Reports

Large Quasi-Circular Features Beneath Frost on Triton

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Specially processed Voyager 2 images of Neptune's largest moon, Triton, reveal three large quasi-circular features ranging in diameter from 280 to 935 kilometers within Triton's equatorial region. The largest of these features contains a central, irregularly shaped area of comparatively low albedo about 380 kilometers in diameter, surrounded by crudely concentric annuli of higher albedo materials. None of the features exhibit significant topographic expression, and all appear to be primarily albedo markings. The features are located within a broad equatorial band of anomalously transparent frost that renders them nearly invisible at the large phase angles ($\alpha > 90°$) at which Voyager obtained its highest resolution coverage of Triton. The features can be discerned at smaller phase angles ($\alpha = 66°$) at which the frost only partially masks underlying albedo contrasts. The origin of the features is uncertain but may have involved regional cryovolcanic activity.

Of the many icy satellites that Voyager spacecraft imaged during their tour of the outer solar system, only the Jovian moon Europa and perhaps Saturn's Enceladus rival the geologically youthful appearance of Neptune's satellite Triton. Each of these objects is covered with clean, high-albedo frosts and ices, and each is topographically smooth in comparison to most other icy satellites. The scarcity of large impact structures on these objects is most often cited as evidence that they have been resurfaced by some form of icy volcanism in recent geological time. In the case of Triton, the presence of active geyser-like eruption plumes (*1*) attests to ongoing geological activity. Now, as a by-product of routine photometric work, we have identified on Triton three large, quasi-circular markings of possible volcanic origin (Table 1).

Photometric or shading correction is a standard image-processing technique by which a photometric model is used to compensate for the broad-scale change in brightness that accompanies the gradual, systematic variations in angles of incidence (i) and emission (e) from limb to terminator across a planetary surface. We have used the recent photometric model of Triton's surface and atmosphere of Hillier *et al.* (*2*). In the approach usually adopted, the local brightness at each visible point on a planetary surface is normalized by that predicted from the photometric model at the corresponding incidence, emission, and phase angle (α). Local normal albedos (r_n) are estimated from multiplication of this brightness ratio by the model reflectance at $i = e = \alpha = 0°$. Such estimates of normal albedo assume that albedo contrasts are independent of phase angle and are accurate only when terrains differ in albedo alone and not in other physical properties that affect the observed brightness, such as surface roughness and regolith particle transparency.

One such shading-corrected Voyager image (Fig. 1A) reveals three crudely circular features. At the spatial resolution of this image (8.2 km/pixel), little can be said about any possible topographic expression of the features; they appear to be primarily albedo markings.

Feature A, the largest of the three structures (935 km in diameter), exhibits internal concentric annular markings and, in scale and planform, bears superficial resemblance to multiringed impact basins such as Orientale on the moon. It contains a central, irregularly shaped region of comparatively low albedo about 380 km in diameter, surrounded by crudely concentric annuli of higher albedo materials. The outermost annulus is distinguished best on its easternmost extremity where a relatively sharp albedo contact occurs. Exterior to this contact is a broadly crescent-shaped region of bright material ($r_n = 0.95 \pm 0.03$) that partially obscures the surrounding terrain. Immediately interior to this albedo contact is an approximately 150-km-wide annulus (outer annulus in Fig. 1B) of slightly darker material. The outer radius of this annulus defines the southern boundary and part of the northern boundaries of the outer annulus. The southern edge of the annulus is partially obscured by a thin veneer of frost that extends nearly all the way across the disk from east to west. The outer ring is poorly defined at its western edge. Likewise, the boundary separating outer annulus from inner annulus is indistinct or gradational. The inner annulus appears to be a heterogeneous transition zone containing irregular patches of brighter outer annulus material interspersed with patches of lower albedo material that more uniformly covers the central portion of the structure.

Feature B, a structure 445 km in diameter that lies to the east of feature A, is perhaps the most clearly distinguishable of the three features. Its albedo is intermediate to inner

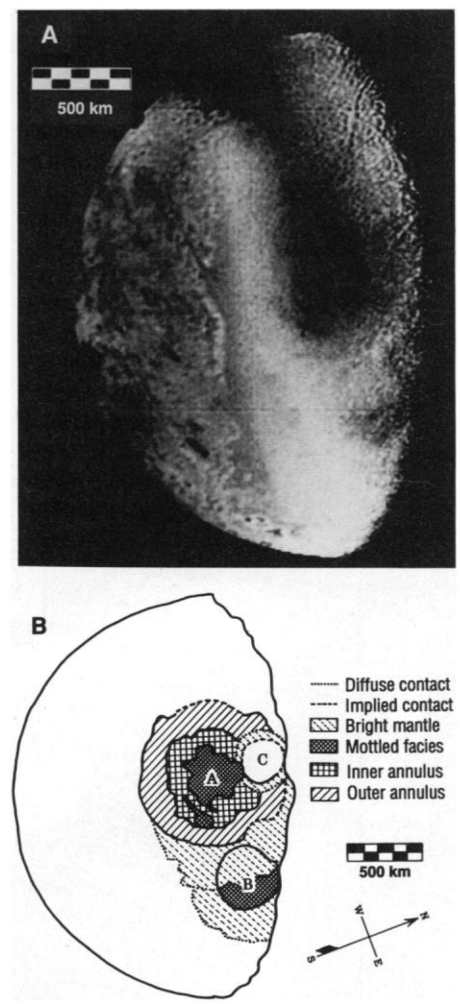

Fig. 1. (**A**) Voyager green-filter image FDS 11394.16 after photometric correction and contrast enhancement. South polar cap is visible at left. Phase angle $\alpha = 66°$. (**B**) Geological sketch map of (A) showing quasi-circular features and related structures. Table 1 gives sizes, locations, and estimated albedos of the features.

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and outer annulus material in feature A. The full circumference of feature B can be traced as an albedo contact, even though the entire western half of the feature appears to be covered by a bright extension of feature A.

Feature B is surrounded on its south and east margins by a 200-km-wide partial ring of bright material like that surrounding feature A.

Feature C, the least discernible of the three features, is a roughly circular, comparatively dark albedo marking located within feature A on the northern edge of the outer annulus. It is best distinguished on its eastern and western edges where it is bounded by two 50-km-wide arcs of slightly higher albedo material (r_n = 0.83 ± 0.06). Other quasi-circular features may also be present (for example, a 300-km feature west-northwest of feature B); however, their identification is even less certain than that of feature C and we have excluded them from this analysis.

These features have evaded detection until now because they are obscured at large phase angles by a veneer of unusually transparent frost that covers nearly the full circumference of Triton's equator (*3*). Most images used for geological analysis were acquired by Voyager at significantly larger phase angles and higher resolutions than the image used for Fig. 1A. The obscuring behavior of the frost is shown in Fig. 2, A through C. Figure 2A shows that the features are nearly invisible at α = 98° (refer to Fig. 2D for location). Careful examination reveals only the northeastern boundary of feature B. In Fig. 2B we have reprojected Fig. 1A and spatially coregistered it to the viewing geometry of Fig. 2A. To show the placement of topographic features in Fig. 2B, we applied a 5 by 5 pixel high-pass filter to Fig. 2A and superposed the smallest scale features from Fig. 2A into Fig. 2B. Although Fig. 2B is similar to Fig. 2A near the limb (southern polar cap), its appearance within the equatorial frost band region (center) is remarkably different. In Fig. 2B, the three features are visible as relatively dark albedo markings. Comparison of Fig. 2A and Fig. 2B also confirms the almost total lack of topographic expression of the features. Figure 2C is a ratio image of Fig. 2A divided by Fig. 2B, a presentation that enhances the photometric differences between the images. Features appearing bright in Fig. 2C are less strongly backward-scattering than dark features. For example, the forward-scattering aerosols in the eruption plumes identified by Soderblom *et al.* (*4*) near the limb show up as bright features in Fig. 2C. The most conspicuous bright region in Fig. 2C is an area that coincides with the center of feature A. Feature B is defined by material that is somewhat more backward-scattering (dark) than feature A materials but still less backward-scattering (brighter) than typical polar cap and frost band material.

The geological setting of the features agrees reasonably with geological units mapped in Smith *et al.* (*1*). The features coincide almost uniquely with a region identified as high-standing smooth plains. They

Table 1. Locations, sizes, and albedos of quasi-circular features on Triton. The albedos are corrected for atmospheric light scattering. Error bars are 1 SD. Model-predicted average albedo of Triton's surface is 0.93.

Feature	Location	Structural component	Diameter (km)	Albedo (r_n)
A	18°N, 9°E	Outer annulus	935	0.88 ± 0.05
		Inner annulus	655	0.81 ± 0.05
		Mottled facies	380	0.75 ± 0.03
B	15°N, 42°E	Circular area	445	0.87 ± 0.06
		Mantled section		0.91 ± 0.03
		Mottled facies		0.85 ± 0.05
C	33°N, 10°E	Circular area	280	0.82 ± 0.06

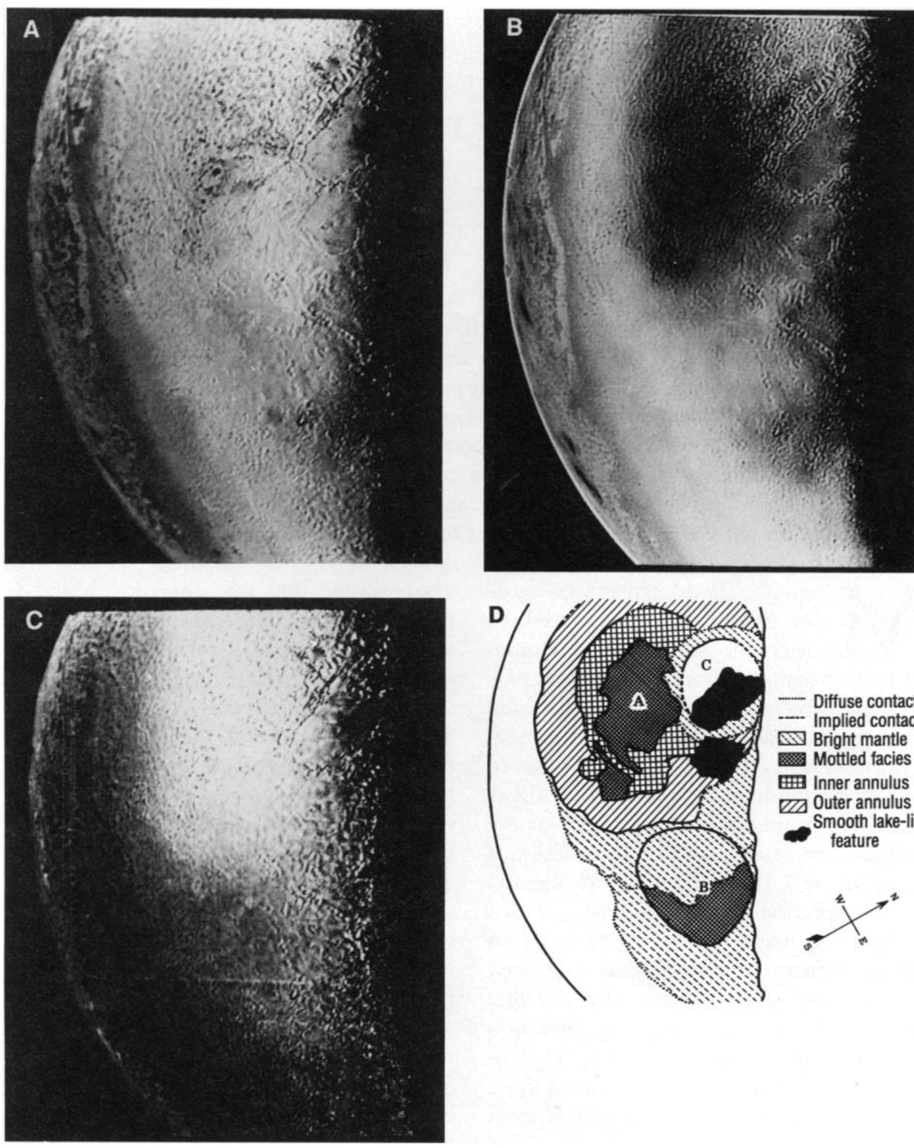

Fig. 2. (**A**) Voyager green-filter image FDS 11396.09 after photometric correction and contrast enhancement. Phase angle α = 98°; resolution, 3.1 km/pixel. (**B**) Image FDS 11394.16 reprojected into the geometry of (A). High spatial frequency information has been transferred from (A) to (B) to show placement of topographic structures. (**C**) Ratio image of (A) to (B). Bright region is an area of anomalously transparent frost. (**D**) Geological sketch map derived from (B).

are bounded to the southeast by hummocky rolling plains. Although the southwest portion of feature A is somewhat indistinct, it appears to extend slightly into the mysterious cantaloupe terrain, being bounded there by a prominent linear ridge. Within the boundaries of the quasi-circular features are many smaller structures of almost certain cryovolcanic origin (*1, 5, 6*). These include two of only three examples of "lake-like" features visible in Voyager images of Triton. The smooth floors and terraced edges of the lake-like features are thought to have been emplaced by multiple episodes of icy volcanic flooding. The entire region is dominated by high-standing smooth materials that appear to have erupted from smaller quasi-circular depressions and extruded in flows several kilometers thick with rounded margins (*1*). Other proposed cryovolcanic formations in the region are irregular pits and pit chains, interpreted as explosive cryovolcanic vents, and dark lobate flowlike features (*5*).

There are at least two possible interpretations of the quasi-circular features. Smith *et al.* (*7*) used the term "palimpsest" to describe a class of roughly circular, large (>50 km) albedo markings on Ganymede and Callisto that are interpreted to be vestigial remains of impact craters that have undergone nearly complete viscous relaxation or that formed as a result of impacts into a fluid mantle (*8*). Palimpsests are generally higher in albedo than their surrounding terrains and exhibit little topographic relief at scales larger than a few kilometers. The quasi-circular features are reminiscent of palimpsests because of their large sizes, crudely circular planform, and subdued broad-scale topography. Unlike palimpsests on the Jovian satellites, these features are generally lower in albedo than their surrounding terrain and lack the characteristic small-scale topographic structure of palimpsests such as hummocky ejecta mantles, basin-related massifs or scarps, or rimmed furrows like Callisto's Valhalla structure (*7, 9*). In addition, the quasi-circular features lie within terrains that are interpreted to be geologically youthful (*1, 5, 10*) because of their paucity of identifiable impact craters. On other planets and satellites, impact structures that are similar in scale to the quasi-circular features are interpreted to be ancient, dating back to the time of terminal bombardment, some 3.5 billion to 4.0 billion years ago. Thus, the interpretation of Triton's large quasi-circular features as possible palimpsests is difficult to reconcile with accepted interpretations of the satellite's geological history.

A more tenable explanation, proposed by Croft (*11*), is that the features are a result of regional cryovolcanic activity. This hypothesis is supported by detailed geological mapping and analyses of high-resolution images of Triton (*1, 5, 6*) that have ascribed cryovolcanic origins to numerous smaller scale structures in this region of the satellite's surface. The overall pattern of the quasi-circular features may be due to an ancient buried impact basin or to an upwelling convective mantle plume. There is presently no clear evidence that the regional topography of quasi-circular features is either elevated or depressed relative to surrounding terrains. The complexity of superposed landforms suggests that the quasi-circular features were emplaced not in a single, massive event but instead by many smaller events concentrated over a regional "hot spot." Thus far, comparable features have not been identified on any other icy satellite.

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12. We are indebted to two anonymous referees and especially S. K. Croft for constructive reviews. We thank B. Boettcher and J. Hovencamp for help with illustrations and M. Roth for manuscript preparation. This study was funded by National Aeronautics and Space Administration grants NAGW-2084 and NAGW-2186.

10 June 1991; accepted 19 November 1991

Channel Initiation and the Problem of Landscape Scale

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Since the 1940s it has been proposed that landscape dissection into distinct valleys is limited by a threshold of channelization that sets a finite scale to the landscape. This threshold is equal to the hillslope length that is just shorter than that necessary to support a channel head. A field study supports this hypothesis by showing that an empirically defined topographic threshold associated with channel head locations also defines the border between essentially smooth, undissected hillslopes and the valley bottoms to which they drain. This finding contradicts assertions that landscapes are scale-independent and suggests that landscape response to changes in climate or land use depends on the corresponding changes in the threshold of channelization.

Most geologic agents of erosion modify the land surface on a variety of spatial scales. Consequently, casual observation of topographic maps, or observations of landscapes from afar, suggest that landscapes are scale-independent (Fig. 1). Indeed, fractal analyses of landscape form have revived the hypothesis that there is no characteristic scale to the landscape and that finer and finer scales of dissection will be found upon closer and closer inspection (*1*). In contrast, detailed topographic maps reveal that there is an internal structure to the landscape expressed as ridges and valleys of finite size and that the scale of this limit to landscape dissection varies in different landscapes (Fig. 1). Gilbert (*2*) first recognized the apparent finite extent to landscape dissection, and Horton (*3*) proposed that this dissection proceeds until hillslope lengths are everywhere just shorter than that which could generate sufficient overland flow to initiate surface erosion and, consequently, channelization. Subsequently, several workers have proposed models to explain channelization and landscape development on the basis of thresholds of erosion (*3–6*). An alternative theory for finite dissection, first proposed by Smith and Bretherton (*7*), states that hillslopes are unstable to lateral perturbations in which advective (*8*) dominates diffusive sediment transport (*9*). A channelization threshold, however, has not been shown to distinguish hillslopes from valleys in a real rather than a model landscape. We present field data that demonstrate that drainage basins tend to be geometrically similar (contributing to a scale-independent landscape appearance) but that finite dissection of the landscape corresponds to the lower bound of an empirically determined topographic threshold for channelization.

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