing item is a full explanation of the crater scaling used in AL05 – although both KZ05 and AL05 claim to use scaling laws by Schmidt and Hausen (1987) with the same correction for complex craters, there may be differences in the details. Since both models start with the same impactor size distribution, it seems that if the difference is 'real' (and not due to, e.g. a mislabeled plot) the difference may be due to the details of the atmospheric interaction (KZ05 invoke additional mechanisms for disruption of the impactor via hydrodynamic instabilities, whereas AL05 use a simple 'pancake' model) and perhaps to small differences in crater scaling.

Our All Titan line crosses the theoretical curve at about $D = 35$ km, and parallels it at larger diameters, but with the observed crater densities being 1.6–7.8 times higher than the isochron. This suggests that larger craters have been preserved from a more distant past than craters with diameters smaller than 35 km. At $D < 35$ km, the observed distribution is only 0.2–0.6 of the isochron, showing that roughly 2–5 times as many of these smaller craters have been erased for each one we see today. The most interesting result is for Xanadu which has a crater density 2–9 times higher than the All Titan curve for $8 > D < 64$ km. Xanadu is the oldest surface identified on Titan thus far, based on crater counts. Actually, all the craters on Xanadu are on the eastern half of the giant landform, so the crater excess in that area is roughly 4–18 times the All Titan curve.

These are highly speculative results, because of the small number of craters, the uncertainty of the impact origin of all the features included in the statistics, and the uncertainty in the theoretical crater production rates. Nonetheless, these curves provide the first statistical evidence for different ages of terrains on Titan. Following the AL05 cratering rate (which we choose because AL05's impactor size–crater size relationship is directly exposed in AL03 Fig. 1, and thus ages can be simply scaled without affecting the assumed impactor population if a new atmospheric interaction or crater scaling approach is developed) implies that many surfaces pitted by craters smaller than 35 km in diameter are less than 200 Myr old. Larger craters have apparently been preserved despite erosion that has depleted or erased smaller craters.

Even if all of the 49 circular features identified are actual impact craters, the surface of Titan is quite young. Even the oldest terrain seen thus far (Xanadu) has vastly fewer craters than equal areas on Rhea, Dione and Tethys. This observationally-derived conclusion is generally consistent with the evolutionary model of Tobie, Lunine, and Sotin (2006) which predicts that only during the last half billion years has Titan had a thick enough crust to be stable from volcanic overturn and to preserve impact features. Xanadu and other radar-bright surfaces may be relicts from this earliest stable crust, but the overall paucity of impact craters and the highly eroded state of the others imply that Titan has been strongly modified by dunes, lake flooding, volcanism, river systems and mass wasting. Titan is a very active world.

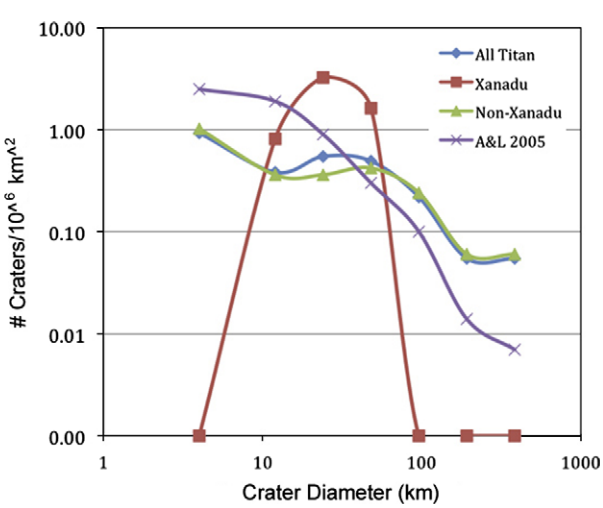


**Fig. 12.** Crater density plot identifies frequency of impact craters imaged by radar for all of Titan (diamonds), just on Xanadu (boxes), non-Xanadu regions (triangles), and the model of Artemieva and Lunine (2005) for a 200 million year old surface.

## 10. Small craters and Titan's atmosphere

At a diameter of about 32 km there is a change in slope of the crater frequency curve, with fewer small craters than predicted from the number with larger diameter. Such a fall off is commonly observed in crater counts on all worlds with the explanations being that resolution limits the detection of craters with small diameters, and erosion processes preferentially remove small craters. For Titan there is another possible explanation – the thick atmosphere destroys incoming projectiles that would form small craters.

Two models have predicted that Titan should have few impact craters with diameters smaller than about 20 km because most of the projectiles that would form them should be destroyed during passage through Titan's atmosphere (Zahnle et al., 2003; Artemieva and Lunine, 2003). A third model predicts that the atmosphere would significantly reduce the number of impact craters smaller than 6–8 km in diameter (Ivanov et al., 1997). We have detected 29 possible impacts craters with diameters between 3 and 20 km. There would be no hesitancy in interpreting at least three of small features that have bright halos as fresh impact craters if they were observed on any other world. In fact, the morphologies of all the small craters are consistent with impact origins.

There are a number of possible explanations for the differences between the atmospheric ablation models and our observations: the features smaller than 20 km may not be impact craters, the models may be incomplete, or Titan's atmosphere did not exist when the craters formed. The third option is one of last resort – especially since the smallest craters are likely the youngest, but the other two are worth consideration. While not all the sub-20 km features are necessarily of impact origin, we believe that most are. The models that predict atmospheric destruction of small projectiles consider them to be made of ice-rich cometary materials, but projectiles made of chondritic or nickel–iron would be more likely to survive atmospheric passage. However, chondritic and metal asteroids are concentrated near 3 AU in the asteroid belt, and few would be expected to collide with Titan. Because of the uncertainty of origin for these small craters we cannot seriously question the models that predict no small craters should exist on Titan. But neither can we disprove an impact origin for the small craters. Our radar detection of possible small craters is much more consistent with the model of Ivanov, Basilevsky and Neukum; but we hope that all the models will be re-examined based on our observational data.

## 11. Conclusion

The surfaces of Rhea, Tethys, Dione demonstrate how Titan might have looked. Titan presumably had a similar impact crater production history but did not end up as a heavily cratered world. In fact, the paucity of impact craters on the quarter of Titan examined with the Cassini radar indicates that the surface of the world has been greatly modified. Radar images show that dunes embay, cross and bury a number of craters, and another is detectable only because its rim rises above the lake that surrounds it. A number of craters are crossed by channels, probably cut by flowing liquids.

The small number of craters makes conclusions concerning variations in their spatial distributions speculative, but Xanadu appears to be the most heavily cratered region yet seen, and dunes are essentially crater-free.

The lack of an agreed upon crater production rate means that model ages for the surface of Titan are uncertain by a factor of five, ranging from a few hundred million to a billion years. By the end of the extended missions the Cassini radar will have covered about twice as much of the surface as seen thus far; perhaps these tentative results will be supported, or other surprises may become apparent.

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