Cassini observations of flow-like features in western Tui Regio, Titan

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Received 8 May 2006; revised 19 July 2006; accepted 24 July 2006; published 30 August 2006.

[1] A large (>3 × 10^4 km^2), lobate, 5-μm-bright region seen by Cassini on Titan's leading equatorial region is best explained as a flow field. We discuss observations from the Visual and Infrared Mapping Spectrometer and Imaging Science Subsystem of the feature and present a map of the field. We establish relative ages of flow features and discuss possible formation mechanisms and the implications of this finding for the evolution of Titan's surface.
Citation: Barnes, J. W., et al. (2006), Cassini observations of flow-like features in western Tui Regio, Titan, *Geophys. Res. Lett.*, *33*, L16204, doi:10.1029/2006GL026843.

1. Introduction

[2] Cassini has seen tantalizing hints of past volcanic activity on Saturn's giant moon Titan. The RADAR instrument saw lobate fronts and overlapping digitate features that may represent surface flows as well as a 180-km diameter circular volcanic feature (Ganesa Macula) [*Elachi et al.*, 2005; *Lopes et al.*, 2005] (R. M. Lopes, Cryovolcanic features on Titan's surface as revealed by the Cassini Titan radar mapper, submitted *Icarus*, 2006) (hereinafter referred to as Lopes et al., submitted manuscript, 2006). The Visual and Infrared Mapping Spectrometer (VIMS) instrument saw a 30-km feature (Tortola Facula) that *Sotin et al.* [2005] inferred to be volcanic, and VIMS also detected excess atmospheric carbon monoxide thought to imply recent geologic activity [*Baines et al.*, 2006]. However we still do not know the full extent of global resurfacing, the nature of the erupting material, when the volcanic activity may have taken place, or whether it continues today.

[3] We report observations from Cassini's VIMS and Imaging Science Subsystem (ISS) instruments of flow-like features located in western Tui Regio. We investigate possible explanations for the features' creation, coming to the conclusion that they may represent young, extrusive, volcanic flows. We measure the features' geometries, relative ages, and composition, and finally we investigate the implications for Titan's global geology.

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0094-8276/06/2006GL026843$05.00

2. Observations

[4] Tui Regio is a region of relatively high 5-μm reflectivity centered near 125°W 24°S that is ~150 km wide and extends for 1500 km in an east-west direction (Figure 1). Its spectrum matches that of "Hotei Regio", another 5-μm-bright spot that has been established to be a surface feature [*Barnes et al.*, 2005], and thus we infer Tui Regio to represent surface, and not atmospheric, markings as well. It is unlikely to be low-lying fog due to the 5-μm-bright areas' spectral behavior at 2.7 μm [*McCord et al.*, 2006]. The fact that these two relatively small, isolated regions remain spectrally distinct despite organic fallout from Titan's atmosphere implies that they are geologically youthful.

[5] VIMS observations of the western portion of Tui Regio (Figure 2a) show at least three long, thin, lobate, spectrally self-similar tendrils emanating from a central point that is the brightest VIMS pixel in the immediate vicinity. The central, bright point is located at 134°W 22°S. The tendrils extend north, southwest, and west-northwest from this central point (Figure 2d).

[6] The infrared spectrum of the central point and the surrounding tendrils is well-modeled as a mixture of the most 5-μm-bright point on Titan and the mid-latitude bright background west and south of Tui Regio. Though this could in principle represent a macroscopic intertwining of 5-μm-bright and background materials at scales smaller than a VIMS pixel, we think that it does not in every pixel because of the smooth gradient in brightness away from the bright point, the relatively uniform spectra across the southwest tendril, and the broad differences between the three tendrils viewed at the same spatial resolution. Some VIMS pixels, particularly the northwesternmost 5-μm-bright pixels, vary substantially pixel-to-pixel and therefore may be the result of an unresolved smaller unit. Additionally, the most 5-μm-bright areas in eastern Tui Regio and "Hotei Regio" are brighter than the central point, despite the fact that VIMS' best resolution there is at least a factor of 2 lower than that for west Tui Regio.

[7] If the brightness gradients are not an artifact of underresolution (at least not in every case), then it follows that they represent a varying intimate mixture of the compositions of both the 5-μm-bright and background material. Since the implied fraction of 5-μm-bright material decreases regularly toward the southwest from the central point, we posit that the central point is a source of 5-μm-bright material that formed the tendrils.

[8] The source is not an impact crater given that the tendrils, which would in that case be interpreted as rays, are not in perfect radial orientation around the central point, nor are their margins impact-ejecta-like.

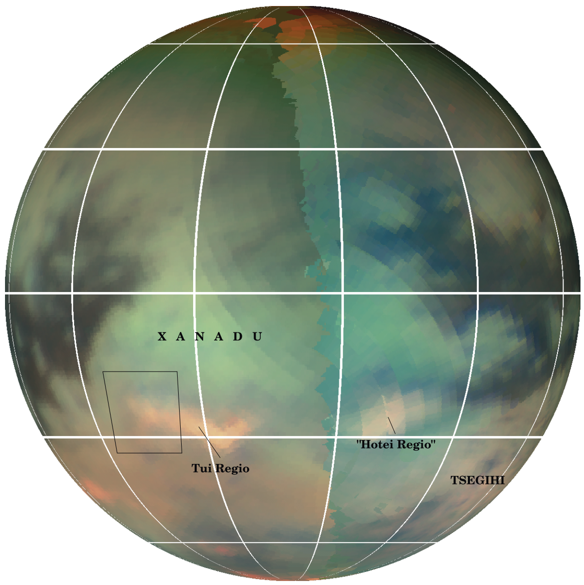

Figure 1. Simulated global view of Titan from above the equator at 100°W showing the 5-micron-bright regions (Tui Regio and "Hotei Regio") and their context. Cassini has never had this view of Titan during a flyby, so we fused the Tb (2004 December 13) and T4 (2005 March 31) VIMS data sets into a single orthographic reprojection. The view is neither incidence-corrected nor haze- and atmosphere-subtracted, resulting in unreliable relative photometry, particularly between Tui Regio and "Hotei Regio". The colors are mapped to atmospheric windows, with red mapped to 4.8–5.2 μm, green to 2.0 μm, and blue to 1.26 μm.

[9] One of the mechanisms for 5-μm-bright terrain emplacement suggested for "Hotei Regio", volcanic airfall [*Barnes et al.*, 2005], also seems unlikely given the abrupt right turn that the western tendril takes 100 km west of the source region. Additionally, an airfall could not have produced the southwestern tendril from the source given that global circulation models of Titan's tidally- and insolation-driven winds [*Tokano and Neubauer*, 2002] do not predict strong northeasterly winds at this site.

[10] Landslides can produce lobate landforms [see, e.g., *McEwen*, 1989]. The tendrils might have then be formed by long-runout landslides, driven by acoustic fluidization as on other planetary bodies [*Melosh*, 1979]. On Earth and Mars, typical maximum values for a landslide's runout length relative to the depth it falls is ~0.03 [*Collins and Melosh*, 2003]. Given the tendrils' length, over 100 km, the landslide hypothesis then implies a commensurate drop of at least 3 km in height – much greater than the greatest topographic differences thus far seen on Titan by RADAR altimetry (~100 m [*Elachi et al.*, 2005]) and the Huygens stereo imaging (~300 m [*Tomasko et al.*, 2005]). In combination with the tendrils heading in many different directions and the flow bifurcation structure as seen from ISS (detailed below), the huge length scale strongly argues that the tendrils do not represent long run-out landslides.

[11] Lava flows on Earth display long, lobate morphologies, and cryolava flows are expected to behave similarly to silicate ones [*Kargel et al.*, 1991]. Therefore the source could represent a vent for the extrusion of molten subsurface material, and the tendrils represent flows of cryolava onto the surrounding plains. Under this scenario, as material is erupted it is brightest at 5 μm, then an unknown maturation process converts this material into background, making old flows less 5-μm-bright. The entire west Tui Regio area would represent the superposition of a number of flows of differing ages and areal extents. This scenario is particularly intriguing in light of recent predictions that more cryovolcanic structures would be detected on Titan [*Tobie et al.*, 2006]. Below we investigate this hypothesis in further detail.

[12] Shown in Figure 2d-inset is a RADAR image of lobate flow features located half a world away near 45°N 30°W [*Elachi et al.*, 2005; *Lopes et al.*, 2005, also submitted manuscript, 2006]. The putative flows in west Tui Regio are of similar length scale and areal extent to these more established flow features. Thus the composition, flow volumes, and eruption style of the two may be the similar as well. Incidentally, VIMS maps of the region surrounding the RADAR flow show a uniform area with the spectral character of Tui's background, implying that the RADAR flow must be geologically old enough to have been entirely matured into our VIMS-defined background.

[13] Broadly extending north and east of the source from north azimuth −30° through approximately north azimuth ~90° is an enigmatic and unusual region that is poorly reflective at 5 μm, but becomes progressively brighter at shorter wavelengths (Figures 2d and 3). This blue spectral unit broadly overlies both 5-μm-bright terrain and the surrounding darker plains of southwest Xanadu. Hence the blue material must have been added to both terrains after they formed, consistent with other material deposited from the atmosphere, perhaps as volcanic airfall.

[14] Global circulation models of tidally- and solar-driven winds predict that the prevailing winds in west Tui Regio should come out of the northwest through southwest and on to southeast over Titan's 16-day rotation period [*Tokano and Neubauer*, 2002]. Given these winds and the source's location at the southwest vertex of the blue terrain, we think that the volcanic activity that produced the extrusive flows also may have released volatiles which then condensed in the air and were blown downwind of the source. Eruptive events may also have released particulate ash that was blown downwind of the source which would also be icy in composition.

[15] As a mapping spectrometer, VIMS obtains images in 352 wavelengths simultaneously, but at lower spatial resolution than those the imaging camera takes at a single wavelength (0.938 μm for Titan). Combination of the two data sets yields a powerful tool to help understand Titan's surface geology, and in the case of west Tui Regio provides corroborating evidence for extrusive volcanism.

[16] The ISS view of western Tui Regio (Figure 2b) shows a generally low correlation with the VIMS 5-μm channels, similar to that seen for other 5-μm-bright regions [*Barnes et al.*, 2005]. The areas of possible tectonic origin, seen in VIMS as 5-μm-bright, show no obvious impact craters, no linear possibly tectonic features, and no channels in the ISS view. For example the area 100 km northwest of the northwesternmost 5-μm-bright terrain has northwest-

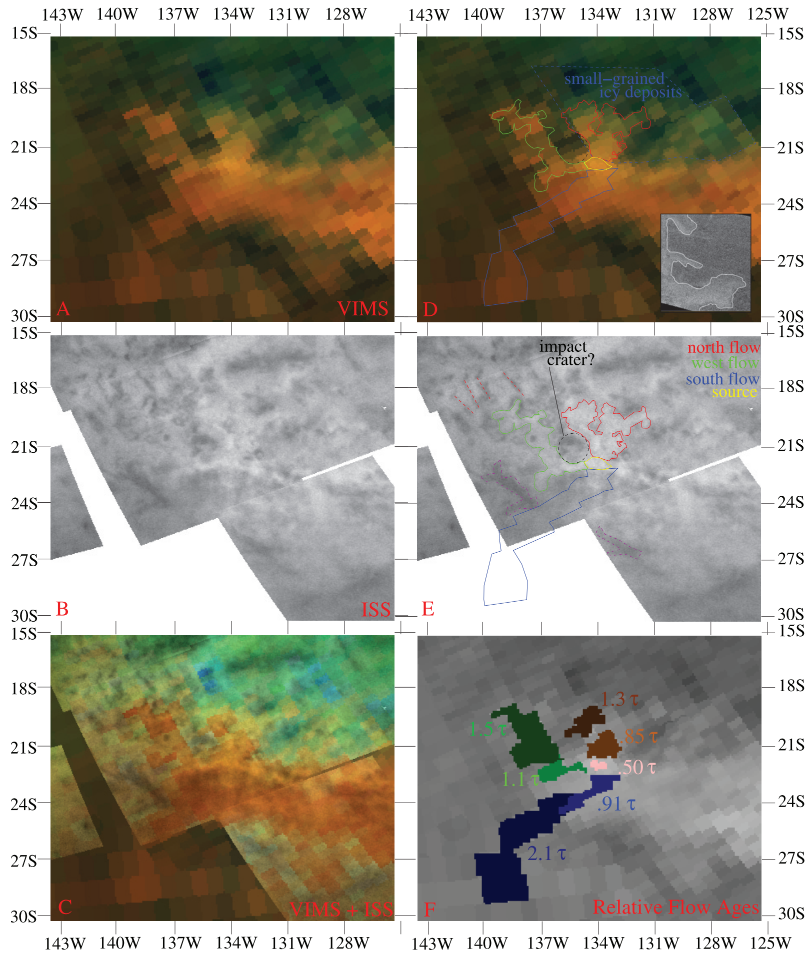

Figure 2. Cylindrical maps of western Tui Regio from (a) VIMS, (b) ISS, (c) a combination of VIMS and ISS that facilitates intercomparison, (d) annotated VIMS, and (e) ISS views, a Ta RADAR map of a different flow field at the same scale [*Lopes et al.*, 2005] (Figure 2d inset), and (f) the relative ages of individual flows. The VIMS mosaic was generated from observations obtained during the Ta Titan flyby on 2004 October 26 and the Tb Titan flyby on 2004 December 13. The viewing geometry (phase angle of 12°–14° for Ta and 16°–18° for Tb) and lighting conditions are similar enough from these two flybys to allow valid comparisons between the two. The lower-resolution data in the southwestern portion of the VIMS mosaic is from Ta and has a spatial resolution of ~40 km/pixel; the medium-resolution data in the remainder has a resolution of ~20 km/pixel, or ~2 pixels/degree. At 25°S, each degree corresponds to 45 km in latitude and 41 km in longitude. Colors are the same as in Figure 1 but the image has been contrast-enhanced. The ISS view is a mosaic generated from images taken during the Tb flyby and has a plate scale of 2 km/pixel. We estimate the absolute location error of the map to be 1–3 degrees. The annotated VIMS and ISS maps illustrate our interpretations as described in the text. The relative ages of lava flows in terms of the unknown weathering timescale τ are shown in Figure 2f, along with the areas to which the ages correspond, on top of a VIMS 5 micron map.

southeast trending dark linear marks that may be related to local tectonics, and sinuous dark features consistent with channels (dashed red lines, Figure 2e). Lack of these features within the 5-μm-bright area is consistent with 5-μm-bright surfaces being geologically young.

[17] The position corresponding to VIMS' central bright point is bright in the ISS view, and bright tendrils snake outward from this point toward the north, east, south, and west, though they become difficult to trace after ~100 km. The west flow, outlined based on the ISS view in green in Figure 2e, shows several lobate features. The area just west of the source is bright, and bifurcates ~100 km west of the source. The northern branch terminates in a clean clover of lobate, flow-like features at the extreme northwestern extent of the VIMS 5-μm-bright terrain. The clover's northeastern branch appears as a bright, digitate lobe extending into a circular dark region, resulting in a distinctive dark horseshoe.

[18] The southwestern tendril is outlined in Figure 2e based on its appearance in the VIMS view. This flow, which we interpret as older than the other tendrils based on the degree of maturation toward background, is not bright in the ISS image. However, the margin of the flow, as seen by VIMS, forms the southeastern margin of the northwest linear dark area outlined in purple in Figure 2e. Other possible bright flows extending south from the source in the ISS view form the northwest margin of the southeastern linear dark area outlined in purple. These examples of the apparent superposition of flow features onto underlying terrain support the hypothesis of recent cryovolcanic resurfacing.

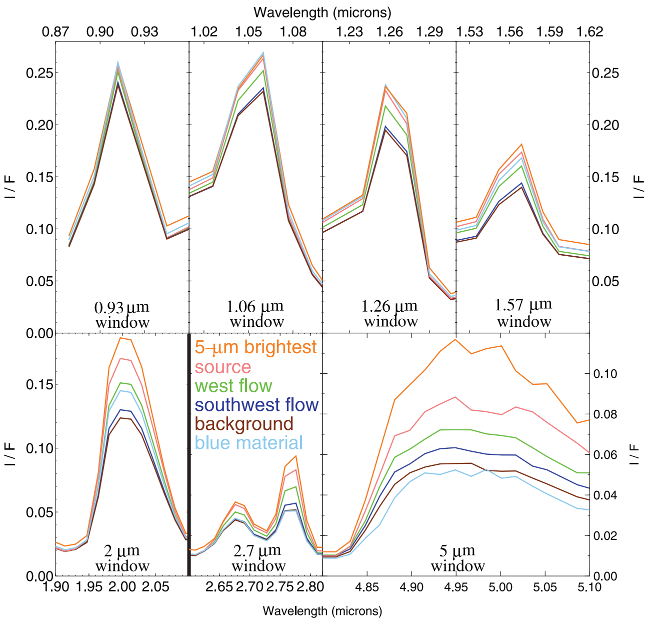

Figure 3. Spectra of the most 5-micron-bright area in Tui Regio (orange), the west Tui source (pink), the western flow feature (green), the southwestern flow feature (dark blue), the background area west of Tui Regio, and the blue airfall material northeast of the source (light blue). We show only those portions of the spectrum where Titan's atmosphere transmits sufficiently so as to allow measurement of surface features. The three flows plotted, along with the other ones that we measured, are well-modeled as linear combinations of the 5-micron-brightest material and background.

[19] Immediately northwest of the source is an obstacle constraining the surrounding flows. This location corresponds in the ISS data to a suspiciously circular feature that may be an impact crater, with a dark ring-lakebed and a bright central uplift. If this feature were an impact crater, then it would explain the right turn that the west flow takes ~100 km west of the source as it follows the local topography around an upraised impact crater rim. The northwesterly flow direction on the west side of this impact crater is similar to the orientation of the possible channels to the northwest, such that the west flow fits into the local gravitational gradient.

3. Analysis

[20] We are able to place our higher resolution VIMS data in context with lower resolution data covering greater area. Hence we observe the entire length of both the western and southwestern flows and estimate those lengths to be 330 km and 430 km respectively. The western flow has a total area of 1.1×10^4 km^2, and the southwestern flow covers 2.6×10^4 km^2. These are similar in extent to the lobate flows associated with Ganesa Macula as viewed by RADAR, which cover 2.37×10^4 km^2 (Lopes et al., submitted manuscript, 2006).

[21] We can place no observational constraints on the flow thickness. Neither are we able to make any measurement of the slope down which the flow runs or the total topography built up at the source. There might not be a volcanic edifice built up at the vent at all, if the eruption style is similar to terrestrial flood basalts. What the measured flow geometries signify is also not clear, as they are not necessarily the result of a single continuous eruptive event. Total flow lengths may be the result of multiple eruptive events in which younger lava flows through preexisting channels and tubes or underneath old flows, remaining insulated and molten to great distances. Therefore we don't know how many single eruptive events took place to create the observed flow features.

[22] We can estimate the relative ages of each flow based on their spectra, which are shown in Figure 3. The brightest nearby pixel at 5 µm is a low-resolution 40 km × 40 km box in eastern Tui Regio. We assume this spectrum to be that of the extruded, 5-µm-bright material. We have modeled the source and flow spectra as a simple mixture of this 5-µm-brightest pixel and the background spectrum to the west of Tui Regio.

[23] We assume that the unknown maturation mechanism that converts 5-µm-bright material to background does so in the exponentially decreasing manner $f_{5mb} = e^{-\tau}$, where f_{5mb} is the fraction of 5-µm-bright material and τ is the time required to mature $1 - e^{-1}$ (~65%) of the 5-µm-bright material into background. We then measure f_{5mb} for the average spectrum of each area designated in Figure 3 using a least-squares fit, and calculate the relative elapsed time since emplacement of each flow in terms of τ. We display the results in Figure 2f.

[24] The measured values function as upper age limits in the case where VIMS is unable to resolve individual flow lobes, as in the far northwestern part of the west flow. The ages for the north flow are suspect due to the overlying blue contaminant.

[25] The picture that emerges from the age analysis is that of a recently extinct cryovolcano that reached its maximum eruption rate between 1τ and 2τ ago, and whose eruptions continued, though smaller, after that time until the last event 0.5τ ago.

[26] Composition of the cryolava is difficult to ascertain from spectra in the Titan regime where observations of the surface are only possible in 8 narrow windows. Unambiguous attribution is only possible when narrow absorption features can be identified. The realization that the 5-µm-bright areas represent volcanic extrusions helps to constrain the composition. A water ice-ammonia eutectic mixture was expected for the composition of Titanian cryolavas prior to Cassini's arrival [*Lorenz*, 1996; *Kargel et al.*, 1991]. Accurate compensation for atmospheric radiative transfer will facilitate identification of the flow material. Ammonium sulfate has been suggested as a candidate composition based on theoretical grounds (A. D. Fortes et al., Modeling of the possible explosive eruption of aqueous ammonium sulfate on Titan, submitted to *Icarus*, 2006).

[27] The blue airfall deposit downwind of the source is likely somewhat-dirty small-grained ice, of a sort. Water ice has a strong absorption centered at 3 µm which explains the blue slope and dark 5 µm reflectivity, but other light molecule solids (such as ammonia and methane) have similar spectral properties. We have not yet been able to identify the composition of the ice unambiguously. Small-grained materials have reflectivities up to ~10% higher than

larger-grained materials [*Nelson et al.*, 2000], which accounts for the blue material being brighter than Xanadu to the northeast.

4. Implications

[28] The character of the west Tui flow field is different from Tortola Facula, the surface feature on Titan previously identified by VIMS and inferred to be volcanic [*Sotin et al.*, 2005]. The spectrum of Tortola Facula differs from western Tui, as does the morphology. However, the size scale of the two features may make them not directly comparable – Tortola would fit inside a single VIMS pixel in Figure 2. The difference could be the result of lava composition or eruption style.

[29] The optical maturation process that transforms 5-μm-bright material to background could be mechanical (aeolian, fluvial, or tectonic), depositional, or chemical in nature. The removal of the outer rind of a chemically uniform lava flow by a mechanical mechanism would reveal fresh material beneath, and thus not change the spectral signature. Chemical weathering could take place via interactions between the lava flow and the atmosphere or rainfall. Channels carved presumably by liquid methane were seen near the Huygens landing site, and methane moisture was detected within Titan's surface by the probe after landing, providing the potential for chemical interaction with the surface minerals [*Tomasko et al.*, 2005; *Niemann et al.*, 2005]. Both water and ammonia are functionally immiscible by liquid methane under Titanian conditions [*Lorenz and Lunine*, 1996], though, meaning that if the erupted material is an ammonia-water eutectic then chemical weathering might only work on its contaminants. The maturation is somewhat consistent with haze deposition, as what we have identified to be the "background" spectral unit spans the globe between 25°S and 55°S. The spectra of Titan's equatorial regions is different, though, so any deposition mechanism isn't globally uniform.

[30] Knowledge of the precise mechanism might allow an evaluation of the weathering timescale τ and place an absolute date on the eruptive activity in west Tui Regio. Combining absolute ages with global mapping of the extent of 5-μm-bright terrain and independent determinations of flow thickness would then directly measure the rate of eruption of cryovolcanic material and thus determine the resurfacing rate and heat flow delivered to Titan's surface by extrusive volcanism.

[31] Both east Tui Regio and "Hotei Regio" have higher 5-μm reflectivities than the west Tui source region, and thus may have younger cryovolcanic flows. Both VIMS and ISS coverage of those areas has been at resolutions too low to resolve individual flow features. Eastern Tui Regio and "Hotei Regio" are good candidates for present-day volcanic activity.

[32] **Acknowledgment.** This work was funded by the NASA/ESA Cassini project.

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